U.S. DESIGN GUIDANCE FOR CLT FLOOR SYSTEMS WITH RESIDENTIAL AND OFFICE OCCUPANCY LOADS

Samantha J. Leonard | PE sleonard@rdh.com
Nathan Brown ncb5048@psu.edu
Corey Gracie-Griffin corey@psu.edu

Special thanks to: Ryan Solnosky, Kevin Parfitt, and Ali Memari
Partial funding by: AIA Upjohn Research Initiative Grant

June 11, 2024

Photo: Josh Partee

PennState College of Engineering | ARCHITECTURAL ENGINEERING

About PSU Architectural Engineering

FOUNDED IN 1910

The primary mission of the department is to advance the built environment through the development of world-class architectural engineers and research.

Making Buildings Better™

About RDH Building Science

FOUNDED IN 1997

RDH is a building science consulting and engineering firm delivering climate-responsive solutions across North America. Our network of building science professionals spans 11 offices.

About RDH Building Science

Our Services and Capabilities

Building Enclosure

- Design Consulting
- Construction Administration
- Construction Management
- Building Commissioning

Façade Engineering

- System Development
- Advanced Analytics
- Structural Engineering

Energy & Climate

- Passive House
- Energy Modeling
- Carbon Strategy

Asset Management

- Asset Planning
- Assessments
- Forensics
- Litigation and Claims

Research, Policy & Training

- Product Development
- Policy Development
- Lab Testing & Monitoring
- Industry Training + Publications

Learning Objectives

- Discover how parametric modelling generates data for the early-stage design of mass timber floor structures.
- Understand how design decisions related to floor structure type and layout, bay size, and prescriptive fire design strategy affect design goals.
- Learn how mass timber floor systems perform for embodied carbon, structural design, and acoustic insulation.
- Apply early-stage design guidance to mass timber floor structures.

Presentation Overview

Introduction

Research Questions

Methods

Results

Conclusions

Introduction

Mass timber in construction, pros and cons, existing tools

What is Mass Timber?

"Large" engineered wood products built up from smaller elements

[Photos from: StructureCraft]

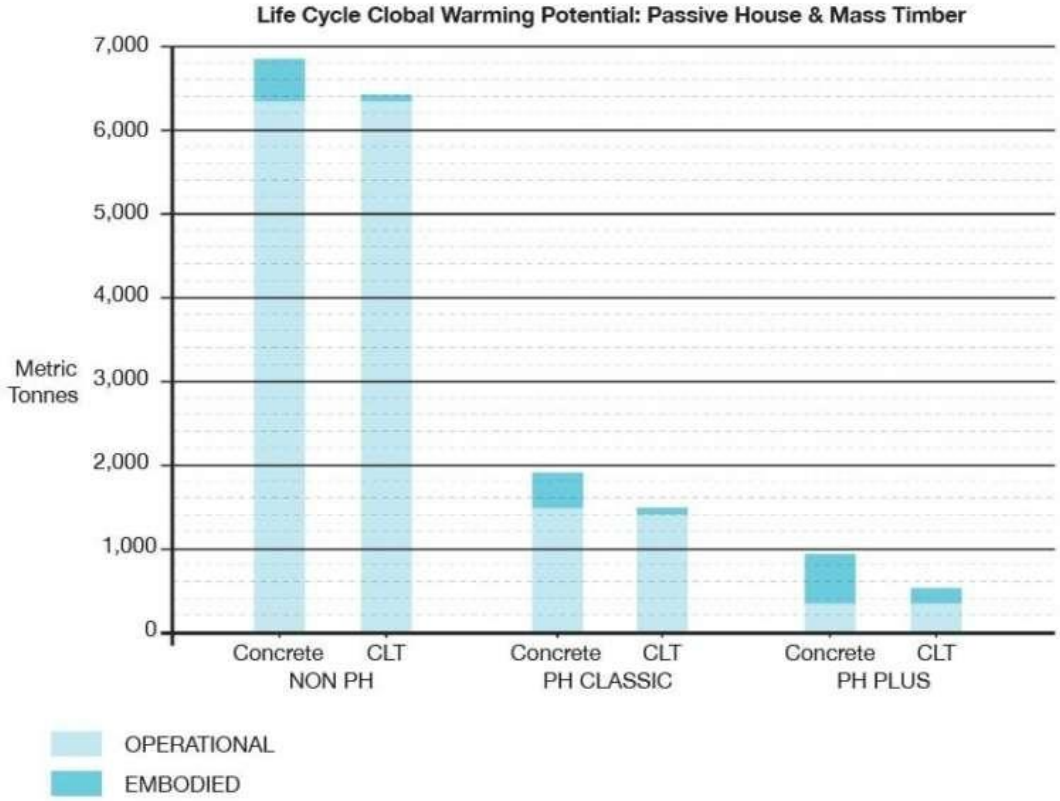
Mass Timber Structural Elements

Cross Laminated Timber (CLT)

Glue-laminated Timber (Glulam)

[Photos from: Engineering News Record and StructureCraft]

Mass timber Can Reduce Embodied Carbon (EC)



[Figure from https://passivehouseaccelerator.com/articles/addressing-embodied-energy-with-mass-timber]

Advantages

- Lightweight
- Prefabrication
- Reduced schedules
- Reduced site work
- Reduced environmental impact
- Inherent fire protection
- Appearance

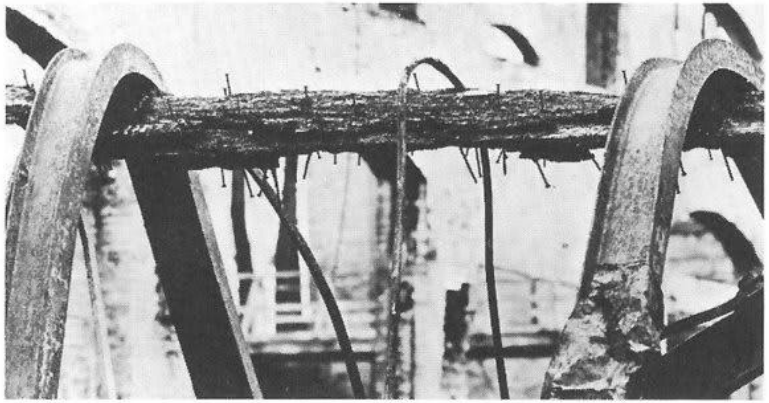


Fig. 20-4. After fire scene. Shows a wood beam supporting twisted steel I-beams. (Forest Products Laboratory)

[Photos from: Forest Products Laboratory]

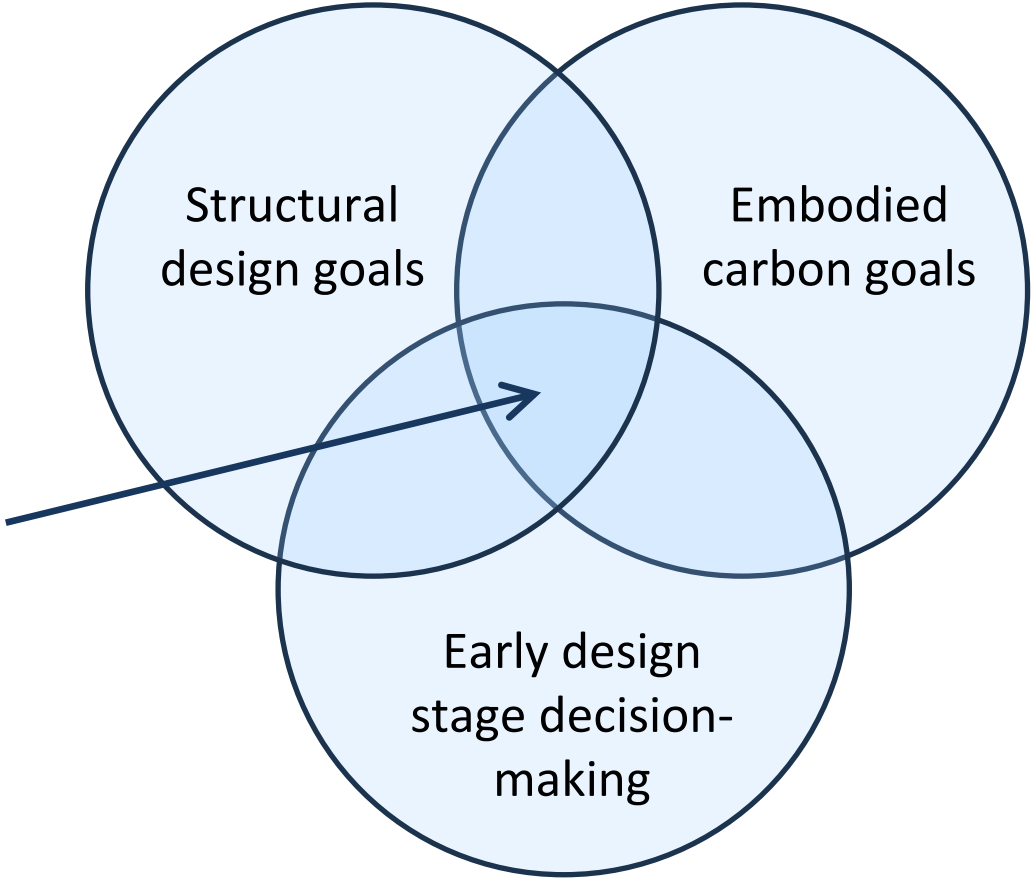
Disadvantages

- Walking-induced vibrations
- Poor acoustic insulation
- Not well suited for large spans, seismic, sensitive needs like labs
- Limited North America manufacturers
- Learning curve
- Construction moisture protection
- **Limited Design Guidance**

[Figure from: WoodWorks]

Research Questions

Limited guidance at intersection of EC and structural design



For mass timber and hybrid mass timber floors…

What are the trends in EC and structural design objectives?

How do they compare to baseline steel-reinforced concrete floor systems?

How do prescriptive fire design options affect EC and floor system depth?

What are the impacts of designing for improved acoustic insulation (STC/IIC) beyond code minimum for floors?

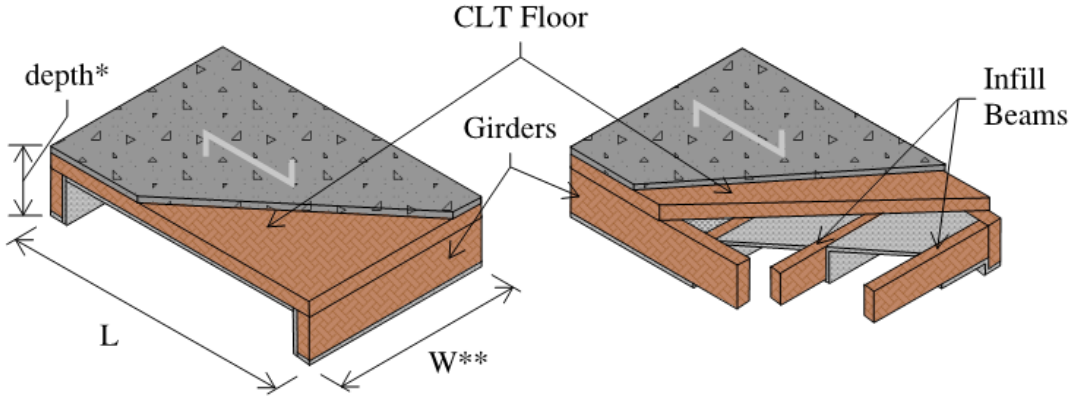
Methodology

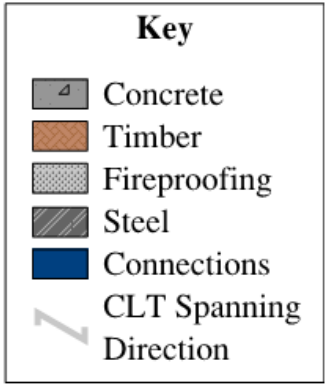
Floor systems, variables, limits states, and outputs

All-timber systems

TG
Timber Floor with Timber Girders

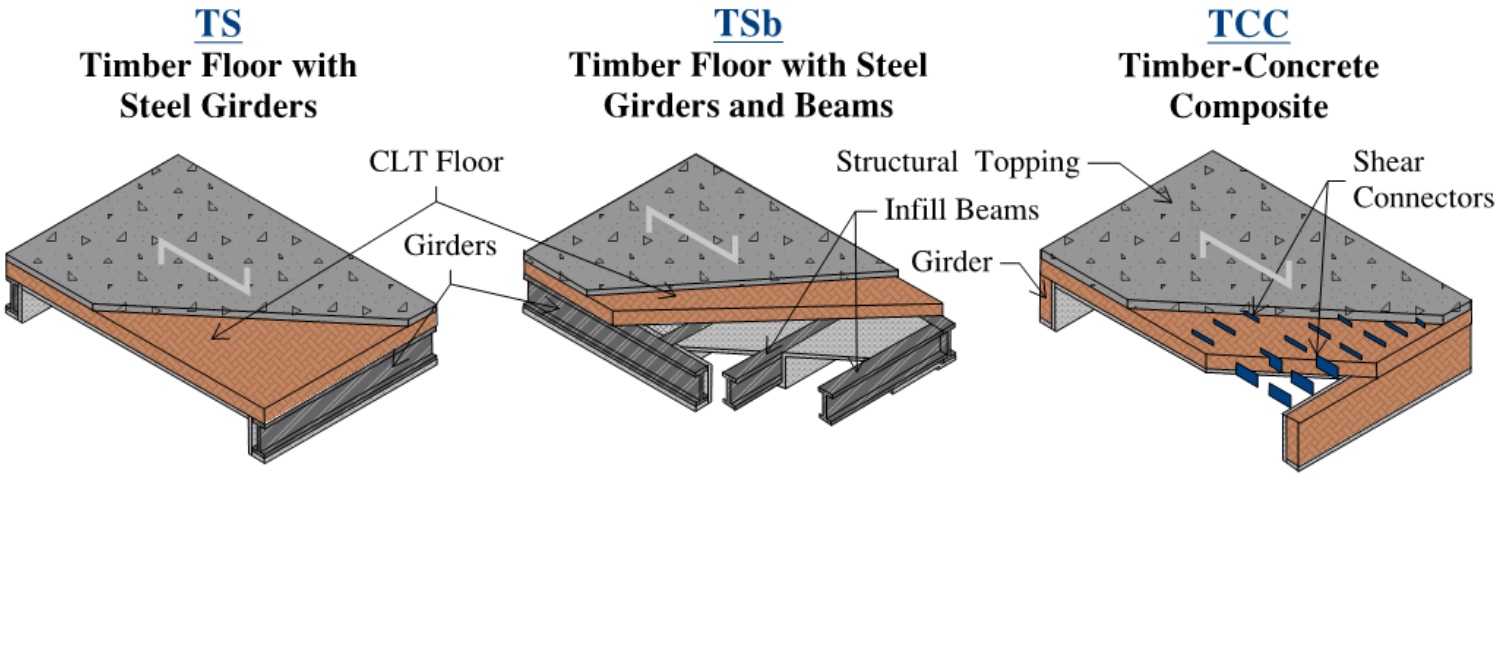
TGb
Timber Floor with Timber Girders and Beams





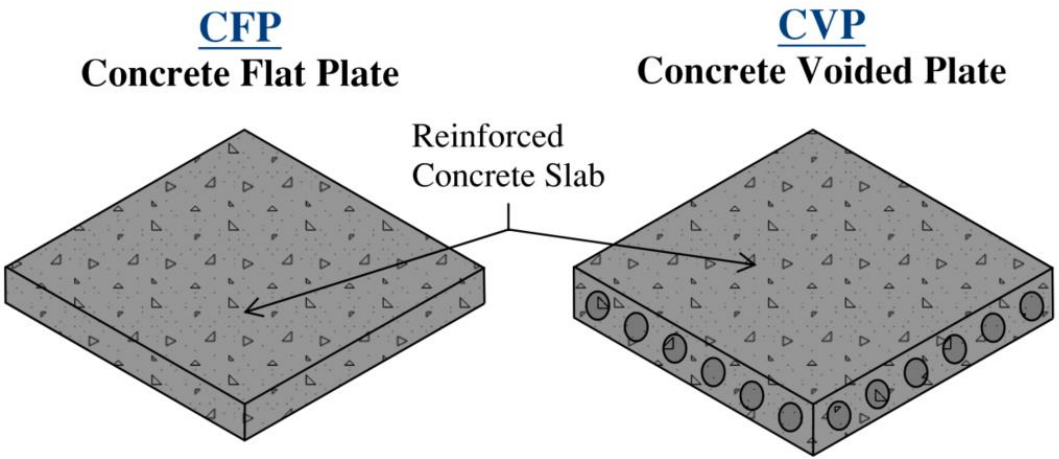
*depth = topping + CLT panel + max framing depth + fireproofing
**Bay width assigned to girder's spanning direction

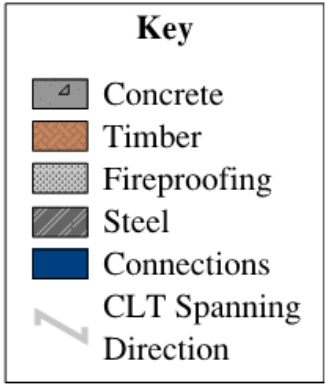
Hybrid-timber systems



*depth = topping + CLT panel + max framing depth + fireproofing
**Bay width assigned to girder's spanning direction

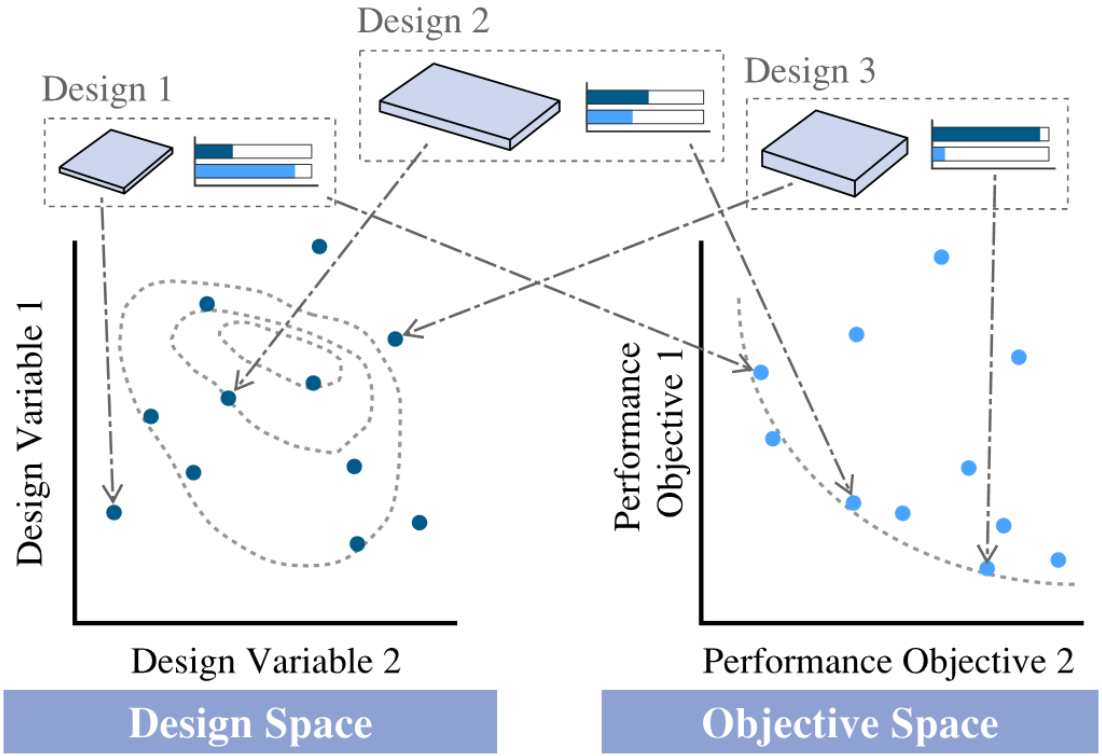
Baseline Concrete Floors





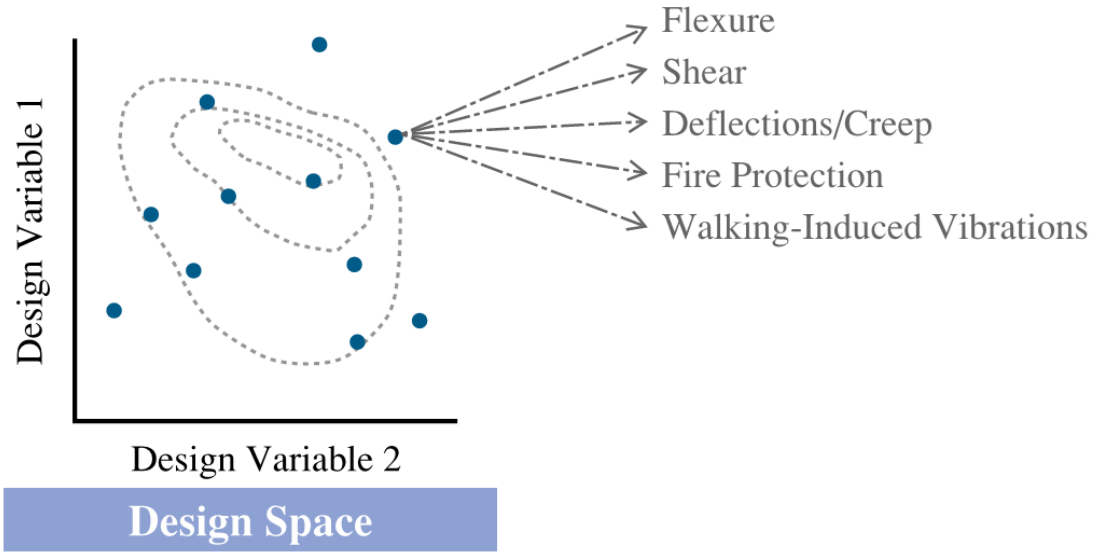
*depth = topping + CLT panel + max framing depth + fireproofing
**Bay width assigned to girder's spanning direction

Design space exploration (DSE) uses parametric modeling to discover trends



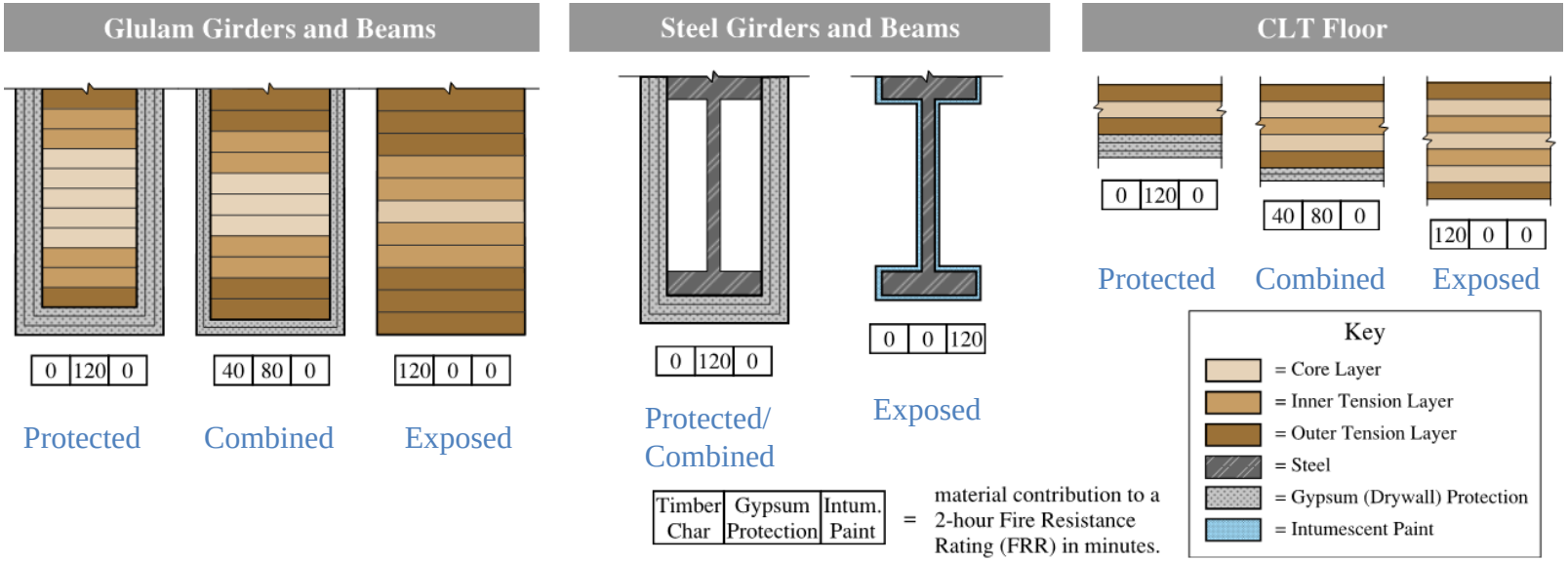
[Figure adapted from Brown, 2020]

Each design is automatically sized for the applicable limit states

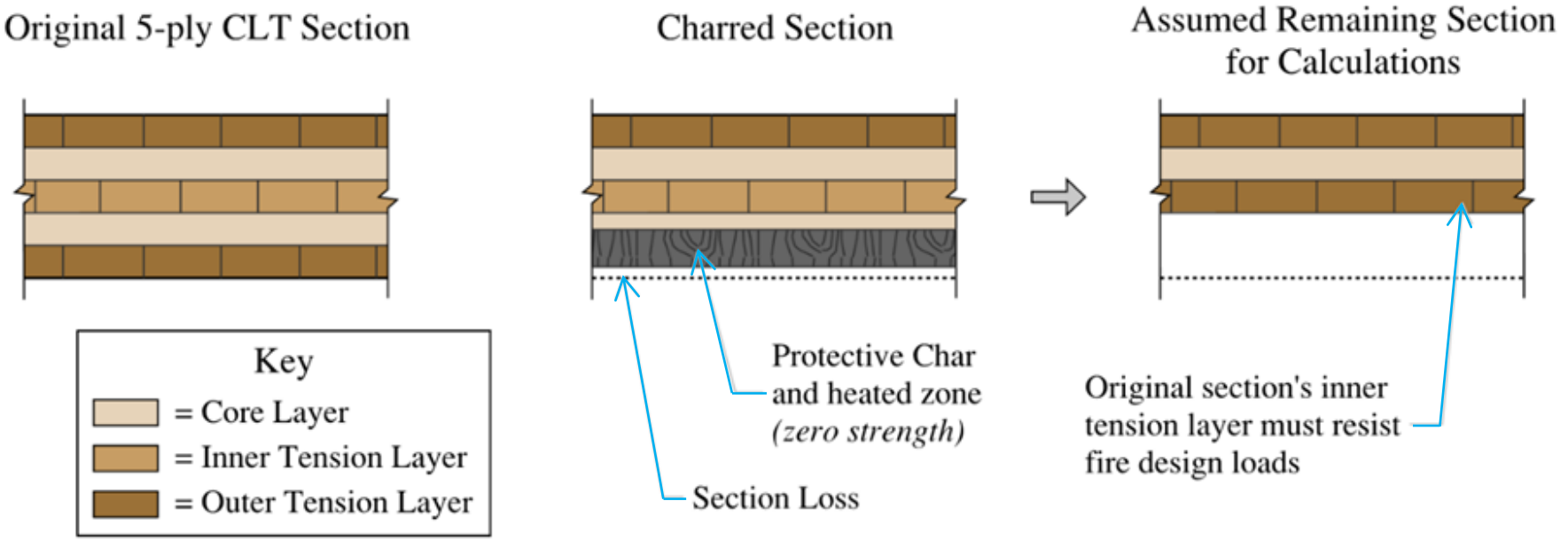


[Figure adapted from Brown, 2020]

Fire design strategies modeled



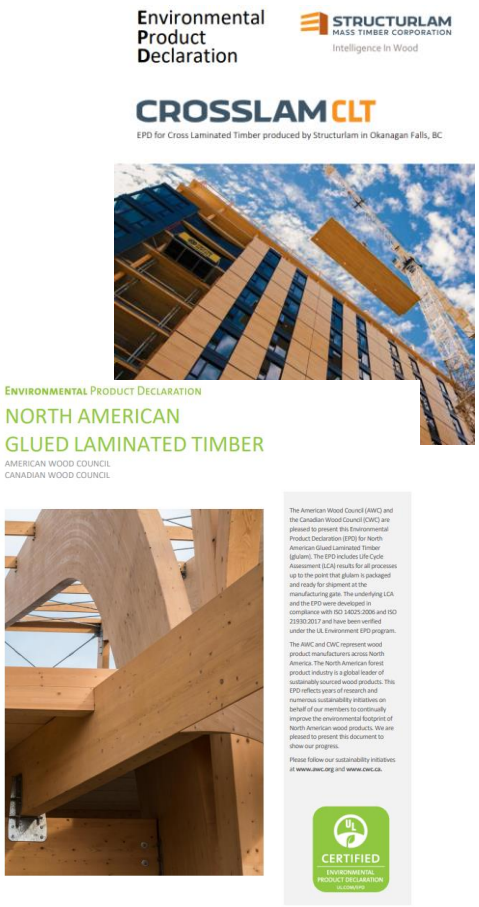
Char design option for fire



Timber carbon storage assumptions vary

0% Carbon storage assumed

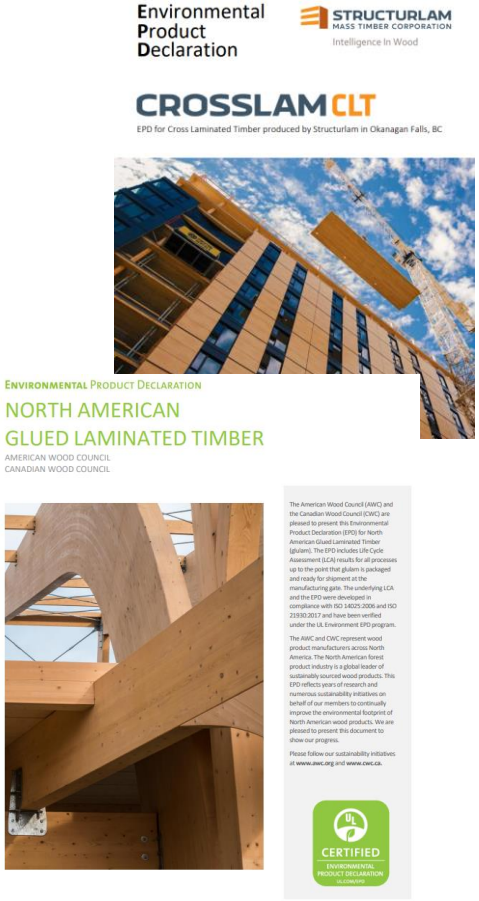
Material Information		Industry-Focused EC Material Coefficients		Academic-Focused EC Material Coefficients	
Material	*Material Assumptions*	*EC Value*	*Data Source*	*EC Value*	*Data Source*
Cross Laminated Timber (CLT)	Carbon storage is neglected	0.27	Average of five North American CLT EPD's following ISO 21930:2017 A and B [31]–[35]	0.437	ICE V3.0 [28] – Timber, CLT
	Carbon storage is included[1]	-1.19		-1.20	
Glued Laminated Timber (Glulam)	Carbon storage is neglected	0.25	American Wood Council EPD for North American Glued Laminated Timber [36]	0.512	ICE V3.0 – Timber, Glulam
	Carbon storage is included[1]	-1.04		-0.90	



Timber carbon storage assumptions vary

100% Carbon storage assumed

Material Information		Industry-Focused EC Material Coefficients		Academic-Focused EC Material Coefficients	
Material	*Material Assumptions*	*EC Value*	*Data Source*	*EC Value*	*Data Source*
Cross Laminated Timber (CLT)	Carbon storage is neglected	0.27	Average of five North American CLT EPD's following ISO 21930:2017 A and B [31]–[35]	0.437	ICE V3.0 [28] – Timber, CLT
	Carbon storage is included[1]	-1.19		-1.20	
Glued Laminated Timber (Glulam)	Carbon storage is neglected	0.25	American Wood Council EPD for North American Glued Laminated Timber [36]	0.512	ICE V3.0 – Timber, Glulam
	Carbon storage is included[1]	-1.04		-0.90	



Limitations

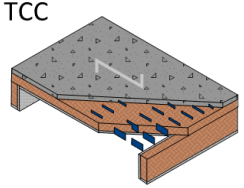
- Focus on EC, not operational carbon
- Connections not included
- Focus on gravity loads
- Modeled a continuous single bay (appropriate for 3 bays minimum)
- Rough estimates for columns
- Residential Loads
- Mid-range representative wood species/grade
- Acoustic assembly self-weight not incorporated into parametric model
- Fire design prescriptive only
- Walking-induced vibrations simplified

Results

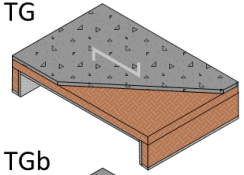
Structural & EC, Concrete Comparisons, Fire Design, Acoustics

What are the trends in EC and structural design objectives for a variety of mass timber and hybrid mass timber floor systems?

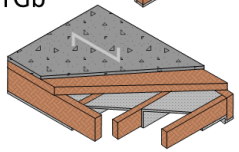
TCC



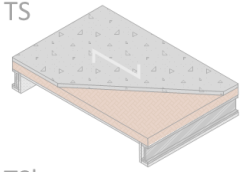
TG



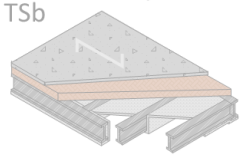
TGb



TS

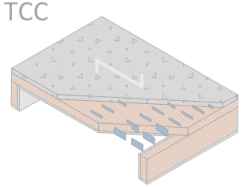


TSb

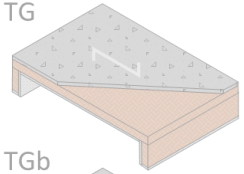


Timber-framed systems

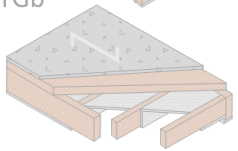
TCC



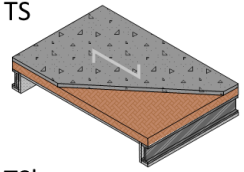
TG



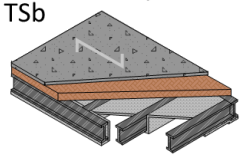
TGb



TS



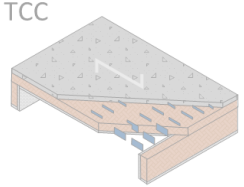
TSb



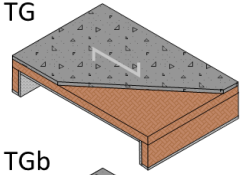
Timber-framed systems

Steel-framed systems

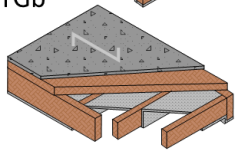
TCC



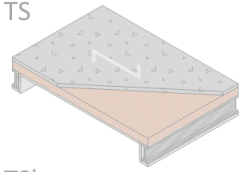
TG



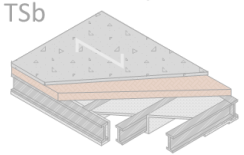
TGb



TS



TSb

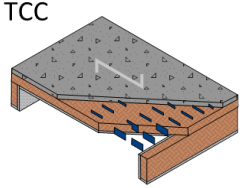


Timber-framed systems

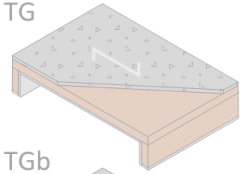
Steel-framed systems

All-timber systems

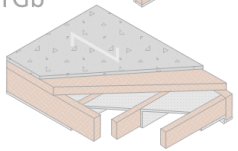
TCC



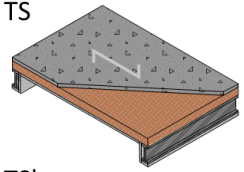
TG



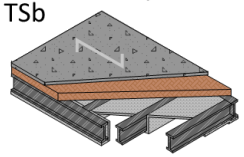
TGb



TS



TSb



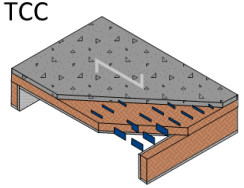
Timber-framed systems

Steel-framed systems

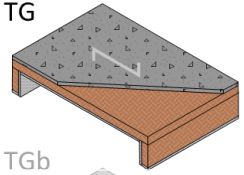
All-timber systems

Hybrid systems

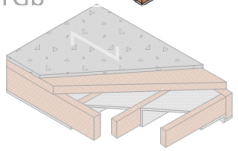
TCC



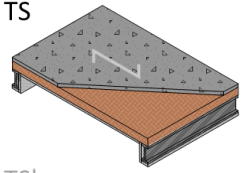
TG



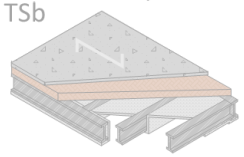
TGb



TS



TSb



Timber-framed systems

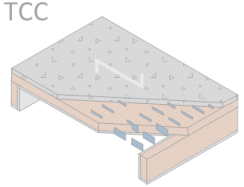
Steel-framed systems

All-timber systems

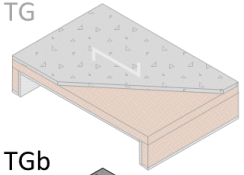
Hybrid systems

Systems without infill beams

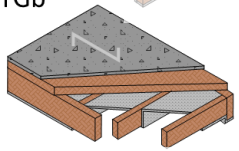
TCC



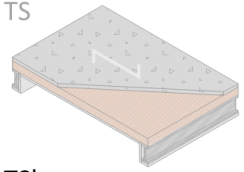
TG



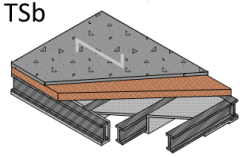
TGb



TS



TSb



Timber-framed systems

Steel-framed systems

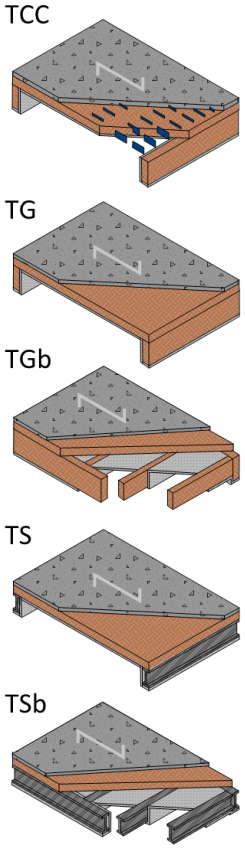
All-timber systems

Hybrid systems

Systems without infill beams

Systems with infill beams

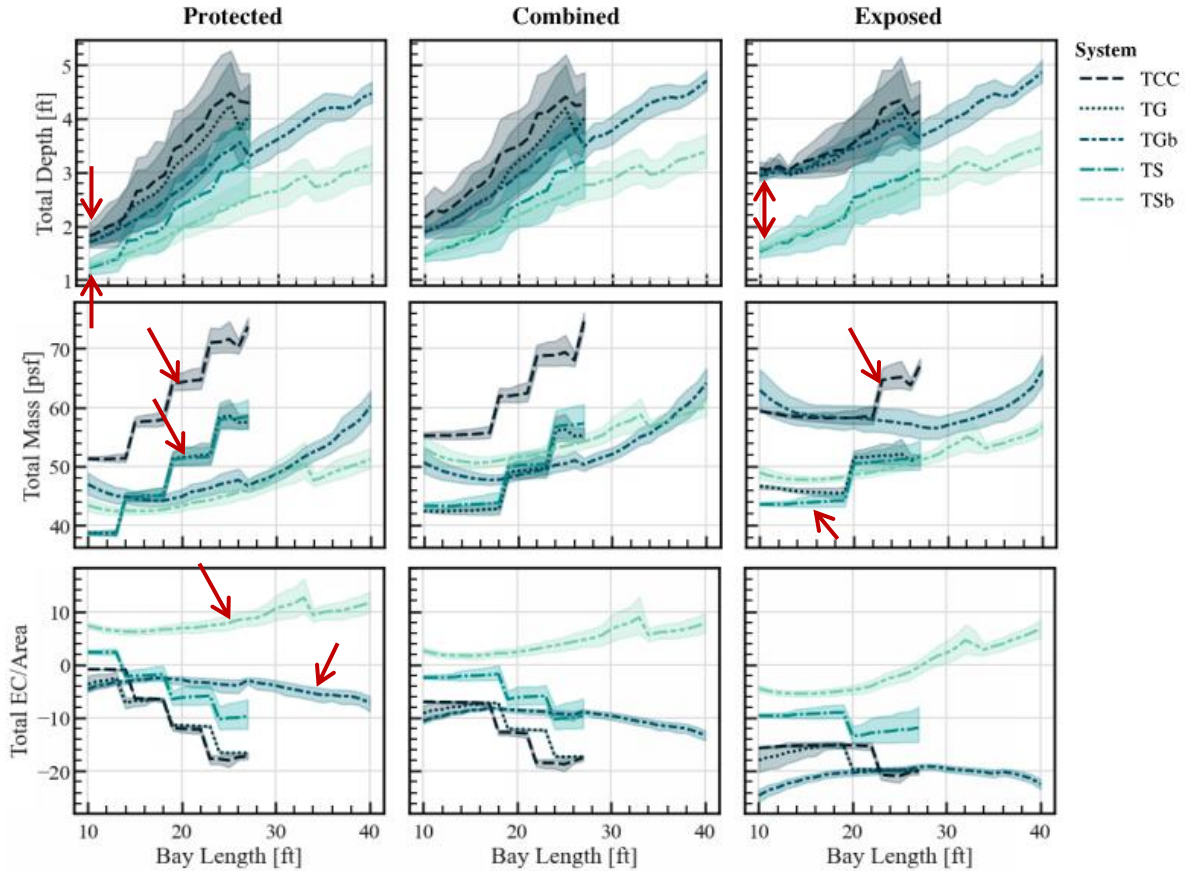
Floor system trends vary by metric and variable combinations



Depth

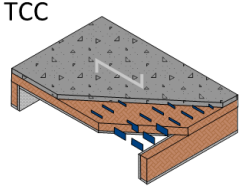
Mass

EC
(75% Carbon Storage)

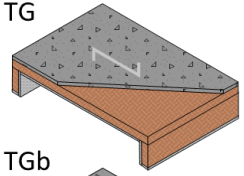


Floor system trends vary by metric and variable combinations

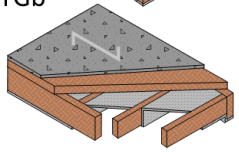
TCC



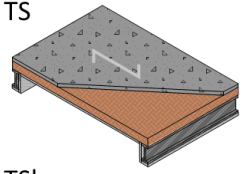
TG



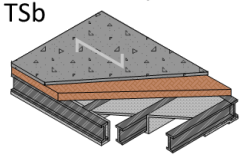
TGb



TS



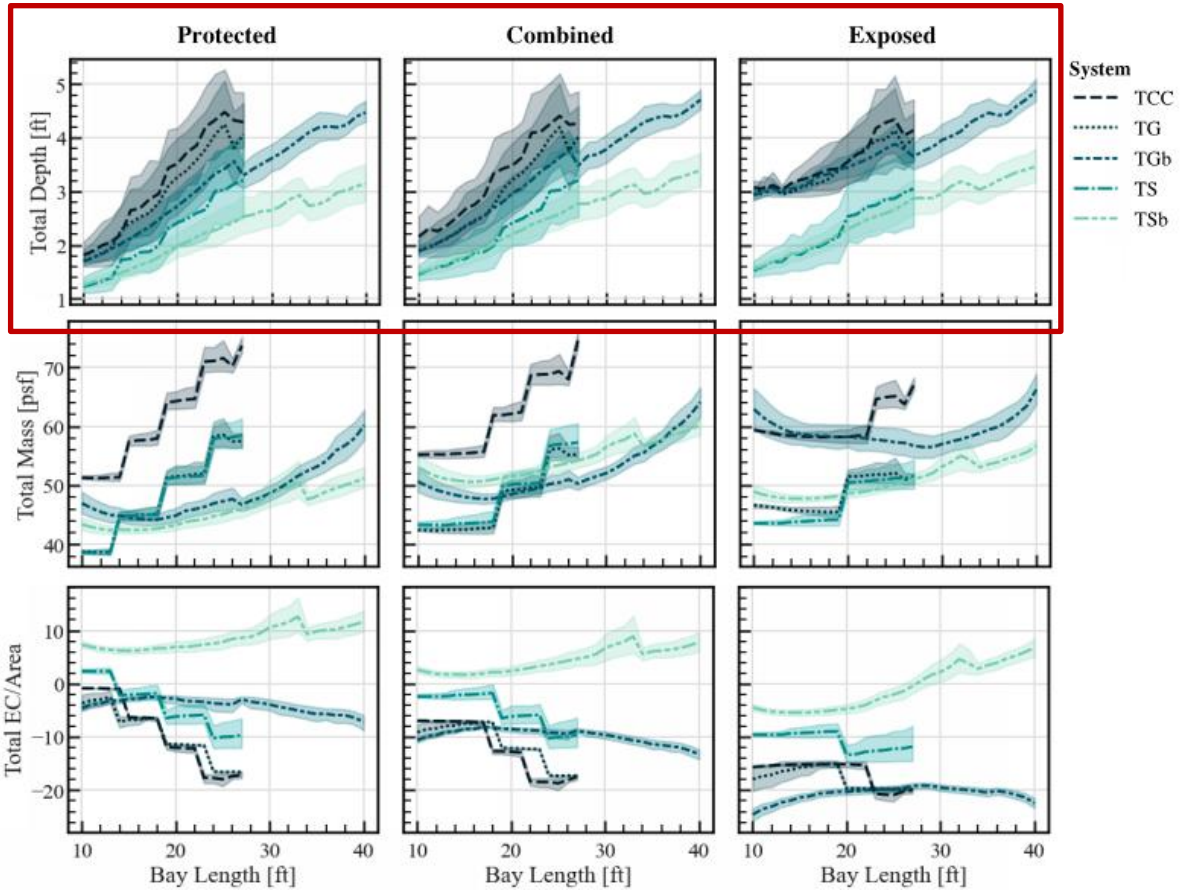
TSb



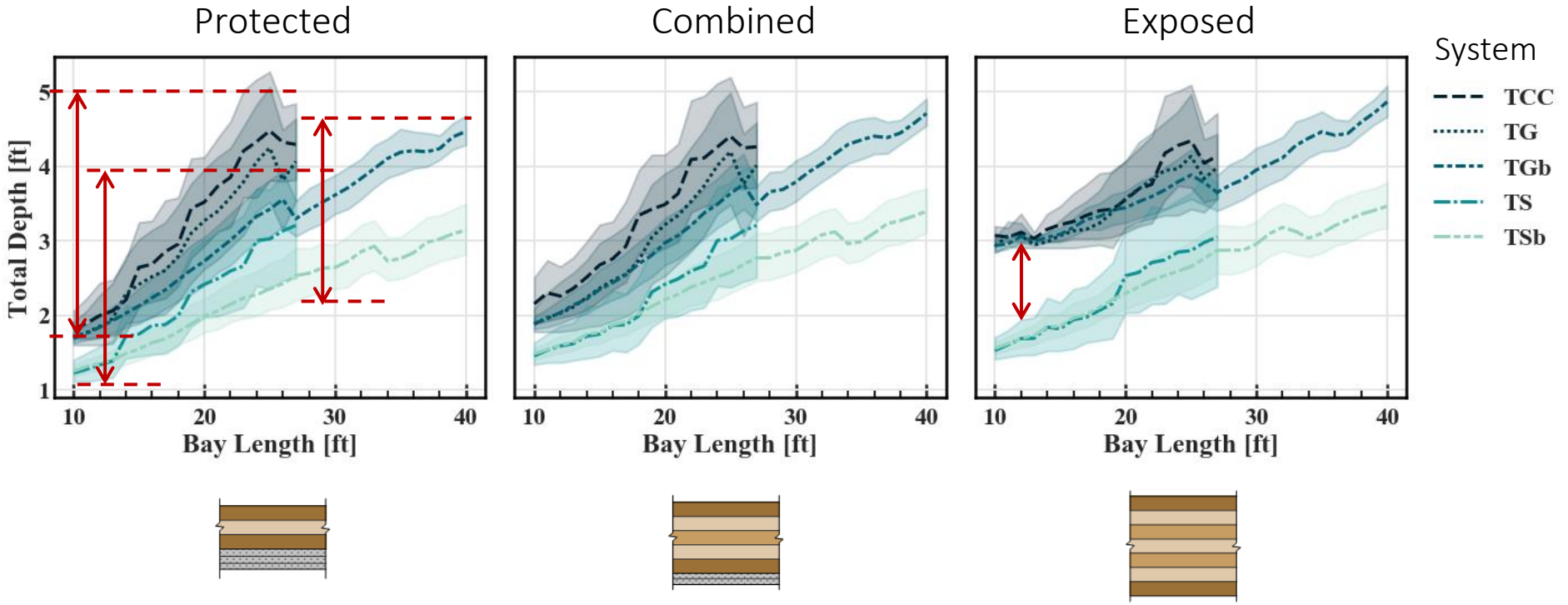
Depth

Mass

EC
(75% Carbon Storage)

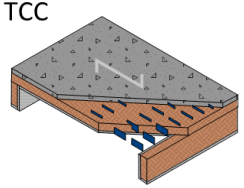


Timber-framed designs are ~1-2’deeper than steel-hybrid

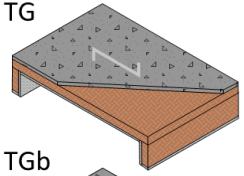


Differences in systems depend on many variables

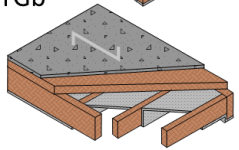
TCC



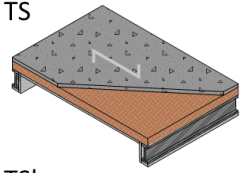
TG



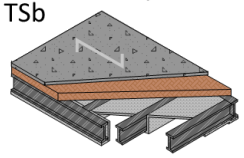
TGb



TS



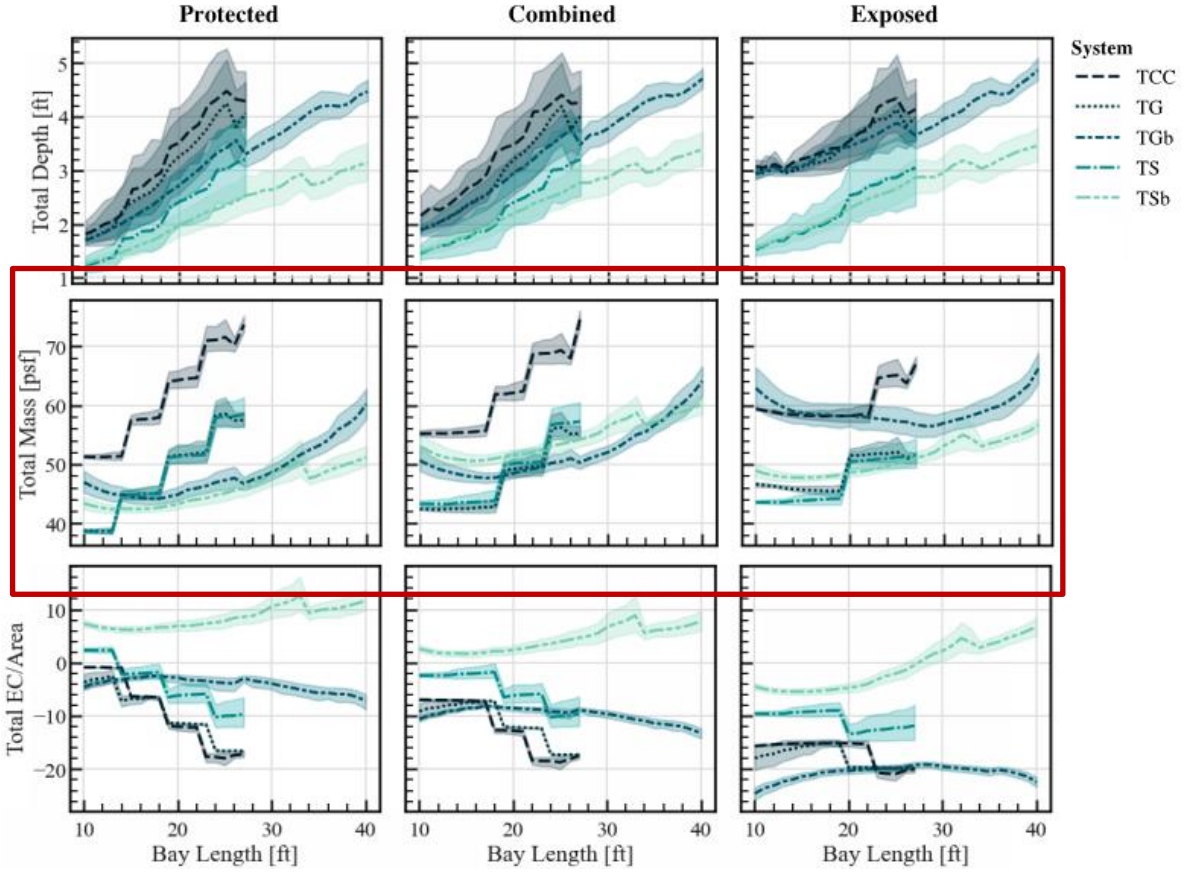
TSb



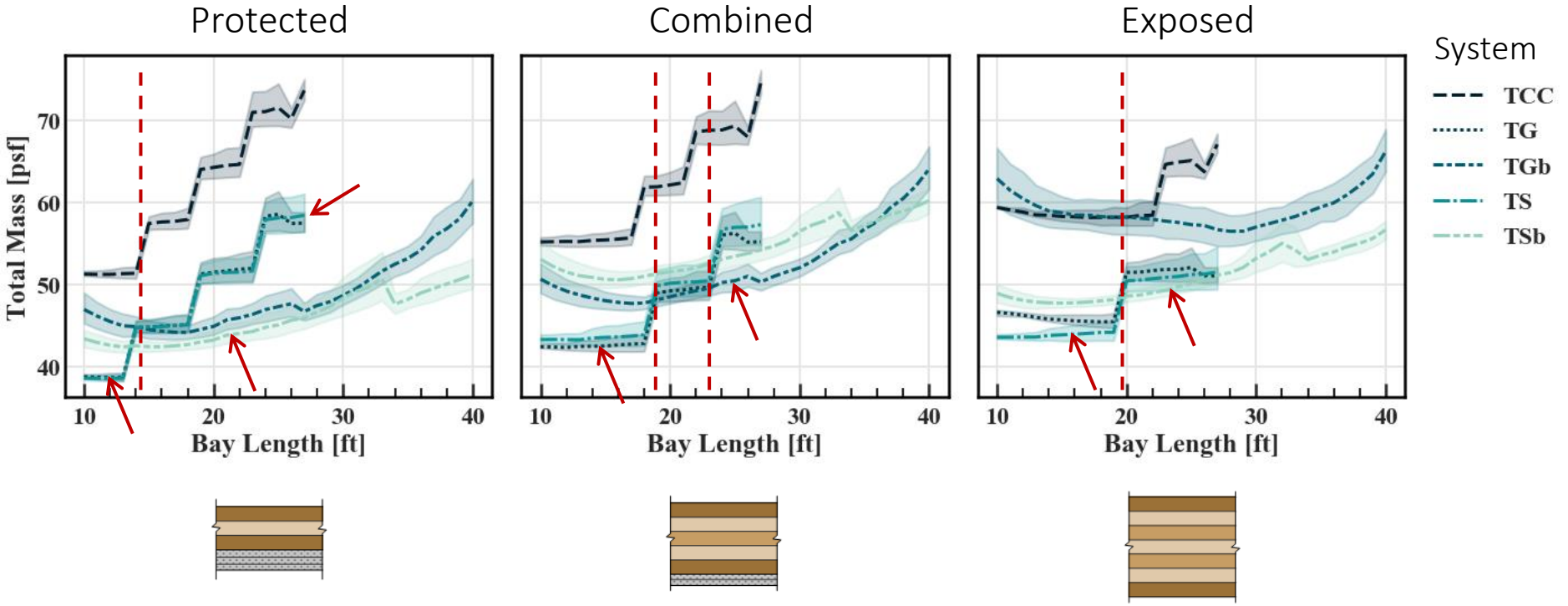
Depth

Mass

EC
(75% Carbon Storage)

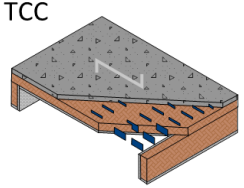


At ↓spans, TG/TS are lightest; at ↑spans, TGb/TSb are lightest

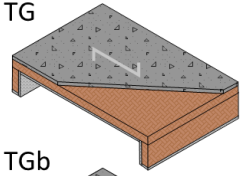


Differences in systems depend on many variables

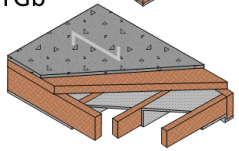
TCC



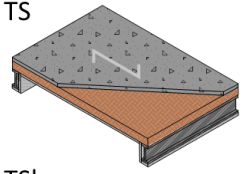
TG



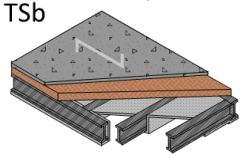
TGb



TS



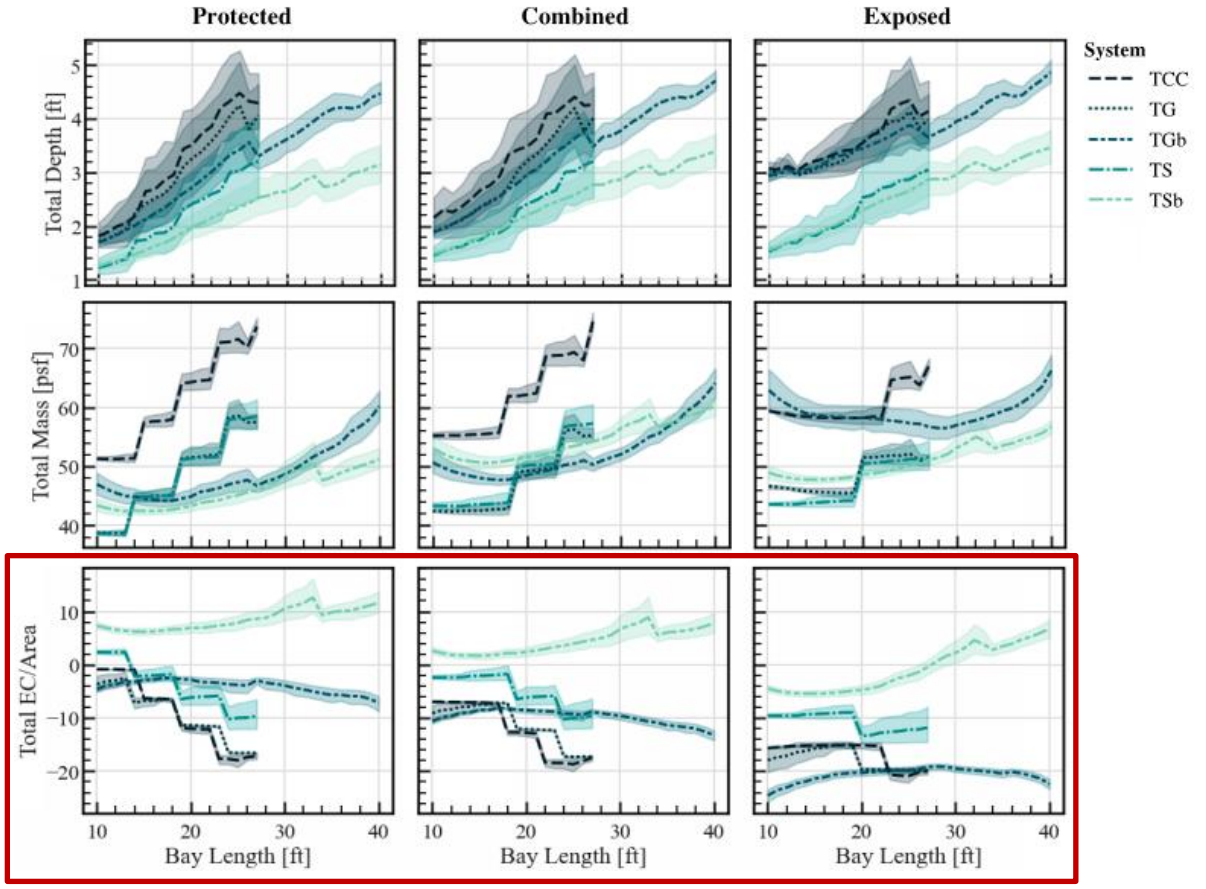
TSb



Depth

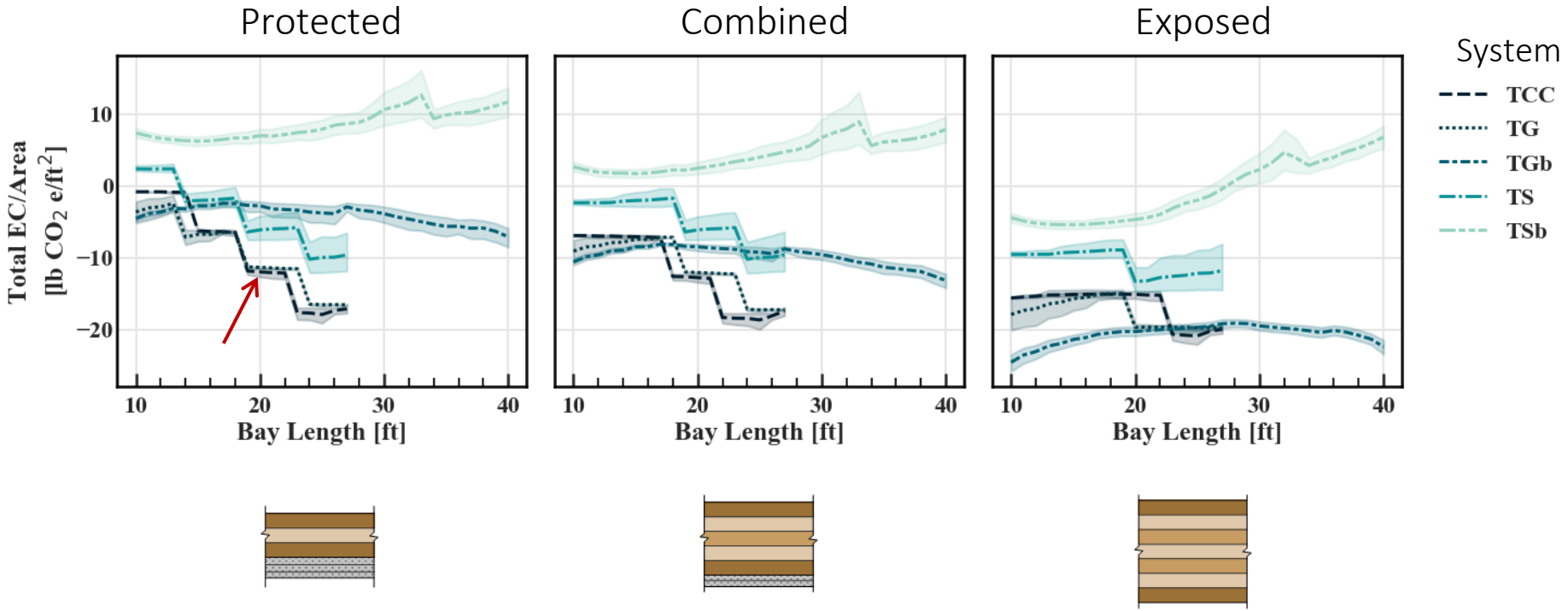
Mass

EC
(75% Carbon Storage)



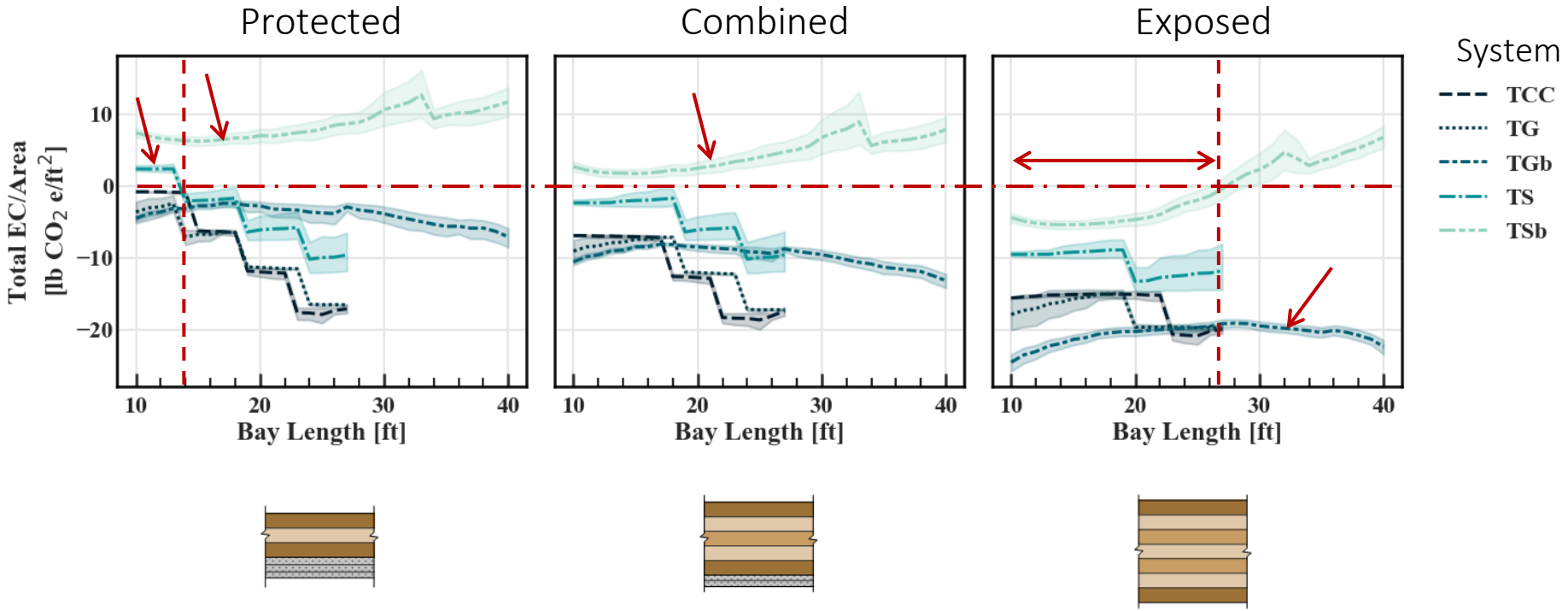
Protected deigns have lowest EC in systems without infills

(75% Carbon Storage)

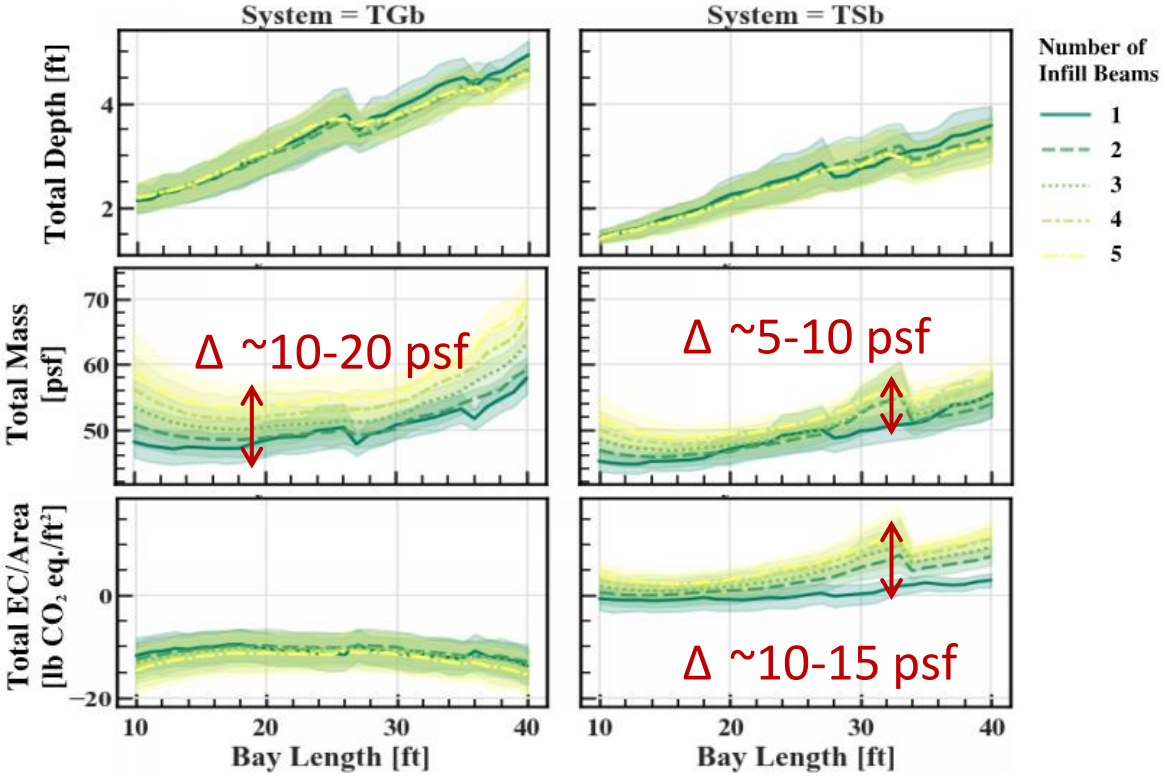


Exposed designs have lowest EC in TGb system

(75% Carbon Storage)

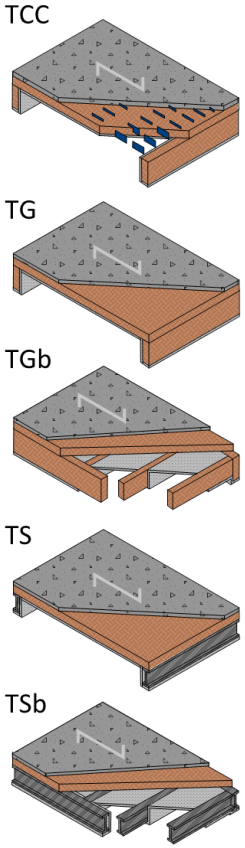


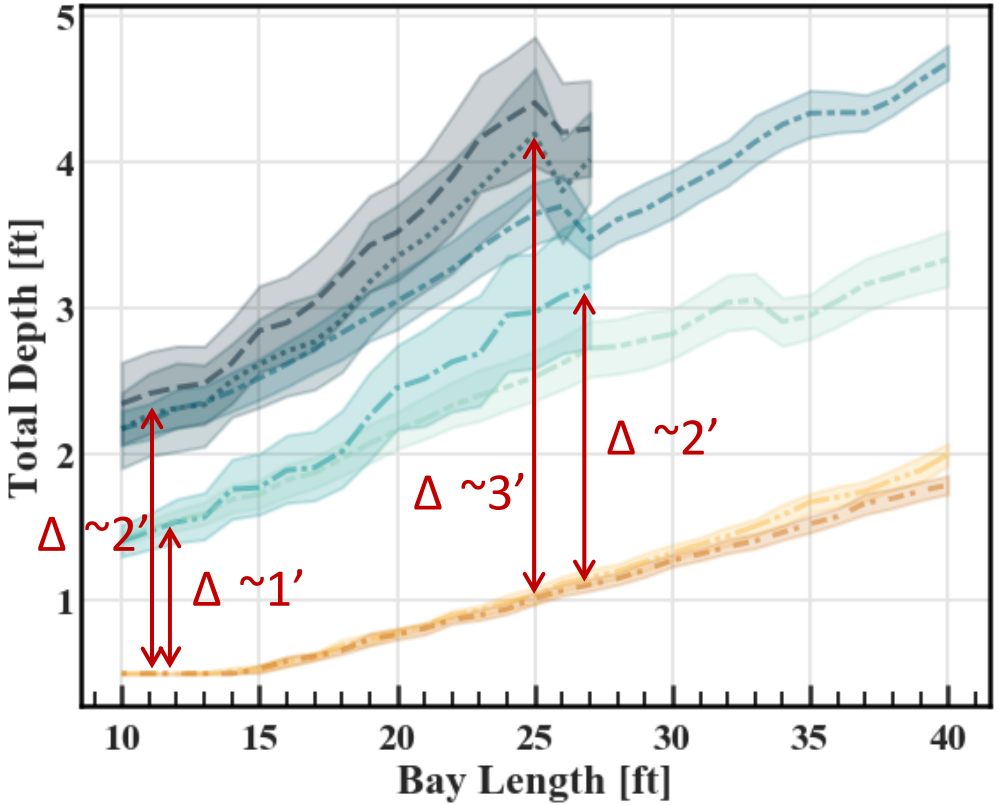
A single infill is typically preferred for TSb and TGb systems



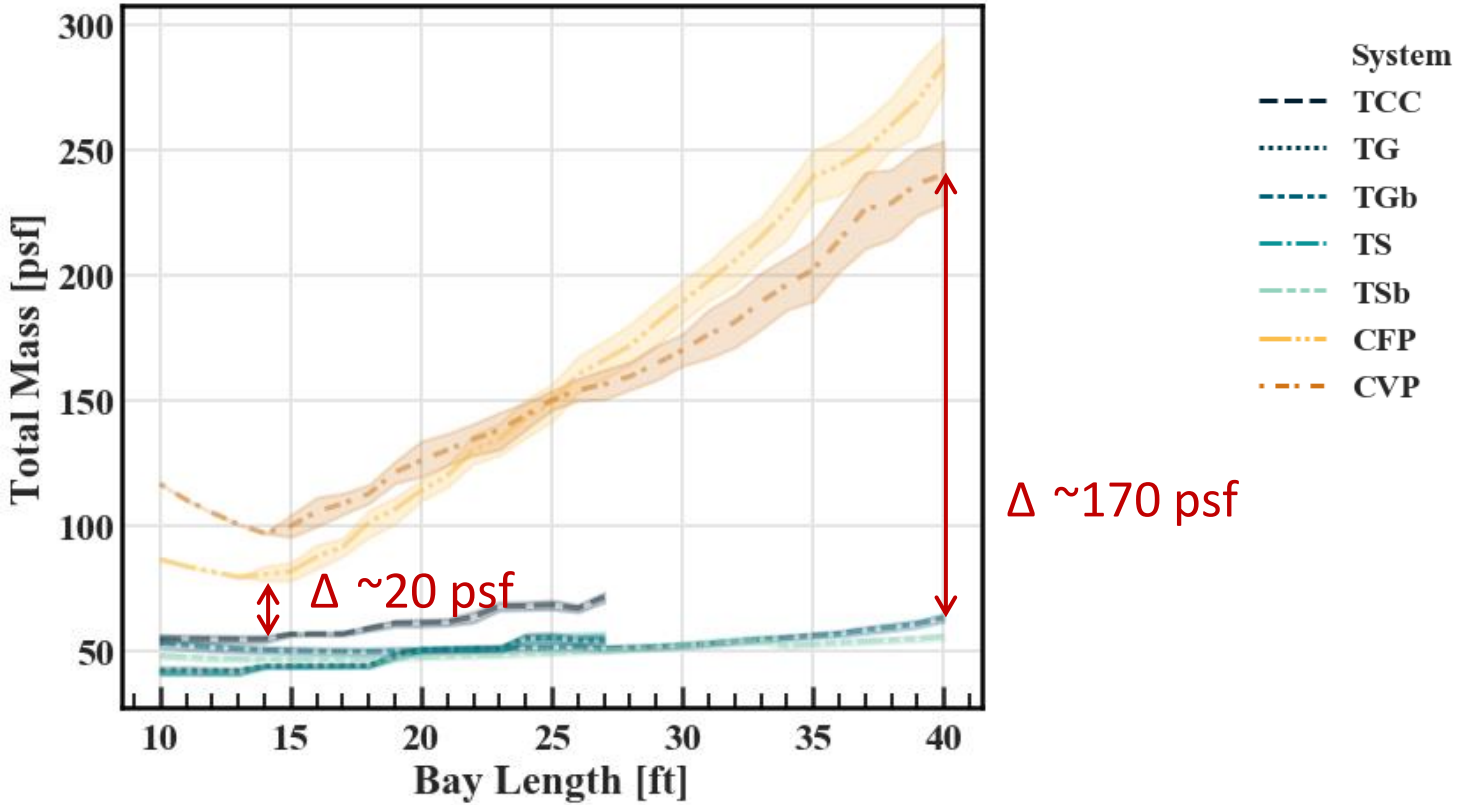
How do mass timber and hybrid mass timber floor systems compare to baseline steel-reinforced concrete floor systems in relation to EC and structural design objectives?

Concrete systems are 1-3’ shallower than mass timber systems



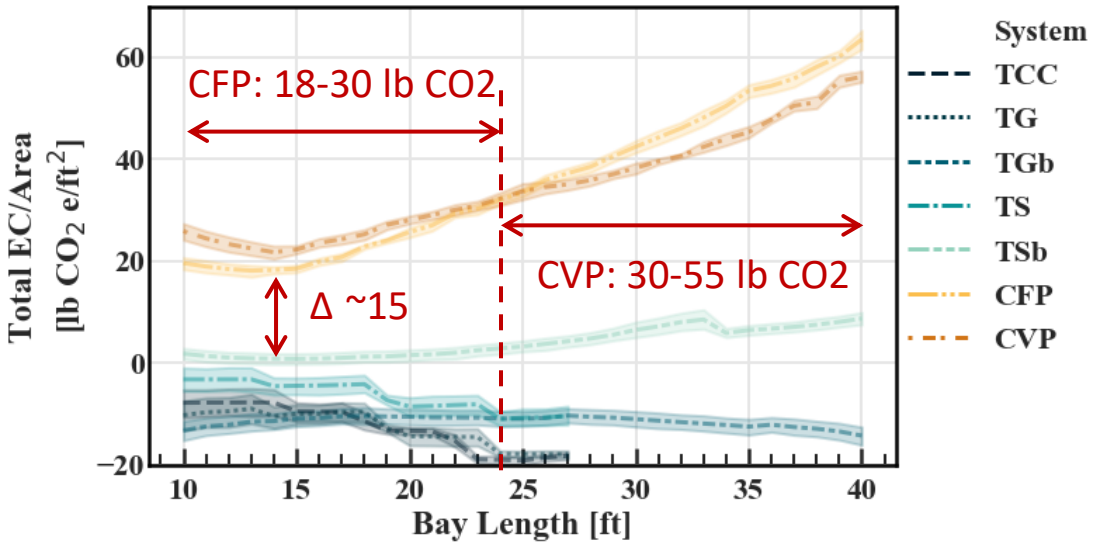


Mass timber systems are much lighter than the concrete baselines

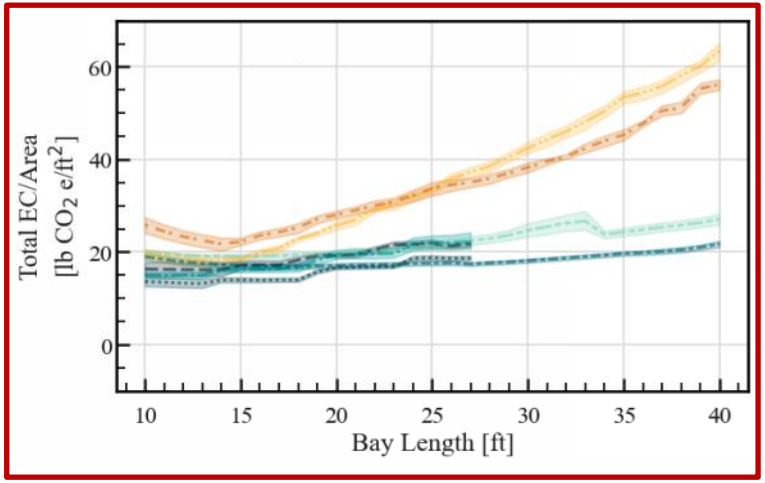


Concrete baseline floors have an EC range of ~18-64 lb CO_2 eq/ft^2

75% Carbon Storage

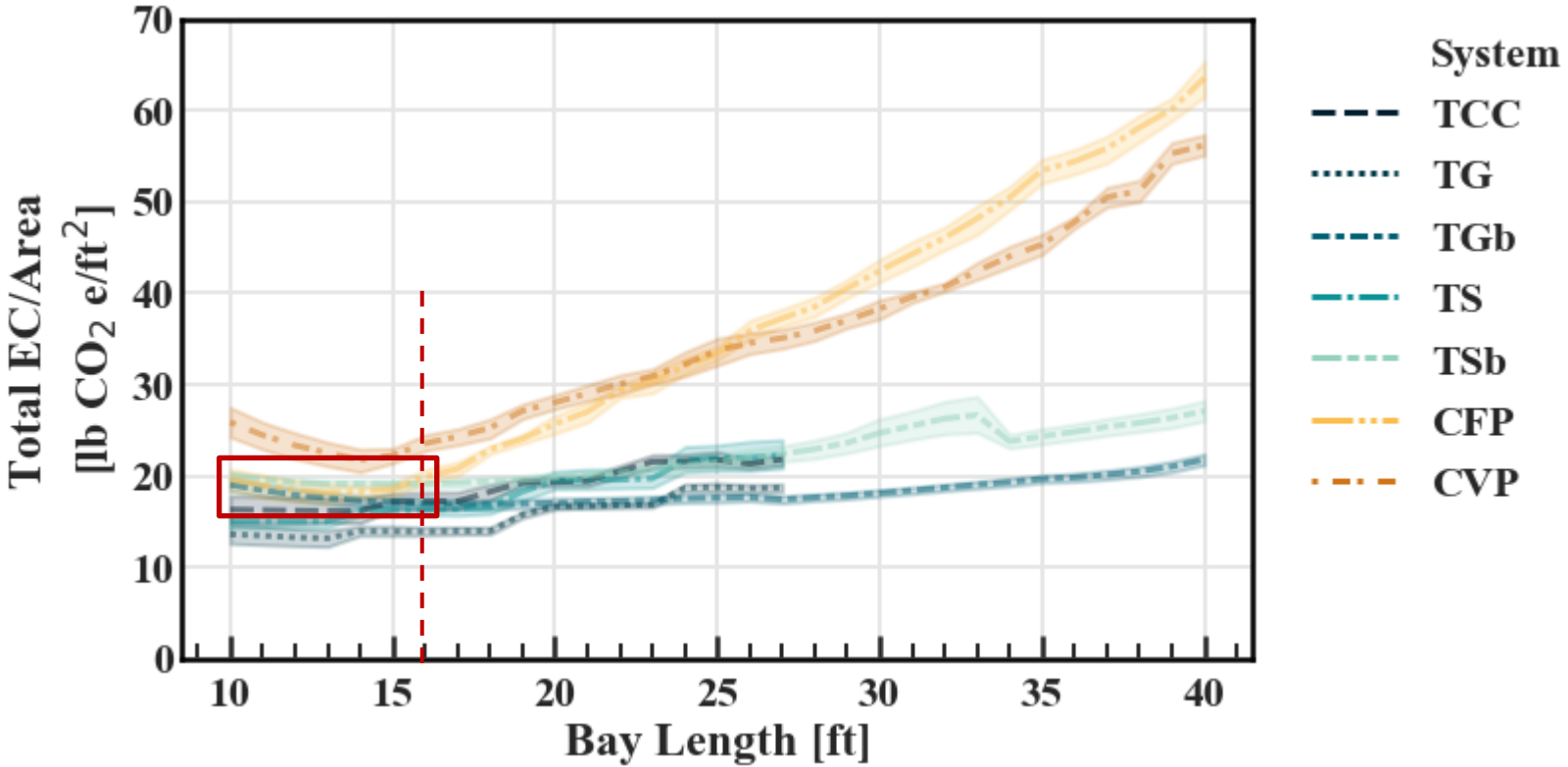


0% Carbon Storage



Concrete flat plate has lower EC than TSb systems below 16’

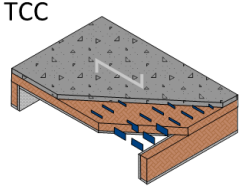
(0% Carbon Storage)



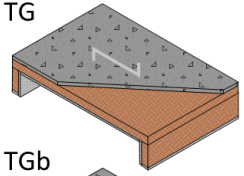
How do prescriptive fire design options affect EC and floor system depth for mass timber and hybrid mass timber floor systems?

Fire design options are comparable in many scenarios

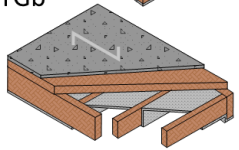
TCC



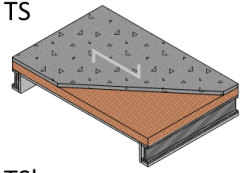
TG



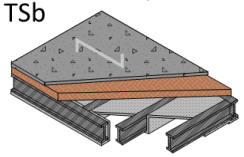
TGb

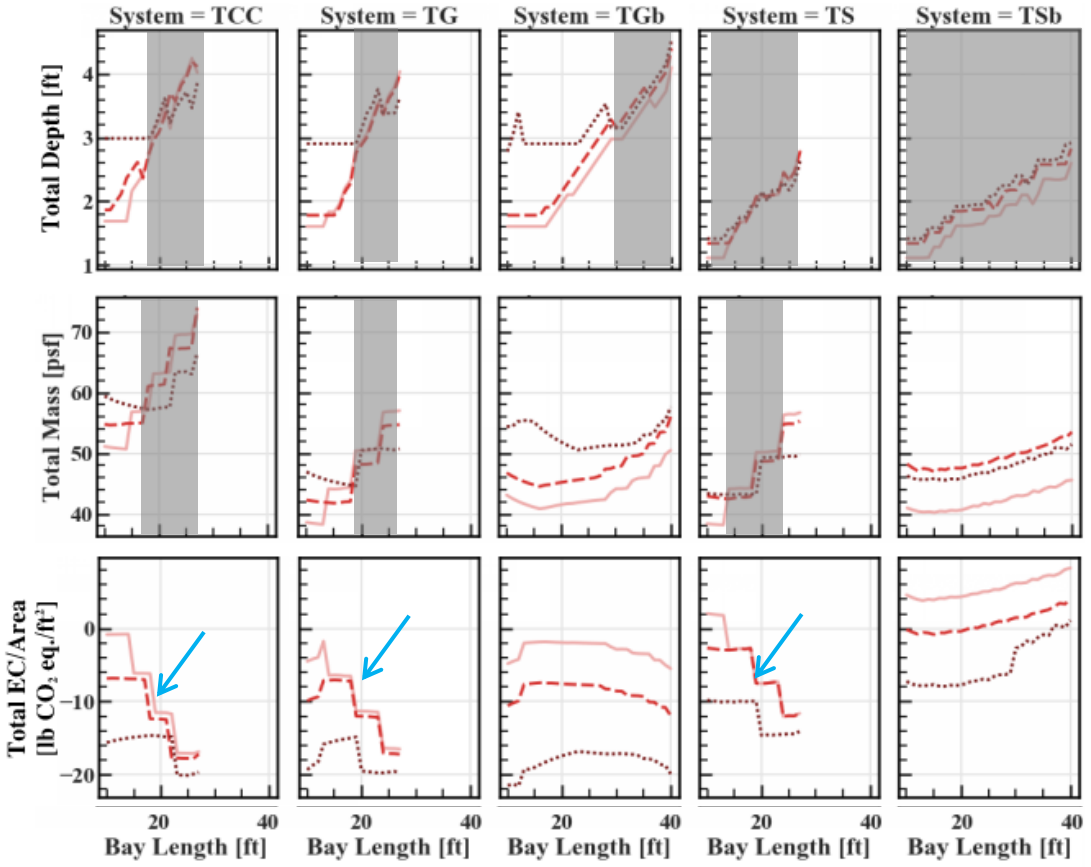


TS

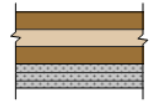


TSb

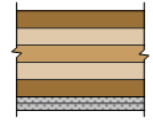




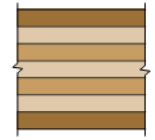
Protected



Combined

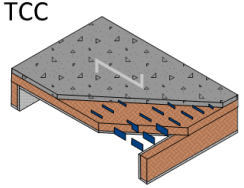


Exposed

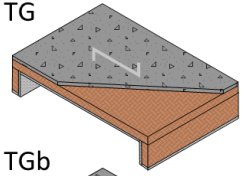


Fire design options are comparable in many scenarios

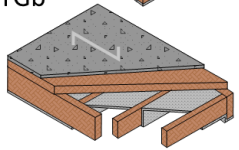
TCC



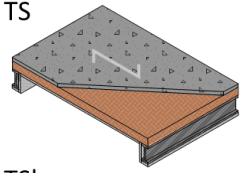
TG



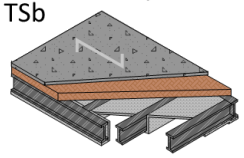
TGb

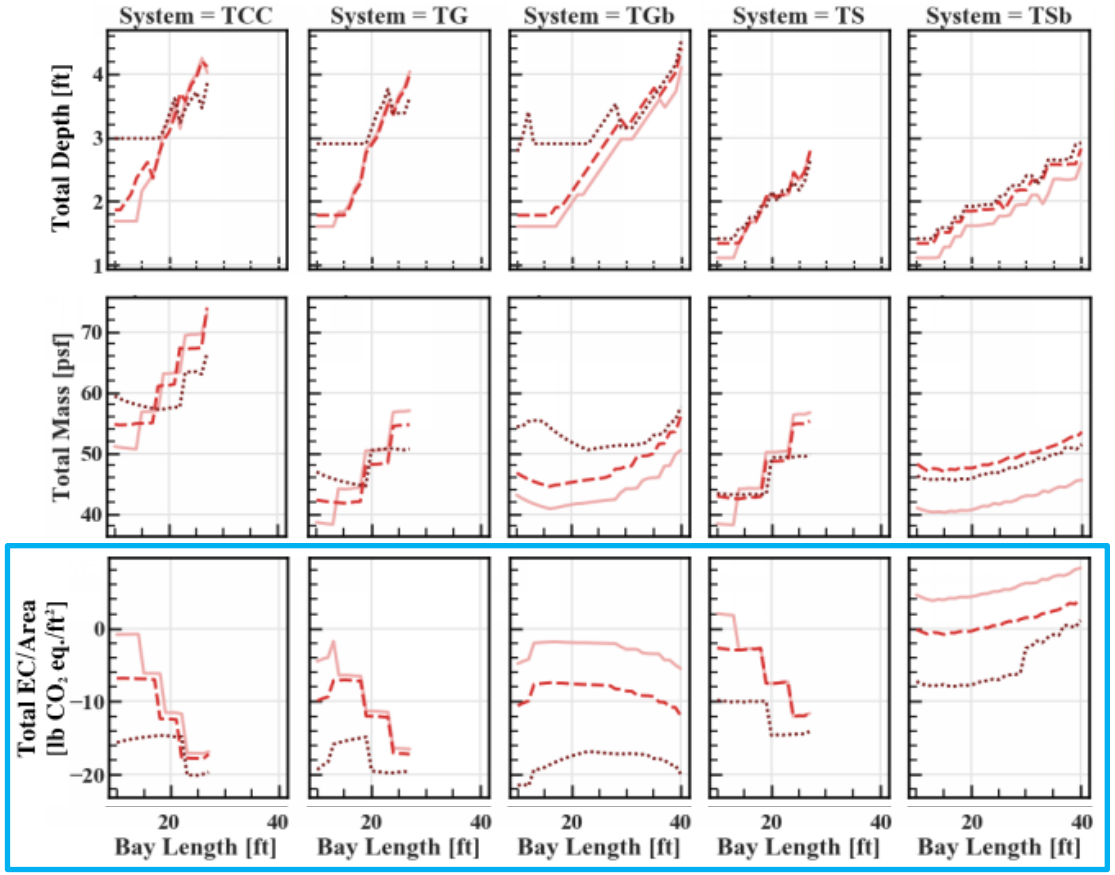


TS

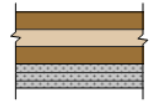


TSb

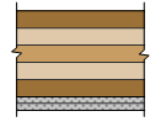




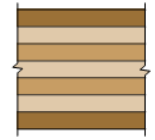
Protected



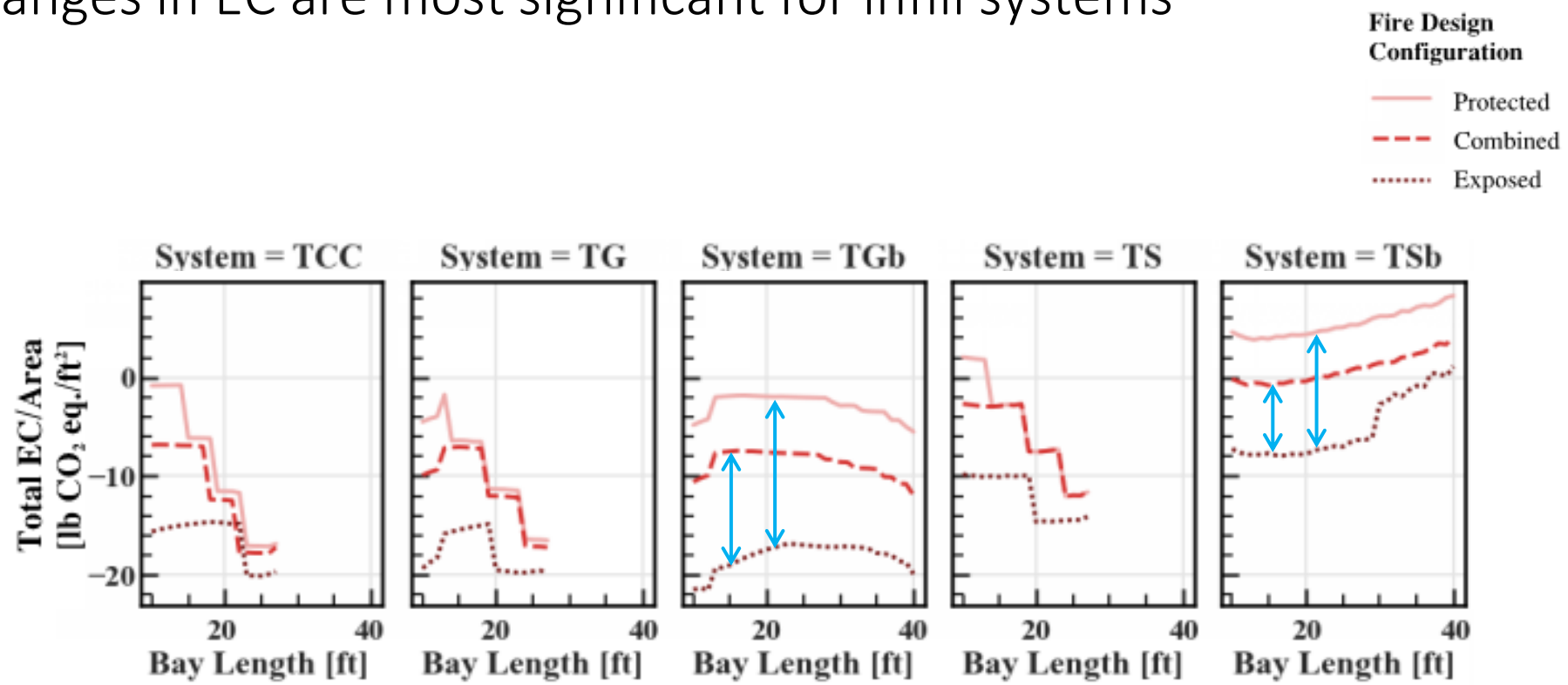
Combined



Exposed

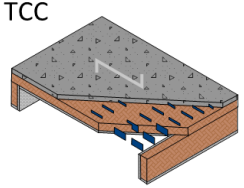


Changes in EC are most significant for infill systems

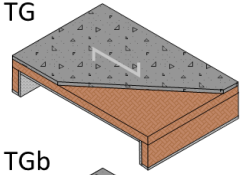


Fire design options are comparable in many scenarios

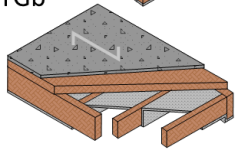
TCC



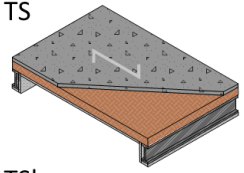
TG



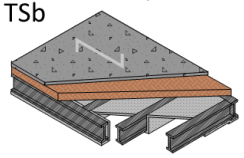
TGb

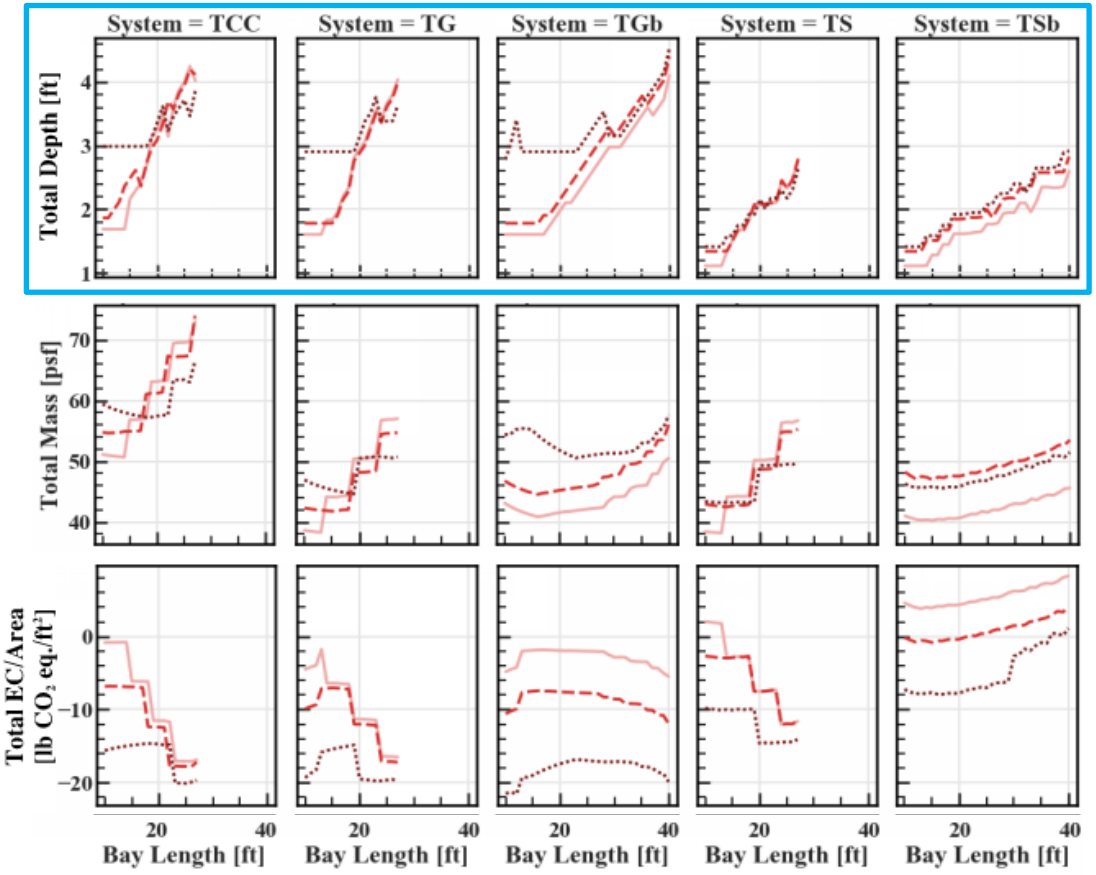


TS

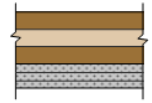


TSb

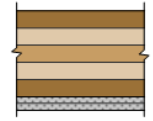




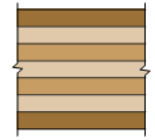
Protected



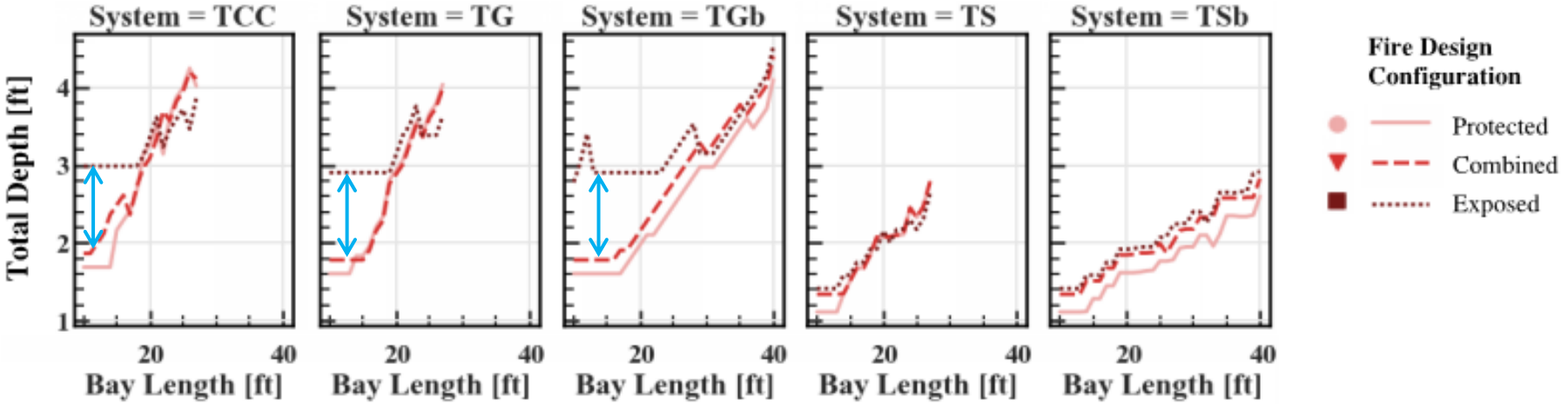
Combined



Exposed

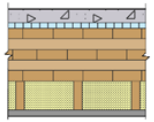
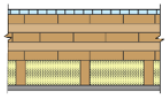
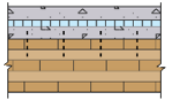
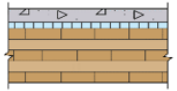
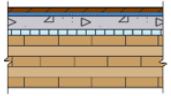
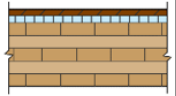
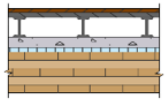
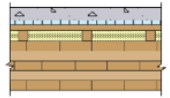
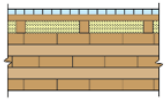


>1’ difference at lowest spans for timber-framed systems



How does designing for improved acoustic insulation beyond code minimum for floor assemblies affect mass timber EC and floor system depth?

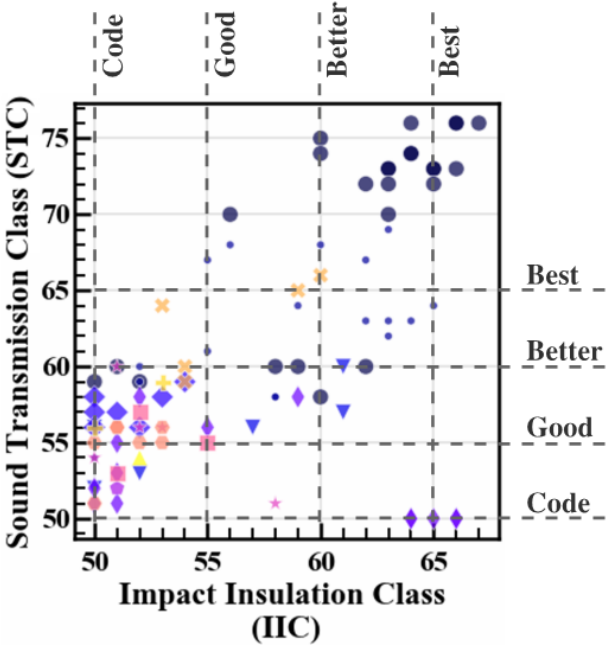
85 Acoustically-Tested CLT Floor Assemblies with EC Data

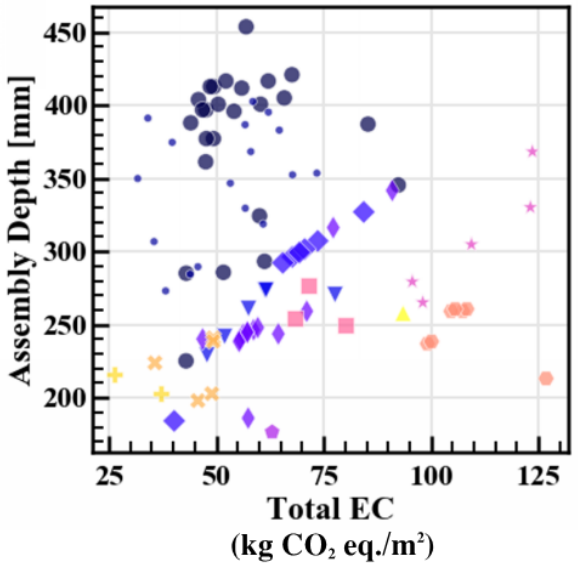
Category	Ceiling side concealed	Ceiling side concealed; no topping	CLT-concrete composite	Concrete or gypsum topping	Concrete or gypsum topping w/ finish floor	No concrete or gypsum topping	Raised access floor	Raised wooded sleepers	Raised wooded sleepers; no topping
Typical Assembly Construction									
# Studied Assemblies	25	17	6	7	13	3	7	5	2

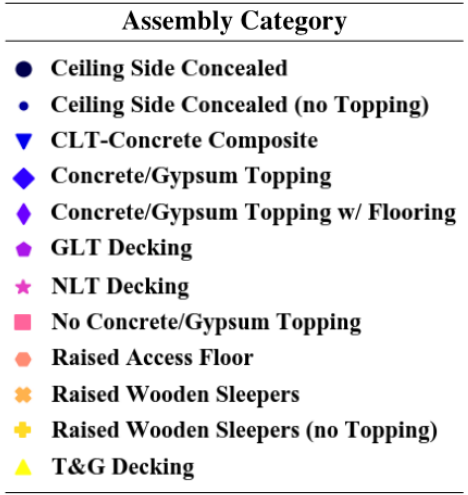
Classifying sound insulation performance

Performance Tier	STC/IIC	Description
Non-code-compliant	<50	Clearly hear normal activities of neighbor
Code Minimum	50	Normal activities of neighbors are somewhat muted
Good	55-59	
Better	60-64	Cannot hear normal activities of neighbor (in most cases)
Best	65+	

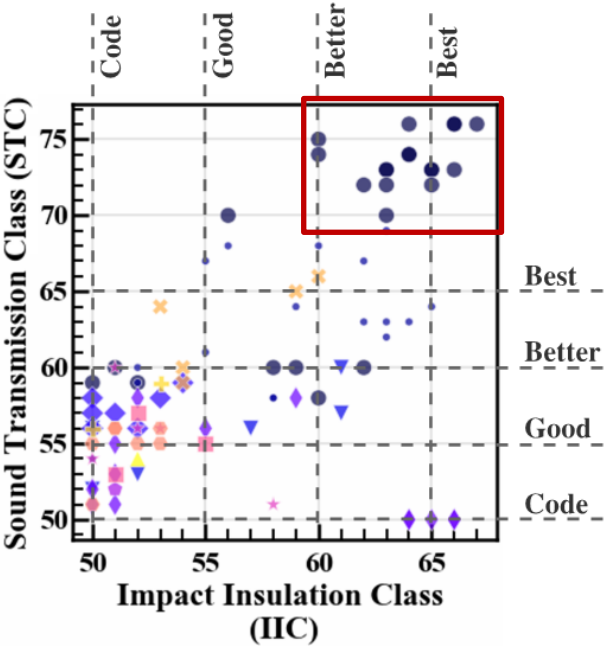
Concealed assemblies offer the greatest STC/IIC

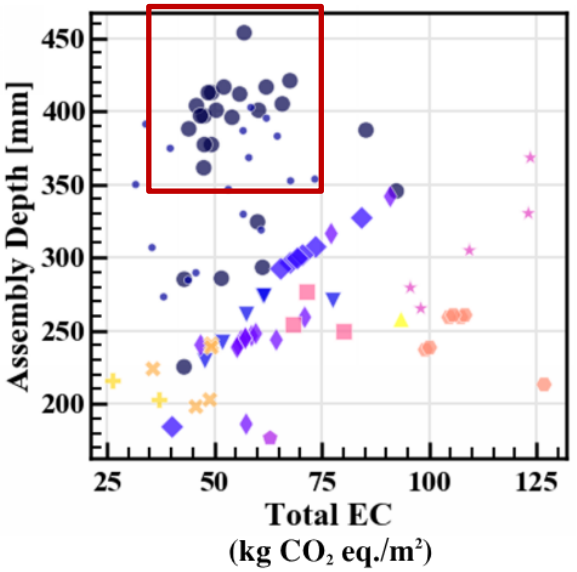


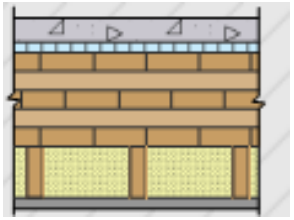




Concealed assemblies offer the greatest STC/IIC



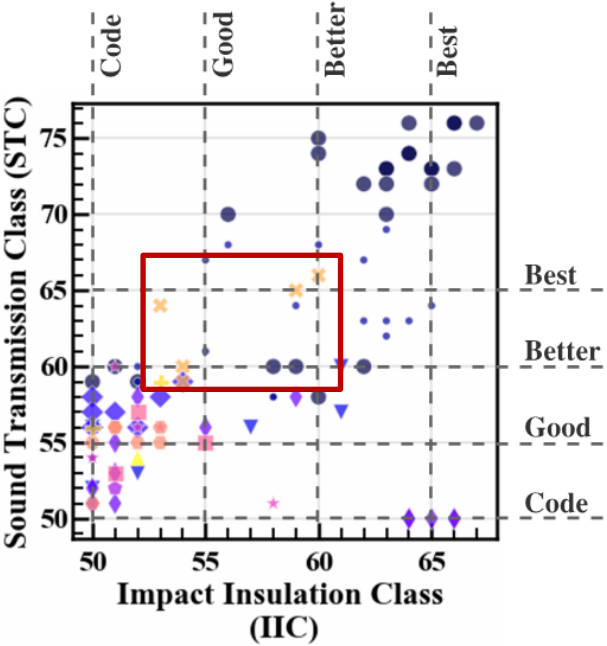


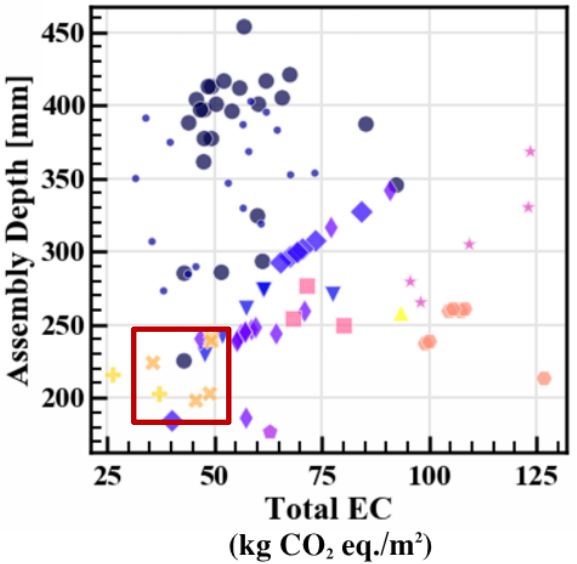


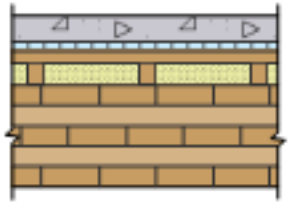
Assembly Category

- Ceiling Side Concealed
- Ceiling Side Concealed (no Topping)
- CLT-Concrete Composite
- Concrete/Gypsum Topping
- Concrete/Gypsum Topping w/ Flooring
- GLT Decking
- NLT Decking
- No Concrete/Gypsum Topping
- Raised Access Floor
- Raised Wooden Sleepers
- Raised Wooden Sleepers (no Topping)
- T&G Decking

Concealed assemblies offer the greatest STC/IIC







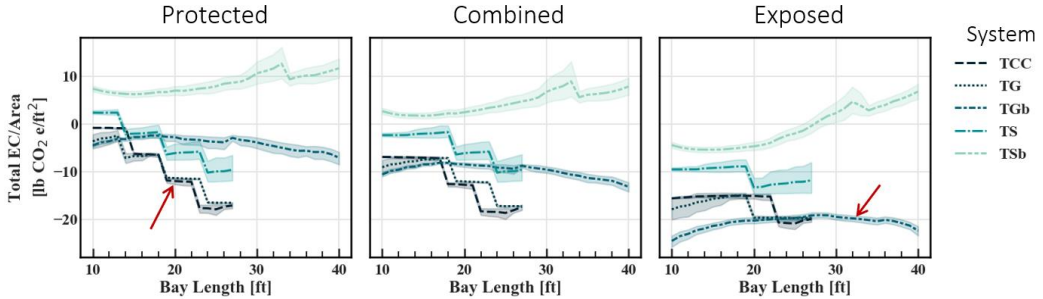
Assembly Category
Ceiling Side Concealed
Ceiling Side Concealed (no Topping)
CLT-Concrete Composite
Concrete/Gypsum Topping
Concrete/Gypsum Topping w/ Flooring
GLT Decking
NLT Decking
No Concrete/Gypsum Topping
Raised Access Floor
Raised Wooden Sleepers
Raised Wooden Sleepers (no Topping)
T&G Decking

Conclusions

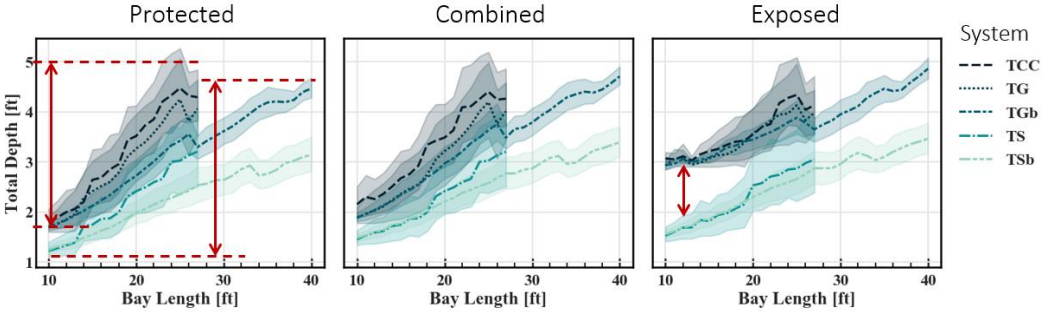
Key Takeaways and Future Work

Key Guidance

- Where EC is a priority, consider protected designs without infills or the exposed TGb designs for greater carbon storage using 75% carbon storage assumption.

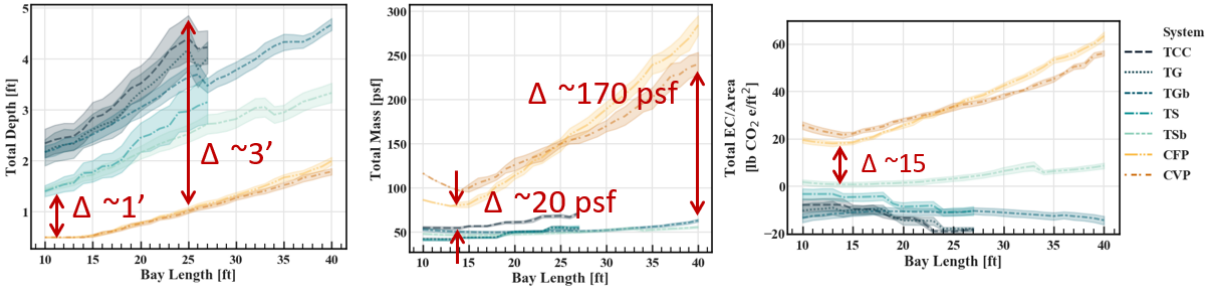


- Where depth is a priority, consider selecting steel-framed designs, which can be 1-2’ shallower.

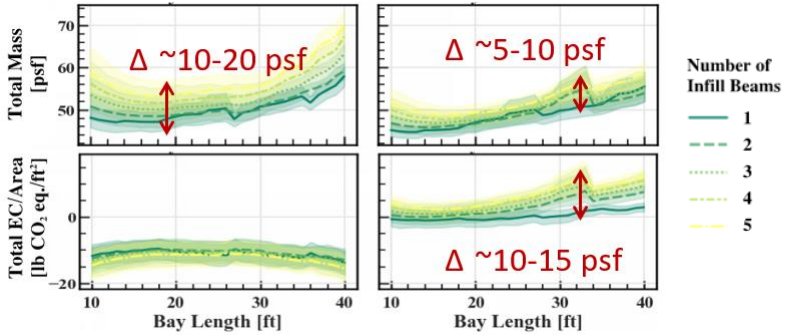


Key Guidance

- Substitute with mass timber where appropriate to achieve lighter systems with lower EC as compared to common baseline concrete floors.

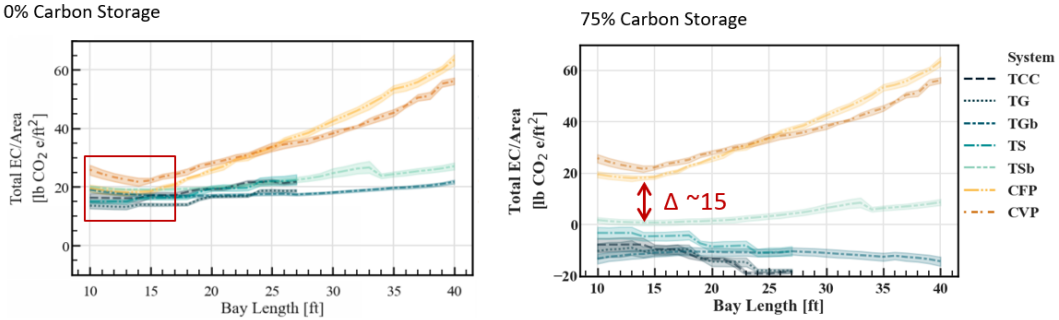


- Consider limiting designs to a single infill beam to reduce mass and EC.

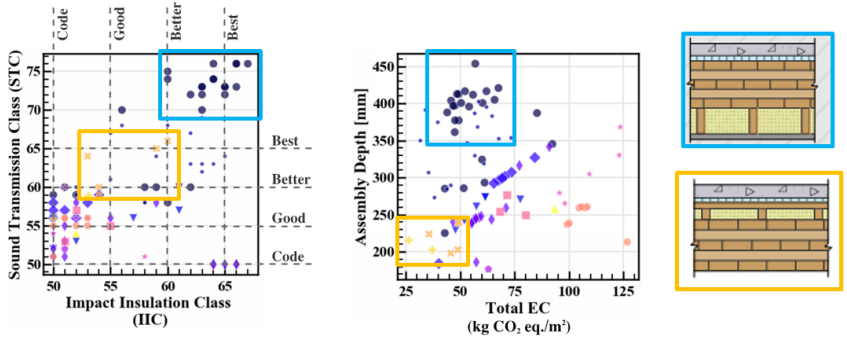


Key Guidance

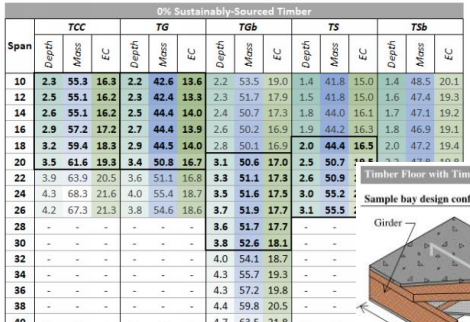
- Carefully consider timber carbon storage assumptions, which affect design guidance



- To maximize acoustic insulation, consider under-ceiling treatment, and to improve insulation with balanced performance metrics, consider wooden sleepers



Future Work – AIA Design Guide and Web Tool



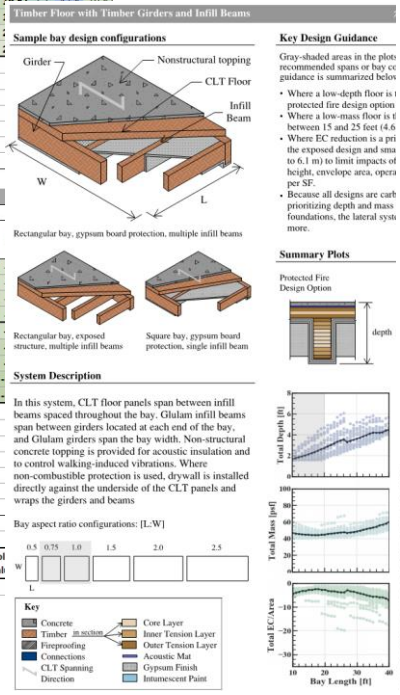
0% Sustainably-Sourced Timber

Span	TCC			TG			TGb			TS			TSb		
	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC
10	2.3	55.3	16.3	2.2	42.6	13.6	2.2	53.5	19.0	1.4	41.8	15.0	1.4	48.5	20.1
12	2.5	55.1	16.2	2.3	42.4	13.3	2.3	51.7	17.9	1.5	41.8	15.0	1.6	47.4	19.3
14	2.6	55.1	16.2	2.5	44.4	14.0	2.4	50.7	17.3	1.8	44.0	16.1	1.7	47.1	19.2
16	2.9	57.2	17.2	2.7	44.4	13.9	2.6	50.2	16.9	1.9	44.2	16.3	1.8	46.9	19.1
18	3.2	59.4	18.3	2.9	44.5	14.0	2.8	50.1	16.9	2.0	44.4	16.5	2.0	47.2	19.4
20	3.5	61.6	19.3	3.4	50.8	16.7	3.1	50.6	17.0	2.5	50.7	18.5	2.3	47.8	19.8
22	3.9	63.9	20.5	3.6	51.1	16.8	3.3	51.1	17.3	2.6	50.9	18.5			
24	4.3	68.3	21.6	4.0	55.4	18.7	3.5	51.6	17.5	3.0	55.2	20.1			
26	4.2	67.3	21.3	3.8	54.6	18.6	3.7	51.9	17.7	3.1	55.5	20.2			
28	-	-	-	-	-	-	3.6	51.7	17.7	-	-	-			
30	-	-	-	-	-	-	3.8	52.6	18.1	-	-	-			
32	-	-	-	-	-	-	4.0	54.1	18.7	-	-	-			
34	-	-	-	-	-	-	4.3	55.7	19.3	-	-	-			
36	-	-	-	-	-	-	4.3	57.2	19.8	-	-	-			
38	-	-	-	-	-	-	4.4	59.8	20.5	-	-	-			
40	-	-	-	-	-	-	4.7	63.5	21.8	-	-	-			

75% Sustainably-Sourced Timber

Span	TCC			TG			TGb			TS		
	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC	Depth	Mass	EC
10	2.3	55.3	-7.8	2.2	42.6	-10.2	2.2	53.5	-13.2	1.4	41.8	
12	2.5	55.1	-7.7	2.3	42.4	-9.5	2.3	51.7	-12.1	1.5	41.8	
14	2.6	55.1	-7.7	2.5	44.4	-10.4	2.4	50.7	-11.4	1.8	44.0	
16	2.9	57.2	-9.6	2.7	44.4	-9.9	2.6	50.2	-10.8	1.9	44.2	
18	3.2	59.4	-11.4	2.9	44.5	-9.6	2.8	50.1	-10.4	2.0	44.4	
20	3.5	61.6	-13.3	3.4	50.8	-14.4	3.1	50.6	-10.5	2.5	50.7	
22	3.9	63.9	-15.2	3.6	51.1	-14.5	3.3	51.1	-10.7	2.6	50.9	
24	4.3	68.3	-19.0	4.0	55.4	-17.8	3.5	51.6	-10.9	3.0	55.2	
26	4.2	67.3	-18.6	3.8	54.6	-17.8	3.7	51.9	-10.8	3.1	55.5	
28	-	-	-	-	-	-	3.6	51.7	-10.6	-	-	
30	-	-	-	-	-	-	3.8	52.6	-11.0	-	-	
32	-	-	-	-	-	-	4.0	54.1	-11.6	-	-	
34	-	-	-	-	-	-	4.3	55.7	-12.2	-	-	
36	-	-	-	-	-	-	4.3	57.2	-12.1	-	-	
38	-	-	-	-	-	-	4.4	59.8	-12.9	-	-	
40	-	-	-	-	-	-	4.7	63.5	-14.2	-	-	

Key: Deepest to Shallowest; Heaviest to Lightest; Highest to Lowest



Timber Floor with Timber Girders and Infill Beams

Sample bay design configurations

Girder
Nonstructural topping
CLT Floor
Infill Beam
W
L

Rectangular bay, gypsum board protection, multiple infill beams

Rectangular bay, exposed structure, multiple infill beams

Square bay, gypsum board protection, single infill beam

System Description

In this system, CLT floor panels span between infill beams spaced throughout the bay. Glulam infill beams span between girders located at each end of the bay, and Glulam girders span the bay width. Non-structural concrete topping is provided for acoustic insulation and to control walking-induced vibrations. Where non-combustible protection is used, drywall is installed directly against the underside of the CLT panels and wraps the girders and beams

Bay aspect ratio configurations: [L:W]

0.5 0.75 1.0 1.5 2.0 2.5

Key

Concrete
Timber in section
Fireproofing
Connections
CLT Spanning Direction
Core Layer
Inner Tension Layer
Outer Tension Layer
Acoustic Mat
Gypsum Finish
Intumescent Paint

Key Design Guidance

Gray-shaded areas in the plots recommended spans or bay co guidance is summarized below

- Where a low-depth floor is protected fire design option
- Where a low-mass floor is t between 15 and 25 feet (4.6
- Where EC reduction is a pri the exposed design and sma to 6.1 m) to limit impacts of height, envelope area, opera per SF.
- Because all designs are carb prioritizing depth and mass foundations, the lateral syste more.

Summary Plots

Protected Fire Design Option

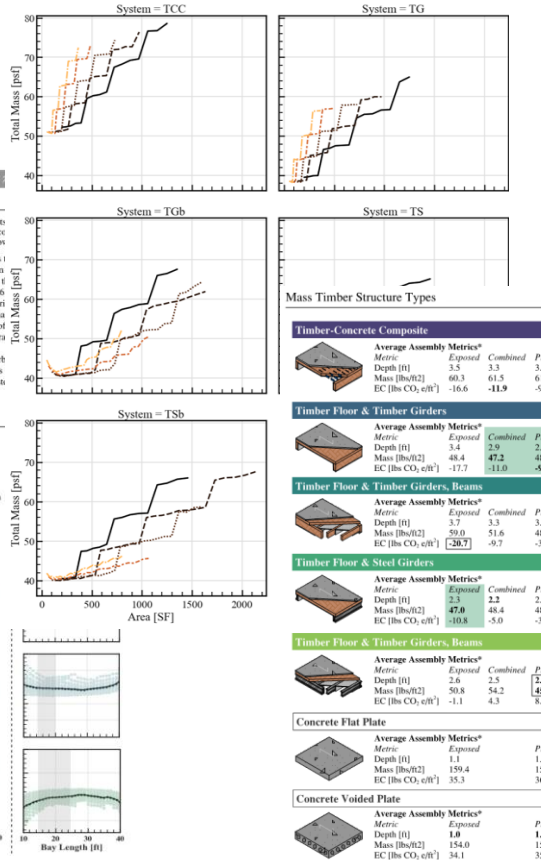
depth

Total Depth [ft]

Total Mass [psf]

Total EC/Area

Bay Length [ft]



System = TCC
System = TG
System = TGb
System = TS
System = TSb

Total Mass [psf]

Area [SF]

Mass Timber Structure Types

Timber-Concrete Composite

Average Assembly Metrics*

Metric	Exposed	Combined	Protected
Depth [ft]	3.5	3.3	3.2
Mass [lbs/ft2]	60.3	61.5	61.1
EC [lbs CO_2 e/ft^2]	-16.6	**-11.9**	-9.1

Timber Floor & Timber Girders

Average Assembly Metrics*

Metric	Exposed	Combined	Protected
Depth [ft]	3.4	2.9	2.9
Mass [lbs/ft2]	48.4	**47.2**	48.1
EC [lbs CO_2 e/ft^2]	-17.7	-11.0	**-9.3**

Timber Floor & Timber Girders, Beams

Average Assembly Metrics*

Metric	Exposed	Combined	Protected
Depth [ft]	3.7	3.3	3.1
Mass [lbs/ft2]	59.0	51.6	48.1
EC [lbs CO_2 e/ft^2]	**-20.7**	-9.7	-3.9

Timber Floor & Steel Girders

Average Assembly Metrics*

Metric	Exposed	Combined	Protected
Depth [ft]	2.3	**2.2**	2.2
Mass [lbs/ft2]	**47.0**	48.4	48.3
EC [lbs CO_2 e/ft^2]	-10.8	-5.0	-3.9

Timber Floor & Timber Girders, Beams

Average Assembly Metrics*

Metric	Exposed	Combined	Protected
Depth [ft]	2.6	2.5	**2.2**
Mass [lbs/ft2]	50.8	54.2	**45.7**
EC [lbs CO_2 e/ft^2]	-1.1	4.3	8.4

Concrete Flat Plate

Average Assembly Metrics*

Metric	Exposed	Protected
Depth [ft]	1.1	1.1
Mass [lbs/ft2]	159.4	159.4
EC [lbs CO_2 e/ft^2]	35.3	36.1

Concrete Voided Plate

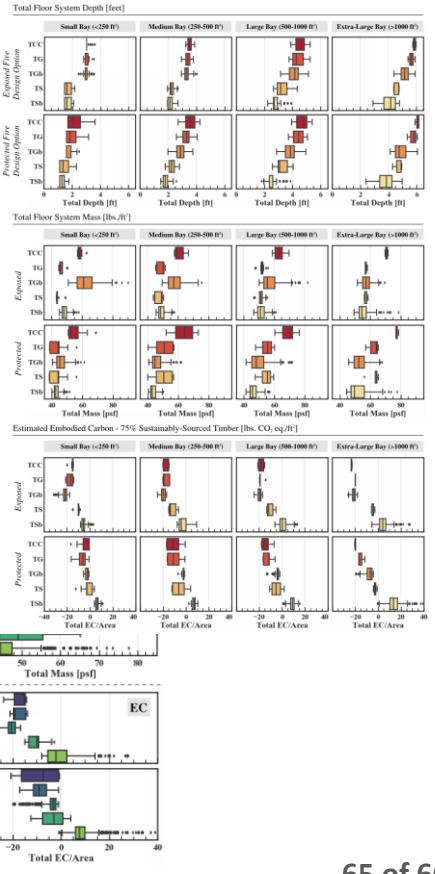
Average Assembly Metrics*

Metric	Exposed	Protected
Depth [ft]	**1.0**	**1.0**
Mass [lbs/ft2]	154.0	154.0
EC [lbs CO_2 e/ft^2]	34.1	35.0

Performanc

Exposed
Protected

Total EC/Area



Total Floor System Depth [feet]

Small Bay (<250 ft²)
Medium Bay (250-500 ft²)
Large Bay (500-1000 ft²)
Extra-Large Bay (>1000 ft²)

Exposed Fire Design Option
Protected Fire Design Option

TCC
TG
TGb
TS
TSb

Total Depth [ft]

Total Floor System Mass [lbs./ft²]

Total Mass [psf]

Estimated Embodied Carbon - 75% Sustainably-Sourced Timber [lbs. CO_2 eq./ft²]

Total EC/Area

EC

Discussion + Questions

sleonard@rdh.com
ncb5048@psu.edu
corey@psu.edu

Brock Commons under Construction: Timber floor and frame with concrete cores
[Photo from: Think Wood]