Timber Tower Research Project

Physical Testing Report #1 Composite Timber Floor Testing at Oregon State University

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Abbreviations & Symbols

Abbreviations

ACI:	American Concrete Institute
APA:	American Plywood Association
	(The Engineered Wood Association)
ASD:	Allowable Stress Design
AWC:	American Wood Council
B/:	Bottom of
C.L./:	Centerline of
CLT:	Cross-laminated timber
CONC:	Concrete
CONV:	Conversion
CSI:	Computers and Structures, Inc.
CYL:	Cylinder
DIAM:	Diameter
EC5:	Eurocode 5
ETA:	European Technical Approval
GLULAM:	Glue-laminated timber
IIC:	Impact Insulation Class
LAM:	Lamination
LRFD:	Load and Resistance Factor Design
N. Axis:	Neutral Axis
NDS:	National Design Specification
NWC:	Normal weight concrete
OSU:	Oregon State University
R/C:	Reinforced concrete
SAP2000:	Structural Analysis Program
SLB:	Softwood Lumber Board
SOM:	Skidmore, Owings & Merrill LLP
SPF:	Spruce, pine, or fir wood species
STC:	Sound Transmission Class
т/:	Top of
TYP:	Typical
UTIL:	Utilization

Symbols

The symbols below come from one or more documents which are referenced in this report. The referenced documents are shown after the symbol description in brackets [X]. Refer to the references section at the end of this report for more information.

A:	Cross-sectional area [2], [3]
E:	Modulus of elasticity [2], [3]
(EI) _{ef} :	Effective bending stiffness of composite section [2]
El _{eff} :	Effective bending stiffness of CLT [3]
El _{app} :	Apparent bending stiffness of CLT or composite section [3]
F ₁ :	Fastener force [2]
G:	Shear modulus [3]
GA _{eff} :	Effective shear stiffness of CLT [3]
l:	Moment of inertia [2], [3]
К:	Slip modulus [2]
K _{app} :	Apparent stiffness of a simply supported beam mid-span load
K _s :	Constant based on the influence of shear deformation [3]
K _{ser} :	Slip modulus at service loading [2]
L:	Length [2], [3]
L ₀ :	Effective length for gamma method calculations [2]
M , M _u :	Bending moment, service and ultimate [2], [3]
P, P _u :	Point load applied to beam, service and ultimate
V, V _u :	Shear force, service and ultimate [2], [3]
a:	Distance between centroids of outer laminations of CLT [3]
a ₁ , a ₂ :	Distance from centroid of section to neutral axis of composite section [2]
b:	Width of section [2], [3]
f'c:	28-day compressive cylinder strength of concrete [8]
h:	Thickness of wood lamination layer, CLT, or topping slab [2], [3]
s:	Spacing of composite connectors [2]
wc:	Density of concrete [8]
z:	Distance from centroid of CLT to centroid of individual wood lamination [3]
γ:	Gamma factor, measure of slip between layers of composite section [2]
σ ₁ , σ ₂ :	Normal stresses of composite section at neutral axis [2]
σ _{m1} , σ _{m2} :	Normal stresses at extreme fiber of layer due to bending moments [2]
τ _{2,max} :	Maximum shear stress in CLT [2]

Section 1: Introduction

1.1 Development of the Floor System and Testing Program

SOM has produced two reports on the use of mass-timber in high-rise buildings. The first report issued in 2013 studied the use of mass-timber for the entire building frame and identified timber-concrete composites as an effective way to satisfy the requirements of a high-rise building. The second report issued in 2014 studied the gravity framing system and identified composite concrete topping slabs as an economical way to satisfy acoustical requirements and increase the span of timber floor systems. The 2014 report also contained recommendations for physical testing of continuous timber-concrete composite floor systems which would be necessary before they could be utilized in the market. Following the 2014 report, SOM engaged Oregon State University (OSU) to develop a testing program to validate the concepts researched to date. The testing program was completed in September of 2016 and consisted of over 20 tests on 14 full-scale specimens. This report provides analytical predictions of floor behavior and the results of the testing program as they relate to the overall concepts developed by SOM. The full testing description and results are documented in a report titled "Structural Tests of Concrete Composite-Cross-Laminated Timber Floors", by C. Higgins, A. Barbosa, and C. Blank, dated March 10th, 2017 [1]. Please contact OSU with requests for copies of the full test results.

1.2 Purpose of the Testing Program

The purpose of the testing program was to research CLT floor systems with a composite concrete topping slab, which are designed to be similar to concrete "flat slab" systems. The program researched key behaviors of timber-concrete composite floor systems including the effectiveness of composite action, two-way bending stiffness, and continuous beam behavior.

1.3 Testing Program Objectives

- Review composite timber floor analytical techniques and predict the behavior of test specimens.
- Test different shear connector types. Document and compare the resulting composite behavior.
- Test composite floors for two-way bending stiffness properties including positive and negative bending stiffness in both the weak and strong axis of the CLT.
- Test composite floors for long-term deflections under both positive and negative bending.
- Test to failure a full-scale floor system mockup with continuous slab connections.

Section 2: Basis for Testing Program

2.1 Model Composite-Timber Building

The details of the testing program were developed based on expected bay sizes for high-rise residential buildings. A "model building" concept was created to demonstrate how the composite timber floor tests would apply to an actual building. The model building for the basis of the testing program was an 11-story building with a rectangular floor plan and two isolated cores for vertical transportation. This building typology is expected to be a common layout that mass-timber systems could be applied to in the future. The overall building geometry is shown in Figures 1 and 2. Figure 1 also highlights an area of typical framing that was the focus for the testing program.



Figure 1: Model Building Typical Floor Plan





2.2 Typical Framing Layout

The typical bay size of the model building is 20ft x 24ft. This bay size allows for flexible planning of interior residential spaces with reasonable CLT floor thicknesses and beam depths. The typical framing bay is shown in Figures 3 and 4, along with a rendering shown in Figure 5. The section of the typical bay modeled by the full-scale specimen is highlighted in Figures 3 and 4.







Figure 4: Section through Typical Framing Zone



Figure 5: Model Building Typical Framing Zone Rendering

2.3 Typical Framing Details

The typical composite CLT section uses conventional composite concrete slab connectors such as inclined screws or epoxied plates. The floor planks are connected to the supporting composite timber beams with vertical screws. Shear in the floor plank is transferred to the CLT beam by direct bearing. End moment of the continuous floor plank system is transferred through the composite CLT beam by a force couple with compression in the thickened concrete and tension in the reinforcement over the support. The typical framing details are shown in Figures 6 and 7. Refer to Figure 4 for locations where typical details apply.



Figure 6: Typical Composite Floor Detail



Figure 7: Typical Composite Beam Detail

Section 3: Timber-Concrete Composite Floor Analysis

This section identifies one method for calculating the stiffness and strength properties of CLT floor systems with composite concrete topping slabs. The most common analytical approach appears to be the "gamma method" from Annex B of the Eurocode 5 (EC5), EN 1995-1-1, Design of Timber Structures [2]. This method was developed to calculate the effective stiffness of two timber elements connected with mechanical fasteners with a known slip modulus. The calculation method is derived from basic principles of engineering mechanics. Derivations of this behavior are not unique to EC5 and date back to Möhler, K. (1956) [10].

The EC5 method is referenced in the US CLT Handbook [3] as a possible method to calculate the effective stiffness of CLT floors due to rolling shear deformations. The gamma method has also been evaluated for timber-concrete composite systems through research by Gerber (2015) [4] and Manaridis (2010) [5]. This report uses the gamma method in conjunction with the provisions of the US CLT Handbook to evaluate the measured stiffness and strength of the composite CLT floor system. Refer to the recommendations section for more information regarding the development of code provisions for composite timber-concrete floor systems.

3.1 Analysis Method

The evaluation of composite CLT-concrete floor systems must consider both serviceability and strength limit states. Serviceability limit states such as floor vibrations and total instantaneous plus long-term deflections are likely to govern the design of the floor system in most cases. The following analysis methods were used to evaluate the stiffness and strength properties of the proposed composite CLT floor system.

- 1. Determine the CLT properties for the floor system considered including the mechanical properties of the wood species per the APA-PRG 320 [6] or from the manufacturer approved APA product reports.
- 2. Calculate the effective cross-sectional properties of the CLT floor (El_{eff}, GA_{eff}) from basic engineering mechanics or from the US CLT Handbook, Chapter 3 [3].
- 3. Determine the composite fastener type and associated slip modulus (Ks) per the manufacturer's literature and technical approvals, such as the ETA-12/0196 [9].
- 4. Calculate the effective composite stiffness properties per Annex B of EN 1995-1-1 [2].
- 5. Calculate the apparent stiffness of the floor system per the US CLT Handbook, Chapter 3 [3], or develop a rolling shear model to consider the stiffness losses due to rolling shear behavior.
- 6. Evaluate the floor system for deflections and vibrations per rational analysis.
- 7. Calculate the normal stresses due to bending moments, shear stresses, and fastener loads of the composite floor system per Annex B of EN 1995-1-1 [2].
- 8. Compare the calculated stresses to allowable limits by code, such as the National Design Specification for Wood Construction ASD/LRFD (NDS) [7], or manufacturer's literature and approvals documents.

3.2 Design Equations

The following design equations are from Annex B of EN 1995-1-1. The equations have been re-written for the specific case of CLT floors with a composite concrete topping slab:



Figure 8: Design Equations per Annex B of EN 1995-1-1, re-written for composite CLT application.

3.3 Example Calculations

The following calculations follow the analysis method discussed in Section 3.1. Calculations have been provided for strong-axis bending of the CLT, with both the slab in compression (positive bending) and slab reinforcing in tension (negative bending). The span length and loading shown in the calculations is based on the simple-span composite connector tests discussed in the next section of the report. The calculated bending stiffness shown in this section is compared against the tested values in the following section.

Calculation:	Effective Stiffness
Cross Section:	CLT, Strong Axis
References:	US CLT Handbook, Chapter 3

Cross Section Properties, Per Foot of Width

EA _{eff} =	68,740	kip
El _{eff} =	339,537	kip.in ²
h2 =	6.750	in
a =	5.438	in
GA _{eff} =	1,028	kip

			z [in]	GA _{eff} Calculations		EA Calculations	Ele	ff Calculati	ons										
Layer	E [ksi]	h [in]		G [ksi]	G [ksi]	EA [kip]	El _{,thk} = Ebh ³ /12	El _{,na} = EAz ²	Sum of Layer										
													[in /kip]	[in /kip]	[іп /кір]		[kip.in ²]	[kip.in ²]	[kip.in ²]
1	1400	1.375	2.750	87.5	0.0013	23,100	3,639	174,694	178,333										
2	47	1.375	1.375	8.8	0.0131	770	121	1,456	1,577										
3	1400	1.375	0.000	87.5	0.0013	23,100	3,639	0	3,639										
4	47	1.375	1.375	8.8	0.0131	770	121	1,456	1,577										
5	1400	1.250	2.688	87.5	0.0012	21,000	2,734	151,676	154,410										
					Total =	68,740		Total =	339,537										

Figure 9: Effective CLT Section Properties of CLT, 5-Ply CLT (Structurlam Crosslam), Grade V2M1

Note: The neutral axis is taken at center of center ply, which is a simplification for an asymmetric CLT section (thinner bottom ply). The simplification results in an over-estimation of El_{eff} by 0.2% and is considered acceptable for the purposes of this calculation.

Calculation:Effective StiffnessCross Section:Composite CLT+R/C, Strong Axis, Positive BendingReferences:As Noted

Cross Section Properties, Per Foot of Width

General Values

Variable	Value	Unit	Reference	Notes
L =	10	ft	Specified	Actual span length
L ₀ =	10	ft	Eurocode 5, Annex B	Gamma method length
K _{ser} =	16.1	kN/mm	Per Manufacturer	Connector slip modulus
K _{ser} =	91.1	kips/in	Per Manufacturer	Connector slip modulus
s =	12	in	Specified	Connector Spacing

Concrete Values

Variable	Value	Unit	Reference	Notes
hc	2.25	in	Specified	Concrete topping thickness
f'c =	5,000	psi	Specified	28-day compressive strength
wc =	145	pcf	Specified	Density of concrete
Ec =	4,074	ksi	ACI 318, Sect. 8.5.1	Modulus of elasticity
Ac =	27	in ²	EC5, Annex B, Eq. B.2	Area of concrete
lc =	11.39	in ⁴	EC5, Annex B, Eq. B.3	Moment of intertia, concrete
EcAc =	110,006	kip		
Eclc =	46,409	kip.in ²		
γc =	0.091		EC5, Annex B, Eq. B.5	Gamma Factor

Composite Properties

Variable	Value	Unit	Reference	Notes
a ₂ =	0.575	in	EC5, Annex B, Eq. B.6	Timber to composite centroid
a ₁ =	3.93	in		Concrete to composite centroid
(EI) _{ef,comp} =	563 <i>,</i> 668	kip.in ²	EC5, Annex B, Eq. B.1	Effective composite stiffness
Ratio,clt =	1.66			Ratio of composite and CLT (EI) $_{\rm ef}$

Figure 10A: Effective Composite Stiffness Calculations, Positive Bending

Calculation:Effective StiffnessCross Section:Composite CLT+R/C, Strong Axis, Negative BendingReferences:As Noted

Cross Section Properties, Per Foot of Width

General Values

Variable	Value	Unit	Reference	Notes
L =	10	ft	Specified	Actual span length
L ₀ =	10	ft	Eurocode 5, Annex B	Gamma method length
K _{ser} =	16.1	kN/mm	Per Manufacturer	Connector slip modulus
K _{ser} =	91.1	kips/in	Per Manufacturer	Connector slip modulus
s =	12	in	Specified	Connector Spacing

Concrete Values

Variable	Value	Unit	Reference	Notes
hc	2.25	in	Specified	Concrete topping thickness
Es =	29,000	ksi	Specified	Modulus of elasticity
As =	0.11	in ²		Area of rebar, (1) #3
ls =	0.00	in ⁴		Moment of intertia, rebar
EsAs =	3,190	kip		
Esls =	0.00	kip.in ²		
γs =	0.776		EC5, Annex B, Eq. B.5	Gamma Factor

Composite Properties

Variable	Value	Unit	Reference	Notes
a ₂ =	0.156	in	EC5, Annex B, Eq. B.6	Timber to composite centroid
a ₁ =	4.34	in		Rebar to composite centroid
(EI) _{ef,comp} =	387,944	kip.in ²	EC5, Annex B, Eq. B.1	Effective composite stiffness
Ratio,clt =	1.14			Ratio of composite and CLT (EI) $_{\rm ef}$

Figure 10B: Effective Composite Stiffness Calculations, Negative Bending

Calculation: Apparent Stiffness Cross Section: Composite CLT+R/C, Strong Axis, Positive Bending References: US CLT Handbook, Chapter 3

Cross Section Properties, Per Foot of Width

Bare CLT Stiffness

Variable	Value	Unit	Notes
L =	10	ft	Actual span length
K _s =	14.4		Table 2, simple span, concen. at midspan
El _{eff,clt} =	339,537	kip.in ²	Eq. 24, bare CLT Value
GA _{eff,clt} =	1,028	kips	Eq. 25, bare CLT Value
El _{app,clt} =	255,260	kip.in ²	Eq. 35, bare CLT value for span conditions
Eff % =	0.75		Ratio of apparent EI to effective EI

Composite Section Stiffness

Variable	Value	Unit	Notes
El _{eff,comp} =	563,668	kip.in ²	Strong axis, composite section value
GA _{eff,clt} =	1,028	kips	Eq. 25, bare CLT Value
El _{app,comp} =	364,102	kip.in ²	Eq. 35, composite value for span conditions
Eff % =	0.65		Ratio of apparent EI to effective EI
Ratio,clt =	1.43		Ratio of apparent composite to clt properties

Apparent Floor Stiffness

Variable	Value	Unit	Notes
$K_{app,clt} = P/\Delta$	7.09	kip/in	$K = P/\Delta = 48EI_{app}/L^3$
$K_{app,comp} = P/\Delta$	10.11	kip/in	$K = P/\Delta = 48EI_{app}/L^3$

Figure 11A: Apparent Stiffness Properties, Positive Bending

Note: GA_{eff} for the composite section was assumed to be equal to the value for bare CLT. The contribution of the topping slab to this parameter was ignored due to the likelihood of cracking due to shrinkage and structural loads. This assumption is conservative but should be studied further.

Calculation: Apparent Stiffness Cross Section: Composite CLT+R/C, Strong Axis, Negative Bending References: US CLT Handbook, Chapter 3

Cross Section Properties, Per Foot of Width

Bare CLT Stiffness

Variable	Value	Unit	Notes
L =	10	ft	Actual span length
K _s =	14.4		Table 2, simple span, concen. at midspan
El _{eff,clt} =	339,537	kip.in ²	Eq. 24, bare CLT Value
GA _{eff,clt} =	1,028	kips	Eq. 25, bare CLT Value
El _{app,clt} =	255,260	kip.in ²	Eq. 35, bare CLT value for span conditions
Eff % =	0.75		Ratio of apparent EI to effective EI

Composite Section Stiffness

Variable	Value	Unit	Notes
El _{eff,comp} =	387,944	kip.in ²	Strong axis, composite section value
GA _{eff,clt} =	1,028	kips	Eq. 25, bare CLT Value
El _{app,comp} =	281,684	kip.in ²	Eq. 35, composite value for span conditions
Eff % =	0.73		Ratio of apparent EI to effective EI
Ratio,clt =	1.10		Ratio of apparent composite to clt properties

Apparent Floor Stiffness

Variable	Value	Unit	Notes
$K_{app,clt} = P/\Delta$	7.09	kip/in	$K = P/\Delta = 48EI_{app}/L^3$
$K_{app,comp} = P/\Delta$	7.82	kip/in	$K = P/\Delta = 48EI_{app}/L^3$

Figure 11B: Apparent Stiffness Properties, Negative Bending

Note: GA_{eff} for the composite section was assumed to be equal to the value for bare CLT. The contribution of the topping slab to this parameter was ignored due to the likelihood of cracking due to shrinkage and structural loads. This assumption is conservative but should be studied further.

Calculation:Bending Stresses and StrainsCross Section:Composite CLT+R/C, Strong Axis, Positive BendingReferences:Eurocode 5, Annex B: Mechanically Jointed Beams

Floor Demands, Per Foot of Width

Ultimate Load Demands

L =	10	ft
Pu =	6.0	kip
Vu =	3.0	kip
Mu =	180	kip.in

Bending Stress Calculations

Variable	Value	Unit	Notes
σ1 =	-0.47	ksi	Average concrete stress, Eq. B.7.
σ _{m,1} =	1.47	ksi	Extreme fiber stress delta, Eq. B.8.
σ _{t/conc} =	-1.93	ksi	Stress at top of concrete
$\sigma_{\rm b/conc}$ =	1.00	ksi	Stress at bottom of concrete, see note
σ2 =	0.26	ksi	Average CLT Stress, Eq. B.7.
σ _{m,2} =	1.51	ksi	Extreme fiber stress delta, Eq. B.8.
σ _{t/clt} =	-1.25	ksi	Stress at top of CLT
σ _{b/clt} =	1.77	ksi	Stress at bottom of CLT

Notes:

1. Ultimate loads back-calculated from code stress limits [7]

2. Ultimate bending stress = 0.85 x 875psi x 2.54 conv. = 1.89 ksi (Util. = 0.94)

3. Cracking of concrete on bottom layer does not appear to be significant

Shear Stress, Fastener Load Calculations

Variable	Value	Unit	Notes
τ _{2,max} =	0.164	ksi	Maximum rolling shear stress, Eq. B.9.
F ₁ =	2.53	kip	Fastener load, Eq. 8.10.

Notes:

1. Shear capacity is 0.75 x 0.135 ksi x 2.88 conversion = 0.292 ksi

2. Fastener capacity is 2.9 kips per manufacturer w/ 6.3" embedment

Figure 12A: Stress Calculations, Positive Bending

Calculation:Bending Stresses and StrainsCross Section:Composite CLT+R/C, Strong Axis, Negative BendingReferences:Eurocode 5, Annex B: Mechanically Jointed Beams

Floor Demands, Per Foot of Width

Ultimate Load Demands

L =	10	ft
Pu =	4.5	kip
Vu =	2.3	kip
Mu =	136	kip.in

Bending Stress Calculations

Variable	Value	Unit	Notes
σ1 =	34.18	ksi	Average rebar stress, Eq. B.7.
σ _{m,1} =	N/A	ksi	Extreme fiber stress delta, Eq. B.8.
$\sigma_{t/conc}$ =	N/A	ksi	Stress at top of concrete
$\sigma_{b/conc}$ =	N/A	ksi	Stress at bottom of concrete
σ2 =	-0.08	ksi	Average CLT Stress, Eq. B.7.
σ _{m,2} =	1.65	ksi	Extreme fiber stress delta, Eq. B.8.
σ _{t/clt} =	1.57	ksi	Stress at top of CLT
σ _{b/clt} =	-1.73	ksi	Stress at bottom of CLT

Notes:

1. Ultimate loads back-calculated from code stress limits [7]

2. Ultimate bending stress = 0.85 x 875psi x 2.54 conv. = 1.89 ksi (Util. = 0.92)

3. Concrete assumed to be fully cracked and has no contribution

4. Ultimate rebar stress = 34ksi (Utilization = 0.63)

Shear Stress, Fastener Load Calculations

Variable	Value	Unit	Notes
τ _{2,max} =	0.179	ksi	Maximum rolling shear stress, Eq. B.9.
F ₁ =	0.97	kip	Fastener load, Eq. 8.10.

Notes:

1. Shear capacity is 0.75 x 0.135 ksi x 2.88 conversion = 0.292 ksi

2. Fastener capacity is 2.9 kips per manufacturer w/ 6.3" embedment

Figure 12B: Stress Calculations, Negative Bending



Figure 13A: Stress Distribution, Positive Bending



Figure 13B: Stress Distribution, Negative Bending



Figure 14A: Strain Distribution, Positive Bending



Figure 14B: Strain Distribution, Negative Bending

3.4 Modeling Considerations

This section discusses one possible modeling technique for composite timber floors intended for two-way spanning behavior and continuous bending. The behavior of these types of composite timber floors is not unlike ordinary concrete flat plate systems, where the effects of cracking and reinforcing must be considered in parallel with the analysis results. Orthotropic plate properties must be used to capture the variation of stiffness in different orthogonal directions. Iterative or full non-linear analysis must be used to capture these effects properly.

One possible modeling technique is to use plate elements as part of any general finite element analysis software. In this example, CSI's SAP2000 was used as it is a relatively common software program. Refer to Figure 15 below which shows the modeling of the full scale test specimen discussed later in the report. The model is constructed with quadrilateral 4-node elements with a maximum size of 1ft by 1ft. The effectiveness of the back-span supports are influenced by two-way spanning behavior of the floor system and must be considered. The results of the analysis are provided in the following section of the report with the test results.



Figure 15: Model of Full-Scale Test with Calculated Stiffness Properties

Note: Gray elements are uncracked sections, brown elements are cracked sections.

The plate elements are assigned the modulus of elasticity of the wood species in the CLT (SPF 1/2, E = 1,400 ksi) and given a thickness of 6.75". This would represent a solid section of timber or "on edge" glulam type member. The properties of this section must then be modified to capture the additional mass of the composite timber floor and the apparent bending stiffness of the CLT and composite section. The apparent bending stiffness assigned must correspond to strong/weak axis bending and positive/negative bending. The strong and weak axis attributes can be assigned for a single property type in the software, but both "uncracked" and "cracked" properties must be defined to consider positive/negative bending. Lastly, the extents of the cracked and uncracked sections are determined by iterative analysis. It is expected that software companies will be able to develop full non-linear analysis programs to determine the extent of cracking if composite timber floor systems become more prevalent in the market. These software programs could also include sectional definition tools to easily generate the orthotropic stiffness properties of the floor system, similar to programs used today for the analysis of epoxy-resin/fiberglass or built-up carbon fiber structures. The property modifiers calculated with the "gamma method" and resulting analysis model assignments are provided in Figures 16 and 17.

Floor Section	El _{app} [kip.in ² /ft]	% of Solid	% of CLT	% of Comp,S,P
Solid Timber, 6.75" Thk	431,000	100.0%	-	-
CLT, 6.75" Thk, Strong	276,200	64.1%	100.0%	-
Composite, Strong, Positive	501,800	116.4%	181.7%	100.0%
Composite, Strong, Negative	341,000	79.1%	123.5%	68.0%
Composite, Weak, Positive	155,200	36.0%	56.2%	30.9%
Composite, Weak, Negative	112,200	26.0%	40.6%	22.4%

Notes:

1. Calculations were re-computed for a 24ft continuous span for full-scale test.

2. Longer spans will result in higher percentages of composite action.

Figure 16: Calculated Properties for Full-Scale Test Prediction

Section Name Section Notes	CTP.9.0-Uncracked		Display Color	Property/Stiffness Modification Factors Property/Stiffness Modifiers for Analysis Membrane f11 Modifier 1 Membrane f12 Modifier 1 Bending m11 Modifier 1 Bending m11 Modifier 0 Bending m22 Modifier 0 Shear w13 Modifier 1		
Type Shell - Thin Shell - Thin Shell - Thick Plate - Thin Plate - Thick Plate Thick Membrane Shell - Layered/Nonlinear		Thickness Membrane Bending Material Material Name Material Angle Time Dependent Propertie Set Time Dep	e.75 e.75 e.75 e. e. e. e.			
Concrete Shell Section Desig Modify/Show Shell I	n Parameters	Stiffness Modifiers Set Modifiers Cancel	Temp Dependent Properties	Shear v23 Modifier Mass Modifier Weight Modifier	245 245 Cancel	

Figure 17: Assignment of Mass & Stiffness Modifiers to 3D Model

Section 4: Test Program Description, Setup & Results

This section outlines the tests performed and summary of results. Refer to the report by OSU for the full documentation of tests performed and data collected.

4.1 Composite Connector Tests

The composite connector tests include (6) 2ft x 10ft long composite specimens and (2) 2ft x 10ft long bare CLT specimens for comparison. Three different types of shear connectors were tested:

- Inclined screws: SWG ASSY, VG CYL type screws
- Epoxied plates: TICOMTEC, HBV perforated metal plates
- Headed "stud rails": Nelson Headed Shear Connectors welded to steel plate

Diagrams for each type of connector are shown in Figure 18.

Each specimen was loaded with a single point load at the center of the 10ft long beam span. The specimens were loaded and resulting displacements recorded. Photographs of one typical test are shown in Figures 19 through 21. The results of the tests are shown in Figure 22. The comparison of the results to the calculated stiffness value in the previous section is shown in Figure 23.

The results show that the HBV plates provided the greatest amount of composite action with little shear slip even at ultimate loads. The VG CYL screws provided partial composite action and had consistent behavior between service and ultimate loading. The "stud rail" type connector provided a composite stiffness similar to the HBV plates at service level loading. However, these connectors had significant shear slip at higher loads and gave less predictable ultimate load behavior. These type of connectors could be studied further as the results show potential for high stiffness and the installation of the connectors was relatively simple.

The calculated stiffness values from the previous section have good agreement with both the bare CLT control specimens and the VG CYL connector tests with constant screw spacing. Calculations were also performed for an infinitely stiff shear connector and plotted for reference. It appears that the calculation methods currently available are acceptable, but could be refined to better consider the apparent stiffness of the composite section. The apparent stiffness calculations assumed no contribution from the topping slab, which may have resulted in calculated stiffnesses less than tested values.

Both the HBV plates and VG CYL screws have acceptable performance for the proposed composite-timber floor system. The choice of one product over the other would need to be determined by the engineer based on the project requirements. It is possible that both products may be used in a building where typical floor areas utilize the screws for economy and long-span/vibration critical areas utilize the epoxied plates for increased stiffness.



Figure 18: Types of Shear Connectors Tested



Figure 19: Typical Shear Connector Test Setup



Figure 20: Typical Shear Connector Testing



Figure 21: Typical Shear Connector Test Failure (Tension Lam Rupture)



Figure 22 (Figure 3.1 of [1]): Shear Connector Test Results. Red lines are bare CLT controls, Magenta line is HBV plate, Orange line is headed studs, and all others are VG-CYL screws.



Figure 23: Comparison of Results to Calculated Values

4.2 Two-way Stiffness Tests

The two-way stiffness tests consisted of (3) 8ft x 8ft panels. Each specimen utilized the VG CYL screw type connector. The panels were supported at the 4 corners and loaded to determine the relative stiffness of the panels for two-way bending. Four aspects of panel stiffness were studied:

- Positive bending (concrete in compression),
- Negative bending (concrete/rebar in tension)
- Strong axis (bottom layer of the CLT oriented in the span direction)
- Weak axis (bottom layer of the CLT oriented perpendicular to the span direction)

A diagram of the test specimen is shown in Figure 24. Photographs of the specimens are shown in Figures 25 through 27. The testing determined that the negative bending stiffness was approximately 75% of the positive bending stiffness in the strong axis, which agrees with the calculated values provided in Section 3. Little difference in stiffness between positive and negative bending was observed for the weak axis. This was likely caused by the composite screw orientation which does not provide significant composite behavior in local screw bending.



Figure 24: Two-Way Stiffness Test Specimen Diagram



Figure 25: Two-Way Stiffness Test Specimen, Prior to Casting



Figure 26: Two-Way Stiffness Test Specimen, After Casting



Figure 27 (Figure 2.17 of [1]): Photograph of Two-Way Stiffness Test



Figure 28 (Figure 3.4 of [1]): Positive versus Negative Bending Stiffness

4.3 Long-Term Deflection Tests

The long-term deflection tests consisted of (1) 4ft x 20ft long positive bending specimen and (1) 4ft x 12ft long negative bending specimen. These specimens were loaded with pre-cast concrete blocks that simulated the expected in-service loading of the floor system. Deflection data was recorded for these specimens for approximately 3 months. Refer to Figures 29 and 30 for photographs of the specimens. Refer to Figures 31 and 32 for the testing data.

The results of these tests are not conclusive. The test setup of the negative bending test may have resulted in additional deflections in the first week of loading, which may not have been the result of creep (such as cracking of the topping slab hours or days after blocks placed). The positive bending test results are more in-line with expectations. The initial deflections when weights are added is approximately 0.375". Over the duration of the next 100 days, the deflections appear to increase by another 0.375", or a 100 day long term multiplier of 1.0. According to ACI 318 [9], the long term multiplier for deflection of concrete members for the same time period is 1.0. It appears that the long term deflections are increasing at a similar rate as the ACI long term deflection curves.

The maximum long-term multiplier considered by the ACI is 2.0. The recommended long-term multiplier from the US CLT Handbook is 2.0. The results of these tests do not suggest revisions to these values for composite CLT and concrete floor systems.



Figure 29: Long-Term Deflection Specimen



Figure 30: Long-Term Deflection Specimen Test



Figure 31 (Figure 3.14 of [1]): Long Term Results for Negative Bending



Figure 32 (Figure 3.15 of [1]): Long Term Results for Positive Bending

4.4 Full-Scale Test

The full-scale test is a mockup of a typical bay floor span and adjacent bays to the natural inflection points. The full-scale test was 8ft wide and 36ft long. The specimen was loaded with a single actuator centered at mid-span which applied two equal loads spaced at 7'-6" apart applied by steel spreader beams. The back-spans of the beams were restrained from vertical movement with threaded rods tied down to the strong floor. These tie downs simulate the weight of the adjacent framing bay. The specimen was loaded incrementally to approximately 800% of the design service loading.

Photographs of the full-scale specimen are shown in Figures 33-40. The results of the test are shown in Figure 41. The comparison of the test results to the 3D Finite Element Model are shown in Figure 42.

The specimen exhibited a stiffness that was in-line with predictions based on tested and calculated stiffness values of the smaller specimens. The resulting system stiffness was 30% greater than what would be required by the building codes for non-brittle partition walls. The measured stiffness of the floor system when loaded to 100% of service loads was maintained until the floor system was loaded to approximately 400% of service loading. This is thought to have occurred due to the partial composite action of the VG CYL screws which did not full engage the concrete topping slab, resulting in fewer tension cracks near the supports. Stiffness loss was observed near ultimate loading where significant slab cracking occurred along with possible yielding of the topping slab reinforcement.

The ultimate failure occurred at approximately 82 kips which was approximately 8x (800%) of the code required service loads. The failure occurred once a "plastic hinge" was observed to form near the supports due to slab reinforcement yielding. After formation of the plastic hinge, much larger tension stresses were developed in the bottom CLT lamination which led to the failure. Ultimate failure occurred once the bottom CLT lamination ruptured.

The ultimate strength of the specimen was much larger than required by code. It is anticipated that the strength of this system will not be a primary factor in the design of these floor systems unless charring is utilized to achieve a fire rating. In that case, the strength of the system could be increased if required with additional thickness, higher material grade, or more composite action from more shear connectors or more effective shear connectors.



Figure 33: Full-Scale Test, Screw Installation



Figure 34: Full-Scale Test, Reinforcement Installation



Figure 35: Full-Scale Test, Concrete Placement



Figure 36: Full-Scale Test, Placement in Testing Frame



Figure 37: Full-Scale Test, Concrete Connection at 100% Service Loads



Figure 38: Full-Scale Test, Test at 800% Service Loads



Figure 39: Full-Scale Test, Failure of Bottom Lamination at 82 kips.



Figure 40: Full-Scale Test, State of Concrete Connection at 82 kips.



Figure 41: Full-Scale Test Results



Figure 42: Comparison of Calculated and Measured Stiffness

Section 5: Recommendations

5.1 Further Analytical Study

The calculation methods shown in this report gave reasonable predictions of measured floor behavior. However, an assumption had to be made regarding the apparent stiffness of the composite section. The shear stiffness of the topping slab was ignored due to the potential for shrinkage cracks or negative bending tensile cracks. This assumption is conservative but needs to be studied further. The following analytical studies are recommended:

- Develop analytical techniques specifically for composite CLT-concrete floor systems.
- Develop design guidelines and code provisions for composite timber floors in the United States.
- Investigate pre-composite considerations such as camber, leveling fill, and shoring.
- Investigate erection stability issues and temporary structural elements if required.
- Predict acoustic resistance properties ahead of physical testing.
- Predict fire resistance and endurance ahead of physical testing.

5.2 Further Structural Testing

The testing program determined that concrete topping slabs could be utilized to create continuous CLT floor systems and enhance the two-way spanning behaviors of CLT. However, several aspects require further testing to establish the reliability of the approach for inclusion in design codes as well as behaviors which must be considered for the design of an entire floor system including beams and columns. The recommended structural tests include:

- Further testing of composite connector types and orientations (screw inclination).
- Validating the approach with different grades and thicknesses of CLT and concrete.
- Determine the behavior of panel edge-to-edge connections.
- Validate the connection of the floor system to columns, CLT walls, and concrete walls.
- Determine the drift capabilities of the system for seismic deformations.

5.3 Non-Structural Testing

The topping slab thickness was selected to provide minimum cover to slab reinforcement and based on the composite connector manufacturer's requirements. The topping slab thickness will need to be validated along with several other non-structural issues. The recommended non-structural tests include:

- Fire Testing. Determine the fire resistance of the system for strength and connections for integrity. Testing should consider positive and negative bending aspects.
- Acoustic Testing. Determine the IIC and STC ratings of the system. Establish the effects of several common flooring systems (carpet, hardwood, tile, required underlayment).
- Durability Testing. Determine the long-term behavior of the composite system and connectors due to expected service and construction conditions. Investigate the need for sealers and/or moisture barriers.

Section 6: Conclusions

The objective of the testing program was to validate the use of concrete topping slabs to create continuous, two-way composite CLT floor systems. The testing shows that this approach is achievable and is able to increase the spanning capabilities of the CLT floor. The existing calculation techniques to estimate composite stiffness appear to be adequate for both positive and negative bending. Additional testing will be necessary before this approach can be adopted by design codes and used in the market without restriction. Project specific testing as part of a performance based design may be required in order to use this system in projects today.

References & Contact Information

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