CLT SHEARWALL DOVETAIL CONNECTION

Professor J. Lawson

August Messano & Alexander Eduardo Esser

California Polytechnic State University, San Luis Obispo

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Table of Contents

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1. Definitions

Adhesive – a substance capable of holding materials together

Bond – the attachment at an interface between adhesive and adherends or the act of attaching adherends together by adhesive

Cross-Laminated Timber (CLT) –a prefabricated engineered wood product made of at least three orthogonal layers of graded sawn lumber or structural composite lumber (SCL) that are laminated by gluing with structural adhesives

CLT Length - dimension of the CLT panel measured parallel to the major strength direction

CLT Panel – a single CLT billet formed by bonding laminations with a structural adhesive

CLT Thickness – dimension of the CLT panel measured perpendicular to the plane of the panel

CLT Width – dimension of the CLT panel measured perpendicular to the major strength direction

Ductility – measure of a material's ability to undergo significant plastic deformations before rupture

Edge (Panel Edge) – the narrow face of a panel that exposes the ends or narrow faces of the laminations

Edge Joint - a joint of the narrow faces of the laminations within a CLT layer with or without gluing

End Joint – a joint made by gluing of two pieces of laminations within a CLT layer by the ends

Face – one of the four longitudinal surfaces of a piece or panel

- **Lamination narrow face** - the face with the least dimension perpendicular to the lamination length
- **Lamination wide face** - the face with the largest dimension perpendicular to the lamination length
- **Panel face** - the face of the CLT length-width plane

Lamination – a piece of sawn lumber or structural composite lumber, including stress rated boards, remanufactured lumber, or end-joined lumber, which has been prepared and qualified for laminating

Layer - an arrangement of laminations of the same thickness, grade, and species combination laid out essentially parallel to each other in one plane

- **Longitudinal –** a layer with the laminations oriented parallel to the major strength direction
- **Transverse –** a layer with the laminations oriented perpendicular to the major strength direction, also referred to as cross layer

Major Strength Direction – general direction of the grain of the laminations in the outer layers of the CLT panel

Minor Strength Direction - perpendicular to the major strength direction of the CLT panel

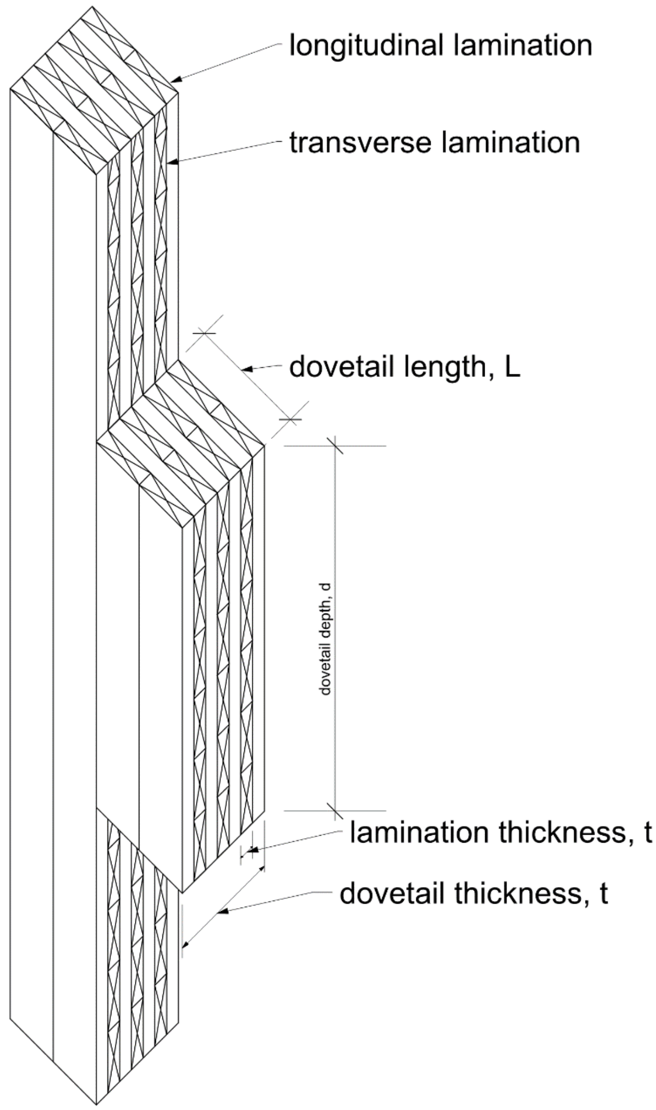

Figure 1 – Dovetail Vocabulary

2. Symbols

A_{brg} = bearing area of a single dovetail
A_v = shearing area of a single dovetail
d = depth of a single dovetail
f_b = bending stress perpendicular to face grain
f_{brg} = bearing stress parallel to face grain
f_s = rolling shear stress parallel to face grain
f_v = shear stress parallel to face grain
F_b = bending stress perpendicular to face grain
F_{brg} = bearing stress parallel to face grain
F_s = rolling shear stress parallel to face grain
F_v = shear stress parallel to face grain
M = moment tributary to one dovetail joint
n = number of transverse laminations in a single dovetail
N = total number of bearing squares on a dovetail
P =design load to a single dovetail
t = CLT wall thickness
t = test model panel or CLT panel thickness
V = shear force transferred through a single dovetail

3. Introduction

3.1 Background on CLT

Cross-laminated timber (CLT) is a large-scale, prefabricated, solid engineered wood panel. In the standard ANSI 320-18, CLT is defined to have at least three orthogonal layers of graded sawn lumber or structural composite lumber (SCL) that are laminated by gluing with structural adhesives. As an engineered wood product, deficiencies that are inherently a part of sawn lumber can be reduced and the benefits of wood can be optimized to produce the desired structural element. In most cases, CLT has an odd number of layers in order to maximize the element's capacity. For example, CLT wall panels are subject primarily to vertical loads so outer layers are oriented with fibers parallel to the load, floor panels are primarily subject to bending stresses so outer layers run parallel to the major span direction. The final outcome is a product with higher dimensional stability and load-bearing capacity compared with regular timber (Gagnon and Pirvu 2011). It can be used as a wall, floor, and roof structural element.

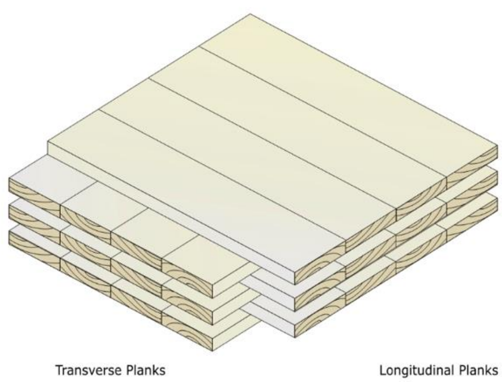

Figure 2 – Panel Configuration

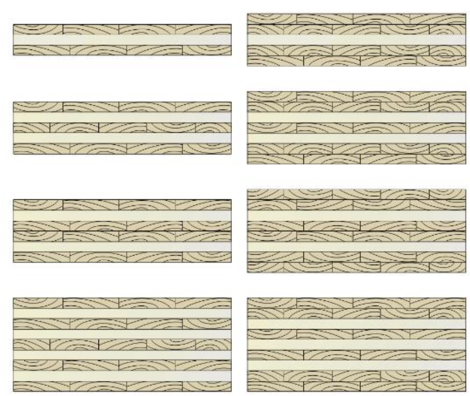

Figure 3 – Examples of CLT panel cross-sections

Cross-laminated timber was initially developed in Switzerland in the early '90's. It was then refined by Austria in 1996 to what it is known as today (Gagnon and Bilek 2018). There was a large increase in industrial use of CLT in the early 2000's, but most applications of CLT are focused on out-of-plane loading (i.e. floor and roof systems). This document explores CLT shear walls designed primarily for in-plane loading. More specifically, the focus is the use of a special type of interconnection joint for CLT shear walls. A major factor to the limited use of CLT shear walls is the absence of ductility in the connections that assists in resisting overturning. This document examines the use of dovetail joints at CLT shear wall core panel edges as a solution that may potentially lead to an increase in R-value.

The R-value, or Response Modification Coefficient, is used in ASCE 7 to define the ductility of a lateral system. ASCE 7 defines R-values for different lateral systems in Table 12.2-1. However

the current R-value of CLT shear walls is 2, which represents little ductility, and it can only be found in the Oregon Building Code. The R-value is so small for CLT shear walls because it is limited in performance by its connectors. If a strong connection can be developed so that the connection is no longer the weak link of the wall, then a larger R-value can be used.

3.2 Advantages of CLT

In this section advantages of CLT use are provided.

Structural Performance - because CLT is made up of orthogonal layers, strength can be added or reduced within an element by simply changing the lumber grade of the lamination or some geometric property to get the desired strength. This provides engineers with a solution when there are geometric parameters for a structural element rather than having to increase size of the member or use steel, concrete, or masonry.

Better Production Efficiencies - cross-laminated timber, like other wood-based products, is relatively easy to prefabricate and results in minimal manufacturing deficiencies when compared to sawn lumber structural elements.

Multistory Construction - traditionally buildings constructed from timber products are limited in building height due to structural performance limitations of timber, fire concerns, and the lightness of wood structural systems. Building codes typically limit building heights to the accessible height of the firetruck ladders available. Due to the inherent nature of thick timber members to slowly char at a predictable rate, CLT panels can maintain significant structural capacity for an extended duration of time when exposed to fire .(Gagnon and Bilek 2018). Cross-laminated timber is comprised of multiple layers of typical 2x sawn lumber with no voids within and so is inherently a lot heavier, it is contains a lot more strength. An increase in building weight and strength allow buildings constructed from CLT to be taller than timber buildings constructed previously.

Reduced Building Weight - cross-laminated timber is a proposed construction material for buildings with more than 5 floors so it must be evaluated with respect to steel and concrete, the standard building materials for large multi-story structures. Cross-laminated timber shear walls are substantially thicker and heavier than traditional stud shear walls but are considerably lighter than concrete or steel structures. The unit weight for typical structural lumber is 35 pcf, concrete weighs about 150 pcf, and steel weighs about 490 pcf. A lighter building will decrease the seismic weight and reduce design loads. Smaller design loads will decrease member sizes and the size of footings.

Miscellaneous - as a wood-based product, CLT can be continuously produced with a very small carbon footprint and so is a sustainable construction material. Another advantage of CLT is that it results in a reduction in labor demand because products are manufactured in panels so labor is primarily reduced to panel connections and erecting the large panels by crane. Cross-laminated

timber can also be constructed faster than alternative materials and reduces project costs. CLT also allows engineers to span elements longer than sawn lumber products allow and thus permits the development of large open spaces favorable to architects. Additionally, CLT has a better fire rating than typical timber products because multiple layers take longer to burn through and the adhesives used at face gluing can be used to slow the burn rate.

3.3 Disadvantages of CLT

Connections - existing CLT products are primarily being connected using metal hardware but most of hardware is inadequate to transfer larger loads that are associated with larger structures. A standard CLT connection has not been established that is capable of transferring large loads and so CLT products are limited to smaller buildings with small design loads.

Standards - cross-laminated timber was exclusive to Austria in the '90s and gained popularity in Canada and the around 2008 and the U.S. a few years later. Due to limited applications, very little testing has been done and testing is what drives design standards and specifications. Without the publication of public design standards then CLT products will be limited in acceptance by governmental review agencies and hence limited in applications.

Production - one of the principal reasons for using wood-based products is because it is renewable. However, if CLT products becomes very popular, supply will increase to meet the demand until potentially supply cannot sustain the demand and the use of CLT will be limited by its availability. If the sustainable managed forests were exhausted of lumber and there was no supply chain then the construction industry would have to return to steel, reinforced concrete, or masonry as building materials. However, if lumber saw a spike in production due to increased use then steel and concrete production would become diminished and the quality of the material may become less so that when a sudden increase in demand comes, engineers may be forced to use less quality material(and a lot more) which may result in a very expensive project and may be catastrophic in the event of an earthquake.

Inefficiencies - Another flaw with using CLT is it uses a lot more material less efficiently. For example, only the major strength axis laminations are used to determine the compression capacity of the shear wall and all the transverse laminations are neglected. The result is the effective area used for transferring compression and tension forces is only about sixty percent of the total cross-section area.

3.4 Scope of Research

Most current applications for cross-laminated timber are for floor and roof systems while it is less common to use CLT for wall systems. Even when it is used for wall systems, CLT walls elements are typically only bearing walls. One of the goals of this research is to apply what is learned so that CLT can be used more effectively as a shear wall system.

Cross-laminated timber shear walls have been avoided in tall buildings mainly because a viable connection for multiple panels has yet to be established. Traditionally, timber shear walls have been joined with some sort of metal joinery hardware but they are not adequate to transfer large panel-to-panel shear forces such as those created by multiple panels undergoing overturning. John Lawson, Associate Professor at Cal Poly San Luis Obispo, has proposed an interlocking dovetail joint as a possible connection for the vertical edge joints of multiple cross-laminated timber shear wall panels.

The dovetail joint has its origin from ancient Egyptian (3000 B.C.) cabinet workers that became the symbol of modern refined cabinet making (Stichting, E., 2018). The nineteenth century left a legacy of patented processes that demonstrated how to create dovetails by skillful hand workmanship, using only a chisel, a handsaw, and a hammer versus modern processes that require a jig and router combination. The dovetail joint is a fan-shaped joint on a board or member, and contains pins on one timber element and interlocking tails on the connecting element. It is a tapered form of simple finger joints that resist twisting and increases the long-grain connection. Different dovetail forms exist such as through, half-blind, secret mitered, and sliding dovetails. Each of these different dovetails have a specific advantage, however, for this research the through dovetail has been used since it is the most basic method and the simplest to construct. The through dovetail is used most commonly for joining corner of frames, cabinets and boxes. However, dovetail connections may also be used for in-line connections. The key difference is that the pins and tails will only be tapered in one plane rather than at corners where they are tapered in two perpendicular planes.

A dovetail connection may be desirable because it reduces labor for connections to joining the dovetails on site. Additionally, CLT shear walls can potentially provide engineers a much stronger timber product than is typical. Dovetail joints for CLT shear walls would be favorable on projects that have long shear wall lines comprised of multiple wall segments, such as warehouses. Also dovetail joints would be favorable where CLT shear wall cores are used, providing an easy way to assemble walls perpendicular to each other.

4. Purpose

The purpose of this research is to explore the dovetail joint concept as a viable connection for the vertical edge joints of cross-laminated timber shear walls cores. Primary objectives are to determine if the dovetail joint can develop enough strength to be used and evaluate the constructability of the joint. To be able to analyze the strength of the connection, it is first important to identify potential limit states of a dovetail timber joint and then calculate the capacity of the different limit states. To identify potential limit states, small scaled-down specimens of idealized shear walls made of plywood were constructed using dovetail joints as the only connection type and then the specimens were tested, in an attempt to force specific limit states to occur for observation, using a Universal Testing Machine. Plywood was used because it is the most similar timber product to cross-laminated timber in that it consists of glued layers with alternating grain orientation. The key difference in plywood is the layers, or plies, are

single, very thin veneer sheets while CLT layers consists of multiple sawn lumber laminations with no edge gluing. It was predicted that plywood limit states would resemble the predicted limit states of CLT. The models were also used to identify potential full-scale constructability issues of the dovetail joints.

5. Analysis

5.1 Full-Scale Analysis Summary

In order to successfully identify limit states of the dovetail joint, it was important to accurately calculate the capacity of the joints. The goal of the analysis was to accurately determine design limit states of CLT dovetail joints so that "allowable" design strengths can be used for a real project. Full-scale dovetail analysis was completed by hand calculations and shall conform to standards ANSI/APA PRG 320-18 and CLT Handbook (U.S. Edition). Limit states associated with bearing, shear, rolling shear, and bending were evaluated analytically. Tension behaviors were ignored for this research because tension test were not conducted. For each limit state the allowable load for a single dovetail was calculated. The limit state with the minimum allowable load was determined to govern the dovetail design for the specified depth.

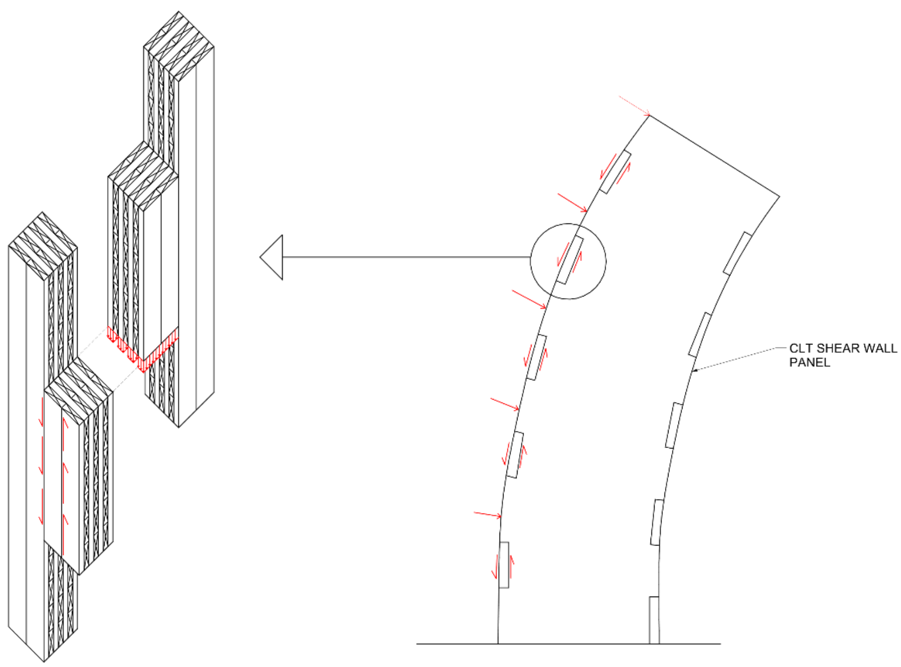

Figure 4 – CLT shear wall core loading

5.2 Limit States

5.2.1 Bending Limit State

The first limit state discussed is in-plane bending failure. Flexural failures are characterized by splitting across the grain of transverse laminations due to the development of tensile bending stresses. Bending stresses are caused by the transfer of vertical loads at some eccentricity to the joint. The moment of inertia of the joint, which is determine from the dovetail joint geometric properties, is directly associated with flexural failures.

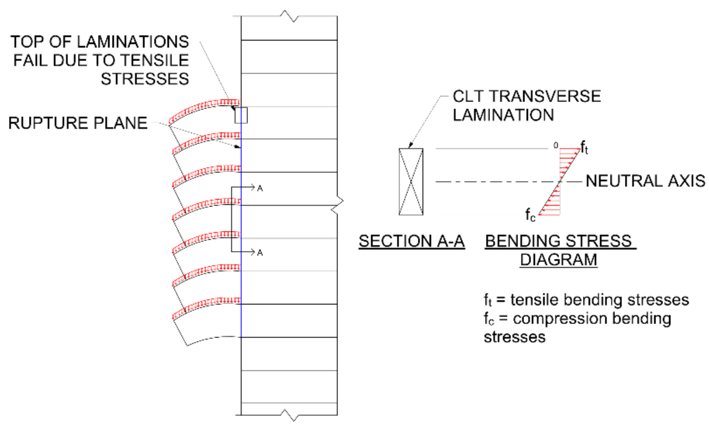

Figure 5 – Bending due to tension in face lamination of CLT floor panel

5.2.2 Shear Limit State

The second potential limit state discussed is horizontal shear failure due to in-plane loading. Horizontal shear failure is characterized by splitting across the grain of transverse laminations. Shear stresses develop due to differential normal stresses. For a rectangular cross-sectional dovetail joint only the cross-sectional area of the joint affects the shear stresses.

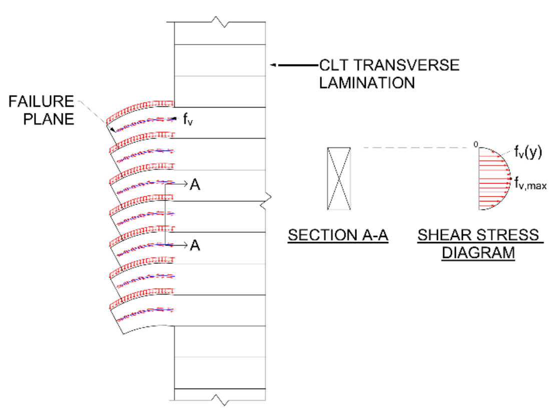

Figure 6 – shear stress due to bending on an inclined plane

5.2.3 Bearing Limit State

The third limit state discussed is bearing failure. Bearing failure is characterized by crushing of laminations with grain parallel to the load. Bearing stresses develop from the transfer of gravity or vertical seismic loads from dovetail joints of one wall to joint surfaces of an adjacent wall. The only properties affecting bearing failures are the horizontal plane of the dovetail joint that acts as the bearing area.

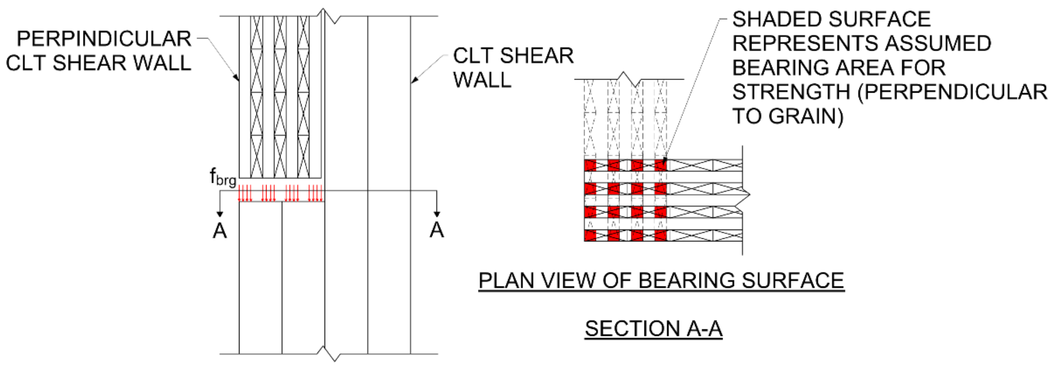

Figure 7- Bearing failure in 5-layer CLT floor panel

5.2.4 Rolling Shear Limit State

The fourth limit state is rolling shear failure. Rolling shear is defined as shear stress leading to shear strains in a plane perpendicular to the grain direction. Due to the very low rolling shear stiffness of timber significant shear deformations may occur. Rolling shear failure is characterized by the development of splits perpendicular to grain.

To provide optimal strength in the connection, dovetail joint dimensions were chosen to minimize the gap between limit states. If the dovetail depth is too long, then then the total number of dovetails (and bearing area) will be reduced and governing limit state would be bearing. If too dovetail depths are too short, then bending failures tend to be the dominant limit

state. The objective of the analysis was to determine the optimal depth of the dovetail in order to balance out the limit states and maximize the capacity of a dovetail joined CLT shear wall edge.

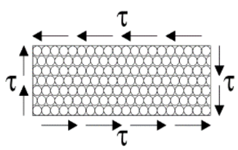

Figure 8 – Rolling shear stress on timber cross-section

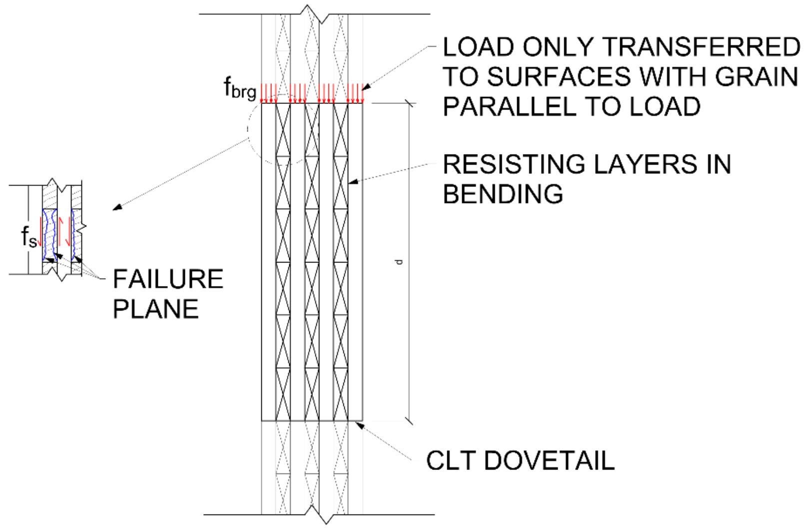

Figure 9 – Rolling shear failures on 3-layer CLT floor panel

5.3 Analysis Equations for Full-Scale Design

5.3.2 – CLT Dovetail Analysis

From *ANSI/APA PRG-320 TABLE A1*, the ASD Reference Design Capacities for laminations with an E2 CLT Layup were provided and are given below:

- E2: 1650f-1.5E Douglas fir-Larch MSR lumber in all longitudinal layers and No.3 Douglas fir-Larch lumber in all transverse layers.

F_b = 525 psi, F_v = 180 psi, F_s = 60 psi, F_c = 1700 psi

<u>Rolling Shear</u> – see *Figure 9*

To prevent failure $F_s \geq f_s$ [5.3.2-1]

$f_s = V/td$ [5.3.2-2]

where t = CLT wall thickness, d = dovetail depth

Each longitudinal layer will transfer shear equal to ¼ of the load to the joint because the parallel layers transfer all bearing loads and there is 4 parallel laminations. The load is then transferred through the face glue joints to the transverse laminations so design shear V is,

$V = P/4$

Because the longitudinal layers at the faces only have one face to transfer the load, the outside layers will transfer 1/4P while the interior layers will only transfer half of that, 1/8P. Now using equation 5.3.2-1 and substituting 5.3.2-2 the following relationship results:

$F_s = P/4td$ [5.3.2-3]

Solve for l,

$d = P/4F_st = P/(4*60psi*9.625in) = P/2310$ [5.3.2-4]

<u>Bearing</u> – see *Figure 7*

$F_c \geq f_c$ [5.3.2-5]

$f_c = P/A_{brg}$ [5.3.2-6]

$A_{brg} = t_{brg}^2 \times N_{brg} = (1.375in)^2 x16 = 30.25\ in^2$ [5.3.2-7]

Substituting 5.3.2-6 into 5.3.2-4 result in:

$P = F_cC_DA_{brg} = 1700psi \times 1.6 \times 30.25in^2 = 82280\ lbs$

Substituting the value for P into 5.3.2-6 solve for d,

d = 82280lbs/2310 = 35.62in., use d = 36 in

<u>Bending</u> – see *Figure 5*

$F_b \geq f_b$ [5.3.2-8]

w = P/nL [5.3.2-9]

Bending will be transferred through transverse, or horizontal, laminations and the load P will be distributed equivalently to each transverse lam (18 total).

w = 82280lbs/(18 x 9.625in) = 475 lb/in

$M = wL^2/2 = 475lb/in \times 9.625^2\ in^2/\ 2$

= 22002 lb-in

$f_b = M/S$ [5.3.2-10]

$S = 1.375in \times (5.5in)^2 / 6 = 6.93in^3$

Calculate F_b using NDS adjustment factors for sawn lumber

$F_b' = 1.3xF_bC_DC_F$

$F_b' = 525psi \times 1.3 \times 1.6 \times 1.15 = 1255.8\ psi$

$f_b = 22002lb\text{-}in / 6.93in^3 = 3175\ psi$

$f_b \geq F_b$ … joint is overstressed in bending so bending governs deign load per joint for d = 36in

$P_{allow} = 2F_bSn/L = [2(1255.8psi)(6.93in^3)(18)]/9.625in = 32550$ lbs/dovetail

<u>Shear</u> – see *Figure 6*

Shear associated with the bending must also be checked

$F_v \geq f_v$ [5.3.2-11]

$f_v = 1.5V/A_v$ [5.3.2-12]

$A_v = A_{lam}$ x number of transverse lams in connection = 1.375in x 5.5in x 18 = 136.13 in^2

Substitute 5.3.2-12 into 5.3.2-11 and solve for V

$V_{allow} = F_v \times C_D \times A_v / 1.5 = 180psi \times 1.6 \times 136.13in^2 / 1.5 = 26137$ lbs or 26 kips

Allowable shear load is 26 kips < 33 k so shear governs design for d = 36 in

P_{allow} = 26 kip/dovetail

6. Analysis Results

6.1 Design Summary

From the CLT dovetail analysis above, rolling shear was evaluated first and the allowable load was determined as a function of the dovetail depth. Then, because the bearing area of the dovetail is known the allowable bearing load to the dovetail was calculated as approximately 82 kips and was used to determine the required dovetail depth, d, to adequately transfer rolling shears. The required depth was 35.23 in. but 36 in. was used to simplify calculations. For a depth of 36 in. and dovetail design load of 82 kips, the dovetail was overstresses in bending so then the allowable bending load per dovetail was calculated to be 32 kips. Finally, horizontal shear was evaluated and the allowable load per dovetail was calculated as 26 kip. It was determined that for a dovetail depth of 36 in. for a 7-layer CLT shear wall the allowable load to a single dovetail was 26 kips and was governed by horizontal shear. The horizontal shear capacity is conservative because the vertical laminations are glued to the failing horizontal lamination faces and will resist horizontal shear failure. The extra capacity was not calculated because it is not clear how much the shear strength the vertical laminations would add and any prediction would need to be confirmed via testing or more complex analysis is required.

6.2 Design Assumptions

6.2.1 Torsion Negligible

Torsion on the individual dovetail pieces was assumed negligible before any testing was conducted. Torsion was primarily neglected because it was assumed all dovetail joints would evenly distribute bearing pressures. However, torsion on individual dovetail pieces was observed to be present and rods were required to provide confinement and prevent further torsion. Subsequent tests proved the rod to be effective in preventing torsion at dovetail pieces.

6.2.2 Compression Perpendicular to the Grain Negligible

Compression perpendicular to the grain in transverse laminations was ignored in all analysis because it was assumed laminations with parallel to grain surfaces are so much stiffer that transverse laminations will experience negligible compression stresses. If bearing on transverse laminations actually proved to be a problem, a thicker wall with more layers must be used.

6.2.3 Bearing Pressures Uniformly Distributed

It was assumed bearing pressures at all dovetail joints were distributed evenly on parallel to grain contact surfaces (see *Figure 6*).

6.2.4 No Edge Gluing

Edge gluing was ignored because ANSI/APA 320-18 states that industry standard is no edge gluing unless higher fire rating is required. When edge gluing is neglected, then bending and horizontal shear stresses are calculated using individual horizontal lamination cross-sectional

properties but if edge gluing is provided all the laminations act as a composite cross-section so the bending and shear stresses will be smaller than laminations with unglued edges. If laminations contain edge gluing then cross-sectional properties should be determined based on the composite section of all effective horizontal laminations within the dovetail depth.

6.2.5 Adhesive Stronger than Laminations

Adhesives shall meet requirements of Section 12.1.2 of ANSI A190.1. One of the requirements is adhesive shall be used with greater strength than CLT laminations. Check adhesive specifications for available strength, if adhesive is not adequate an alternative glue with the desired strength shall be used or an alternative design procedure must be used.

7. Test-Specimen Analysis

Additional analysis was completed for the small, scaled-down test specimens that aimed to predict loads that will cause failure in the test specimen dovetail joints. Analysis for test specimens was also conducted to determine if the testing machine was capable of producing the required failure loads.

7.1 Test-Specimen Analysis Equations

Note: Reference design values were taken from *HANDBOOK OF FINNISH PLYWOOD*. The following equations were used to calculate design stresses:

$f_{brg} = P/t^2$ [7.1.1-1]
$f_s = V/A_v$ [7.1.1-2]
$f_v = 1.5V/A$ [7.1.1-3]
$f_b = M/S$ [7.1.1-4]
$M = Pt$ [7.1.1-5]
$S = td^2/6$ [7.1.1-6]

Figure 10 – test specimen with 2.5" dovetail depth

Reference design values:
From *Table 3-2. Birch plywood* ,
$F_c = 27.2\ N/mm^2 = 3944$ psi
From *Table 3-2. Birch plywood*,
$F_b = 34.1\ N/mm^2 = 4944.5$ psi
From *Table 3-7. Birch plywood*, $F_v = 9.5\ N/mm^2 = 1377.5$ psi
From *Table 3-7. Birch plywood*, $F_s = 2.67\ N/mm^2 = 387.15$ psi
To account for load duration and safety factors, each design value shall be multiplied by a factor, $k = k_{mod}/\gamma_m$. k_{mod} is the load duration factor and γ_m is a safety factor. From the *Handbook of Finish Plywood* $k_{mod} = 1.1$ and $\gamma_m = 1.3$ so,
$k = 1.1/1.3 = 0.8462$

Rolling Shear – Test Model

$F_s \geq f_s$ [7.1.1-7]

$f_s = P/A_v$, where P is distributed evenly to the 7 vertical layers

$A_v = td$ [7.1.1-8]

$P_{allow} = 7F_sA_v$ [7.1.1-9]

Note : P_{allow} is the allowable load per dovetail

Bearing – Test model

$F_{brg} \geq f_{brg}$ [7.1.1-10]

$f_{brg} = P/t^2$

$P_{allow} = F_{brg}t^2$ [7.1.1-11]

Horizontal Shear – Test Model

$F_v \geq f_v$ [7.1.1-11]

$f_v = 1.5P/A_v$

$P_{allow} = 0.67F_vA_v$ [7.1.1-10]

Bending – Test Model

$F_b \geq f_b$ [7.1.1-11]

$f_b = M/S$ where

Section modulus, $S = td^2/6$ and design moment at each dovetail, $M = Pt$

$P_{allow} = F_bS/t$ [7.1.1-14]

Table 7-1: Test-Model Predicted Loads

			Reference Design Values (psi)				Predicted Design Loads (lbs) per dovetail				Test Loads per dovetail (lbs)
Dovetail length	A_v (in^2)	A_{brg} (in^2)	F_c	F_b	F_v	F_s	P_c	P_b	P_v	P_s	P
0.5”	0.375	2.81	3337	4184	1166	328	1877	174	292	861	522
2.5”	1.875	1.13	3337	4184	1166	328	1877	4358	1458	4305	3966
5”	3.75	0.563	3337	4184	1166	328	1877	17433	2915	8610	3075

8. Experiment and Testing

Experimental test specimens were created to investigate potential change in limit states while varying dovetail dimensions as well as evaluating construction issues that have not been recognized. In order to create several variations in the experimental model dovetails, limit state load predictions were computed for the plywood test models.

The plywood test models were 1 $ft.^3$ and ¾ in. thick with 13 layers. A test model thickness of ¾ in. was chosen because it is the thickness on a 1:12 scale of the 10 in. CLT wall panel (7 layers)

investigated in this report. The depths of the test models were also chosen based on a 1:12 scale of the CLT dovetail depths associated with different limit states. For example, on a 1:1 scale it was predicted that a 30 in. or 2.5 ft. deep dovetail depth would lead to CLT shear failures, so on the scaled down model a 2.5 in. deep dovetail was used for the first plywood model, shear failure was also the predicted failure mode for the test specimen with a 2.5 in. long dovetail. It was then desired to investigate governing limit states for longer and shorter dovetails. It was predicted that ½ in. long dovetails would result in bending failures and 5 in. long dovetails would result in bearing failures, both depths at the 1:12 test specimen scale. The following sections give a description of the conducted experiments and predictions of the specimen's allowable load capacity for the purpose of determining the appropriateness of the setup and equipment. The experiment contains four different models with varying dovetail sizes that were tested to comprehend their failure modes. An additional five-story scale model of an elevator shear wall core was constructed as a proof of concept and also to ascertain any constructability flaws.

8.1 Small-Scale Specimen Testing Method

In order to successfully evaluate the potential structural behaviors of a CLT shear wall core it is crucial to construct precise dovetail connections to ensure strong correlation between the test specimen's behavior and what is expected in a full-scale building. Ultimately, the goal in constructing dovetail joints is to prevent any gaps between the dovetail surfaces. Since the dovetails were traditionally constructed by hand (hand saw and chisel), it was decided to utilize a commercially available dovetail jig and mechanical wood routers due to limited construction time and higher precision and accuracy. In the actual timber industry, a full-scale panel joint would be constructed by using CNC (Computer Numerical Control) machines. A CNC machine converts the design produced by Computer Aided Design software (CAD) into numbers that can be considered as coordinates of a graph which control the movement of the cutting device.

To understand the different failure modes of the dovetail connections, the specimens can be either tested in compression or tension along the corner edges. In this research, two opposite sides of the specimens were tested in compression by using a universal testing machine. Therefore, all the specimens are cut approximately one inch shorter on top of two walls facing each other. The remaining two walls have to be shortened at the bottom, so that the entire applied load is solely taken by the dovetails at the four corner. The applied load increases until complete failure of the dovetails are visual and the assembly was unable to withstand any additional load.

Figure 11 – Universal Testing Machine; Testing Specimen in Compression

The failure load was predicted in the test model analysis for limit states of Baltic Birch plywood. The primary objective for predicting the failure load was

to consider how much to vary the dovetail design between the three models to achieve different limit states, as well as compare the total load expected to fail it with the largest load that the testing apparatus could apply.

8.2 Testing Equipment

The following tools and equipment were used to build the specimens:

- **Wood Router** is a hand power tool that hollows out an area in relatively hard wood, They are mainly used in woodworking, especially cabinetry for corner connection. Different router bits are used for different shapes.
- **Dovetail Jig** is a metal template that allows to construct different dovetails more efficiently and quicker by using it with a wood router.
- **Router Bit** is an attachment to the wood router that come in different sizes and shapes. For these specific specimens two different router bits are used: tapered bit (17/32”-7 degrees) and (13/32”).

Figure 12 – Wood Router power tool

Figure 13 – Dovetail Jig

Figure 14 – Tapered bit (17/32”-7 degrees)

Figure 15– Straight bit (13/32”)

8.2.2 Equipment Setup

Before test-specimen models are constructed, a few things should be considered to guarantee accuracy of the joints:

1. For both wood routers (with each different bit), calibrate the center of the bit with a centering pin and install the template guide that will protect the router bit from touching the dovetail jig.
2. For higher accuracy and a cleaner cut, only new wood router bits should be used.
3. Verify that the power tool used for cutting the plywood is cutting exactly perpendicular since the dovetail jig is most effective if all components are perpendicular to each other.

Figure 16 – Using Centering Pin

4. Use higher quality plywood (Baltic Birch) ensures better results since the router will tear out little veneer layers of the plywood.
5. Always use a sharpened pencil and wear protection glasses and ear protection!

8.3 Construction Process

The following procedure explains every step to create a 1'x1'x1' box with pure dovetail corner connections out of ¾" Plywood:
1. Create two identical 3"x4"x16" pieces out of any low cost wood species. However, it is important that both pieces are planned to an exact perpendicular rectangular shape.
2. Center and screw the dovetail jig on top of one of both wood pieces. After the first trial, the jig's location can be adjusted minimally due its slotted screw holes.
3. Cut four identical 1'x1' boards out of the plywood sheet
4. Mark the thickness of the plywood on one edge to adjust the depth of both router bits
5. Clamp the dovetail jig between two 1'x1' boards. Verify that both boards are at the same height. For numerous repetition, it is recommended to screw a small piece of wood as stop collar.

Figure 17 – Clamping dovetail jig between both boards (Step 5)

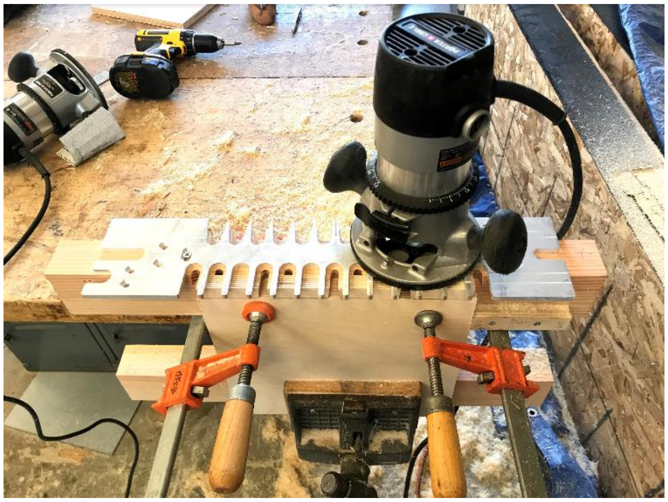

Figure 18 – Routing along dovetail jig (Step7-8)

6. After deciding the dovetail size, mark clearly what section has to be routed to avoid unwanted mistakes. The jig allows ½" increments to size the dovetails.
7. Use first the router with the tapered bit (17/32"-7 degrees) and cut out the side of the jig that is NOT tapered.
8. Use the second router with the straight bit (13/32") and cut out the side of the jig that is tapered.
9. To avoid mistakes, always check that opposite side matches the dovetails
10. To prevent minor tearing out of plywood, move the router slowly from left hand side to right hand side (against circular motion of router bit)
11. Unclamp the jig and hammer it softly to the right hand side until the teeth of the jig hits the center of the unrouted voids to cut out the remaining parts and clamp it back together.

12. After finishing with routing, clean up lightly the connection with sandpaper and put the corner pieces together.
13. If the dovetails are too loose or tight, loose up the screws of the jig and adjust delicately in a parallel motion up or down. Be aware that the several trials are needed to achieve the perfect tightness of the dovetail connection.
14. If dovetail jig is calibrated, repeat steps for all four corners.

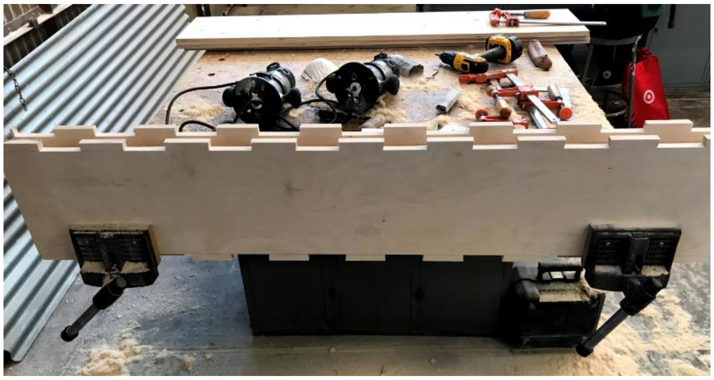

Figure 19 – Final result after removing dovetail jig. Dovetail offset is clearly visual.

9.Experiment Results

From the testing done, it can be concluded that the limit states of dovetail joints vary as a function of the dovetail depth. Extremely long dovetail depths result in a bearing failure while very shallow depths result in bending failures.

9.1 Test I

The first test specimen was constructed with 2.5" deep (see *Figure 19)* dovetails and had two dovetails at each wall segment intersection, the model had a total of 8 dovetails. From *Figure 20*

Figure 20 – Test 1 failure mode

Figure 21 – Test 1 Dovetail failure mode

and *Figure 21* below, it can be observed that failure modes are characterized by a combination of rolling shear and bearing. The bearing failures are marked by the crushing of the layers at the top of the dovetail. Rolling shear failure is characterized by the delamination of the adjacent plywood layers. Dovetails also were observed to slide in Test 1, which led to the development of a confining element for subsequent tests.

9.2 Test II

Two specimens with ½" dovetail depths were tested in the second test, one with confining rods and one without them. The confining rods were added after sliding at the dovetails was an issue with the first test model. Failure modes of the model without confining rods was marked by torsional failures while the test model with confinement failed in a bending failure of the dovetail, as is observed in *Figure 22* and *Figure 23* below.

Figure 22 – Test 2 (without rod) dovetail failure mode

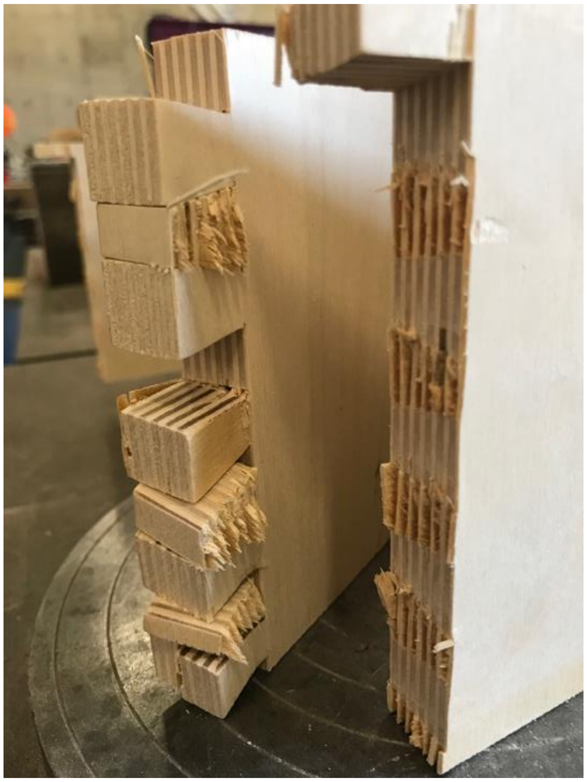

Figure 23 – Test 2 (with rod) dovetail failure mode

9.3 Test III

One specimen with 5” deep dovetails was tested in Test III. Only one dovetail was at each wall intersection for a total of four dovetails to transfer the test load. Test III represented failure behaviors that result from extremely deep dovetails. By using deeper dovetails, the total sum of bearing areas of the dovetails is reduced while the increase in depth increases the dovetails’ bending, rolling shear, and horizontal shear capacity. It was predicted that dovetail depths around 3” and deeper would fail in bearing and this was the case as can be seen in *Figure 22*. The threaded rods and nuts, as seen in *Figure 22*, did not take any load but were simply installed to hold together the assembly by joining and confining opposite sides.

Figure 24 – Test 3 dovetail failure mode

9.4. Full Scale and Test Model Correlations

The CLT dovetail capacity analysis was used to determine the optimal depth of the dovetail to prevent one limit state from being extremely weak by balancing the connection’s design to maximize the strength of all limit states collectively. The optimal depth was calculated to be 36” and so a 30”, or 2.5”on the test model scale, was chosen for the first test specimen. A dovetail depth of 36” (3” on test model scale) was not used because the jig used for the dovetail fabrication could not precisely create 3” deep dovetails but could cut 2.5” and 3.5” deep dovetails. From the analysis equations, it was predicted that larger depths would be marked by bearing failure because the number of dovetails was reduced and so the bearing area available was reduced and larger bearing stresses resulted. This is exactly what was observed with the small-scale model in Test III, which had the model with the deepest dovetail. It was also predicted in the analysis that as the dovetail depth is reduced it will be more susceptible to horizontal shear, rolling shear, and bending failures, with very shallow dovetails predicted to fail in bending. The 2.5” failure mode in the analysis was predicted to be governed by shear. The predictions made from the analysis were corroborated by the failure modes observed in tests II and test III, thus it can be assumed that the full-scale limit-state predictions have some accuracy.

10. Constructability and Feasibility

10.1 Importance of Constructability

Constructability and feasibility need to be considered when examining dovetail joints as a possible connection for cross-laminated timber because if the connection requires a lot of time to manufacture or a lot of time to erect then the construction process for a project is delayed. Additionally, for multistory structures with CLT shear walls as the only lateral system the delay in construction could be critical and costly such that CLT shear walls are not an economical

option. Finally, if the joint tolerances are such that it cannot be constructed in a way that can properly transfer the design loads through the joint then the dovetail joint concept would be unreliable and undesirable.

10.2 Construction Issues and Solutions

The primary issues that arise with the use of dovetail joints with CLT shear walls are related to the manufacturing of the joint in the shop and joining the panels together in the field. A major concern with using dovetail joints is if one dovetail pin or tail makes contact before another above or below, that joint will take a disproportionate load compared to the others and potentially be overloaded. The overloaded joint could potentially experience larger design stresses than predicted and could lead to early failure at that joint. If the two meeting surfaces of a pin and tail do not match well, then the distribution of the pressure is uneven across the tooth surface. Uneven pressure distribution could cause uneven internal distribution of rolling shear or horizontal shear, creating early failure. Also, uneven pressure distribution may result in an inclined bearing plane and permit walls to slide out of the dovetail joint. In order to get optimal structural integrity from the dovetail joint the joints of adjacent walls must sit flush with one another and manufactured with very small tolerances. A solution to non-uniform bearing in the testing setup was the connection of parallel walls. Parallel walls were connected by bolting four metal connecting rods perpendicular to the walls, two near the top and two near the bottom. This adjustment led to the development uniform bearing stresses and the prevention of out-of-plane sliding at the joints.

In the first test (2.5” deep dovetails) of the small-scale test specimens, plywood segments were observed to slide out of the dovetail connections. This revealed a significant construction element that may need to be considered for full-scale design as an unpredicted limit state appeared. It was predicted that for 2.5” deep dovetails the failure mode would be shear, however bearing failures were observed to be the governing limit state. Shear failures in the small-scale test specimens were not observed because the plywood segments slid out of the dovetail connection and shear stresses were not able to fully develop.

10.3 Assembly Issues and Solutions

10.3.1 Transportation

Before the design of a CLT structure, one has to consider the practicability of transporting the CLT elements to the construction site and investigate if the different dimensions allow the CLT panels being transported successfully. In the United States the average transportation dimension limits of a delivery vehicle that does not require any special oversize permits, is approximately 60 feet long and 10 feet tall. Commonly, the majority of CLT elements are being transported by flatbed semi-trailers, which allows to load the CLT panel onto the entire length of a 60 feet trailer. Consequently, it is crucial to inspect the exact transportation route since the flatbed semi-trailer has a turning radius restriction that imitates certain streets and traffic.

10.3.2 Lifting and Handling CLT Panels

After transporting the CLT elements to the destination, they must be placed into their final location with a certain type of crane. Usually the location and circumstances of the construction site dictate the systems and techniques being used. Additionally, time and safety are of paramount importance because they directly influence the client's budget and more importantly, it can lead to fatal accidents on the construction site. Thus, it requires foresighted planning and cautious preparation to avoid any type of incident during lifting CLT panels, especially for tall structures.

The most common method for placing vertical CLT elements is simply to drill a hole through the panel and pull a flexible sling, strong textile rope or a type of steel chain that is calibrated (for the permitted working load) and validated. Since that drilled hole is close to the top of the CLT wall, it does not impact the structure performance and therefore is not analyzed any further in this report. After placing the CLT panel, the lifting hole will be most likely be filled with a type of expanding foam.

Figure 25 – Placing CLT member vertically with hole and sling

10.3.3 Assembly

During building the to-scale CLT elevator core model, we confronted several issues and came up with possible solutions. One big question for a contractor is how to install and assemble the four CLT shear walls together. In industry CLT shear walls have been simply butt-jointed with screws which does not create as many constructability issues as having pure dovetail connections. Therefore, we came up with a possible solution of inserting a steel cable through the CLT element by leaving out a 2-by lumber during manufacturing that creates a horizontal channel. The steel cable can be installed before transportation and would be ready to use on site. The same steel cable, which is threaded at the ends, must go through the adjacent corner dovetail and allows the CLT core walls to be confined. Below, the complete assembly can be seen broken up in different steps. First, the two walls facing each other, with the horizontal installed steels rods in the interior of the wall, are placed in their exact location with temporary bracing. Secondly, the other two walls are lifted into place, perpendicular to the first two placed walls and connected to the horizontal steel cable. Since the end of the steel cable is threaded, the contractor can use a hydraulic jack device to tighten the walls together. For safety, all the walls should be temporarily braced.

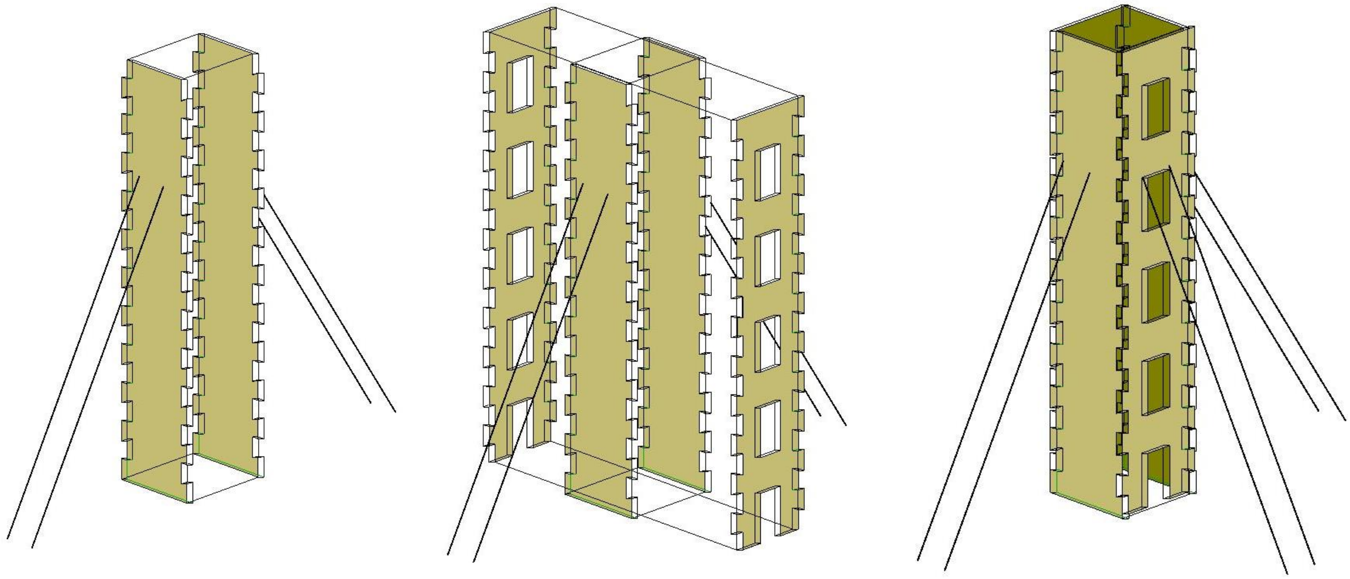

Figure 26 – Possible solution for assembly steps of CLT shear walls with temporary bracing

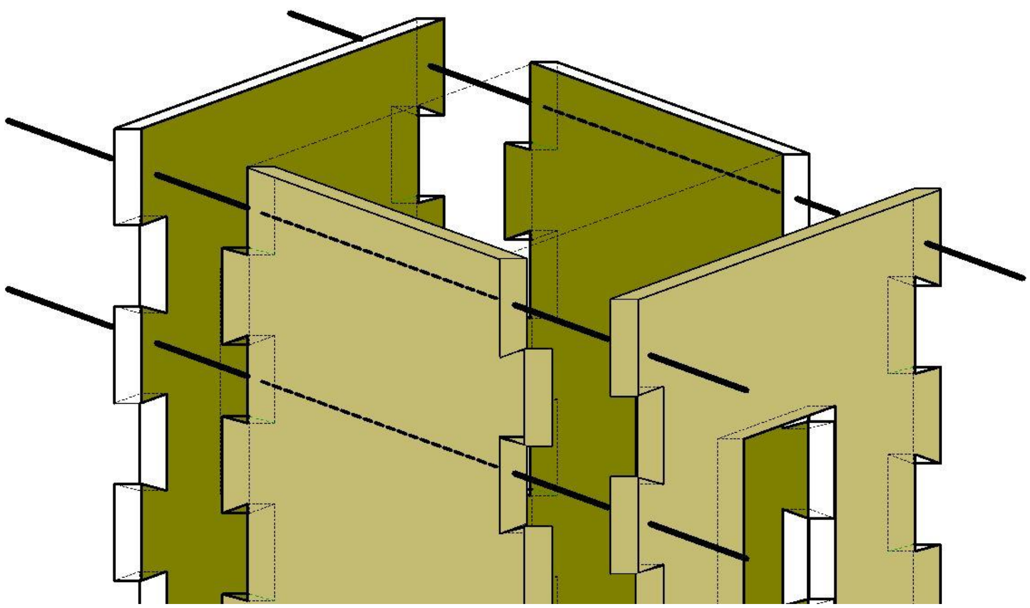

Figure 27 – Steel cable penetrating CLT shear wall that pulls all four panels together and provides

10.3.4 Temporary Protection against Weather

If wood-based material is not installed directly after arriving at the construction site, it should be carefully organized where to store the elements (stacking elements to match installation sequence) and possibly protected against rainy weather condition. However, since the CLT

panels consist of perpendicular layers of 2-by members, it will reduce shrinking and is therefore not as delicate as a single wood member.

11. Conclusions and Recommendations

11.1 General Conclusions

As cross-laminated timber has become an increasingly popular construction material, its use as a shear wall element has also demanded attention. Primary obstructions to the use of CLT shear walls have been the lack of an economic connection type that does not compromise the structural integrity and has the robustness that CLT shear wall panels deserve. Dovetail connections provide a great option for the connection of CLT shear walls. With more experimentation, the optimal dovetail geometry can be further developed. The small-scale testing done in conjunction with this report proved that very deep pins and tails will result in bearing failures at the joints. If the depth of the pins and tails is too short, the results from tests show that the dovetail will fail in bending along the neck of the joint. In order to duplicate the results of this report it is important to choose the correct geometry of the test-specimen.

If care is not taken in selecting an effective size for the test model then it is likely to witness failures within the span of the model instead of at the connection. If too large of a model is constructed for testing then it is possible too many joints will be produced so that the connection is no longer the weak link, rather some sort of failure may result due to how the load is transferred from the test machine. It is also very important to carefully select how the test will be conducted.

The test method used was limited to compression or tension tests because the available testing apparatus. In order to have conducted tension tests, additional elements needed to be designed to attach the testing apparatus to the test model. Most of the options considered for developing alternative tension tests required face fasteners through some rigid tension plate mounted on the surface of all wall segments. Due to the small scale of the testing model, tension tests could have resulted in plywood panels pulling apart due to a reduction in cross-sectional area because of the face fasteners required. It would have also been difficult to ensure adequate tightening of the fasteners on the interior of the model. Compression tests provided an easier test method.

For compression tests to be conducted wall segments just needed to be offset but no additional testing apparatus was required. However, after observing walls sliding out-of-plane in Test 1 and torsional behavior in Test 2, bolted rods were added to connect parallel wall segments and provide confinement.

11.2 Further Research and Analysis

11.2.1 Future Analysis

If any future analysis associated with CLT wall segments is conducted it is first recommended to review the *Standard for Performance-Rated Cross-Laminated Timber* and the *CLT Handbook: Cross-Laminated Timber.* Both resources provide an introduction to cross-laminated timber products' fundamental mechanical properties. If further resources are required for analysis *Cross laminated timber (CLT): Design approaches for dowel-type fasteners and connections* is a great source for analyzing potential CLT fasteners for connections. More articles relative to CLT product analysis can be found by using database access offered by universities and using cross-laminated timber as the key search term.

11.2.2 Future Research

It was initially assumed that torsion behaviors would be negligible at dovetail connections however for shorter joints torsion was the dominant behavior. In this experiment, rods were simply added to provide confinement and reduce localized torsional effects at the point of bearing. If CLT shear wall cores are going to be further developed, then it is necessary to investigate a potential solution that provides confinement of the core system. During earthquakes, large axial forces develop near the end of shear walls and so potentially large tension forces will be an inherent design load of CLT shear wall cores and mechanisms to transfer these large forces to footings will need to be developed. Another area for research regarding CLT shear wall cores is how to transfer large shear forces from the walls to the foundation.

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