An Approach to CLT Diaphragm Modeling for Seismic Design with Application to a U.S. High-Rise Project

Adapted from a paper by Scott Breneman,[a] Eric McDonnel[b] and Reid B. Zimmerman,[c] presented at the 2016 World Conference on Timber Engineering

ABSTRACT:

A candidate cross-laminated timber (CLT) diaphragm analysis model approach is presented and evaluated as an engineering design tool motivated by the needs of seismic design in the United States. The modeling approach consists of explicitly modeling CLT panels as discrete orthotropic shell elements with connections between panels and connections from panels to structural framing modeled as two-point springs. The modeling approach has been compared to a developed CLT diaphragm design example based on U.S. standards showing the ability to obtain matching deflection results. The sensitivity of the deflection calculations to considering CLT panel-to-panel connection gap closure is investigated using a simple diaphragm example. The proposed modeling approach is also applied to the candidate floor diaphragm design for the Framework project, a winner of the U.S. Tall Wood Building Prize Competition, currently under design. Observations from this effort are that the proposed method, while a more refined model than typically used during building design, shows promise to meet the needs of innovative CLT seismic designs where appropriate simpler diaphragm models are not available.

Framework
Portland, Oregon
Architect: LEVER Architecture
Structural Engineer:
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Rendering courtesy LEVER Architecture

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INTRODUCTION

Recent years have seen significant establishment of product and testing standards and building code adoption of cross-laminated timber (CLT) within the U.S. design environment. Examples include creation of a product performance specification, ANSI/APA PRG 320, inclusion of design provisions into the U.S. national engineering wood design standard, the 2015 edition of the American Wood Council's (AWC) National Design Specification® (NDS®) for Wood Construction, and inclusion as a code-recognized building component in the 2015 International Building Code (IBC).

Designers in the western high-seismic regions of the United States have significant interest in using mass timber products, including CLT, which has led to a wave of research pertaining to the behavior of CLT panels as components of vertical seismic force-resisting systems. Internationally, several full-scale test efforts have shown that all CLT buildings can perform well under high seismic demand.[1,2] One highly anticipated effort in the U.S. is the definition of a CLT shear wall system for use as a seismic lateral force-resisting system and determination of corresponding Seismic Design Factors for use in the U.S. seismic design standards.[3] Other efforts include investigating high-performance, low-damage and rapidly repairable seismic force-resisting systems.[4,5]

Complementary to these efforts is needed research in the behavior of horizontal force-resisting systems—floor and roof diaphragms. Many experimental studies have been performed on CLT connection behavior that can be of significance to CLT diaphragms.[6,7] CLT connection design has also been incorporated into the 2015 NDS. Analytical studies have investigated extrapolating the connection behavior to full diaphragm system behavior.[8] Research to build an experimentally validated understanding of CLT diaphragm system behavior and tie this understanding to standard design practices in the U.S. is in its inception. While the authors have heard of experimental research on full diaphragm system behavior potentially underway soon, no results of such experimental studies are known to be available.

Current engineering design of CLT diaphragms is based on known CLT component and connection behavior scaled up to system behavior using rational engineering mechanics and analysis. The goal of this work is to explore this process and apply the state of knowledge of CLT diaphragm behavior to practical engineering design to meet the building code requirements of high-seismic design in the United States. In particular, this paper will concentrate on one aspect of engineering design: modeling of CLT diaphragms to calculate deflections and distribute forces resulting from earthquake loading.

U.S. STANDARDS ENVIRONMENT FOR DIAPHRAGM DESIGN

Many of the general building code requirements and design standards for horizontal diaphragm design of engineered buildings in the United States are contained in Chapter 16 of the IBC and Chapter 12 of ASCE/SEI 7-10: Minimum Design Loads for Buildings and Other Structures (ASCE 7). Of significance to designers using these standards is the classification of the in-plane diaphragm behavior as either idealized as rigid, idealized as flexible, or modeled as semi-rigid. While idealizing diaphragms as rigid or flexible is vastly preferred by most designers for most building designs, ASCE 7 does not automatically allow such an assumption for all diaphragm systems. For seismic design, ASCE 7 has scenarios where a rigid diaphragm can be assumed without further justification such as regular concrete slab diaphragms with a span-to-depth ratio of 3:1. There are also scenarios where diaphragms sheathed with wood structural panels or untopped metal deck can be assumed to be flexible. However, if none of the scenarios apply to classify a diaphragm as flexible or rigid, then the designer has the choice to either use semi-rigid diaphragm modeling or attempt to justify an idealization of rigid or flexible diaphragm behavior via detailed calculations. The justification of idealized diaphragm behavior is performed by comparing calculated diaphragm deflections to calculated vertical force-resisting system deflections. As CLT diaphragms are not within the scope of the automatic idealizations of diaphragm behavior, seismic design of CLT diaphragms in the typical U.S. building codes requires some understanding of CLT diaphragm deflections.

Internationally published example CLT design projects known to the authors assume rigid diaphragm behavior[9] or show through experiment that the diaphragm behavior performs rigidly relative to CLT shear wall systems.[1,10] However, assuming rigid behavior is not compatible with current seismic standards in the U.S. Additionally, there is significant interest in using CLT and other mass timber floors with a wide variety of vertical force-resisting systems, including CLT walls, traditional wood structural panel sheathed shear walls, steel moment frames and concrete shear walls. The use of CLT diaphragms with differing vertical force-resisting systems may require a building-specific analysis to determine appropriate diaphragm modeling approaches.

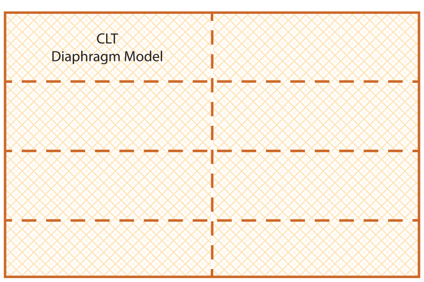
CLT DIAPHRAGM MODELING

A variety of rational models of engineering mechanics can be applied to calculate CLT diaphragm deflections and distributed lateral forces among the structural elements. Unlike more homogenous diaphragm systems, or diaphragm systems consisting of many smaller components, mass timber panel diaphragms—e.g., CLT, glued-laminated timber (glulam) and structural composite lumber—consist of large stiff panels with discrete connection zones. A significant portion of the in-plane diaphragm deflection occurs in these connection zones. Such a diaphragm system is not unique to mass timber systems, as a similar configuration can be found in untopped precast concrete systems.[11] The spectrum of potential modeling approaches to CLT diaphragms include:

- Homogenous models
- Discrete panel and lumped connection models
- Discrete panel and distributed connection models

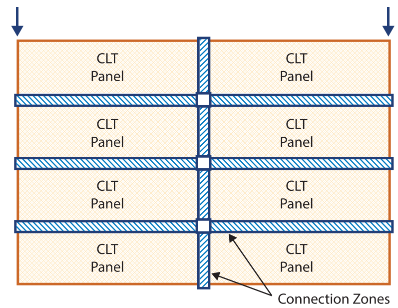
Homogenous models use smoothed analytical models derived in a manner such that the influence of panel-to-panel connection behavior is averaged over the model of the diaphragm. See Figure 1. Such an approach does not explicitly model individual panels and panel connection zones. This approach is commonly used in engineering of conventional wood structural panel diaphragms where net effective properties have been verified with experimental studies and implemented in the U.S. standards—e.g., the diaphragm deflection equations in the 2015 and earlier editions of AWC's *Special Design Provisions for Wind and Seismic* (SDPWS). An eventual goal of mass timber diaphragm research may be to develop, calibrate and standardize such homogenous design methods and models for general purpose CLT diaphragm design. Given the variety of innovative connection and structural configurations possible with CLT, such standardization is not as a simple task.

FIGURE 1:
Homogenous CLT Diaphragm Model



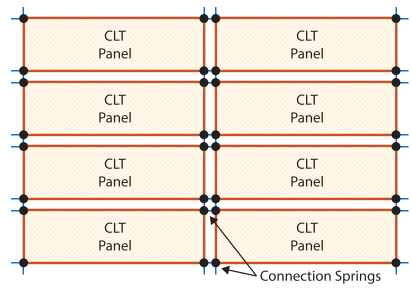
Discrete panel models explicitly model individual CLT panels and connections zones. Such models explicitly include panel-to-panel connections. The models may or may not include the connections to and between supporting framing. There is a large range of possible levels of detail to model connection zones. One extreme, used in the domain of research and product development, is to model each screw or nail with non-linear force-deformation relationships. Several less detailed, intermediate modeling approaches have been considered by the authors for application to building design efforts. A distributed connection model includes a representation of the connection zones as linear or 2-D modeling elements. For example, a panel-to-panel connection can be represented by shell or membrane elements with properties capturing the stiffness of the connection both parallel and perpendicular to the connection line as shown in Figure 2. In commercial finite element model (FEM) structural analysis software, the discretized FEM analysis model can be generated using automatic meshing of the element areas.

FIGURE 2:
Discrete Panel Model with 2-D Connection Zones



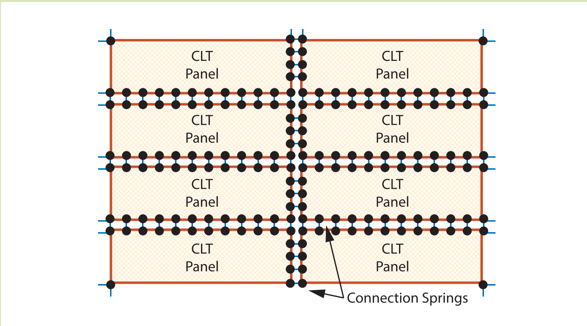
Another discrete panel modeling approach is to aggregate the force-deformation behavior of the connection zone to the ends of the panels. Generalized two-point spring elements are one means of implementation of this approach. See Figure 3. This approach has the advantage of having a relatively small number of modeling elements, but may have a relatively large number of different element properties, particularly when there are many different panel sizes.

FIGURE 3:
Discrete Panel Model with Corner Connections



Intermediate to the preceding approaches is to discretize the connection zones by placing two-point springs at regular spacing, such as every 24 inches (~600 mm), along the connection zone as shown in Figure 4. With the large number of elements to be placed under such an approach, parametric generation of the analysis model using scripting, spreadsheets or other model development tools can greatly aid in the modeling.

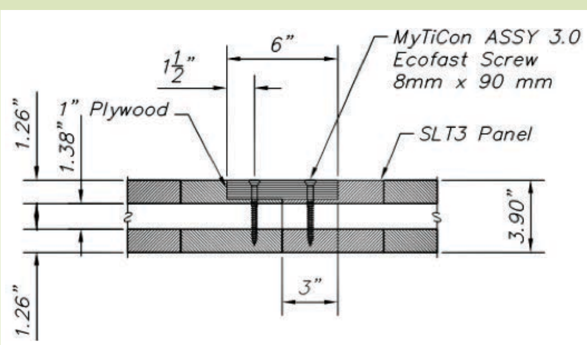
FIGURE 4:
Discrete Panel Model with Spaced Connections



A PROPOSED HOMOGENOUS CLT DEFLECTION MODEL

Given growing interest in CLT floor and roof systems, there is a need for more designers to be familiar with the design of CLT diaphragms. To help meet this need, Spickler, et al. developed a white paper that covers in detail the design of a regular rectangular CLT diaphragm.[12] The design example builds upon worldwide research and U.S. standards to present an example diaphragm design of a 135-ft (41.1-m) long by 65-ft (19.8m) wide diaphragm constructed of 8-ft (2.44 m) wide CLT panels. The panels are 3-ply, 3.9 inches (99 mm) thick, and comprised of North American Spruce-Pine-Fir lumber. The typical panel-to-panel connection evaluated in the example is detailed with plywood splines as shown in Figure 5 from the white paper.

FIGURE 5:
Design Example Panel-to-Panel Connection



Source: Spickler et al

The design example presents a homogenous diaphragm deflection model based on a modification of the diaphragm deflection equation used for conventional wood structural panel sheathed diaphragms in U.S. standards including the SDPWS. The proposed modified four-term equation for the maximum deflection at the center of a rectangular diaphragm of length, L, and depth, B, is:

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

Where v is the maximum shear at the edge of the diaphragm and is calculated from the uniform line load, w, applied to the length of the diaphragm, as $v = wL/2B$.

The only change in this proposal from the conventional wood diaphragm deflection equation is the variable C in the third term which calculates the contribution of connection slip to the total deflection. The variable C, as shown in ATC-7 Guidelines for the Design of Horizontal Wood Diaphragms,[13] is defined by:

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

where P_L and P_W are the length and width of typical panels. The term, e_n, is the connection slip at the outer edge of the diaphragm under the maximum shear load, v. The derivation of this slip term can be found in ATC-7 where it was derived for application to typical wood structural panel diaphragms. The derivation assumes rectangular panels of equal size, the linear elastic connection stiffnesses at all four sides of the panels, and that the connection stiffnesses are equal for loads parallel to and perpendicular to the panel-to-panel connection line.

The first term of the deflection equation is flexural bending of a simply supported beam resisted by concentrated diaphragm chord areas, A_{ch}, resisting tension and compression at a distance, W, from each other. The second term is shear deformation of the CLT panels themselves and can be written in an alternative form as $wL^2/8A_{clt}G_{eff}$. Where A_{clt} is the gross cross-sectional area of the CLT diaphragm resisting the shear load and G_{eff} is the effective shear modulus. A method to estimate the shear modulus for CLT panels used in the design example can be found in Flaig and Blaß.[14] The fourth term is the geometric translation of any chord slip under loading into lateral deformation of the diaphragm.

While validation and possible modification of the proposed homogenous diaphragm deflection calculation will be a valuable step for future research, this proposed deflection model is a form familiar to U.S. structural designers and provides a candidate baseline from which explicit CLT diaphragm deflection modeling can proceed as needed.

CANDIDATE MODELING APPROACH

Following the lead of the CLT diaphragm white paper example, investigations have been made by the first author into how to create finite element analysis models consistent with the proposed deflection model that can be extended to more complicated diaphragm configurations that do not easily map into the rectangular hand calculation deflections. For example, it is common for CLT diaphragm connection details to vary between the short edges of CLT panels, where panels are connected to supporting framing with long self-tapping screws, and the long edges of CLT panels, where panels are connected to adjacent panels via a panel-to-panel connection such as a spline. Some possible panel-to-panel connections do not have equal stiffness properties parallel to the connection and perpendicular to the connection. For example, butt joints with self-tapping screws driven at an angle to the surface and perpendicular to the connection line are more flexible parallel to the connection where the screws are in straight shear and more rigid perpendicular to the connection where screws are in combined shear and tension or compression. The discrete panel, lumped connection modeling approach has been developed and explored to accommodate a broader range of possible diaphragm configurations and connection details.

This approach is implementable using common commercial structural analysis software with the goal of achieving an appropriate balance between model complexity and model accuracy applicable to a practical design process. Using SAP2000 as a commercial analysis platform, this work has lumped the behavior of many connectors as spring elements to adjacent framing at panel corners. While this level of modeling is more detailed than typical diaphragm design models in professional practice, it is perceived by the authors as not too onerous for innovative CLT seismic design in the U.S.

CLT panels are modeled with four-node membrane elements to capture in-plane behavior only. Orthotropic material definitions have been used to capture the asymmetric behavior and allow for explicit definition of the in-plane shear modulus of the panels derived from laminae properties and inter-laminae bonding properties.[14] The thickness, t, of the element matches the full thickness of the CLT panel and the in-plane moduli of elasticity of the panels are defined such that in-plane section stiffness in the major and minor panel axes are equal to the axial stiffness of the laminations parallel to the direction. For example, the modulus of elasticity of the CLT membrane material in the major strength axis of the element, E_1, is set to:

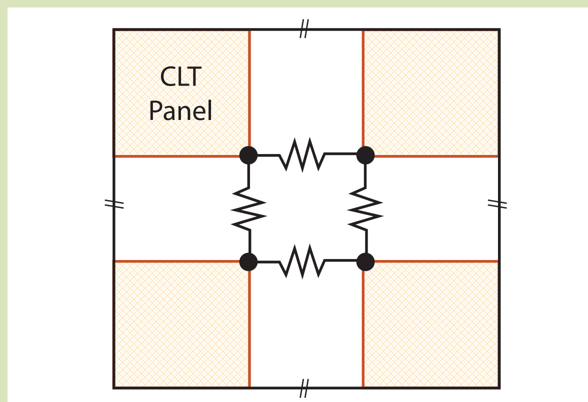
$$E_1 = \frac{t_{0,net}}{t} E_0$$

where $t_{0,net}$ is the net thickness of the longitudinal CLT layers and E_0 the modulus of elasticity parallel to grain of the longitudinal layers. Note that this equation ignores the contribution of the transverse CLT layers. Alternatively a second term can be added to the equation above equal to $\frac{t - t_{0,net}}{t} E_{90}$ where E_{90} is the elastic modulus of wood perpendicular to grain. However, this refinement was not included in the current work. Poison's ratio between the two in-plane axes of the membrane is set to 0.

In this work, the modulus of elasticity, E_0 has been taken as that for the wood grade in accordance with the NDS for simplicity. Test results often show the expected modulus of elasticity to be higher than that represented in the NDS. When a diaphragm is being analyzed for earthquake effects that represent full unreduced seismic loads, as opposed to equivalent lateral force loading where forces have been divided by a seismic force reduction factor, it is often preferable to use expected or average material properties. CLT manufacturers are sometimes able to provide more accurate expected moduli of elasticity taken from their testing programs.

The panel edge connections are modeled using two-point springs located at corners of the panels schematically shown in Figure 6. These springs have stiffness in two directions. The stiffness along the length of the spring models the resistance to deflections perpendicular to the connection, that is, compression between or separation of the panels. The stiffness perpendicular to the spring in the plane of the diaphragm models the resistance to shear deformations between panels. The force-deformation relationship of springs is an aggregate of connectors along the panel edge. In the work to date, the spring stiffness values have been set to tributary stiffness of one half the connection along the panel, which matches the total connection stiffness to shearing parallel and perpendicular to the connection. For in-plane rotational effects between the panels, this model slightly overestimates the large scale (rigid panel) rotational stiffness between panels and slightly underestimates the localized (node) rotational stiffness of the connection between nodes in adjacent panels.

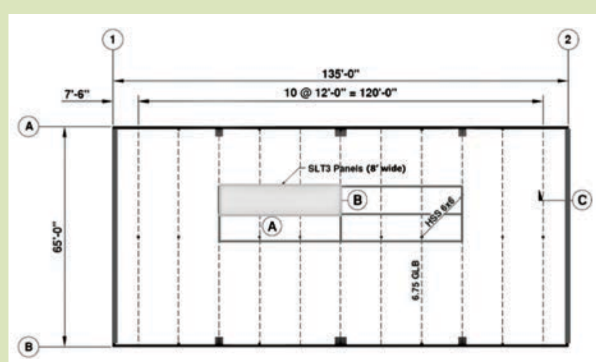
FIGURE 6:
Plan View of CLT Panel-to-Panel Model



COMPARISION WITH IDEALIZED CLT DEFLECTION MODEL

The test for this modeling approach was to duplicate the hand calculations of the 135-ft (41.2 m) by 65-ft (19.8 m) deep example diaphragm shown in Figure 7 from the white paper by Spickler et al.

FIGURE 7:
Plan of Example CLT Diaphragm



For a comparison of the FEM approach with the four-term deflection calculation approach, a 64-ft (19.5m) deep diaphragm was modeled and compared to revised hand calculations from the example. The total deflection of the 64-ft deep diaphragm to a lateral load, *w*, of 1000 lbf/ft (14.6 kN/m) calculated via the four-term deflection equation as 1.197 in. (30.40 mm). The values of each of the four terms of the deflection equation are chord flexure equals 0.261 in. (6.63 mm), panel shear equals 0.304 in. (7.72 mm), connection slip equals 0.427 in. (10.8 mm), and chord slip equals 0.204 in. (5.2 mm). While all four terms significantly contribute deflection, in this example, the connection slip term has the largest contribution.

A corresponding analysis model was developed in SAP2000 to duplicate the hand calculation matching the assumptions of the four-term equation as closely as possible. See Figure 8. For example, the flexural deflection in the hand calculation assumed a simply supported beam, so care was taken in the SAP model to duplicate these support conditions using a single restraint point on each end and modeling constraints along grid lines 1 and 2 to tie the edge of the diaphragm to the restraint points.

FIGURE 8:
Model of CLT Diaphragm Design Example

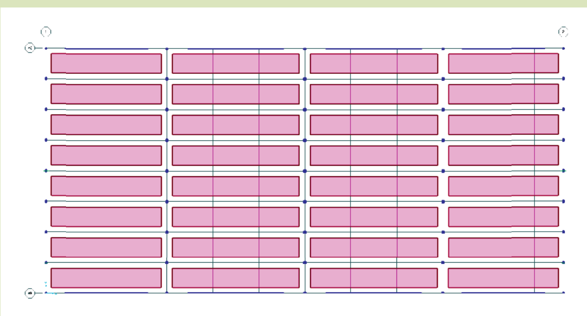
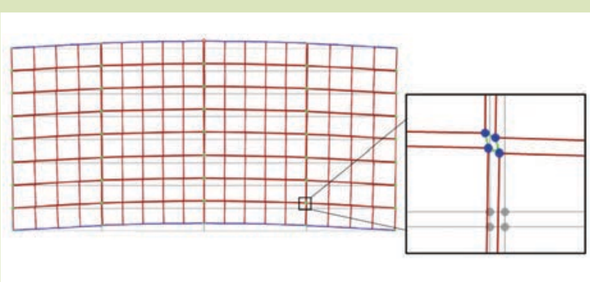


FIGURE 9:
CLT Diaphragm Deflection (exaggerated)



The resulting maximum deflection of the FEM analysis was 1.029 in. (26.1 mm), 14% less than the hand calculations. See the deflection shape in Figure 9. Investigation into the results revealed the largest divergence between the hand calculations and the FEM analysis was the impact of chord slip on the deflections. In the FEM analysis, when the chord slip occurs at chord splices along lines A and B, the model distributes a portion of the chord loads onto the adjacent panels and panel-to-panel connections. This stiffening effect does not happen in the four-term deflection equation method. When chord slip is not included in either approach, the deflection from the four-term (now three-term) equation is 0.992 in. (25.2 mm) and from the FEM analysis is 0.966 in. (24.5 mm), only 2.6% less.

From an engineering perspective, this is a very favorable result validating the modeling approach. While it is not surprising that a FEM analysis of a simple diaphragm can closely match equivalent hand calculations, it is important to note that none of the modeling properties of the FEM analysis were tuned to achieve matching results.

ANALYTICAL IMPACT OF GAP CLOSURE

The discrete panel lumped connection modeling approach is being used to study the effect of different assumptions on the behavior of the CLT diaphragms models. One such study is the impact of panel-to-panel gap closure in regions of compression at the panel connections.

The derivation of the connection slip term of the hand calculation of diaphragm deflection assumed equal stiffness between panels in shear, tension and compression of the panel-to-panel zone. Given that typical conventional wood structural panel-sheathed diaphragms are constructed with a small gap between adjacent sheathing panels, this assumption appears rational. As CLT panels may not be constructed with intentional gaps between them, but may be intentionally clamped down tight against each other, the assumption of equal connection stiffness in tension and compression is worth investigation.

To investigate this assumption, a modified version of the analytical model described in the prior section was made using bilinear connection springs for the panel-to-panel connection perpendicular to the connection line. The bilinear spring was constructed similar to a gap element but using a finite stiffness in compression was 1,000 times the stiffness of the connection in tension. Comparing to a physical property of the CLT, 1,000 times the connection stiffness was approximately the axial stiffness of 3 in. (76 mm) of length of the CLT panel in compression. With this modification made throughout the model, the resulting maximum deflection was calculated as 0.987 in. (25.1 mm), a 4.0% reduction from the deflection (1.029 in., 26.1 mm) with no closure of the connection in compression. While the difference between these two deflections is small, more thorough studies of CLT diaphragm behavior may reveal the importance of connection closure on global behavior for other configurations.

APPLICATION TO PROJECT DESIGN

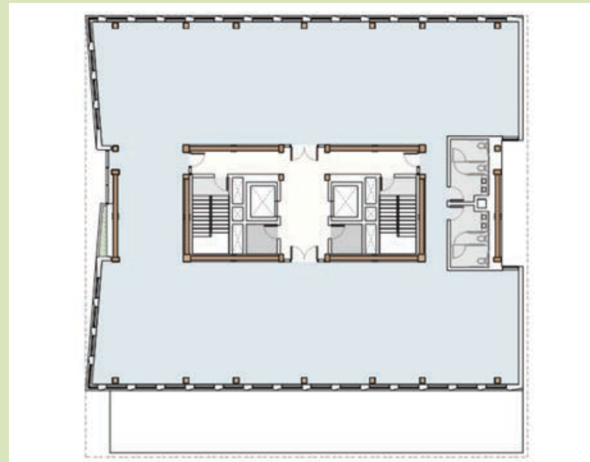
To further demonstrate the modeling approaches developed, these techniques are applied to the schematic floor diaphragm design of the Framework project in Portland, Oregon. Framework is one of the two winners of the U.S. Tall Wood Building Prize Competition announced in September 2015 and currently under design. (See www.tallwoodbuildingcompetition.org.)

The Framework site is located on a quarter block in Portland's Pearl District. For an architectural rendering and typical office-level floor plan, see page 7. The mixed-use occupancy building will be 12 stories tall above grade and approximately 140 feet (42.6 m) in height, with a total building area of approximately 90,000 gross square feet (8360 m^2). The structural gravity and lateral systems are composed primarily of mass timber, including CLT floor and wall panels, and glulam beams and columns. When completed, Framework is anticipated to be the tallest modern timber building constructed in the United States.

When completed, Framework is anticipated to be the tallest modern timber building constructed in the U.S.

Rendering courtesy LEVER Architecture

FIGURE 10:
Framework Project Office Floor Plan



The characteristics of the current Framework project design include:

- Approximate floor plan dimensions of 100 ft (30.5 m) east west by 85 ft (25.9 m) north-south
- Five-ply CLT floors supported on glulam beams and glulam columns
- Lateral force-resisting system of eight CLT post-tensioned rocking shear walls
- Diaphragms cantilevering approximately 30 ft (9.1 m) to the north and south of the shear walls in the central core

FIGURE 11:
Schematic Framework Project Structural Layout

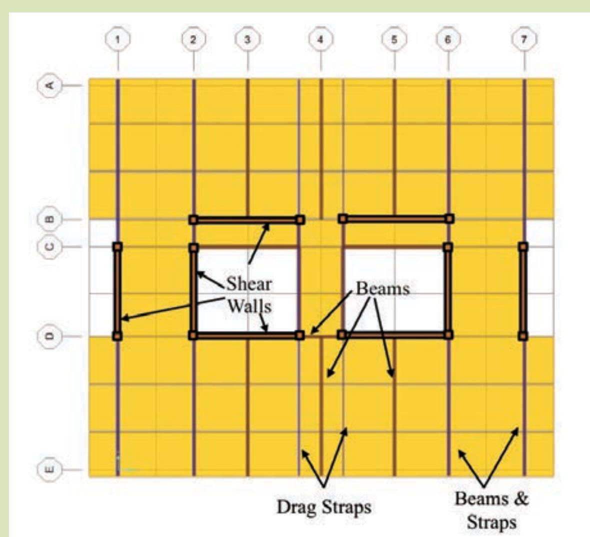
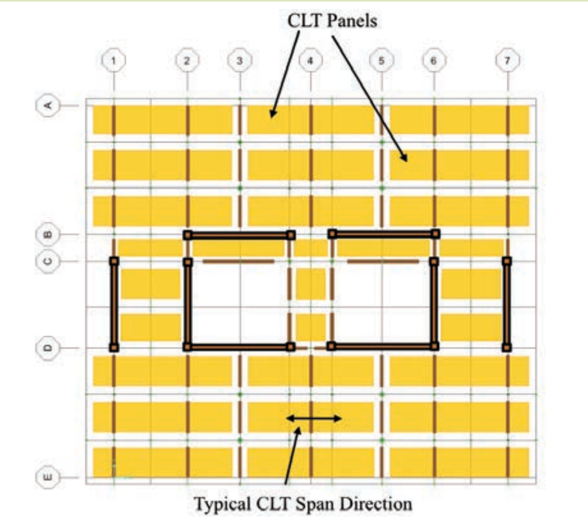


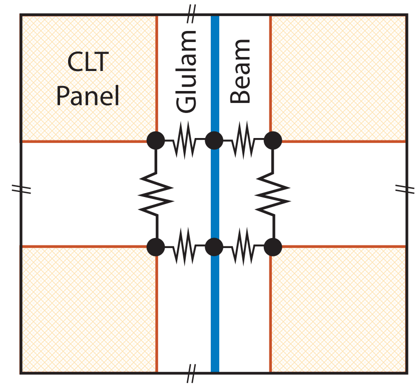
FIGURE 12:
Schematic Framework Project CLT Panel Layout



The schematic diaphragm design of the floor plates includes two types of panel-to-panel details. Splice Type A, located at locations with higher force demands, is a lap joint connected together with self-tapping screws through both panels. Splice Type B, used at locations of lower force demands, has a plywood spline recessed into the upper CLT surface with self-tapping screws through the spline to both panels, similar to the detail in Figure 5. The typical connections from panel to panel are modeled with springs at the corners as previously discussed and shown in Figure 6. The panel-to-panel spring stiffness values used are based on testing performed at the University of British Columbia[7] with additional test data provided by MyTiCon Timber Connectors of Surrey, British Columbia, Canada.

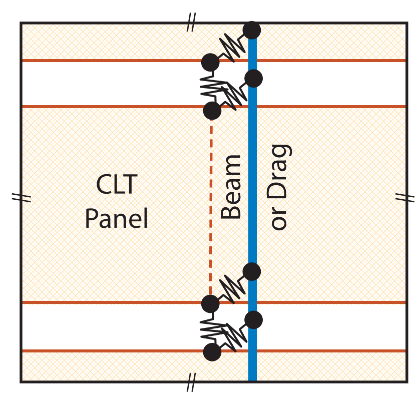
For the Framework diaphragm, the effects of continuity ties such as drag straps and beams may be significant to diaphragm behavior and have been included in the diaphragm model. Where two CLT panels meet over a glulam beam, the detailing consists of self-tapping screws from each panel to the beam below with no direct connection between the panels. To model this condition, a spring arrangement is modeled as shown in Figure 13. The springs from the panels to beams are defined to represent the stiffness of the connection parallel and perpendicular to the length of the beam.

FIGURE 13:
CLT Panel-to-Beam-to-Panel Model



Another connection condition not modeled in the FEM analysis representing the white paper design example occurs where beams are located under and/or drag straps are located over CLT panels. In this situation the connection of the panel to the beam or drag strap is modeled without breaking the continuity of the CLT panel. Independent nodes are created at the beam and/or strap and panel so connectivity between the beam and/or strap and the panel is only through a discrete connection zone spring as shown in Figure 14.

FIGURE 14:
Continuous CLT Panel-to-Beam or Drag Model



At connections between continuous CLT panels and a beam, the connection spring includes stiffness for the connection along the length of the beam and perpendicular to the beam. At connections to only drag straps, the connection spring only includes stiffness along the length of the drag strap.

Application of these modeling techniques to the schematic Framework diaphragm design resulted in 24 different spring types for different connections types and tributary length of connection zones.

The Framework project is being designed using performance-based seismic design with the objective of having only very localized, economically repairable damage under a design-level seismic event corresponding to an earthquake having a return period of 475 years. Damage is also limited, although to a lesser degree, at the maximum considered earthquake, approximately corresponding to an earthquake with a return period of 2,475 years. With these objectives, the diaphragms are being designed to remain essentially elastic. Consequently, the loading used to investigate the diaphragm modeling is not based on code-prescribed minimum diaphragm loads, but rather the peak floor accelerations obtained from nonlinear response history analysis of the rocking wall design. This analysis is being performed separately by the latter two authors and is not presented further in this work. The resulting floor accelerations used in this study are 93% g in the east-west direction and 68% g in the north-south direction and represent the accelerations at a typical floor. The diaphragm accelerations at the roof are higher at 103% g east-west and 82% g north-south but are not presented in this work.

It is interesting to note that a new alternative diaphragm design method in ASCE 7-16 has been developed which includes a method to estimate similar accelerations when using a seismic force-resisting system recognized by ASCE/SEI 7-16. The Elastic Design Option is described in ASCE/SEI 7-16 as "An option where elastic diaphragm response in the maximum considered earthquake is targeted." Assuming a special concrete shear wall seismic system and calculating the floor accelerations using the Elastic Design Option of the ASCE 7-16 alternative diaphragm design method results in peak design floor acceleration of 82% g and design roof acceleration of 99% g. While the motivation for this new standard provision was not for voluntary design beyond code minimums, the similarities in the design criteria and nonlinear response history analysis results on this project suggest the new alternative diaphragm design method may have potential for application to the design of high-performance diaphragm systems.

Applying an acceleration load of 93% g in the east-west direction results in peak diaphragm deflections of 0.56 in. (14 mm) located at the outer edges of the cantilever. See Figure 15 for the exaggerated deflection shape. The peak diaphragm deflection in response to 68% g loading in the north-south direction is 0.60 in. (15 mm) located along grid 4. See Figure 16. Inspecting the deflection shapes, one readily notes that connection slip is a major contributor to the total diaphragm deflection in both directions of loading.

In the current model, restraints are provided at the location of each CLT rocking shear wall. In the north-south direction, the use of a restraint (i.e., an essentially rigid support) leads to the deflected shape shown in Figure 16. It should be noted that the use of a more realistic flexibility for the supports could change the deflected shape and force distribution.

Further refinements of the diaphragm design and analysis models for the Framework project will continue as the project nears completion of design (e.g., modeling a flexible support in lieu of a rigid support at each shear wall location).

FIGURE 15:
Diaphragm Deflection to E-W Load (mm scale)

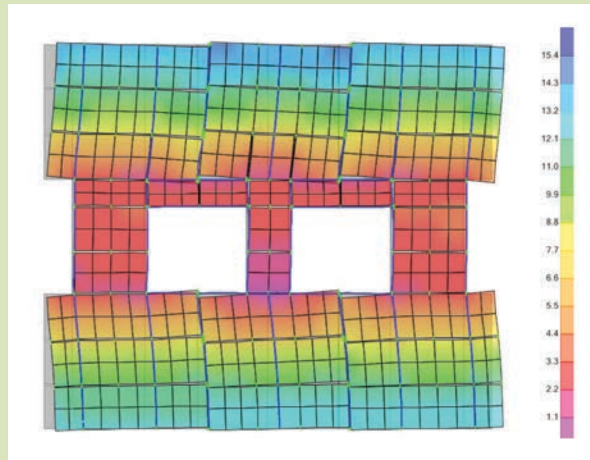
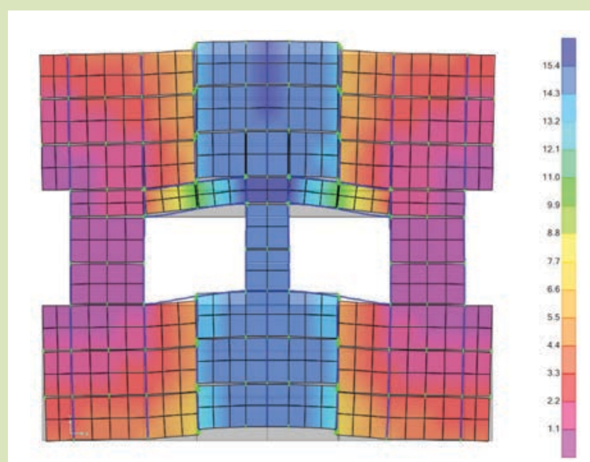


FIGURE 16:
Diaphragm Deflection to N-S Load (mm scale)



CONCLUSIONS

The goal of this exploration is to exercise modeling and design approaches for CLT diaphragms in a realistic building design and share the lessons learned to the engineering community. Observations from this work include:

Modeling

- Simple panel deflection models based on equivalent homogenous models such as the four-term deflection equation in Spickler et al[12] are extremely valuable to the design community. While some information exists, further refinement and validation of this approach is anticipated.
- The discrete panel, lumped connection modeling approach appears suitably precise for CLT diaphragm behavior provided the material and connection properties are adequately known.
- The discrete panel, lumped connection modeling approach can be applied to the variety of connection situations that occur in realistic building designs. While not trivial in effort, the approach may be suitable for CLT diaphragms in high-seismic regions for which homogenous panel deflection models are not applicable.

Ongoing Research

With growing interest in CLT and other mass timber products among North American building designers, the following documents, research and data are likely to be prioritized:

- Greater variety of design guidelines and examples
- Continued research on the strength and stiffness of CLT connections, in their many variations, in forms usable by designers and building officials.
- Testing regarding the stiffness perpendicular to the connections in future panel-to-panel connections
- Full-scale and reduced-scale CLT diaphragm system testing to validate diaphragm design models

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While aided by large group of professionals and organizations, the content and opinions of this paper are the authors' alone. We are open to feedback and learning about old or new information related to the topics and encourage readers to communicate with us.

References

1 M. Popovski and I. Gavric, "Performance of a 2-Story CLT House Subjected to Lateral Loads" ASCE Journal of Structural Engineering, Vol 142, No. 4 2016.

2 A. Ceccotti, C. Sandhaas, M. Okabe, M. Yasumura, C. Minowa, and N. Kawai. "SOFIE project – 3D Shaking Table Test on a Seven-Storey Full-Scale Cross Laminated Timber Building" Earthquake Engineering Structural. Dynamics, Vol 42, 2013.

3 S. Pei, J. van de Lindt, M. Poposki, "Approximate R-Factor for Cross-Laminated Timber Walls in Multistory Buildings." ASCE Journal of Architectural Engineering, Vol 19, 2013.

4 F. Sarti, A. Palermo and S. Pampanin, "Development and Testing of an Alternative Dissipative Posttensioned Rocking Timber Wall with Boundary Columns" ASCE Journal of Structural Engineering, 2016.

5 M. Gu, W. Pang and S. Schiff, "Displacement Design Procedure for Cross Laminated Timber (CLT) Rocking Walls with Sacrificial Dampers" In Proceeding of 2015 ASCE Structures Congress.

6 K. Bratulic, G. Flatscher, and R. Brandner, "Monotonic and Cyclic Behavior of Joints with Self-Tapping Screws in CLT Structures". In COST Action FP1004 Experimental Research with Timber, 2014.

7 A. Hossain, R. Lakshman, and T. Tannert, "Shear Connections with Self-Tapping Screws for Cross-Laminated Timber Panels" In Proceedings of ASCE/SEI Structures Congress 2015.

8 S.Ashtari, T. Haukaas and F. Lam, "In-plane Stiffness of Cross-Laminated Timber Floors". In Proceedings of World Conference on Timber Engineering, 2014.

9 D. Vassallo, I. P. Christovasilis, M. Follesca, and M. Fragiacomo, "Design of a Four-Story Cross Laminated Timber Building in Italy". Wood Design Focus Vol 23, No. 4, Forest Product Society, 2013.

10 B. Dujic, K. Strus, R. Zarnic, and A. Ceccotti, "Prediction of Dynamic Response of a 7-Storey Massive XLam Wooden Building Tested on a Shaking Table" In Proceedings of World Conference on Timber Engineering, 2010.

11 W. Zheng and M. Oliva, "A Practical Method to Estimate Elastic Deformation of Precast Pretopped Double-Tee Diaphragms". PCI Journal, March-April 2005.

12 K. Spickler, M. Closen, P. Line, and M. Pohll, "Cross Laminated Timber Horizontal Diaphragm Design Example". Informally published, August 2015. http://structurlam.com/wp-content/uploads/2015/10/Cross-Lam-Horizontal-Diaphragm-Design-Example-Rv10.pdf

13 ATC-7 Guidelines for the Design of Horizontal Wood Diaphragms. Applied Technology Council, Berkeley, CA, 1981.

14 M. Flaig and H. J. Blaß. "Shear strength and shear stiffness of CLT-beams loaded in plane" In: Proceedings. CIB-W18 Meeting 46, Vancouver, Canada, 2013, Paper 46-12-3