A State of the Art Review of Cross-Laminated Timber Floor Systems

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Abstract

Increased availability of cross-laminated timber (CLT) in North America combined with its successful use in projects worldwide has generated interest in its properties and performance within the U.S. design community. With the inclusion of CLT in the 2015 International Building Code and upcoming design standards, curiosity is evolving with a number of developers, architects and structural engineers looking to use CLT in upcoming projects. One application under frequent consideration is the use of CLT within horizontal floor and roof systems to create long-spanning structural decks. This paper is for engineers designing floor systems with CLT for the first time, who are unfamiliar with available design methodologies and current research results. Topics will include CLT system material properties and behaviors relevant to floor design, design approaches for strength and serviceability, and analysis methods. Particular attention will be given to long floor span applications typically governed by deflection and vibration, including a review of theoretical and experimentally based evaluation approaches.

Origins of CLT

Cross-laminated timber is a relatively new engineered wood component manufactured from dimensional lumber to create large panels of solid wood. CLT is a member of a new class of massive (or "mass") timber products. Mass timber is a concept for large dimension engineered structural wood components that complement the dimensional sawn lumber, solid sawn timbers, and structural composite lumber products used frequently in building framing. The large component sizes and the strength and rigidity of the laminated system allows CLT to be a viable alternative to concrete, steel and masonry components in many building applications.

Application of CLT technology to buildings initiated in the early 1990s Austria and Switzerland. Since that time, manufacturing and construction with CLT has proceeded in Europe where the annual CLT production capacity is currently greater than approximately 5 million cubic feet of CLT panels. As the use of the CLT has expanded in Europe, the experience with design and construction using CLT has similarly matured.

Status in North America

In North America, the availability and acceptance of CLT is much newer than in Europe however the adoption is happening at a fast rate considering the speed at which material design standards and building code modifications occur. The ANSI approved product standard ANSI/APA PRG 320 *Standard for Performance-Rated Cross-Laminated Timber* provides a basis for standardization of CLT quality, manufacturing and structural properties (APA, 2012) in North America. With the availability of the PRG 320 Product Standard, CLT will be a code referenced building component in the 2015 International Building Code.

The sizes of panels available are limited by the size of the manufacturing equipment and shipping constraints. North American manufactured CLT is available in panels as large as 8ft or more in width and 40 feet or more in length.

US CLT Handbook

A foundational document for designers using CLT in North America is the US CLT Handbook available for free from www.masstimber.com. This handbook covers the spectrum of design topics needed to cover when designing a building using CLT including structural properties, connections, enclosures, acoustics and fire performance. The US CLT handbook provides introductory and detailed information on how to design CLT into building project. While not referenced by the building codes, this document provides a basis of design and had been used in the design of US CLT applications using an alternative means approval process.

CLT Manufacturing

CLT is manufactured from dried dimensional lumber with adhesives applied between laminations in a fashion similar to glue-laminated (glu-lam) beams. Similar to plywood, CLT has an odd number of layers, where the direction of the exterior layers are parallel and create the strong direction of a CLT panel and the perpendicular interior-only layers define a relatively weaker direction of a panel. See Figure 1 and Figure 2 for assembly drawings. Individual boards are dried to a moisture content of 12 +/- 3% and commonly finger jointed into long boards before being assembled into a panel.

The PRG 320 product standard specifies that the laminations have a 5/8 inch minimum thickness and a 2 inch maximum thickness as well has prescribed thickness to width requirements. Common board sizes used in North American CLT manufacturing include 2x3, 2x4 and 2x6 boards. The PRG 320 standard covers CLT panels up to 20 inches thick.

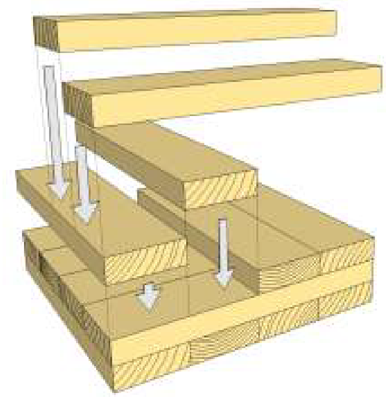

Figure 1 CLT Layup

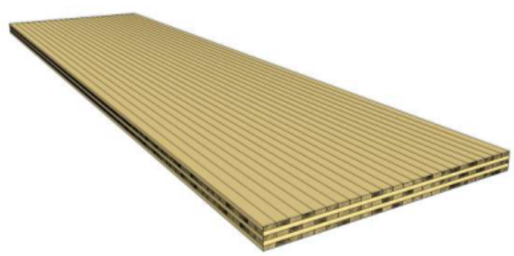

Figure 2 CLT Panel

With the cross-laminated construction, CLT panels dimensionally stable in both long directions of the panel. Dimensional changes across the thickness of the panel are limited because of the use of dried lumber during manufacturing.

Either PRG 320 defines seven stress grades of CLT panels which provide minimum strength requirements using visually graded or machine graded dimensional lumber. CLT Grades E1 through E4 use machine stress rated lumber for the layers parallel to the major axis. CLT Grades V1 through V3 use visually graded lumber for the layers parallel to the major axis. All the CLT grades defined in the PRG 320 use visually graded lumber for layers perpendicular to the major axis. Manufactures can also supply additional CLT grades beyond those define in PRG 320.

Applications of CLT

In buildings, CLT panels can be used in floor, roof and wall framing. Buildings have been built where all of the structural framing above the foundations, including walls, floors and roof, have been constructed from CLT.

Other applications of CLT panels are in bridge decks, and temporary applications such as crane rig mats and temporary road bases. The PRG 320 product standard does not directly apply to these applications as PRG 320 is intended for applications installed in locations protected from the weather, such as within a building envelope.

The remainder of this paper will focus on the structural properties and design methods of CLT applicable to floors and roofs which predominant attention given to performance to out-of-plane loads onto the horizontal applications. This discussion is introductory material and should not be used as a substitute for referring to the CLT Handbook, or other referenced standards and guides.

Structural Properties of CLT

For out-of-plane bending and shear behavior and in-plane tension and compression behavior, the CLT layup creates a stronger and stiffer Major Strength Axis and a weaker and softer Minor Strength Axis. The subscripts 0 and 90 are used throughout the CLT Handbook, PRG 320 and specific CLT Product reports to differentiate properties in the major and minor directions, respectively.

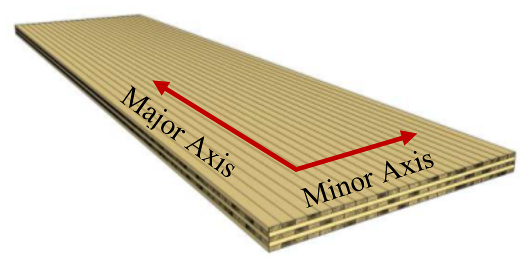

Figure 3 CLT Strength Axes

Reading the CLT Handbook, you can observe that many different approaches have been developed by researchers and manufacturers to calculate section properties of the composite CLT panel construction. Such intricacies are not necessary to design with CLT sections that are covered by a CLT grade and layup defined in either the PRG 320 or a product report providing information following PRG 320.

The flexural and shear strength of out-of-plane loading of CLT members in the PRG 320 product standards uses an extreme fiber capacity approach to calculate capacities based up the constitutive size and grade of lumber used in the CLT. This extreme fiber capacity approach and the method to derive the section properties are described in detail tin the CLT Handbook.

Out-of-Plane Bending Strength. For out-of plane flexural bending design, such as for gravity loads on a floor panel, the applied bending moment, M_b, must be less than the adjusted moment capacity and is written in the form:

$$M_b \leq F'_b \, S_{eff}$$

where the adjusted moment capacity, $F'_b S_{eff,}$ is calculated from the reference moment capacity, $F_b S_{eff}$, multiplied by modification factors familiar to engineers designing with wood as presented in the CLT Handbook. The most frequently applied modification factor is the well know load duration factor, C_D. Other modification factors of the Wet Service Factor, C_M, the Temperature Factor, C_t, and the Beam Stability Factor, C_L, are listed as potentially applicable to CLT panels in bending in the CLT Handbook; however, they do not typically apply to CLT floor or roof panels within a building envelope.

The PRG 320 standard and manufacturers' product reports provide the reference moment capacity, $F_b S_{eff}$, as an allowable design value. Following the format of the NDS, conversion of a reference moment capacity to an LRFD moment capacity can be performed using the K_F, ϕ and λ factors listed in Chapter 3 of the CLT Handbook.

Provided the reference bending capacity in the major strength direction, $F_b S_{eff,0}$ and the reference bending capacity in the minor strength direction, $F_b S_{eff,90}$, the flexural strength design checks at allowable stress levels are simply

$$M_{b,0} \leq C_D \, (\cdot) \, F_b S_{eff,0}$$

$$M_{b,90} \leq C_D \, (\cdot) \, F_b S_{eff,90}$$

where $(\cdot)$ provides for the atypical application of additional modification factors.

As required in PRG 320, the reference bending capacity, $F_b S_{eff}$, is 0.85 times the calculated bending capacity using the extreme fiber capacity approach from the constitutive lumber grades. This is important to note if you are calculating the moment capacity of a section from the properties of the lumber making up the CLT panel.

Out-of-Plane Shear Strength. The extreme fiber capacity method results in a similar approach for shear strength where the applied force to capacity check is

$$V_{planar} \leq F'_v \, (Ib/Q)_{eff}$$

where V_{planar} is the induced shear and $F'_v(Ib/Q)_{eff}$ is the adjusted shear capacity where for ASD:

$$F'_v(Ib/Q)_{eff} = C_D \, (\cdot) \, F_v(Ib/Q)_{eff}$$

Available CLT product reports use the term V_s for published values of the reference shear capacity, $F_v(Ib/Q)_{eff}$, resulting in shear strength checks of

$$V_{planar,0} \leq C_D \, (\cdot) \, V_{s,0}$$

$$V_{planar,90} \leq C_D \, (\cdot) \, V_{s,90}$$

Out-of-Plane Stiffness. The PRG 320 and compatible products reports provide calculated stiffness properties for flexural and shear deformation of a CLT panels to out of plane loads. The method of calculation of the approximate stiffness properties is described in detail in section 3.3 of the CLT Handbook.

The panel stiffness properties provided by PRG 320 and product reports are $EI_{eff,0}$ and $GA_{eff,0}$ for flexural and shear deformations in the major axis and $EI_{eff,90}$ and $GA_{eff,90}$ for deformation in the minor axis.

As shown in Figure 3, the major strength axis of the CLT panel is typically aligned with the long direction of the panel. In typical floors or roof applications, the CLT panel primarily acts as a one-way floor system where multiple panels are installed adjacent to each other spanning from one supporting wall or beam to another. For such panel layouts, calculating floor or roof deflections under uniform loads can be performed by analyzing a strip of the CLT as a beam. The strength and stiffness in the minor axis can be taken advantage of at overhangs and penetrations through the panel.

Using any structural analysis method which has the capability to model the specific flexural and shear stiffness of the CLT, a designer can directly calculate deflections as either a beam or a two way spanning floor system.

An alternative simplified beam analysis method is presented in the CLT handbook Chapter 3, Section 2.1.3 where an apparent flexural stiffness, EI_{app}, combines the effective flexural and shear stiffness values.

$$EI_{app} = \frac{EI_{eff}}{1 + \dfrac{K_s EI_{eff}}{GA_{eff} L^2}}$$

The constant K_s depends on both the support conditions and loading pattern applied to the single span beam. K_s for a pinned beam with a uniformly distributed load equals 11.5 and K_s for a pinned beam with a concentrated load at mid-span equals 14.4.

CLT Floor Design for Vibration

Designs of occupied floor systems for many structural systems are often governed by controlling floor vibrations for perceived occupant comfort and other serviceability concerns. CLT floor design is no different.

Prescriptive Span Limit. One method proposed by researchers at FPInnovations (Hu and Gagnon, 2012) to help select a CLT section which will generally have acceptable performance to occupants to walking excitations is presented in the CLT Handbook Chapter 7. This approach calculates an acceptable span limit based upon the section properties and has been calibrated to subjective performance evaluations of bare CLT specimens. The recommended span limit can be written as:

$$l \leq \frac{1}{12.05} \frac{(EI_{app})^{0.293}}{(\rho A)^{0.122}}$$

where l is the span, EI_{app} is the apparent stiffness of a 1 foot strip of a single pin supported span with a uniform load, ρ is the specific gravity of the CLT and A is the cross section area of a 1 ft wide strip of the CLT section.

FPInnovations also recommends keeping the fundamental frequency of the CLT floors above 9 Hz and provides an estimate of the fundamental frequency of bare CLT floor as

$$f = \frac{2.188}{2l^2} \sqrt{\frac{EI_{app}}{\rho A}}$$

As EI_{app} in the above two equations depends on the span length, application of these criteria require iterative calculations to determine recommended span length for a given CLT section. Fortunately, CLT manufactures commonly publish the recommended span lengths for their standard CLT sections.

This recommended span limit was developed through testing of single span, bare CLT floors; however, the CLT handbook recommends the same limit for CLT floors with multiple spans, suspended ceilings and/or light-weight floor toppings. An interim suggestion for addressing heavy-weight floor toppings (>20 lbs / square foot) is also provided in the CLT handbook.

Alternative Vibration Criteria. As span lengths increase and the weight of superimposed dead loads increase, the period of vibration of the floor system can be difficult and uneconomical to keep above 9 Hz. Other established vibration control criteria can be combined with the understanding of CLT floor behavior to design such floors for acceptable floor vibration performance. One such method is the velocity control method of the AISC Design Guide 11 (Murray et al., 2003) chapter 6 which was used in the design of long span CLT floors in the *Timber Tower Research Project* (SOM, 2013).

The velocity control method requires the selection an acceptable velocity limit and selection of the loading condition. DG 11 Figure 6.2 suggests a threshold of perception of velocity by occupants at 8,000 micro-inches/sec for frequencies of vibration at and above 8 Hz. At a frequency of 4 Hz, the velocity perception threshold increases to 16,000 micro-inches/sec.

For floor vibrations induced from footfall, DG 11 Table 6.2 defines three levels of footfall loading parameters for different walking paces:

Walking Pace	f_o (Hz)	U_v (lb Hz^2)
Fast	5.0	25,000
Moderate	2.5	5,500
Slow	1.4	1,500

Table 1 DG 11 Footfall Loading Parameters

Where f_o is the frequency of the walking excitation and Uv is a convenient loading term derived in DG 11. In cases where the natural frequency of vibration of the floor system, f_n, is significantly greater than 0.5 f_o and 5 Hz, DG 11 provides a convenient estimate of the maximum velocity from footfall, V, of

$$V = U_v \, \Delta_p / f_n$$

Where Δ_p is a floor flexibility factor defined as the deflection to a *unit* load at the point of application. A two-dimensional analysis of the floor system can be performed to calculate the floor flexibility factor to a unit point load. Alternative method exist to estimate the floor flexibility including two-way spanning behavior without performing a two-dimensional plate analysis.

In the Timber Tower Research Project, SOM applied two velocity control criteria. 1) In sleeping rooms, the velocity limit was selected as 8,000 micro-inches/sec to slow walking excitation. 2) In living areas a velocity limit of 16,000 micro-inches/sec to moderate walking pace was applied.

An advantages of this approach include being able to directly account to heavy-weight superimposed loads on the floor system which effect the natural frequencies of the floor and to apply rational vibration criteria for natural frequencies below 9 Hz based upon occupant perceptions. Furthermore, more accurate estimates of the floor stiffness and period through consideration of special boundary conditions, as in the Timber Tower research project, or by including the contribution of topping slabs, as in Hamm et al (2010), can explicitly consider floor configurations which are significantly outside the limitations of the recommended span limit approach of the CLT Handbook.

Vibration sensitive situations such as the response from rhythmic activities and providing acceptable performance to sensitive equipment and occupancies, such as operating rooms, should receive much more rigorous evaluation than the methods outlined here.

Conclusions

While CLT is a relatively new building component, product standards and design method exist to perform the necessary structural design for CLT floor systems. This paper provides an introduction to the strength, deflection and serviceability design guidelines available to CLT floors. This document is intended as a starting point for engineers considering such applications from which they can begin their education on this new and exciting structural component.

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