Structural Design Process for Estimating Cross-Laminated Timber Use Factors for Buildings

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Cross-laminated timber (CLT) construction has received significant attention for potential North American markets; however, few claims have been substantiated with structural design details that assess the amount of CLT to be used in various classifications of buildings. This article presents a design process used for the development of archetype buildings to estimate the potential CLT demand. Three types of structural systems were identified: platform construction, rocking walls with a separate gravity system, and hybrid construction consisting of reinforced concrete elevator cores and rocking walls. Platform construction was used for buildings 1 to 6 stories in height, the rocking wall system was used for buildings 6 to 12 stories in height, and the hybrid structural system was used for buildings 12 to 18 stories in height. The assumptions and design process for each of these archetypes are presented in this paper. Based on the structural analyses, CLT use factors were developed for predicting market demand as well as cost estimation of CLT building projects.

Keywords: Cross-laminated timber; CLT; CLT use factor; Platform construction; Balloon construction

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INTRODUCTION

Cross-laminated timber (CLT) is an emerging construction material in North America. Originally developed in Europe, CLT has gained significant interest in the North American market (Karacabeyli and Douglas 2013; Pahkasalo *et al*. 2014; Grasser 2015; Espinoza *et al*. 2016). Recent changes to the building codes and design standards in Canada and United States have opened the opportunity for constructing buildings taller than 19.8 m with wood due to large cross sections to resist fire (IBC 2015). It is widely believed that light-frame construction will continue to be the structural system of choice for residential buildings from 1 to 5 or 6 stories, which includes single-family housing, townhouses, and smaller apartment buildings (Grasser 2015). The strength and fire requirements associated with taller buildings restricts the use of light-frame wood construction (ICC 2018b). However, CLT can meet the performance requirements of buildings above 6 stories in height and different occupancies (ICC 2018a).

Several North American buildings have been, or are in design or construction, constructed with CLT in the 6 to 12-story range such as Frameworks in Portland, Oregon (Lever/KPFF), the Earth Systems Science Building in Vancouver, Canada (Perkin+Will/Equilibrium), and the Multi-Disciplinary Design Building in Amherst, Massachusetts (Lear Weinzapfel). In addition to this mid-height class of buildings, several buildings in the 18 to 20 story range have also been completed, including the Brock Commons dormitory building in Vancouver, Canada (Acton Ostry Architects), the 20-story

Forte building in Melbourne, Australia (Lendlease), and the 12-story Frameworks building in Portland. There are also development stage building projects for buildings with 20+ stories, such as the 21-story building in Amsterdam, Netherlands (ARUP) and a 40-story building in Stockholm, Sweden (Berenson Architecture). The number of projects utilizing CLT is expected to increase over the next several years as the supply chain in North American develops.

Several factors are driving the increased interest in CLT as a building material for taller buildings. CLT has a favorable environmental impact compared to concrete and steel as a result of carbon sequestering, lower energy requirement for manufacture, and lighter weight for transportation (Adam *et al*. 2012; Chen 2012). In addition to environmental factors, increased interest has also resulted from economic considerations (Karacabeyli and Douglas 2013). CLT is lighter than the concrete and steel structural systems typically used for commercial and mid-rise buildings, thereby resulting in a cost savings for the design and construction of the foundations due to smaller loads (gravity and seismic), faster construction rates, and smaller construction crew sizes. Recent experience with construction of tall CLT buildings is that the building structural system can be constructed at a rate of one-story per week with a crew as small as 4 people and a crane operator. These advantages result in significant savings in construction financing, and an early initiation of revenue streams from lease or sales of the occupied space. Together, these advantages have sparked interest in utilizing CLT for these classes of buildings.

In an effort to estimate the potential CLT demand in United States markets for buildings up to 20-stories tall, a need exists to estimate the volume of CLT required per square meter of building footprint for different building archetypes; this number is called the *CLT use factor*. The CLT use factor is a factor used on a per story basis (*i.e*., a 5,000 m^2 building that is 5 stories tall would require (5000m^2 * CLT use factor * No. of Stories m^3 of CLT material.) Lower and upper bound CLT use factors of 0.195 and 0.262 m^3/m^2 were assumed by Bédard *et al*. (2010); however, the lower value was used in CLT market predictions.

An evaluation of European CLT buildings presented by Crespell and Gagnon (2010) has CLT use factors that range from 0.149 m^3/m^2 to 0.457 m^3/m^2; the majority of the reported use factors were greater than 0.305 m^3/m^2. With a CLT use factor determined, it can be applied to forecasting data in relevant building classes. In this manner, the potential demand can be determined for investor decisions. This projected CLT demand could also be used to assess the impact of CLT production on the current lumber supply considering both species and grade requirements.

The objectives of this research were to outline the assumptions and analysis used to determine the CLT structural requirements for three archetype building classifications, and to estimate CLT use factors that are needed for CLT construction cost estimation and for predicting CLT market demand.

The level of analysis used might be considered to be equivalent to a preliminary analysis for a real design. This level of analysis does not include significant detailing of connections or progressive collapse analysis. The analysis included initial estimation of the gravity and lateral force resisting systems. This scope was not to develop an exact analysis for any particular building, or the detailing required for the particular structural systems chosen. Such a detailed analysis would require a specific architectural layout for the building, which is beyond the scope of this work.

LITERATURE REVIEW

The manufacture, fire resistance, and structural performance of CLT buildings have been investigated in Europe, Canada, Japan, and the United States for the past few decades. In recent years, several research projects have been funded to improve the manufacture (Gu and Pang 2016; Wang *et al*. 2015) and fire performance of CLT (Janssens 2015; Su and Muradori 2015). The structural performance of CLT has been or is being investigated in several projects (Pei *et al*. 2013; Yasumura *et al*. 2016; Ganey *et al*. 2017). This paper builds on previous work to develop a design methodology that estimates the amount of CLT required for three typical building archetypes: a 6-story platform framed building, a 12-story rocking wall building, and an 18-story hybrid building with a concrete core with CLT floors. These three types of construction were chosen to simulate the current CLT construction options at various building heights. Each building design provides an estimated CLT demand volume.

The first step in predicting CLT building markets is to develop reliable estimates of building construction growth. The electric power industry has a vested interest in developing reliable estimates of new building construction, given that approximately 70 percent of electric energy consumed in the US is in operational energy of buildings. For the Northwest United States, the Seventh Northwest Conservation and Electric Power Plan (7PP) provides historical and forecasted estimates of the types and quantity of commercial and residential buildings (NPCC 2016). The Northwest Energy Efficiency Alliance (NEEA) performs a routine study to assess the current energy consumption in the Northwest. This study is known as the Northwest Commercial Building Stock Assessment (NCBSA) (NEEA 2014). Unlike the 7PP, the NCBSA focuses on commercial building types by assessing a variety of buildings with different use and occupancies. Throughout the years, the variety of building uses explored by this study has continued to expand. NCBSA provides information regarding the characteristics of different building types, as well as an indication of the popularity of specific building heights of certain occupancies.

CLT usage in buildings is emerging in the Northwest; however, reliable forecasts of long-term adoption and market diffusion are lacking. Laguarda Mallo and Espinoza (2015) gathered data on the perception of CLT in multiple aspects of building design, including environmental and structural performance areas. Their conclusions were that the level of awareness was low, environmental aspects were the primary benefits, and the main barrier to market expansion was the building code. To assess the diffusion into the Northwest market, Beyereuther *et al*. (2016) focused on the incorporation of CLT into various building types forecasted to be constructed in the Northwest over the next 20 years. This study utilized both moderate and aggressive growth rate scenarios that were based on historical trends, the projected CLT demand volumes indicated this technology warrants further investigation.

CLT manufacturing in the United States is governed by national voluntary product standard ANSI/APA PRG 320-2018 (2018). This standard provides geometric tolerances of both the overall panel and individual laminations. Manufacturers are limited by the lumber species and grades that may be utilized for the panel layers. It also specifies minimum performance requirements, necessary quality assurance tests for product approval by APA, and testing methods for assessing on-going performance requirements. Mechanical properties of the laminations are used to calculate allowable CLT design values using methods provided in the CLT Handbook (Karacabeyli and Douglas 2013).

EXPERIMENTAL

Current design methodologies using CLT are not readily available to the designer as compared to more widely implemented, code-compliant building technologies. Chapter 23 of the International Building Code (IBC) (ICC 2018) recognizes CLT as a building material and the National Design Specification for Wood Construction (NDS) (AWC 2018) provided design value adjustments for floor panels, but lateral design with CLT is relatively undeveloped. The current method for using CLT as a lateral system in the U.S. is utilizing performance-based design methodologies. Details of this are provided in Chapter 1 of ASCE 7 (2016), which requires the designer to demonstrate that the system will meet the minimum expectations of the building code. CLT walls can either be platform or balloon framed in a building. Platform framing is where the floors of each story are built on top of the walls of the floor below and each floor is constructed independently. Currently, a FEMA P-695 (2009) study is underway to develop seismic design parameters needed for platform CLT shear walls (Pei *et al*. 2013). Once these parameters are adopted, engineers will no longer need to employ performance-based methodologies for platform CLT construction. Karacabeyli and Douglas (2013) provide methods for determining the lateral capacity of walls, but do not provide values that may be used by an engineer for seismic design. Platform walls are usually limited to buildings under 6-stories; the combination of gravity and lateral demands cause design failure of the diaphragm elements under the shear walls. The limiting property is compressive strength perpendicular to grain of the floor panels.

If CLT is to be utilized in mid- to high-rise buildings, balloon-framed walls are required. Balloon framing is where the walls are continuous from the foundation to the roof and the floors are hung off the walls at the height required. In regions of high seismic hazard, these walls typically consist of post-tensioned rocking walls that are coupled with energy dissipation devices that add ductility to the system. Rocking walls are balloon-framed walls that are allowed to rock about their base to provide the building with a higher displacement capacity and reduce the damage experienced during a high lateral force event. However, these systems are not currently undergoing a FEMA P-695 study for a standard code system, therefore engineers must utilize performance-based methodologies to implement these systems into a building. Regardless of the lateral system of choice, extensive testing regarding the connections and gravity-lateral system interaction are required.

In order to complete an accurate assessment of CLT demand, forecasted heights and sizes of different building types for both commercial and residential uses provided by the 7PP (2016) and NCBSA (2014) were used. This data informed selection of archetypical buildings that represent a distribution of expected building configurations. Preliminary design methods for gravity and seismic forces were completed for the archetypes to provide a required volume of CLT.

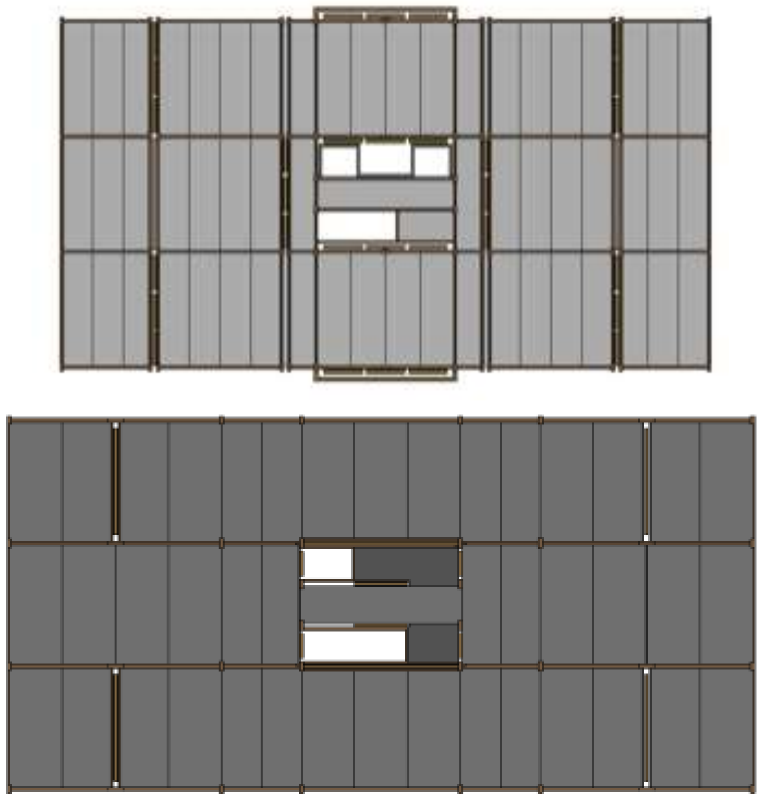
Building archetypes used in this study were defined by three main parameters: lateral system, building area per floor, and building height. Archetypes were separated into three height categories: low-, mid-, and high-rise. All three archetypes were assumed to be classified as Occupant Risk Category II, following the ASCE 7 (2016) methodology. For this study, low-rise buildings were defined as having 1 to 6 stories and utilizing platform construction methods. A maximum story height of 6 stories was chosen due to the inability of platform systems to satisfy strength demands above this height. This corresponds to the current findings of the FEMA P-695 study for CLT platform walls being conducted at Colorado State University (Pei *et al.* 2013). Mid-rise buildings were defined as having 7 to 12 stories and used balloon framed construction methods. The 12-story height limit was dictated by the strength limitations of CLT rocking wall systems. Building that were 13 to 20 stories were defined as high-rise and had a concrete core as the lateral resistance system. This made the high-rise archetype a hybrid building with CLT and concrete. Both the mid- and high-rise building types were assumed to utilize the CLT floors and roof, and glulam beams and columns for the gravity system.

Information provided by both the 7PP and NCBSA were used for selecting a range of footprints and heights (7PP 2018, NEEA 2014). The 7PP divides multi-family residential buildings into height categories: 1 to 3 and more than 3 stories (2018). NEEA separates commercial buildings into three groups by height: 1 to 3, 4 to 6, and taller than 6 stories (2014). This study captures the 7PP and NEEA data, but was also expanded to include the building sizes that may incorporate CLT in the future. Based on recent projects in North America that have incorporated CLT, a maximum height of 20 stories was assumed for the building archetypes.

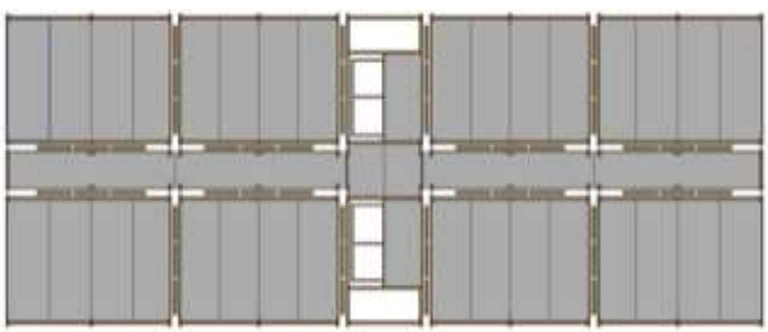
NCBSA presents existing residential and commercial building sizes that range from less than 465 m^2 to greater than 9,290 m^2 per floor. To divide this range, footprints began at 93 m^2, then increased to 465 m^2, and increased again to 929 m^2. After 929 m^2, increments of 929 m^2 were used until reaching a maximum value of 9,290 m^2 per floor. Practical limitations on typical lot size in the Northwest were used to set a maximum footprint of 9,290 m^2. Although the NCBSA footprints are for existing buildings, use of the data is a reasonable assumption as it is likely that a majority of buildings in the Northwest will be represented in these archetype floor sizes. For each story height and footprint, a building archetype was produced. The parameters that define the categories of the building archetypes are presented in Table 1 and sample floorplans are included in Fig. 1.

Table 1. Summary of Building Archetypes

	Height Classification		
Building Footprint (m^2)	Low-Rise (1-6)	Mid-Rise (7-12)	High-Rise (13-20)
93	**Platform Construction** CLT Shear Wall Lateral System Timber Frame Gravity System	**Balloon Frame Construction** CLT Post-Tensioned Rocking Wall Lateral System Timber Frame Gravity System	**Hybrid System** Concrete Core Wall Lateral System Timber Frame Gravity System
465			
929			
1,858			
2,787			
3,716			
4,645			
5,574			
6,503			
7,432			
8,361			
9,290			



a) Floor Plan for Low-Rise Archetype



b) Floor Plan for Mid-Rise Archetype

c) Floor Plan for High-Rise Archetype

Fig. 1. Wall layout for building archetypes. a) low-rise, b) mid-rise, c) high-rise

Preliminary Gravity Design and Seismic Demands

For all building archetypes, designs were based on a location in Seattle, WA. Per the City of Seattle building code (2015), a minimum snow load of 1.2 kN/m^2 was utilized, which was greater than the flat roof snow load calculated in accordance with ASCE 7 (2016). This snow load includes a rain-on-snow surcharge. The roofs of all archetypes were assumed to be flat; therefore no unbalanced snow load scenarios were considered. In addition, increased snow loads due to drift were not considered in this study. It was also assumed that primary and secondary drain systems would be sufficient to avoid ponding issues.

The coordinates and associated seismic design parameters are presented in Table 2. Seismic demands on a given building archetype are dependent on its mass. This mass consists of both the expected superimposed dead loads on the building, as well as the self-weight of structural elements. Superimposed dead loads may be selected at the designer's discretion, but element self-weight requires initial member sizes to be selected, which are the result of a preliminary gravity design.

Table 2. Seattle Site Seismic Parameters

Parameter	Value
Latitude	47.623° N
Longitude	122.335° W
Site Class	D
Mapped Spectral Accelerations (S_s, S_1)	1.372g, 0.478g
Design Spectral Accelerations (SD_s, SD_1)	1.098g, 0.580g

Superimposed dead loads for each archetype were held constant, but structural element self-weight varied for the different building heights. Determining the seismic mass for each building archetype required numerous assumptions to be made regarding loading, grid spacing, utilized materials, roof conditions, and story height. Depending on the building category, different assumptions were applied to address the individual lateral systems.

Gravity loading utilized for the preliminary design consisted of dead, live, and snow loads. It was assumed that other types of loading would not govern the design of the gravity system. Allowable stress design methodology (ASD) was used to determine loads in accordance with ASCE 7 (2016). Superimposed dead loads for all building archetypes included the following assumptions:

- Mechanical, electrical, plumbing and fire: 0.24 and 0.48 kN/m^2 for floors and roofs, respectively
- Interior partition walls: 0.48 kN/m^2
- Gypcrete and floor topping: 0.72 kN/m^2

The self-weight of most of the structural elements were kept consistent between building archetypes. These included the following:

- CLT Floor Diaphragms: 5-ply (175 mm) with a specific gravity of 0.5
- Glulam Beams: 311 x 610 mm Douglas-fir glulam beams spaced 4.88 m o.c.

The beam spacing of 4.88 m o.c. was chosen to satisfy vibration-controlled spans of CLT floor panels. Methods given in Chapter 7 of the CLT Handbook can be used to determine a vibration-controlled span for a CLT floor panel. This span maintained vibration serviceability (Karacabeyli and Douglas 2013). The glulam beam size was chosen to satisfy strength and typical deflection criteria described in the NDS and IBC (L/360 for live load and L/240 for dead plus live load). The following assumptions were made: beams are continuously braced on the compression side and simply-supported at the ends, and all members of the gravity system were assumed to be kept dry and in normal temperature conditions.

For the low-rise building archetypes, platform walls contributed to the self-weight dead load that acts on the gravity system. In addition to the lateral demand, platform framed walls carried gravity loads, which requires walls on lower stories to be thicker than their upper story counterparts. The Colorado State University FEMA P-695 study used platform wall thicknesses of 5, 7, and 9-ply for the 5th and 6th stories, 3rd and 4th stories, and 1st and 2nd stories, respectively, to meet the required demands (Amini *et al.* 2018). For consistency, these thicknesses were utilized for computing the dead load contribution of the platform walls on the gravity system.

Live loads were conservatively assumed to be 2.39 kN/m^2 for all archetypes, which corresponds to the minimum office live load in ASCE 7-16. This is a conservative assumption for residential buildings that require a minimum live load of 1.92 kN/m^2 (ASCE 7 2016). Live load area reductions allowed by ASCE 7 for large tributary areas were utilized where applicable.

Columns

Columns were the only component of the gravity system that change in size as the archetype height increases. As expected, increased archetype buildings heights required the column sizes to increase. It is a common practice to change column sizes every 5 to 10 stories for construction purposes, depending on the designer's preferences. For the mid- and high-rise buildings, this practice was applied. However, for the low-rise buildings, a single column size was used for the entire building. The individual story height was assumed to be 4.28 m for all buildings. This story height provides adequate room for utilities, when column spacing and beam depth are considered, as well as maintaining a reasonable ceiling height for occupants. Column boundary conditions were assumed to be pin-pin for the standard glulam columns that were designed in accordance with NDS 2018. Glulam properties used for all columns were for Combination 3-DF-L2D with 4 or more laminations (NDS 2018). For each rise classification, the column design for the building with the most stories was applied to all the buildings in that rise classification. That is, a 6-story, 12-story, and 20-story archetype was used for the column design for low-, mid-, and high-rise, respectively. The column sizes utilized for each building height classification are shown in Table 3.

Table 3. Column Sizes Utilized for Each Archetype Building Category

	Column Cross Section (mm)		
Height Classification	Low-Rise	Mid-Rise	High-Rise
Stories 1-5	222 x 343	311 x 457	311 x 686
Stories 6-10	222 x 343 [1]	222 x 21	311 x 495
Stories 11-15	-	222 x 229 [1]	273 x 381 [1]
Stories 16-20	-	-	222 x 10.5

[1] Only stories that apply to the respected building category utilize the column size provided.

Seismic demands for the archetype buildings were determined in accordance with the Equivalent Lateral Force (ELF) method in Chapter 12 of ASCE 7 (2016) using seismic parameters for the Seattle site (Table 2). Site Class D was assumed for the site class *in lieu* of a site-specific geotechnical investigation. This site has a reasonably high short- and long-period design accelerations and is representative of a high seismic risk site. Other sites could be included, but after the design accelerations and the base shear are determined, the initial design of the building will be a scalar of the wall lengths required for this site. The base shear and vertical force distribution equations from ASCE 7 are presented in Equations (1) and (4) respectively.

$$V = C_s W \tag{1}$$

where C_s is the seismic response coefficient determined using Eq. 2 and W is the effective seismic weight of the structure.

$$C_s = \frac{S_{DS}}{\left(\frac{R}{I_e}\right)} \tag{2}$$

In Eq. 2, S_{DS} is the design spectral response acceleration for short period buildings, R is the response modification factor, and I_e is the building importance factor (assumed to equal 1 for this analysis),

$$F_x = C_{vx} V \tag{3}$$

where F_x is the equivalent static lateral force applied to the building at level x, and C_{vx} is the vertical distribution factor as determined using Eq. 4.

$$C_{vx} = \frac{w_x h_x^k}{\sum_{i-1}^{n} w_i h_i^k} \tag{4}$$

In Eq. 4, w_i and w_x are the portion of the total effective seismic weight of the structure (W) located or assigned for level i or x, h_i *or* h_x are the height from the structure's base to level i or x, and k= 1.0 for this analysis, since it was assumed that the building period would be in the short period range.

For the CLT platform walls, Pei *et al*. (2013) showed that a Response Modification Factor (R) for CLT platform walls of 4.5 is sufficient to meet code performance at maximum considered earthquake (MCE_r) level events; however, in the interest of conservatism an R=4.0 was assumed for the analysis reported herein. This is approximately what the R-factor value used in Canada currently is as well. The final Response Modification Factor for CLT platform construction is being determined by standard committees in the United States at this time.

For CLT rocking walls, a higher amount of energy dissipation and higher displacement capacity was expected compared to platform walls with mechanical connections (Wilson 2018; Wilson *et al*. 2019). In a rocking wall system, the structural fuses placed between CLT panels dissipates significant seismic energy relative to the small amount dissipated by crushing at the bottom corners of the wall. This reasoning, in conjunction with engineering judgement, was used to select an R value of 6 for use in the initial ELF analysis to determine a preliminary length of wall required.

Slightly different procedures were used to determine the seismic demands for low-rise buildings versus mid-rise buildings. Seismic demands were not calculated for high-rise buildings; concrete cores were assumed for the lateral system, and therefore the lateral force resisting system would not contribute to the volume of CLT used in the building. For low-rise buildings, the assumed dead loads were used to determine the weight per square meter of floor. This value was used to determine the total weight of all low-rise archetype buildings. For each low-rise height configuration, the seismic response coefficient (C_s) was determined in accordance with the ASCE 7 ELF method (2016). By using these values for R and C_s, the seismic base shear for each low-rise archetype was determined.

Platform Framed Construction for Low-Rise Buildings

Preliminary lateral design of the low-rise archetypes provided the contribution of CLT demand from the lateral force resisting system. The required amount of CLT walls was assumed to be dependent on the shear capacity of the wall panels. The shear capacity of a CLT wall panel is usually governed by the capacity of the shear connections at the base of the wall. By utilizing a specific number of connections at the base, the overall shear capacity of the wall was determined.

The capacity of a platform wall was calculated using shear connection capacities of 51.6 kN, which match those in the FEMA P-695 study (Amini *et al*. 2018). It was assumed that 4 shear connectors would be installed on each side of a wall panel for a total of 8 per wall panel making the shear capacity of a single wall panel 411.5 kN. All wall panels used for design were assumed to be 1.22 m wide, which results in shear connections being spaced slightly less than 304 mm apart on each side of the wall, which is reasonable to avoid local failure mechanisms in the CLT. It was assumed that the shear capacity of the connectors would not exceed the shear capacity of the wall, therefore driving the failure into the shear connectors. The wall panels were assumed to be V2M1 grade panels manufactured by Structurlam; the shear capacities of the 5-, 7-, and 9-ply panels were taken from the *CrossLam CLT Technical Design Guide* (2017).

Table 4. Volumes of Wall Demanded for Low-Rise Buildings in m^3

Building Footprint (m^2)	Number of Stories					
	1	2	3	4	5	6
93	1.25	4.93	11.89	22.14	33.22	52.27
465	6.20	24.66	56.21	71.61	128.8	190.7
929	12.43	49.33	88.77	135.7	250.4	351.8
1,858	24.83	77.64	154.0	250.2	493.5	681.2
2,787	37.26	116.5	230.9	375.3	740.2	1,022
3,716	49.67	155.3	355.1	500.5	987.0	1,362
4,645	62.10	167.8	443.9	625.6	1,234	1,703
5,574	74.50	165.8	532.7	750.7	1,480	2,044
6,503	86.93	193.4	538.8	875.8	1,727	2,384
7,432	99.36	263.1	615.8	1,001	1,974	2,725
8,361	111.8	295.9	692.8	1,126	2,221	3,065
9,290	124.2	276.3	769.8	1,251	2,467	3,406

The capacity of a 1.219 m wall panel was used to calculate the total length of wall required for to meet the base shear for a given archetype building. It was assumed that the required length of wall for a given archetype would be used. This assumption means that the volume of CLT walls predicted was the minimum required for the lateral system and that any additional walls would be light-framed. For simplicity, the buildings were assumed to be a rectangular. Rectangular buildings require wall lengths in proportion to the dimension of the building in the direction analyzed. This is because the tributary mass to a given wall would be proportional to the tributary area to the wall line. If the size of the building archetype dictated that lateral walls be required on the exterior of the building, no more than 50% of the exterior wall area could be used for lateral walls to allow for windows and doors. Walls that exist on the interior of the building archetype were assumed to be the full width of the respective direction. The required wall length in conjunction with the applicable panel thickness was used to compute the CLT demand for the low-rise building archetypes (Table 4).

Balloon Frame Construction for Mid-Rise Buildings

The mid-rise building archetypes utilized balloon framed CLT rocking walls. The CLT wall volume required for these mid-rise buildings was determined by calculating the required CLT for a single building archetype. That archetype functions as the basis for determining the required wall volume for all mid-rise building archetypes.

Rocking wall systems are defined as an alternative system; they are not a code standardized system in ASCE 7 (2017). Rocking walls have evolved from concrete wall systems with studies conducted by Perez *et al*. (2004) and with Nazari *et al*. (2016). Numerous studies have been performed in New Zealand assessing the behavior of laminated veneer lumber (LVL) rocking walls (Loo *et al*. 2015; Kovacs 2016; Sarti *et al*. 2016). In the U.S., CLT rocking wall tests, both as stand-alone walls and coupled walls, have been performed by Ganey *et al*. (2017). An individual rocking wall consists of a CLT panel, or panels spliced together, one or more post-tensioned (PT) rods, and a stiff foundation. The CLT panel is oriented in the strong direction on edge so that the parallel laminations are the majority of the bearing area. Running down the center through a cavity, or along the outsides of the panel, PT rod(s) are placed. These PT rods are anchored to the foundation, as well as to the top of the wall through a bearing connection. The engineer specifies the forces to which the PT rod(s) are tensioned. At the base of the wall, as a result of the PT force and the geometry of the foundation, translation in the two principle horizontal directions of the panel is restrained. Detailed wall behavior for rocking walls is described by Ganey (2015) and Ganey *et al*. (2017).

CLT rocking walls do not provide sufficient strength, stiffness, or ductility a lateral system when a seismic event is considered. Therefore, the use of energy dissipation devices that couple the rocking walls together is necessary. One popular type of dissipater is U-shaped flexural plates (UFP), which are placed between wall panels and deform with rocking action. A study conducted by Baird *et al*. (2014) investigated the behavior of these dissipaters, as well as provided means of determining the design parameters. This adds additional stiffness to the system, as well as an increase in energy dissipation that allows sufficient performance during seismic events.

The single building archetype that served as the basis for determining the wall volume for all mid-rise building archetypes is 12-stories tall, the tallest in the mid-rise classification. Each floor of the archetype consisted of 1,766 m^2 and a footprint of 26.8 by 65.8 m. (Wilson *et al*. 2019; Wilson 2018). This analysis was modified for the square footprint used in this study. Although these building dimensions were not specifically included in the archetypes considered in this study, the calculations followed the same procedures and assumptions for determining gravity and lateral loads.

From previous investigations, it was found acceptable to execute preliminary design of the rocking wall lateral system utilizing analytical procedures that exclude numerical model development (Wilson 2018; Wilson *et al*. 2019). One analytical procedure exists for determining the moment strength capacity of a single CLT rocking wall that excludes the use of energy dissipation devices. This analytical procedure, applied to rocking walls in this project, is known as the cross-sectional analysis procedure and is described in detail in Ganey (2015). This procedure was first developed for concrete frames by Pampanin *et al*. (2001), and later modified by Newcombe *et al*. (2008) and Ganey (2015) for LVL and CLT walls, respectively. Cross-sectional analysis utilizes a displacement-controlled procedure for determining the moment capacity of an individual wall panel. This procedure requires parameters of the system to be chosen for the CLT wall, as well as the PT rod(s) utilized for the wall, therefore assumptions were made regarding the system. The parameters utilized for cross-sectional analysis are provided in Table 5.

Table 5. Cross-Sectional Analysis and Rocking Wall System Parameters

Component/Parameter	Value
CLT Wall	
Minor Direction Modulus (E_1)	4,290 MPa
Major Direction Modulus (E_2)	5,360 MPa
Compression Strength (F_c)	37.2 MPa
Post Tension Rod	
Diameter (D)	44.5 mm
Yield Strength (F_y)	879 MPa
Ultimate Strength (F_u)	1,030 MPa
Number of Rods	4
U-Shaped Flexural Plates (UFP)	
Bend Diameter (D_U)	76 mm
Thickness (t_U)	13 mm
Width (b_U)	279 mm
Modulus of Elasticity (E_U)	200 GPa

It was assumed that all mid-rise CLT walls were 9-ply panels that were 2.44 m wide and spliced together to achieve the total height of the building. This width was chosen to avoid oversize shipping costs (WSDOT 2017). It was further assumed that the wall dimensions would be kept consistent throughout the height of the building. The 9-ply panels structural properties match the V2M1.1 layup combination by Structurlam (2016). The critical material characteristics are the modulus of elasticity in the major and minor directions, as well as the compressive strength in the major direction of the panel. For this project, the average material property values were used. Structurlam (2016) provides the average the moduli of elasticity in both panel directions. However, the compressive strength value provided is based on an allowable design value for the parallel laminations. The species group utilized in this panel layup was Spruce-Pine-Fir (SPF). An average compressive strength parallel to grain was needed to determine average the response on the rocking walls. The localized crushing of the wall toe would not result in failure of the building; this mechanism is similar to failures in compression perpendicular. This serviceability failure supports the decision to use an average parallel compression strength. The average value was obtained from Wood Handbook (USDA 2010) for Lodgepole Pine, which is a species within the species group SPF. For the major and minor directions of the panel, an effective modulus was taken with respect to the percentage of laminations in the direction that contained parallel to grain stresses and those oriented perpendicular to grain stresses.

The rocking walls were designed to ensure that the PT rod did not yield. It was assumed that four 44.5 mm diameter PT bars would be installed for each wall panel. The chosen PT bars are manufactured by Dywidag (2006) and have an ultimate capacity of 1,030 MPa. The initial PT force of 1,780 kN (445 kN per rod) was applied to each rocking wall. The parameters in Table 5 were used to calculate the moment capacity of the wall at 2% drift. The drift limit of 2% was chosen because it is the story drift limitation for most structural systems in Chapter 12 of ASCE (2017). This wall configuration resulted in a calculated moment capacity of 2,510 kN-m. The calculations also confirmed that no yielding of the PT rods occurred at a story drift of 5%.

After determining the moment capacity of a single CLT rocking wall, the strength of the system, including UFP's, was determined. It was assumed that the maximum overturning demand would occur at the base of the structure; the system configuration was conservatively based off of this value. The overturning demand was determined by the seismic loads computed using the ELF procedure in ASCE (2017). As a result of the flexibility of the rocking wall system, it was assumed that the building would possess a rigid diaphragm and that the moment demand would be equally distributed to each line of walls on a given floor. It was further assumed that there were 10 and 8 groups of rocking walls in each direction, respectively. Within those walls, each group would possess 4 individual rocking walls that would be coupled with UFP's with parameters defined in Table 5. The UFP dimensions combined with equations provided by Baird *et al*. (2014) provided the information to determine that 30 UFP's between two wall panels are required to meet the strength demands. The combined wall strength and the UFP strength provided was sufficient for meeting the seismic demands. The system strengths in the North-South and East-West directions of the building were 304,100 kN-m and 380,100 kN-m, respectively.

A linear correlation was assumed between the weight of each archetype and the length of wall necessary to satisfy seismic demands. This approximation from the 12-story building provided the information needed to determine the required CLT for all mid-rise archetype buildings. The weight of the 12-story archetype per square meter of floor and roof was determined to be 3.38 kN/m^2 and 2.76 kN/m^2, respectively. With these weights the weight of all mid-rise archetypes were determined, as provided in Table 6.

Table 6. Total Building Weight for Mid-Rise Archetypes (MN)

Building Footprint (m^2)	Number of Stories					
	7	8	9	10	11	12
93	2.1	2.5	2.8	3.1	3.4	3.7
465	10.7	12.3	13.8	15.4	17.0	18.6
929	21.4	24.5	27.7	30.8	34.0	37.1
1,858	42.8	49.1	55.4	61.7	67.9	74.2
2,787	64.2	73.6	83.1	92.5	101.9	111.3
3,716	85.6	98.2	110.8	123.3	135.9	148.4
4,645	107.0	122.7	138.5	154.2	169.9	185.6
5,574	128.5	147.3	166.1	185.0	203.8	222.7
6,503	149.9	171.8	193.8	215.8	237.8	259.8
7,432	171.3	196.4	221.5	246.6	271.8	296.9
8,361	192.7	220.9	249.2	277.5	305.7	334.0
9,290	214.1	245.5	276.9	308.3	339.7	371.1

The total wall length required by the 12-story archetype was determined to be 175.6 m. This wall length was scaled using the relative building weights. Wall length was converted to CLT volume and is reported in Table 7.

Table 7. CLT Wall Volume for Mid-Rise Building Archetypes (m^3)

Building Footprint (m^2)	Number of Stories					
	7	8	9	10	11	12
93	45	59	75	92	112	133
465	224	294	373	461	559	666
929	448	588	745	922	1,118	1,332
1,858	897	1,175	1,491	1,845	2,236	2,664
2,787	1,345	1,763	2,237	2,767	3,354	3,997
3,716	1,793	2,350	2,982	3,689	4,471	5,329
4,645	2,242	2,938	3,728	4,611	5,589	6,661
5,574	2,690	3,525	4,473	5,534	6,707	7,993
6,503	3,138	4,113	5,219	6,456	7,825	9,325
7,432	3,587	4,700	5,964	7,378	8,943	10,658
8,361	4,035	5,288	6,710	8,301	10,061	11,990
9,290	4,483	5,875	7,455	9,223	11,179	13,322

Hybrid Construction for High-Rise Buildings

For the high-rise archetype used in this study, it was assumed that the lateral force resisting system consisted of reinforced concrete shear cores around the elevator shaft and stairwells. This assumption means that there is no shear wall demand for CLT. All CLT used in the high-rise buildings was assumed to be only the 5-ply panels for the floors and roof.

RESULTS AND DISCUSSION

The CLT demand for each height classification can be provided as wall volume, diaphragm volume or the total volume. This volume can also be discussed as volume of CLT panel thickness, *i.e*. 5, 7 or 9-ply. However, all of these CLT volumes are specific to each archetype building. A more general value, the *CLT use factor*, allows the information to be applied to a variety of similar buildings. This versatility is the reason we have chosen to report CLT use factors.

Platform Construction

The low-rise buildings have both wall and diaphragm CLT volume and contain a combination of 5-, 7- and 9-ply CLT; the total volume of CLT for each low-rise archetype building is provided in supplemental material. The CLT use factors for low-rise buildings increased with additional stories, which was expected as panel thickness requirements for walls increased with height (Table 8). However, it should be noted that for buildings in the 2- to 6-story range, the CLT use factor slightly decreases with increasing building footprint.

Table 8. CLT Use Factor (m^3/m^2) for Low-rise, Platform Construction Archetype Buildings

Building Footprint (m^2)	Number of Stories					
	1	2	3	4	5	6
93	0.19	0.20	0.22	0.23	0.25	0.27
465	0.19	0.20	0.22	0.21	0.23	0.24
929	0.19	0.20	0.21	0.21	0.23	0.24
1,858	0.19	0.20	0.20	0.21	0.23	0.23
2,787	0.19	0.20	0.20	0.21	0.23	0.23
3,716	0.19	0.20	0.21	0.21	0.23	0.23
4,645	0.19	0.19	0.21	0.21	0.23	0.23
5,574	0.19	0.19	0.21	0.21	0.23	0.23
6,503	0.19	0.19	0.20	0.21	0.23	0.23
7,432	0.19	0.19	0.20	0.21	0.23	0.23
8,361	0.19	0.19	0.20	0.21	0.23	0.23
9,290	0.19	0.19	0.20	0.21	0.23	0.23

Balloon Construction

The total CLT volume for each mid-rise archetype building was a combination of 5-ply diaphragms and 9-ply walls. The mid-rise CLT use factors are greater than the use factors for either the low or high-rise classifications (Table 9). It is not surprising that the mid-rise classification has higher CLT use factors, because uses CLT for both diaphragms and walls, with all walls being 9-ply. The rocking walls are also far less stiff than those used in low-rise construction (platform construction), which results in longer total wall length being required. The CLT use factors did not change as building footprint increased, due to the linear relationship between mass and length of building. Gravity loading does not impact the design of the rocking walls due to the design using independent structural systems for gravity and lateral loading, so the table was condensed accordingly.

Table 9. CLT Use Factor (m^3/m^2) for Mid-rise, Balloon Construction Archetype Buildings

Building Footprint (m^2)	Number of Stories					
	7	8	9	10	11	12
93 – 9,290	0.24	0.25	0.27	0.27	0.28	0.29

Hybrid Construction

For hybrid construction the entire CLT demand, provided in the supplemental materials, was 5-ply diaphragms. The CLT use factor for all high-rise building was 0.17 m^3/m^2. This result was expected, since the volume of CLT required for these buildings is restricted to the floors and roof system. Lateral loads are resisted by the concrete cores and have no effect on the gravity system.

Use Factor Evaluation

CLT use factors are a simple way to determine possible CLT demand for a single building or a class of buildings. Application of this factor to forecasted new construction provides a CLT volume. Bédard *et al*. (2010) discussed two CLT use factors: 0.20 m^3/m^2 and 0.26 m^3/m^2, assuming 0.20 m^3/m^2 for projected demand. Crespell and Gagnon (2010) quantified use factors in completed European buildings. These factors, most of which are more than 0.30 m^3/m^2 are based on European implementation of CLT, with all partition walls being CLT. The values calculated through the design processes detailed in the methods section of this manuscript fall within the range of the literature values. The highest CLT use was for mid-rise buildings. These buildings had the same diaphragm use as the low and high-rise buildings. The additional volume was from a combination of longer shear wall lengths required to meet lateral load demands and thicker CLT panels.

Summary

Structural design methodology and associated assumptions were presented to provide estimates of CLT volume for three different CLT types of lateral force resisting systems. The buildings were divided into applicable height classes: low-rise (1-6 stories), mid-rise (7-12 stories), and high-rise (13-20 stories). Each height class had a unique lateral system. Platform construction was assumed for low-rise buildings, post-tensioned rocking walls were assumed for the mid-rise buildings, and a hybrid reinforced concrete core building was used for high-rise structures. All of the archetype buildings have CLT systems in the floors and roof. The amount of wall length required for each structural system was estimated based on the footprint of the building and the number of stories. These results were then used to estimate the volume of CLT each archetype building would require, which was used to calculate CLT use factors. These use factors can be applied to a variety of building types and facilitate generalized demand estimates.

CONCLUSIONS

The presented analysis covered the three architype buildings that are currently viewed as the main architypes that CLT would be used as major structural components of the building. The analysis used the required methodology for these types of buildings in the United States. The resulting analysis, while only at a preliminary level of detail, provided the ability to estimate the volume of CLT required by determining the CLT use factor (volume per m^2 of floor area) for three archetypical buildings 1-6, 7-12, and 13-20 stories in height. These factors were found to be:

1. Low-rise buildings (1 to 6 stories) that utilize platform construction were found to have CLT use factors ranging from 0.19 to 0.27 m^3/m^2, as stories ranged from 1 to 6.
2. Mid-rise buildings (7 to 12 stories) that utilize balloon construction and use rocking-walls with post-tension rods and seismic energy dissipative connections between panels were found to have CLT use factors ranging from 0.24 to 0.29 m^3/m^2, as stories ranged from 7 to 12.
3. High-rise buildings (13 to 20 stories) utilizing a hybrid structural system, such as CLT diaphragms and concrete cores to resist lateral loads, and CLT and glulam to resist gravity loads were found to have a CLT use factor of 0.17 m^3/m^2 for all numbers of stories.

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