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Modal response spectrum analysis of cross-laminated mid-rise timber buildings equipped with multiple shear slotted-in steel plates connections

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Abstract

Mass timber products are increasingly used in mid-rise to high-rise buildings. Cross-laminated timber (CLT), in particular, is highly used and plays a major role in timber construction. Balloon-type construction appears to be a particularly advantageous system when using CLT panels –it enables to avoid the compression perpendicular-to-grain in floor diaphragms and the disruption of load patterns in CLT walls. Conversely, balloon-type construction requires high-performance connections to transfer high forces and dissipate energy when under seismic loads. Since most of the knowledge draws to low-rise CLT buildings, there is a lack of design guidance and provisions for mid-rise to high-rise CLT buildings. In this paper, the seismic response of a 15-story CLT building equipped with multiple-shear slotted-in steel plate hold-down connections is studied. Special attention is paid to examining how such CLT shear-wall connections affect the overall seismic response of the lateral force-resisting system (LFRS). Linear static analysis and linear dynamic analysis were conducted separately to find and compare the fundamental period of the building, the base shear, and the uplift forces. The results give valuable insights into the structural behaviour of balloon-type CLT construction. Specifically, the analyses confirm that the building is prone to effects of the lateral flexibility and transfers high uplift loads to the foundations under design-level seismic actions. Simplified representations of connection properties showed inappropriate predictions of lateral inter-story drifts, uplift forces, and base shear. Specified design assumptions are needed since seismic parameters and equivalent-static design methods for CLT assemblies are not covered by current building codes. As LFRS of multi-story mass timber CLT buildings largely relies on connection properties and related behaviour, further research is needed to accurately evaluate the effective structural performance of connections such as stiffness, strength, and ductility, and draw anticipated failure modes.

Key words: CLT, mass timber construction, mid-rise buildings, hybrid structure, seismic response spectrum analysis, mechanical connections

1 Introduction

1.1 Mass Timber construction

Recent advancements in wood processing and manufacturing have led to efficient engineered mass timber products such as glued-laminated timber (glulam) and cross-laminated timber (CLT) in wood construction. CLT structural applications have grown recently, and CLT has entered into markets dominated in the past by traditional structural materials such as steel or concrete [1]. Thanks to easing transportation and fabrication, planar-like inherent shape, and two-way bearing capability, CLT can be used for building walls or floor members [2]. Plus, CLT products are quick to be assembled or combined with other non-wood elements, such as steel girders [3] or concrete slabs to create more efficient structures. All those factors make CLT one of the products of choice for mid- and high-rise timber buildings around the world such as the Tallwood house in Vancouver (Canada) [4] and the HoHo in Vienna (Austria) [5].

Platform-type and balloon-type construction are two major methods of assembly employed when building using CLT. Platform-type structural systems are widespread in Europe for one to two-storey timber houses [6]. In this type of construction, a floor platform is built on top of each story's walls and columns, and the following story lays on that platform; the process is repeated for subsequent floors. With this type of system, there is a discontinuity of load pattern in the vertical load-bearing elements, as each platform (floor) collects loads from the upper floors and redistributes it to the lower vertical elements (walls and columns) [7].

Balloon-type structural systems, on the other hand, have vertical load bearing elements (walls, columns) whose length covers two storeys or more without interruption [7]. This method of construction is preferred in North America for fast-erected mid-rise to high-rise buildings: systems from 6 to 20 storeys [6]. From a structural viewpoint, balloon-type is generally preferred in such situations as it enables to avoid the disruption of load patterns in walls while preventing the compression perpendicular-to-the-grain of CLT diaphragms [8]. For balloon-type CLT systems, there is not yet reliable connections for joining the panels, especially in tall buildings, since they are subjected to high forces. Nevertheless, shear slotted-in plate connections can potentially be used to connect vertical panels one another [9]. Such a building system that combines CLT panels and steel connections is usually required to display high load-carrying capacity, stiffness, and yet, high ductility to dissipate energy from dynamic loads generated by earthquakes. From NBCC 2015 [10] code-compliance prospective, research of force reduction factors of CLT buildings equipped with slotted-in connections is needed.

1.2 Seismic design of timber buildings

For conventional low- to mid-rise buildings, where lateral response is governed by their fundamental mode of vibration, building codes usually allow the seismic design through equivalent linear static analysis (LSA) [11]. LSA is a simplified force-based design procedure where equivalent static story forces, due to earthquake or wind, are applied to the structure [11]. LSA formulae and design models are mostly crafted for reinforced concrete and steel structures, such as the empirical equation used to estimate the fundamental period of multi-story buildings. Although some of these models can be extended to common wood structures, common codes do not specifically cover mid and high-rise timber structures. For CLT in particular, the fundamental period equation does not account for different assembly methods and building systems, both pivotal aspects that govern the seismic response and performance of timber buildings [12].

Approximations on the fundamental period have significant implications. Hafeez et al. [13] shown that the fundamental period calculation using the code is very conservative; thus leading to higher design acceleration values and, in turn, to higher design lateral loads. The ultimate implication of that approximation is the low structural efficiency of timber constructions and higher construction costs. Nevertheless, there are methods to accurately estimate the fundamental period of non-conventional structures, among which – linear dynamic analysis (LDA).

LDA enables to accurately capture the main vibrational modes of timber buildings and their associated vibration periods. As a result, LDA can lead to properly sizing timber elements and higher structural and economic efficiency. However, there is a major setback in employing modal analysis for CLT buildings at this date. The mechanical properties of connections used for joining CLT panels significantly influence the seismic behaviour of the building. With reliable data on mechanical properties of slotted-in connections (such as stiffness and strength) still missing in both codes and literature, the LDA outputs' reliability is very affected. Such an issue is tackled in this study by first conducting a micro-scale simulation of the connections in ANSYS to determine their stiffness and strength, which are subsequently used to perform the LDA of the building in SAP 2000.

1.3 Aim and scope

This work mainly aims at evaluating the seismic characteristics and performance –fundamental period, uplift forces, base shear, and inter-story drift– of a 15-story CLT building through a modal response spectrum analysis. The paper also provides a comparison based on outputs from a linear static analysis performed following the National Building Code of Canada Edition 2015 [10].

2 15-Story mass timber building

2.1 Functional description of the building

The 15-story multi-family residential building is located in Vancouver, Canada, see Fig. 1a. It has a 520 square meters footprint that can accommodate a maximum of 4 residential units, with merged living room and kitchen space, 2 bedrooms, 2 bathrooms, and one balcony (Fig. 1.c). The building is accessed by an entrance lobby on the ground floor. Located in the centre of the building, an elevator and a staircase grant access to upper floors. The building is 48 m tall and has an inter-story height of 3.2 m.

Figure 1. a) Axonometric view; b) Structural; c) architectural plan; d) Shear wall; e) Connection detail

2.2 Lateral Force-Resisting System (LFRS)

The 15-story mass timber structure rest on a 2-story underground concrete podium. The lateral force-resisting system consists of glulam-CLT composite floor diaphragms and CLT shear walls. Floor diaphragms transfer loads to walls through their glulam beams. The balloon-type CLT walls constitute a tube-in-tube structural assembly, also known as hull-core system (Fig. 1b). The external tube as well as the internal one is made of double-sided 5-ply CLT walls which allows a ventilation layer in between. CLT panels for walls, which are 9.6 m long each, are joined with dowelled multiple-shear slotted-in plate connections, acting as hold-downs; and steel plates with self-tapping screws, which prevent panels from sliding (Fig. 1.d and 1.e). A constant spacing between the walls is ensured by timber lintels placed at each level.

2.3 Design considerations for the LFRS

The building complies with design provisions of the National Building Code of Canada Edition 2015 [10] and Wood Design standards CSA 086-14 [14], with members and connections sized to meet the ultimate limit state (ULS) and serviceability limit state (SLS) code requirements.

Overstrength and ductility force modification factors, and , have been taken as 1.5 and 2.0, assuming that the connections are designed to display necessary levels of ductility and dissipative capabilities. Adopted values of and have recently been recommended by Popovski et al. [15], and Chen and Popovski [16] for balloon-type mass timber systems. Fig. 2.b. depicts the elastic and design response spectrum (accounting for and) for a building placed in Vancouver for ULS limitation requirement.

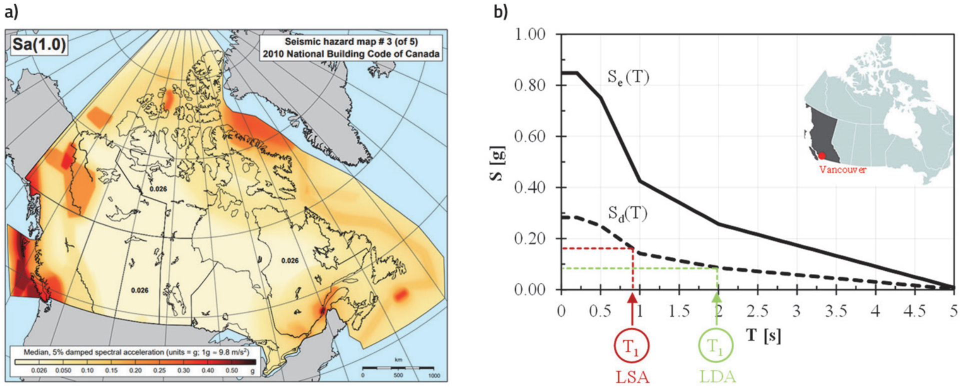

Figure 2. a) Spectral acceleration for a period of 1.0s at a probability of 2 %/50 years for soil class ; b) elastic (black line) and design (black dash line) response spectrum for a structure placed in Vancouver for ULS limitation requirement

2.4 Building's Numerical Model and LDA Considerations

A micro-scale model has been first developed in ANSYS with the aim of determining accurate stiffness and strength values for the dowelled multiple-shear slotted-in plate connections. CLT material has been modelled accounting for the cross-orientation of lamellas and considering a bi-linear orthotropic behavior of wood. Hill's potential theory has been adopted as wood strength criteria. Table 1 gives a set of elastic properties used for CLT. Local crushing of wood has been accounted using a *foundation* material around the dowels (Fig. 3a), as proposed by Hong and Barrett [17]. Two assumptions have been made to account for the mechanical interaction between undamaged and damaged wood; specifically, two modes have been considered for CLT and *foundation* responses respectively: (i) elastic-elastic and (ii) elastoplastic-elastoplastic. Additionally, a tri-linear isotropic behaviour of steel has been considered to model dowels, bolts, and slotted-in plates. A friction coefficient of 0.2 has been assumed for the CLT/steel con-

tact surfaces. To avoid the premature failure caused by the opening of CLT layers, displacement restrain has been set in the Y-direction (Fig. 3a). Incremental displacement-control static tensile analysis has been carried out on the micro-scale model to obtain the load-displacement curve and particularly the elastic stiffness .
The mechanical characteristics of the slotted-in connections (Table 2) simulated through the micro-scale ANSYS model has been input for the macro-scale model developed in SAP 2000. In SAP 2000, frame elements have been used to model CLT lintels; spring elements to model hold-down connections (using results from the ANSYS simulation); and shell elements to model CLT walls. For spring elements, only one degree of freedom was accounted for (in the Z-direction), with an assumption of infinite rigidity in the X- and Y-direction. For frames and shells, both in-plane stiffnesses of elements have been considered (Fig. 3c). Bi-directional base hinges (X- and Y-direction) have been used to anchor the building to the ground. To account for the rigid behaviour of floor diaphragms, constraints have been placed on walls, at the location of each floor (Fig. 3b).

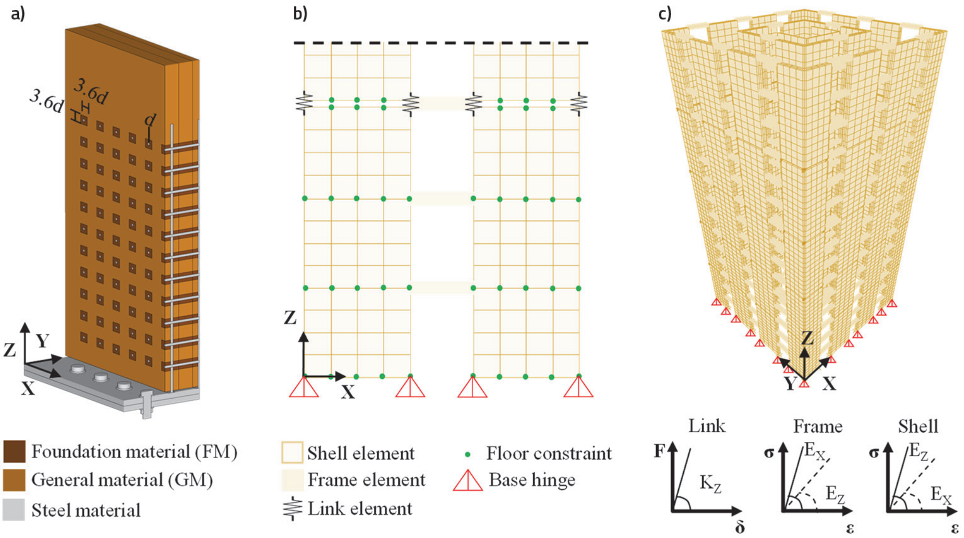

Figure 3. a) Micro-scale FE model implemented in ANSYS; b) Shear wall; c) Macro-scale FE-model implemented in SAP2000

Table 1. Main properties of the micro-scale model

Properties	E_L [MPa]	E_T [MPa]	E_R [MPa]	$G_{RL=RT}$ [MPa]	G_{RT} [MPa]	ν_{LT} [-]	ν_{RL} [-]
General material	10700	631	631	1087	206	0.5	0.08
Foundation material	481	83	83	82	28	0.5	0.08
Steel material	210000	210000	210000	80000	80000	0.3	0.3

Table 2. Hold-down connection properties

Element	K_Z [kN/mm]	n°_{dowels} [-]	$n^{\circ}_{CLT\ layer}$ [-]	$n^{\circ}_{slotted\text{-}in\ plates}$ [-]
Hold-down	540	121	5	3

Table 3. Properties of the macro-scale model

Elements	E_L [MPa]	E_T [MPa]	E_R [MPa]	$G_{RL=RT}$ [MPa]	G_{RT}[MPa]	ν_u [-]
CLT	7176	4914	∞	731	73	0.4

$E_L = E_Z$ is the equivalent modulus of elasticity of CLT wall panels in the direction parallel to the grain of the outer layers while $E_T = E_X$ (in Z-X plane) is the equivalent modulus of elasticity of CLT wall panels in the direction perpendicular to the grain of the outer layers. For a 5-layer CLT panel they can be calculated as suggested by Blaß & Fellmoser [18] and Follessa et al. [19], and reported in Table 3. CLT lintels as well have the same properties but flipped of 90° ($E_L = E_x$ and $E_T = E_Z$).
The linear dynamic analysis undertaken in this study consists in identifying the significant vibrational modes (modes with mass participating factor higher than 5 %). A quadratic combination has been used to combine the effects of selected vibrational modes. The conventional [20] damping as per wooden structures has been used.

3 Results and discussion

3.1 The fundamental period

Table 4 lists periods of the first 5 vibration modes of the building in X- and Y-directions. Specifically, fundamental period is given by 1st vibration mode. Results of modal analysis highlight that this building is very flexible with a of for both X- and Y-directions, resulting close to double of design period () estimated using NBCC2015 code formula for linear static analysis (LSA). As a matter of fact, flexibility of the LFRS brought in by the timber connections and intrinsic properties of the CLT panels is not covered by simplified LSA approach, while well captured through the numerical model in which stiffness of vertical CLT joints and CLT panels have been properly implemented.

Table 4. Natural periods of the building deriving from modal analysis

Mode [-]	**1**	**2**	**3**	**4**	**5**
Period [s] X	1.96	0.50	0.25	0.24	0.22
Period [s] Y	1.96	0.50	0.25	0.24	0.22

3.2 Inter-story shift

Table 5 shows the lateral deflection and the inter-story drift of the building obtained from the LDA. The lateral deflection values X_i obtained from analysis have been multiplied by to give an estimate of the final deflection. Inter-story drift on each floor has been evaluated as ratio between the lateral deflection difference of and floor and the inter-story height . Results show that code limit of is never exceeded and the maximum value of is reached on the top floor. This means the LFRS of the building provides enough stiffness to avoid excessive damage of non-structural elements.

Table 5. Lateral deflection and inter-story drift of structure according to linear dynamic analysis

Floor	X_i [mm]	$X_iR_dR_o/I_E$ [mm]	δ **[%]**
15	138	413	1.12
14	126	377	1.07
13	114	343	1.02
12	103	310	1.04
11	92	277	1.04
10	81	243	0.99
9	71	212	1.00
8	60	179	1.00
7	49	147	0.94
6	39	117	0.90
5	30	89	0.85
4	20	61	0.74
3	13	38	0.54
2	7	20	0.40
1	2	7	0.23

3.3 Uplift and base shear forces

Table 6 presents the maximum uplift () and base shear () forces acting on the hold-down connections and CLT shear walls, respectively, based on the modal response spectrum analysis along X- and Y-directions. Table 6 also reports and values based on LSA.

Maximum uplift and shear forces on CLT panels are very different according to the analyses. As building behaviour is strongly affected by its lateral stiffness, the introduction of the stiffness parameter K_Z, which is not included in the LSA, leads the building to be more flexible. Particularly, the LDA shows lower forces induced into CLT panels and connections than LSA, considering that both stiffness and dynamic behaviour of building has been included in the former. As for the base forces, the total shear forces on each floor show a considerable divergence when evaluated according to LSA (Fig. 4.a) and LDA (Fig. 4.b).

Table 6. Maximum uplift and shear forces on CLT panels according to linear static and dynamic analyses

Properties	$T_{X,max}$ [kN]	$T_{Y,max}$ [kN]	$V_{X,max}$ [kN]	$V_{Y,max}$[kN]
Linear static	2346	2224	356	334
Linear dynamic	1244	1238	199	148
Comparison	-47 %	-44 %	-44 %	-56 %

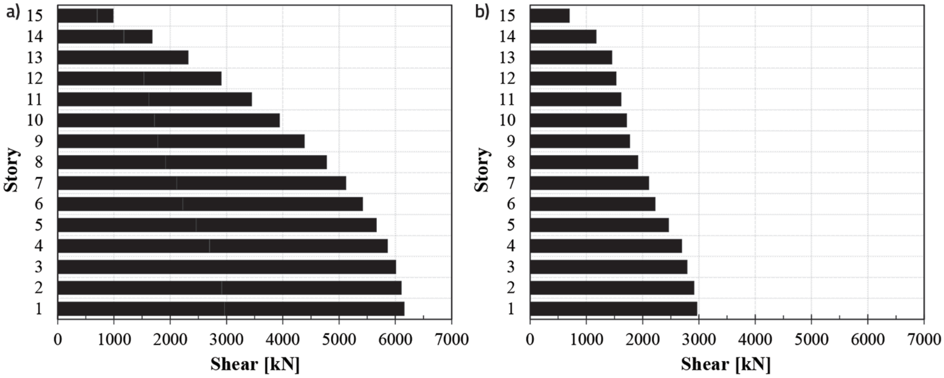

Figure 4. Total shear forces on each story according to: a) linear static; b) linear dynamic analyses

4 Conclusion

Linear static and dynamic analyses have been carried out on the 15-story CLT building. Results of the numerical analyses showed that:

- LSA cannot be considered a reliable tool since it does not account for the effective lateral stiffness of building. Consequently, the fundamental period has been estimated equal to while the base shear and uplift forces has been found and , respectively.
- LDA seems to be a reliable approach considering known a priori stiffness of connections. The calculated fundamental period has been found equal to while the base shear and uplift forces were and , respectively.
- High divergence of forces has been obtained from the two methods, with approximatively halved values for LDA.
- The micro-scale model analysis, used to characterize the stiffness of connection K_Z,

is a key step to a reliable evaluation of the dynamic behaviour of building equipped with such connections—due to the lack of code provisions for slotted-in steel plate connections.

- Results alight to outcomes provided in other studies and form a basis for further exploring the behaviour of mid-rise balloon-type CLT buildings.

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