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ASSESSMENT OF THE FUNDAMENTAL PERIOD OF MULTI-STOREY CROSS LAMINATED TIMBER BUILDINGS

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ABSTRACT: Cross laminated timber has entered the building industry as an alternative to reinforced concrete with interest for employing them in buildings in high seismic regions because they are lightweight. It is envisaged simplified methods have limitations in predicting design level demands on CLT systems due to the complexities and challenges associated with the material. The objective of this work is assessing the efficiency of proposed analytical methods in predicting the fundamental period (T_1) of building superstructures made of CLT. This is because T_1 is the basis for the equivalent lateral force method in seismic analysis of buildings. The assessment is conducted by comparing predictions from verified numerical modal models with estimates from available empirical formulas. Suggestions are made for the minimum requirements for assessing CLT buildings under dynamic loads.

KEYWORDS: Analytical formulas, buildings, cross-laminated timber, fundamental period, seismic design

1 INTRODUCTION

Timber has been identified as a renewable and sustainable construction material capable of being part of the solution to the global warming menace [1-3]. This is because carbon dioxide ((CO_2) the primary anthropogenic greenhouse gas, accounting for 78% of the human contribution to the greenhouse effect) can be absorbed and stored by timber and timber-related products in their lifetime [1]. This reflects that engineered wood products (EWP) such as cross laminated timber (CLT) has better green credentials than mineral resourced-based construction products including concrete and steel. Development of Fire Engineering tools in recent times have also been at the forefront in erasing the concerns associated with timber as a combustible construction material in the building industry [4]. This has enabled the adaptation of massive EWP and other timber materials as new structural forms to meet sustainable housing demands and challenges.

CLT construction systems are manufactured with three or more layers of lumber arranged and bonded in an orthogonal manner enhancing its split resistance to in-plane loading. Commercially they are available in thicknesses ranging between < 100mm and about 500mm [5,6]. Developed and used in Europe for nearly two decades CLT construction systems have become popular across the globe for putting up low- to medium-rise buildings. CLT products have high stiffness to mass ratios and have similar load carrying characteristics to reinforced concrete (RC) [6]. These make them suitable for building in high seismic-prone regions and in areas with soft soil conditions. Consequently, they have become popular as an alternative to RC for the construction of floors and walls including shear walls [4]. However, among the challenges in respect of using new building systems especially those prefabricated from timber like CLT, is employment of empirical design formulas that are applicable to simple design cases, and which may not work well for those new products. Most design codes and guidelines [7-9] recommend that seismic analysis of buildings whose responses are not significantly influenced by contributions from higher-order modes be conducted using the Equivalent Static Force Procedure (ESFP). Such buildings are required to satisfy some criteria for regularity both in footprint and in elevation. The prediction of the fundamental period (T_1) is therefore the most important parameter in determining the base shear to be proportioned along the height of the building [7,8]. Various formulas have been proposed for predicting the fundamental period (T_1) of buildings as a precursor in determining the horizontal seismic forces under the ESFP. For buildings with heights up to 40 *m* the Eurocode [7] recommends estimating T_1 from Equation (1):

$$T_1 = C_t H^{0.75} \quad (1)$$

where C_t is 0.085 for moment resisting space steel frames, 0.075 for moment resistant space concrete frames and eccentrically braced steel frames and 0.05 for all other structures; and *H* is the height of the building, in *m*, from the foundation or from the top of a rigid basement. Similar expressions such as given on Equation (1) are outlined in the National Building code of Canada (NBC) [8] and the

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Indian standard (IS) – criteria for Earthquake Resistant Design of Structures [9]. However, the NBC [8] suggests estimating the fundamental period for other moment resisting frames as $T_1 = 0.1N$, where N is the total number of storeys above exterior grade to level n. The fundamental period for all other buildings may be obtained from Equation (2), according to the Indian Standard [9], where H is the height of the building in m and d is the base dimension of the building at the plinth level along the considered direction of earthquake shaking in m.

$$T_1 = \frac{0.09}{\sqrt{d}} \tag{2}$$

The objective of this study is to assess the capabilities of existing empirical formulas in various design guidelines in accurately estimating T_1 of CLT buildings. In particular, the study focuses on the so-called platform buildings in which CLT floor framings are supported on load bearing CLT walls; with an erected floor serving as the platform for building the next storey. The assessment is based on using verified numerical models capable of fully representing construction features that exist in actual buildings. Attention is placed on predicting mode shapes and associated modal frequencies. This includes demonstrating whether the discrepancies that can arise out of using simplified assumptions and approaches outlined in various design guidelines for seismic analysis may be acceptable for emerging construction systems.

2 NUMERICAL MODELS

This section describes the scope, assumptions, and calibration of the numerical model techniques employed in this study.

2.1 SCOPE AND ASSUMPTIONS

The numerical models presented in this study represent CLT buildings that are rectangular on plan and satisfy Platform Construction methodology. Building models ranging between 4- and 12-storey heights with footprint and wall locations shown in Figure 1, were considered to match current trend of multi-storey mass timber buildings. Axes of material symmetry (1, 2, 3) of CLT plates are considered to lie parallel to orthogonal axis directions x, y, z that define the length, width and thickness of elements. Linear-elastic small deflection theory is assumed valid since amplitudes of system displacements are several orders of magnitude less than overall building superstructure dimensions.

The limitation of the scope to buildings with rectangular floors was adopted because it illustrates choices of design variables that ensures geometrical regularities for the ESFP in the event of seismic analysis and design without limiting the generality of the adopted concepts. Buildings which are regular in both footprint and elevation are typical for many practical occupancy applications.

2.2 MODELLING TECHNIQUES

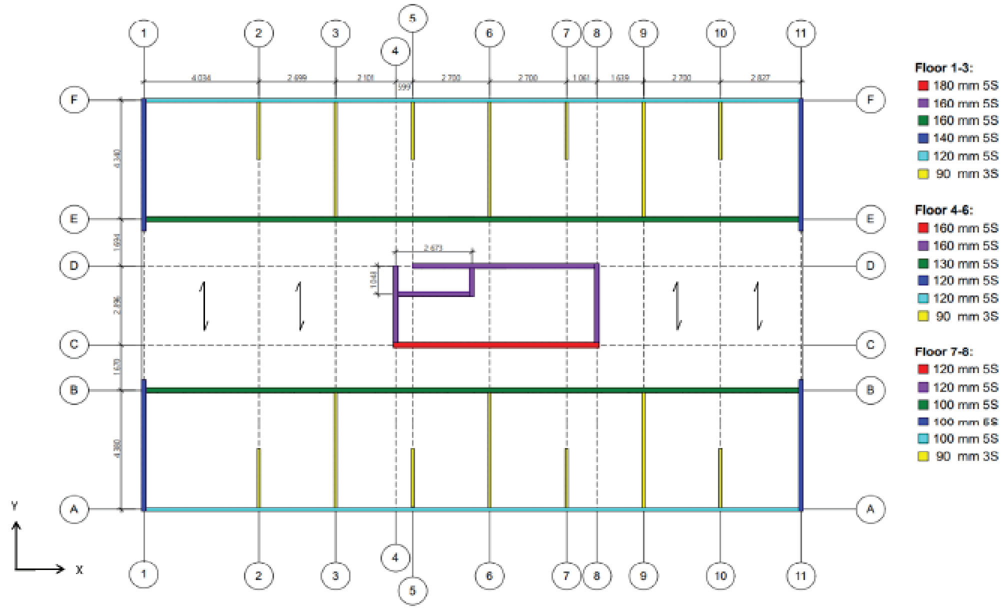
The Numerical models were developed using the commercial software package TimberTech [10] whose choice was made because it has the capabilities for simulating direct CLT walls and floors with various connectors to make accurate representation of platform construction arrangements. Furthermore, the program is associated with ease of creating elements and structural systems that facilitates openings for windows, doors, stairs and lift wells.

Successful numerical models depend on accurately simulating the system's geometry and applying the appropriate material properties, boundary conditions and the expected external forces. In developing the geometries of the buildings, the floor plans were laid out with nodes at the locations of both internal and external walls. Thin plates of required thickness and heights representing CLT walls were inserted in between nodes to create loading bearing (including shear walls) and partition walls. Lintels were introduced for window and door openings. CLT floor elements were modelled, supported on both exterior and interior walls along the shorter plan dimension of the buildings. This created a platform upon which upper storeys were added on until the roof. CLT floor elements (180 mm thick) and roof (200 mm thick) were assigned residential and roof live loads respectively. Table 1 and Table 2 respectively summarize CLT type and material properties employed for modelling and analyses with the adoption of a Poisson's ratio of 0.3 for all CLT materials [11]. Figure 2 illustrates an 8-storey FE model with footprint as illustrated in Figure 1.

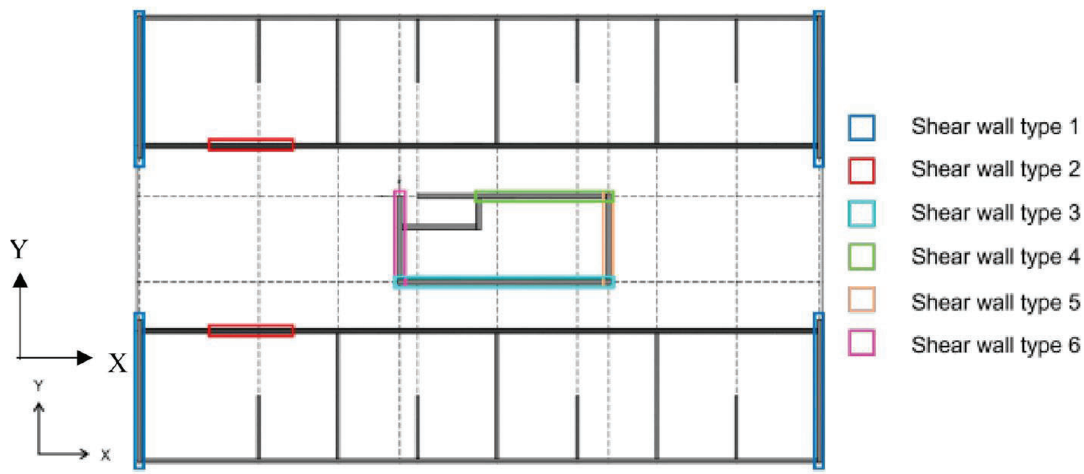
Table 1: *CLT type and layup configuration used in FE models*

CLT-panel layup	Thickness (mm)
CLT 90 3S (30-30-30)	90
CLT 100 5S (20-20-20-20-20)	100
CLT 120 5S (30-20-20-20-30)	120
CLT 140 5S (40-20-20-20-40)	140
CLT 160 5S (40-20-40-20-40)	160
CLT 180 5S (40-30-40-30-40)	180
CLT 200 5S (40-40-40-40-40)	200

As has been mentioned, TimberTech provides the flexibility of link elements between wall and floor elements. The stiffness applied to the different types of link elements, were estimated from the results of experimental analysis from Gavric et al. [12]. For the angle brackets and hold-downs, a linear relationship between the number of screws and stiffness value is



(a) Floor plan of the case study building



(b) Shear wall location in the case study building

Figure 1: *Floor plan and shear wall locations of the case study building*

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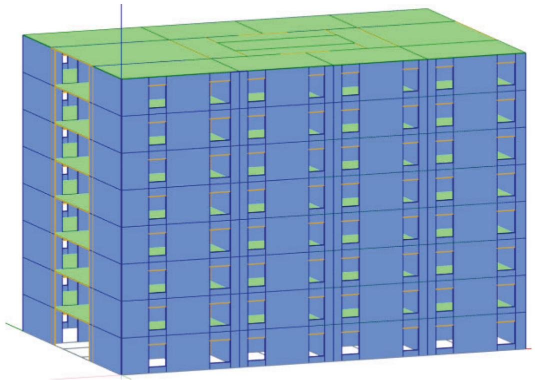

***Figure 2:** FE model of 8-storey CLT building*

***Table 2:** Apparent properties of CLT used in FE models**

CLT-panel layup	Units	Value
Density, ρ	Kg/m^3	460
Elastic moduli:		
E_1	GPa	11.0
E_2	GPa	4.00
E_3	GPa	0.40
Shear moduli:		
G_1	GPa	0.69
G_2	GPa	0.04
G_3	GPa	0.04

**Parallel to face laminations (direction-1); perpendicular to face laminations (direction-2); direction-3 is perpendicular to plate.*

assumed, and the values for tensile and shear stiffness are estimated by Equation (3): where k_a is the analytical stiffness value from (Gavric et al. 2015), n_a is the number of nails used in the analytical connector, and n_{exp} is the number of nails used in the experiment. Table 3 illustrates estimated hold-down stiffnesses employed along the storey heights of FE models.

***Table 3:** Stiffnesses of hold-down anchors in FE analyses*

Storey level	Type of hold-down	# of brackets	Tensile stiffness [KN/mm])
1	HD-1	5	13.3
2	HD-2	4	10.6
3	HD-2	4	10.6
4	HD-3	3	7.95
5	HD-3	3	7.95
6	HD-3	3	7.95
7	HD-4	2	5.30
8	HD-4	2	5.30
>9	HD-5	1	2.65

$$K_a = \frac{K_{exp}}{n_{exp}} \tag{3}$$

2.3 NUMERICAL MODEL VERIFICATION

Results from field campaign of ambient vibration measurements of one of the two identical Palisaden student residence buildings on the campus of the Norwegian University of Life Sciences (NMBU) in Ås, Norway, were used to verify the numerical models. The case study building shown in Figure 3 is 8-storey high and matches the configurations of the numerical model described in Figures 1 and 2. Shallow CLT spine elements form structural walls, and horizontal floor and roof slabs which act as structural diaphragms. Except for stair and lift wells on plan, the horizontal floor elements have widths up to 2.5 m and span continuously over 15 m in line with the shorter plan axis dimension. Horizontal floor and roof elements are supported on both exterior and interior CLT walls, reflecting that building configuration conforms to the Platform Construction type.

***Figure 3:** Photograph of case study building*

From the lower to the upper storeys the thicknesses of the wall elements decrease, thus the storey masses decrease along the building height, (Figure 1a). CLT floor slab elements have a constant thickness of 180 mm whilst the roof slab elements composed of 200 mm thick CLT plates. The thickness of roof elements indicates that design snow loads are of much significance in Ås, Norway than corresponding design live loads for the floors. Walls designated to act as shear walls are those indicated in Figure 1b. The structure has a central core as shown in Figure 1, which houses a staircase, an elevator and services ducts. The core is surrounded by CLT walls connected to the floor and roof elements thus constituting part of the lateral load transfer system.

Figure 4 compare modal natural frequencies and mode shapes of the numerical model with the results from the field campaign of modes 1–3. As can be seen from Figure 4, modal model results are in good agreement with results from the ambient vibration measurements. Discrepancies between modal model and test results especially between

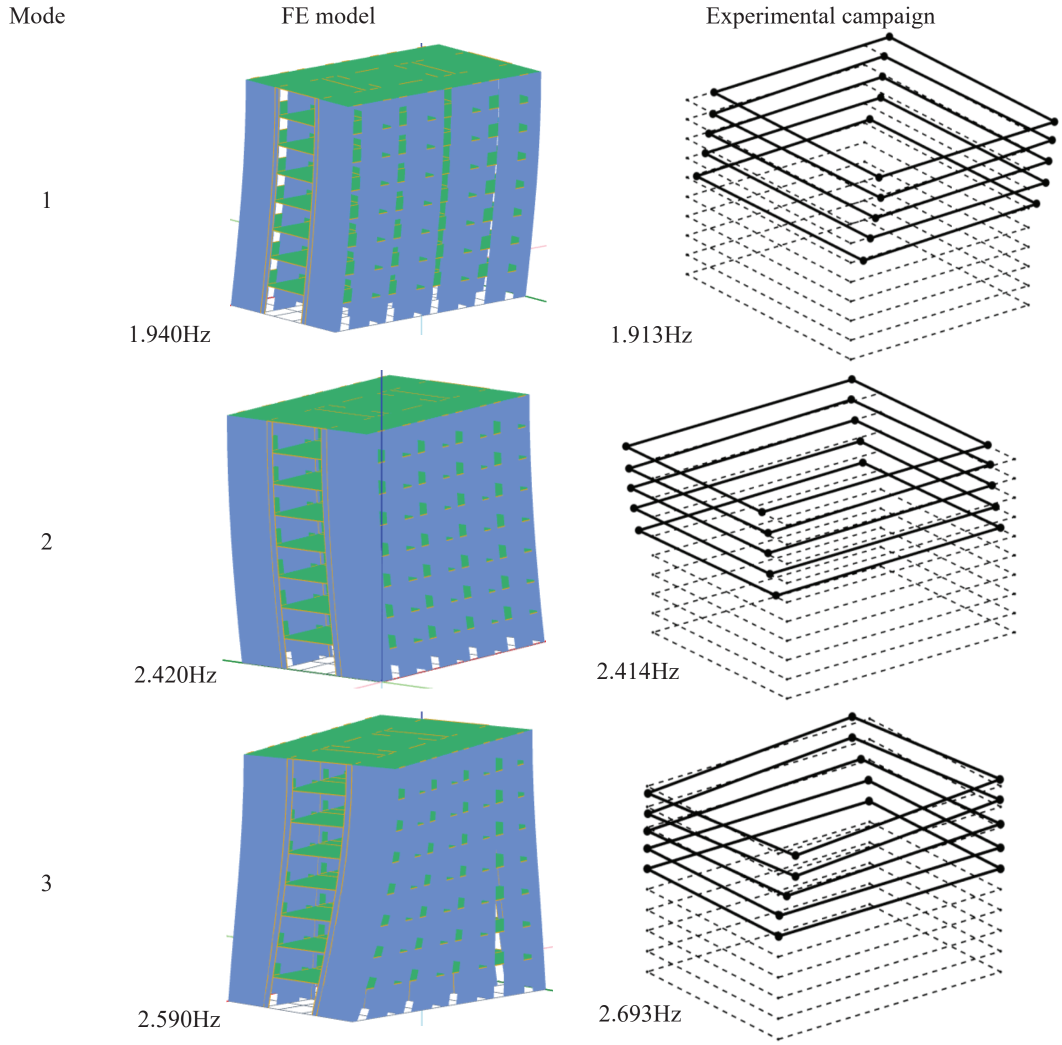

Figure 4: *Comparison of modal frequencies and modal shapes of FE model modal analysis and field campaign of results of the case study building*

mode 3 natural frequencies may be attributed to simplification of the numerical model not accounting for the stiffness due to the end-wall non-CLT materials adjacent to the communal corridor space present in each storey. Presence of non-CLT wall construction elements potentially added to the overall system stiffness consequently influencing low-amplitude ambient vibration measurements. Furthermore, variations between the model and field campaign results may be due to numerical model not accounting for minor differences in material properties and construction imperfections. Also, construction features including door and window openings were simplified and differences between real and model superstructure and wall anchoring conditions were ignored. Overall, the authors consider the obtained balance between the model accuracy and computational efficiency reasonable for extending the presented modelling techniques to assess the reliability and robustness of simplified formulas in estimating T_1.

3 ESTIMATING THE FUNDAMENTAL PERIOD OF CLT PLATFORM-TYPE BUILDINGS

Analytical formulas provided in various design codes [7-9] are employed in estimating T_1 of CLT platform-type buildings. Evaluations are compared with predictions obtained from verified numerical models which offer the needed basis for commenting on the accuracy and

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reliability of extrapolating empirical design formulas to systems outside their calibration range.

From Eurocode 8 [7], Equation (1) is applied on the case study building in which C_t is defined by Equation (4)

$$C_t = \frac{0.075}{\sqrt{A_c}} \quad (4)$$

where, A_c is the total effective area of shear walls in the first storey of the building, in m^2 defined by Equation (5):

$$A_c = \sum \left[A_i \left(0.2 + (l_{wi}/H) \right)^2 \right] \quad (5)$$

A_i is the effective cross-sectional area of shear wall i in the direction considered in the first storey of the building, in m^2; H is the building height in m, from the foundation; and l_{wi} is the length of the shear wall i in the first storey in the direction parallel to the applied forces, in m, with $l_{wi} \leq 0.9$. The choice of Equation (4) for calculating C_t is made to reflect the application of CLT shear walls in the case study building and corresponding numerical model. Further comparisons are made with Equation (2) which is part of the Indian Standards [9] provisions for seismic analysis of buildings. From Equation 2, C_t is defined as $C_t = 1/\sqrt{d}$

Table 4 compares model predictions of T_1 of the case building with alternative analytical estimations. As may be observed from Table 4, there are huge discrepancies between the predictions from the Eurocode 8 (Equation (1)) [7] approach and the verified numerical model. However, there appears reasonable variations between the provision from the Indian Standard (Equation (2)) [9] and the numerical model estimates.

Table 4: *Comparison of FE model prediction versus analytical approaches of T_1*

Weak stiffness direction			
Analysis Type	C_t	T_1[s]	%Var
FE	--	0.515	0.000
Eq.-1 [7]	0.068	0.736	42.91
Eq.-2 [9]	0.258	0.548	6.488

Strong stiffness direction			
Analysis Type	C_t	T_1	%Var
FE	--	0.413	0.000
Eq.-1 [7]	0.055	0.587	42.10
Eq.-2 [9]	0.209	0.443	7.236

This suggests that not accounting for both floor plan dimension in addition to the building height in the desired seismic direction affect the accuracy of the formula as may be seen from the Eurocode method versus the Indian design guide formula. For both directions of the building on plan the simplified approach in estimating the fundamental period of the case study building by Equation 2 (from the Indian design guidelines) predicts less than 10% variation from the numerical method. Construction features such as CLT plates edge-to-edge jointing, wall to floor connections, location of shear walls as well as the presence of openings for staircase, lifts, doors and windows all affect the modal stiffness to mass ratios in low amplitude vibration of CLT platform-like buildings. This is demonstrated in the numerical model and providing factors that account for such features in analytical expressions may improve their accuracy for seismic analyses for regular CLT buildings.

4 EFFECT OF BUILDING HEIGHT

Analytical formulas provided in the various design codes [7-9] for the prediction of T_1 for buildings classified as regular in both footprint and elevation, mostly depend on the building height, H in m. As demonstrated in Equations (1) and (2), it is expected that the distribution of stiffness and mass along the height of the building will facilitate over 90% of the energy released in the fundamental mode during seismic action. Therefore, the calibrated numerical model is applied in evaluating effect of building height on T_1 and comparing them with the analytical formulas. Analyses are carried out for four to twelve storeys reflecting a height of between11.8 m and 35.4 m.

Table 5 Compares the FE models prediction of T_1 with analytical provisions based on varying the building height. A couple of inferences may be made from Table 5. First, increasing the number of storeys resulting in increasing the building height results in increasing the fundamental period. This may be attributed to the fact that

Table 5: *Effect building height on T_1 based FE model versus analytical approaches*

Weak stiffness direction			
# of storeys	T_1[s]		
	FE	Eq.-1 [7]	Eq.-2 [9]
4	0.259	0.438	0.274
6	0.385	0.593	0.411
8	0.515	0.736	0.548
10	0.625	0.870	0.686
12	0.735	0.998	0.823

Strong stiffness direction			
# of storeys	T_1[s]		
	FE	Eq.-1 [7]	Eq.-2 [9]
4	0.205	0.349	0.221
6	0.310	0.473	0.332
8	0.413	0.589	0.443
10	0.508	0.694	0.554
12	0.613	0.795	0.664

increasing the storey height results in increases in the systems overall mass without corresponding increases in the overall stiffness. This may be because of changes in wall thickness and uneven distribution of connection details along the building height. Second, numerical predictions compare relatively well with the analytical formula that takes into consideration the building footprint dimension in the direction of ground motion under consideration. Relatively high discrepancies are noted between FE model predictions and the analytical method that considers only the building height.

As the above comparisons between verified numerical models and analytical predictions of T_1 of CLT platform-type buildings demonstrate, it is impossible to judge the suitability of simplified formulas provided in design codes in a generalised manner. The ability of some current simplified representations to estimate T_1 is associated with significant errors whilst others perform relatively better. Implication of this is use of explicit formulas or numerical models not accounting for basic building geometric properties such as floor plan dimension may not be a reliable way of estimating T_1. Additionally, CLT plates have orthotropic representation and slabs, and walls often contain features like intra-plate construction joints. Therefore, design level models should be based on explicit formulas that predict the fundamental frequencies of CLT structures accounting for orthotropic nature of the material and other architectural variables.

5 CONCLUSIONS

Numerical model representations have the capabilities of incorporating construction features that include building plan geometry, material characteristics and other architectural features. This enables the development of viable cost-effective simulations as alternative to expensive field campaigns for determining vibration characteristics of multi-storey CLT buildings. Model techniques also have the advantage of being employed to evaluate the effect of various parameters on a system.

Analyses from the modelling approach presented in this study and compared with analytical methods provided in various design codes point out the limitations in applying simplified analytical formulas for assessing the seismic demands on CLT buildings. Verified numerical analyses prove that in addition to the building height, floor plan dimension in the desired seismic direction should be accounted for in estimating the fundamental period as basis for determining the seismic forces on the structure. This is because the distribution of system mass to stiffness ratios depends on both footprint and the storey height of the building. Furthermore, presented analysis show that construction features influencing modal stiffnesses such as metal shear connectors and tiedown anchors in connections should be accounted for predicting low amplitude vibrations characteristic and forces due to extreme seismic events on CLT buildings.

REFERENCES

[1] IPCC, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151, 2014.

[2] Buchanan A. H.: How will timber buildings help New Zealand meet the Kyoto protocol commitments? New Zealand Timber Design Journal, (13):9-13, 2005.

[3] International Energy Agency (IEA) for the Global Alliance for Buildings and Construction (GlobalABC). Global Status Report for Buildings and Construction Towards a zero-emissions, efficient and resilient buildings and construction sector, ISBN No: 978-92 807-3768-4, 2019.

[4] I. Smith, and A. Frangi. Structural use of timber in tall multi-storey buildings, structural engineering document 13: International Association for Bridge and Structural Engineering, Zurich, Switzerland, 2014.

[5] American National Standards Institute (ANSI). Standard for performance-rated cross-laminated timber, Standard ANSI/APA PRG 320-2012. Page 29. New York, NY, USA: ANSI; 2012.

[6] A. Ceccotti. New technologies for construction of medium-rise buildings in seismic regions: the XLAM case. Structural Engineering International, 18(2),156–65, 2008.

[7] European Committee for Standardization (2004c). EN 1998-1 (English): Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings. The European Union, 2004.

[8] National Research Council (NRC). National building code. Ottawa, Canada: NRC; 2010, 2015.

[9] IS:1893:2016. "Criteria for Earthquake Resistant Design of Structures," Bureau of Indian Standards, New Delhi, [Online]. 2016. Available at: https://archive.org/details/1893Part1.

[10] Design software for timber structures TimberTech Buildings Version 95 - 2022 user's manual; 95-12/2022, 2022.

[11] Wallner-Novak M., Koppelhuber J. and Pock K. Cross-Laminated Timber Structural Design. proHolz Austria, p. 191. 2014. www.proholz.at.

[12] Gavric I., Fragiacomo M. and Ceccotti, A. Cyclic behavior of CLT wall systems: Experimental tests and analytical prediction models. Journal of Structural Engineering, 141(11), 04015034, 2015.

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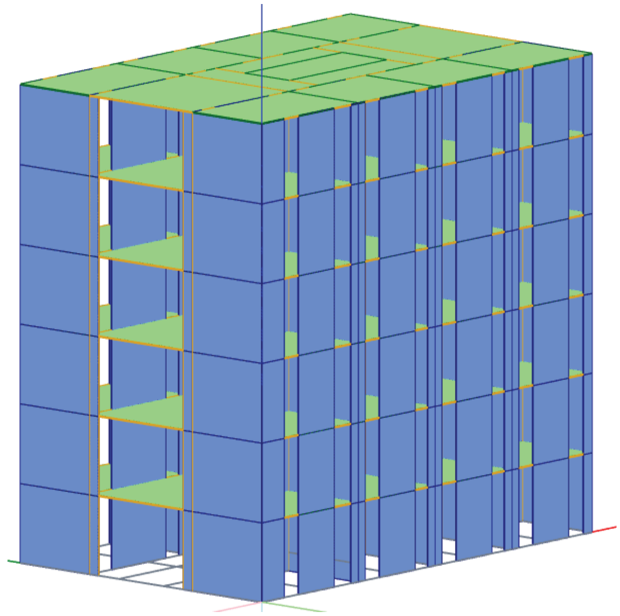
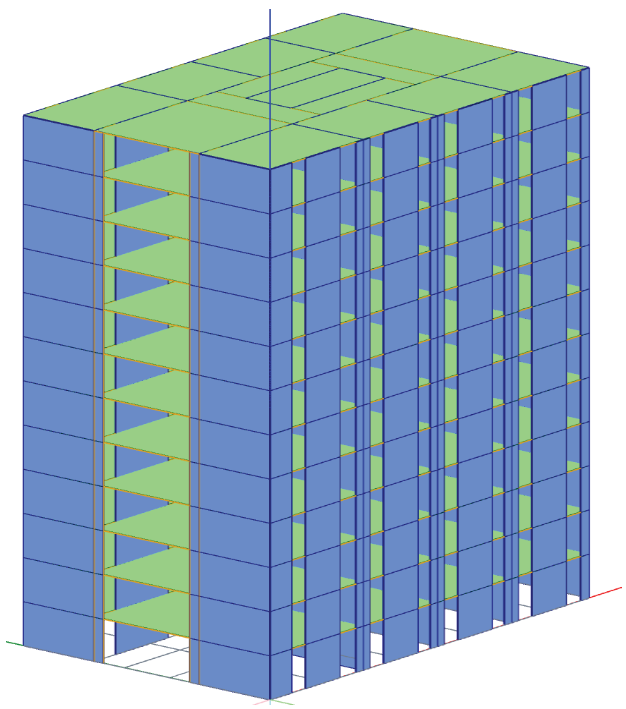
APPENDIX A1: SELECTED NUMERICAL ANALYSIS MODELS OF CLT BUILDINGS



(a) FE Analysis model of 6-storey CLT building



(b) FE Analysis model of 12-storey CLT building

Figure A1: *FE analysis models of 6- and 12-storey CLT buildings*