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Advancing Timber for the Future Built Environment

A SURVEY ON THE DYNAMIC PROPERTIES OF MID- AND HIGH-RISE MASS TIMBER BUILDINGS

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ABSTRACT: Understanding the dynamic properties of timber buildings is crucial for their lateral design. However, there is no specific formula to estimate the elastic period of timber buildings in current building codes. Different vibration testing on existing timber buildings enables researchers and engineers to form a database for developing empirical formulas for fundamental period estimation to assist future design. This study surveys the dynamic properties of 32 mid-to-high rise mass timber buildings with various structural systems from both field and full-scale laboratory forced or ambient vibration testing. The measured fundamental periods and damping ratios are compared with the recommended values from the available resources. The results showed that existing empirical formulas overestimate the period of mass timber buildings with reinforced concrete cores. Meanwhile, the fundamental periods of cross laminated timber (CLT) and braced frame buildings exhibit a scattered distribution across various empirical formulas from different codes, without consistently matching a specific one. Additionally, timber buildings of the same height but with different structural systems do not have identical fundamental frequencies. Furthermore, the damping values were shown to vary with building height. The average damping ratio for buildings shorter than 20 m is greater than 2%, whereas for taller mass timber buildings, it is generally below 2%.

KEYWORDS: mass timber buildings, fundamental period, damping ratio, vibration testing

1 – INTRODUCTION

Seismic and wind performance assessment of buildings requires an in-depth understanding of their dynamic properties, such as natural frequency (period), damping ratio, and mode shapes during the design process. The fundamental period is a key parameters used in base shear calculation, response spectrum analysis in seismic design, as well as dynamic response and vibration comfort assessment in wind design [1]. The fundamental period of a building is determined by its lateral stiffness and mass, which are closely dependent on structural configurations. When the lateral stiffness and seismic mass distribution of a building are unknown during the design stage, accurately predicting its fundamental period becomes challenging. While finite element models can be useful, they are time-consuming and require validation against test results. Therefore, simplified or empirical equations are essential where the period of a building needs to be estimated in engineering practice [2]. Different empirical formulas are recommended by codes for fundamental period estimation during the analysis stage depending on building type, height, plan dimensions, and/or number of floors [3]. These formulas have been derived based on regression analysis of the measured fundamental periods from the vibration data of concrete and steel buildings and may not directly apply to mass timber structures [4].

The damping ratio is another critical dynamic property that influences a building's seismic and wind response; it is a key input for calculating maximum accelerations and defining the design response spectrum curve in wind and seismic design, respectively [5]. Despite its importance, the exact value of the damping ratio is often not specified in design codes or standards due to a lack of data and its high variability. Damping is influenced by multiple factors, including material properties, connection details, and non-structural components, making it difficult to generalize across different building types. In timber structures, damping characteristics are more complex due to the anisotropic nature of wood, the interaction between structural and non-structural elements, and variations in construction techniques. As a result, damping evaluations often rely on engineering judgment on available measured data rather than standardized values. To improve design assumptions and enhance the accuracy of dynamic analyses, research is urgently needed to establish reliable damping values based on measured data from completed timber structures [6].

There is ongoing research on vibration testing of existing timber buildings to extract the modal characteristics of

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these structures and develop a comprehensive database [4]. This study aims to collect the results of vibration tests conducted on mid-to-high-rise timber buildings worldwide from published literature. The fundamental period and damping ratio of multi-story mass timber buildings with different lateral force-resisting systems (LFRS), such as cross-laminated timber (CLT) platform and balloon-type shear walls, mass ply panel (MPP) shear walls, reinforced concrete (RC) shear walls, mass timber moment frame, steel braced frame, and glulam braced frame, are compared with values recommended in the NBCC [7], Canadian CLT Handbook [8], Eurocode 1-4 [9], Lagomarsino et al. [10], ASCE 7-16 [11], and the Italian Seismic Code (NTC 2008) [12].

2 – BACKGROUND

2.1 BUILDINGS DESCRIPTION

In this study, the modal characteristics of 32 full-scale lab prototypes (ranging from 2 to 10 stories) and timber buildings (ranging from 5 to 18 stories) located in North America and Europe, extracted by forced, hammer, and ambient vibration tests, were collected. The timber buildings were divided into four general groups based on their LFRS: mass timber shear walls, such as platform or balloon CLT and MPP shear walls; (RC) shear wall cores; mass timber moment frame; and steel/timber bracing. The investigated timber building case studies include mass timber products in hybrid combinations of timber-concrete, timber-steel, and timber-concrete-steel, as listed in Table 1. Additionally, height, number of stories, and slenderness ratio (height/shorter length) of each building are also included. It should be noted that light wood frame buildings are not part of this study. Some of the case studies, such as B-4, B-11, B-30, and B-31, include one or more podium-type RC levels on the lower stories. These case studies were not considered timber-concrete hybrids and were categorized based on the LFRS of the non-RC stories. Furthermore, in some case studies (B-2, B-3, B-7, B-8, B-13, B-14, B-20, B-21, and B-28), numerical modelling results were available and included to investigate discrepancies between the measured periods of the tested buildings and the corresponding finite element models. For most case studies, numerical modeling was conducted in two stages: an initial model was developed based on common engineering practices, and then the modeling assumptions, along with material properties, were calibrated based on test results. In this study, only the

Table 1: Buildings information.

	Building ID	Description	Number of stories	Height (m)	Slenderness ratio	Reference
Mass timber shear Wall	**B-1**	CLT Balloon- GLT[a] post and beam-CLT floors	8	26.4	2.3	[13]
	B-2	CLT Platform-CLT floor	8	26.9	1.8	[14]
	B-3	CLT Platform-CLT floor	7	19.6	1.3	[15]
	B-4	CLT Balloon-CLT floor	7	18.0	2.0	[13]
	B-5	CLT Balloon-GLT post and beam-CLT floor	8	22.7	1.2	[16]
	B-6	CLT Platform+Balloon-GLT post and beam	13	40.9	1.4	[17]
	B-7	CLT Balloon-GLT post and beam-CLT floor	6	29.0	1	[18]
	B-8	CLT Platform-CLT floor	7	22.0	0.7	[19]
	B-9	CLT Platform-CLT floor	5	14.5	2.4	[20]
	B-10	CLT Balloon -GLT post and beam-CLT floor	4	16.0	0.4	Authors data point
	B-11	CLT platform-CLT floor	9	28.0	1.5	[21]
	B-12	CLT Platform-CLT floor	3	7.7	1.1	[22]
	B-13	CLT Platform-GLT post and beam-CLT floor	9	27.0	2.0	[23]
	B-14	CLT Platform+Balloon-CLT floor	5	14.5	3.6	[24]
	B-15	CLT Platform-CLT floors	3	8.4	2.2	[25]
	B-16	CLT Balloon-GLT post and beam-CLT floor	8	28.0	1.8	[26]
	B-17	CLT Platform-CLT floor	2	4.8	1.0	[27]
	B-18	CLT Platform+MPP-LVL post and beams	10	34.1	3.4	[28]
	B-19	MPP-LVL post and beams	3	9.1	0.7	[29]
Concrete Core	**B-20**	CLT wall-RC core	5	15.6	0.8	[30]
	B-21	Sheathed stud- RC core	5	15.6	0.8	[30]
	B-22	Solid timber- RC core-CLT floor	8	31.0	0.75	[31]
	B-23	Timber Frame-RC core	8	26.6	0.75	[31]
	B-24	GLT column- CLT floor- RC core	18	53.0	0.9	[32]
	B-25	GLT post and beam -RC core	6	22.1	1.1	[33]
	B-26	GLT post and beam-RC core	5	21.8	N/A[b]	[33]
Steel/Timber Brace	**B-27**	GLT brace frame	14	49.0	2.0	[13]
	B-28	GLT post and beam-GLT brace	18	88.8	2.4	[34]
	B-29	GLT post and beam-GLT brace [c]	18	88.8	2.4	[34]
	B-30	Steel brace-GLT column-CLT floor	12	40.0	0.7	Authors data point
	B-31	Steel brace-GLT post and beam	5	19.7	0.5	Authors data point
	B-32	Steel brace and columns-CLT floor	12	36.9	0.6	Authors data point
MF[d]	**B-33**	GLT post and beam-CLT floor	4	18.3	N/A	[33]

[a] Glue laminated timber
[b] Not available
[c] B-28 and B-29 are the same building with different test methods,
[d] Moment frame

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results from the initial numerical models are considered for comparison with the experimental period of the case study building. Ambient vibration tests were the dominant test method, except in case studies B-8, B-9, B-12, B-15, B-18 and B-29, where forced vibration tests were used. Case studies B-28 and B-29 represent the same building but were tested using ambient and forced vibration methods, respectively. For case study B-17, an impact hammer test was conducted to determine the lab prototype dynamic properties. Vibration tests on B-3, B-5, and B-7 were conducted at different stages, both before and after the installation of non-structural elements, to investigate their effect on the dynamic properties of mass timber buildings. Case study B-16 was monitored on an hourly basis to examine the effect of wind speed on the dynamic properties of a mass timber building. B-33 is the only case study that includes a mass timber moment frame as the LFRS.

2.2 EMPIRICAL FORMULAS

Building codes consider fundamental period in the estimation of structure response coefficients for seismic and wind design. Using simplified empirical formulas that account for building height or the number of stories is common in the codes, as shown in (1). The parameters C_t and x (applicable for timber buildings) are defined in Table 2 for different design provisions and literature sources:

$$T = C_t(h \; or \; N)^x \qquad (1)$$

where T, h, and N represent the period (second), building height (meter), and total number of stories respectively. The 2020 NBCC provides different coefficients for buildings with various LFRS types. For shear wall and braced frame buildings, the empirical formulas include the building height, while for moment frame buildings, the number of stories is used in the formula [7]. The Canadian CLT Handbook introduces an empirical formula to calculate the fundamental period of wood buildings. This formula is derived from a database containing measured periods of more than 35 wood buildings worldwide, regardless of their LFRS [8]. Eurocode 1-4 [9] provides an empirical formula to estimate the first natural period of multi-story buildings, for those taller than 50 meters. The formula is based on data from 163 rectangular-plan buildings with different structural materials. However, data collection showed greater variation in period values for shorter buildings compared to taller ones. To address this, a larger dataset of 185 buildings, incorporating various materials and structural types, led to an alternative formula, as shown in Table 2 [10]. ASCE 7 provides empirical formulas to calculate the approximate fundamental period of steel and concrete buildings with different LFRS. However, it includes coefficients for a general category of other structural systems, which is used for mass timber buildings in this paper [11]. NTC 2008 provides a period formula for masonry buildings, applicable to CLT buildings due to their wall-based structure [12,14].

Table 2: Fundamental period and equation parameters

Resources	Parameter	
	C_t	x
NBCC [7]	0.05^a, 0.025^b, 0.1^c	0.75^a, 1.00^b, 1.00^c
CLT Handbook [8]	0.035	0.80
EC1-4 [9]	0.022	1.00
Lagomarsino et al. [10]	0.02	1.00
ASCE 7 [11]	0.0488	0.75
NTC 2008 [12]	0.05	0.75

[a] Shear wall building,
[b] Braced frame buildings,
[c] Moment frame buildings

For damping ratio, the 2020 NBCC states that the critical damping ratio for wind response calculations is based on experiments with real structures. The recommended values are 1% for steel frames, 2% for concrete frames, and 1.5% for composite buildings with steel frames and concrete cores or dual steel-concrete lateral systems; no values are recommended for timber buildings [35]. Additionally, the Canadian CLT Handbook recommends damping ratios of 2% for wood buildings without finishings and 3% for those with finishings [8].

3 – RESULTS AND DISCUSION

3.1 FUNDAMENTAL PERIOD

The measured fundamental periods of the case study buildings and the empirical formulas are presented in Fig. 1, showing a clear correlation between building height and period. This suggests that the natural period of mass timber buildings can be estimated using simplified formulas that include building height. In Fig. 1, the bottom horizontal axis represents building height, corresponding to empirical formulas that use height for period estimation, while the top horizontal axis represents the number of stories, aligning with formulas that use story count to estimate the fundamental period. The results show that the Canadian CLT Handbook formula gives the lowest fundamental period compared to the other codes for buildings of the same height. The fundamental period range of 2- to13-story timber buildings with mass timber shear walls ranged from 0.09 s to 1.4 s (frequency of 0.7 Hz to 11.0 Hz). For 5- to 18-story buildings with RC shear walls, the fundamental period range was 0.2 s to 0.6 s (frequency of 1.8 Hz to 4.0 Hz). The period range for 4- to 18-story buildings with either steel or timber bracing was 0.3 s to 2.0 s (frequency of 0.5 Hz to 3.0 Hz).

The scattered distribution of mass timber shear walls data points across the empirical formulas from different codes shows the need for developing a specific empirical formula for buildings with mass timber shear walls. Case studies B-18 and B-19 deviate from the general trend; B-18, a hybrid system with CLT and MPP walls and a high slenderness ratio of 3.4, exhibits a significantly longer fundamental period. Similarly, B-19, with MPP walls as the LFRS, shows a slightly higher period than predicted by empirical formulas. These are the only buildings in the dataset of mass timber shear wall that use MPP shear walls. Further investigation is needed on dynamic properties of mass timber buildings with MPP walls. The data points for mass timber buildings with RC cores indicate that current empirical formulas generally overestimate the period of timber buildings with RC cores. This discrepancy exists because timber buildings are significantly lighter than concrete structures. The data points for steel/timber brace frame (BF) buildings indicate that the NBCC empirical formula predicts the highest periods, exceeding all the data points. The measured periods of these buildings are closer to the empirical formulas recommended by the Canadian CLT Handbook and the NTC. The case studies B-28 and B-29 represent the same building tested under ambient and forced vibration conditions, respectively, with only a 1.4% difference in the first period. This confirms that forced and ambient vibration tests yield nearly identical fundamental frequencies. The experimental period of B-33, the only moment frame building, matches well with the empirical formula recommended by the 2020 NBCC.

A regression analysis was conducted to predict the fundamental period of CLT shear wall buildings, excluding B-18 and B-19. The regression equation, with a correlation coefficient R^2 equal to 0.8, is shown in (2) and Fig. 2, where C_t and x are close to the values recommended by Canadian CLT Handbook.

$$T = 0.0355(h)^{0.824} \tag{2}$$

Additionally, buildings with RC cores exhibit different fundamental period values compared to CLT shear wall buildings of the same height. However, more data is needed to establish a reliable formula for predicting the fundamental period of such structures, as the available data set contains fewer than 10 data points, which does not satisfy the minimum required sample size for regression analysis [36]. More data on mass timber braced and moment frame buildings is also needed to develop a specific empirical formula.

A regression analysis was conducted on all the data to derive an empirical equation for all mass timber buildings, regardless of their LFRS. The regression results, with an R^2 value of 0.7, are shown in Fig. 2. The calculated value for C_t and x are presented in (3).

$$T = 0.0367(h)^{0.812} \tag{3}$$

3.2 DAMPING RATIO

Since slender and tall buildings tend to have lower damping values [35], the variation of damping ratio with building height is analyzed and presented in Fig.3. As shown in Fig. 3a, damping ratio generally decreases with increasing building height, which led to further investigation by grouping buildings into 10-meter intervals (Fig. 3b). The average damping ratio for buildings shorter than 20 m is greater than 2%, whereas for taller mass timber buildings, the average value is below 2%. Previous studies on damping in tall concrete steel, and composite steel concrete buildings have shown

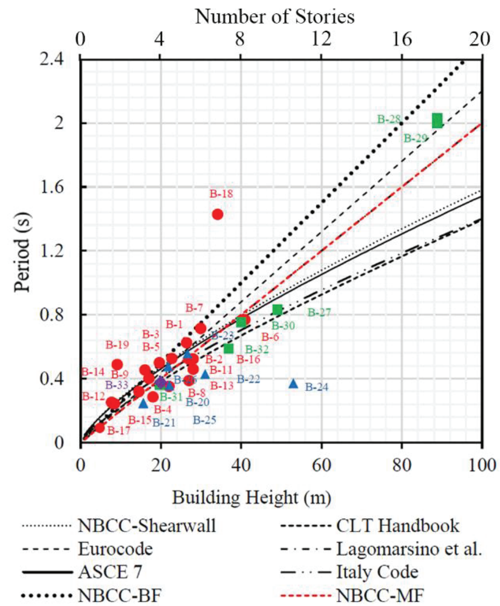

Figure 1. Empirical fundamental period vs. building height; a) mass timber and CR shear walls, b) steel/timber brace frame

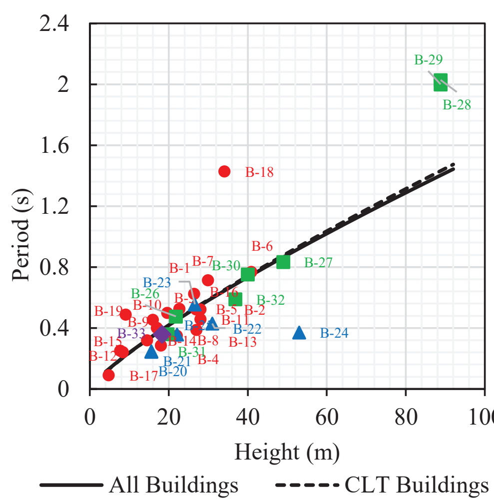

Figure 2. Regression analysis

a decrease in the damping ratio as building height increases. This reduction occurs because, in tall buildings, the primary structural members become significantly larger, reducing the relative contribution of non-structural elements to energy dissipation [37]. Additionally, 88% of the recorded damping ratios in current study fall between 1% and 3%.

A comparison between B-28 and B-29 shows that the damping ratio is twice as high in FVT compared to AVT, indicating that damping varies with the amplitude of vibration. Similarly, hourly monitoring of B-16 reports that the damping ratio is highly dependent on wind speed, which represents vibration amplitude [26]. As the vibration amplitude increases, the damping ratio also increases, since more energy dissipation mechanisms, such as cracks, friction at connections, and interactions

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between structural and non-structural elements, are activated at higher amplitudes.

3.3 NUMERICAL MODELING RESULTS AND NON-STRUCTURAL ELEMENT EFFECTS

The difference between the initial numerical modeling period and the test values is shown in Fig. 4. The comparison of test and numerical period values reveals a discrepancy of up to 96%, highlighting the need for calibrating numerical models with test results to achieve more reliable assumptions in finite element modeling of mass timber buildings.

The period and damping ratio of the case studies before and after the addition of non-structural elements are shown in Fig. 5. A comparison of the period values before and after the inclusion of non-structural elements in B-5 and B-7 shows a reduction of 11% and 21%, respectively, indicating the stiffening effect of these elements. However, in B-3, the period increased by 25%,

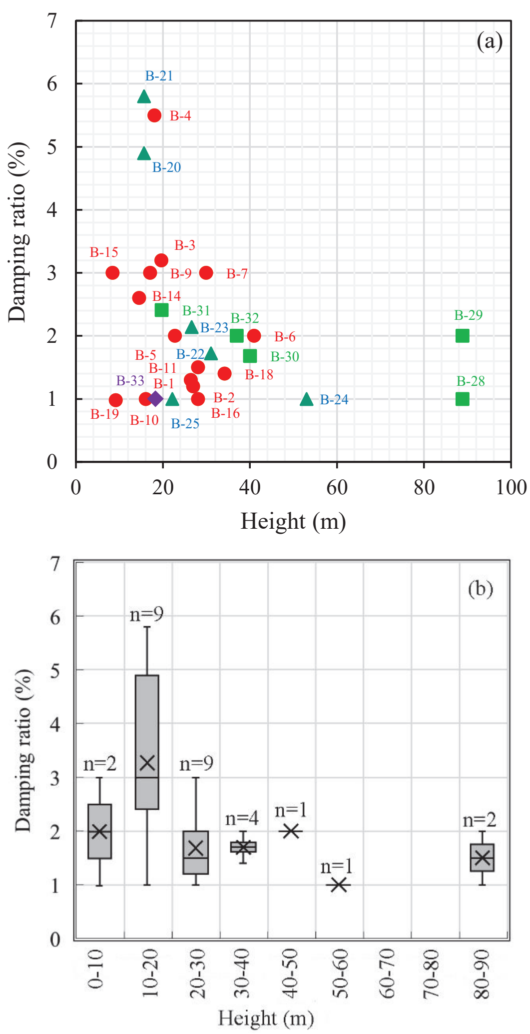

Figure 3. Damping ratio vs. building height: (a) scattered data, (b) grouped in 10 m intervals.

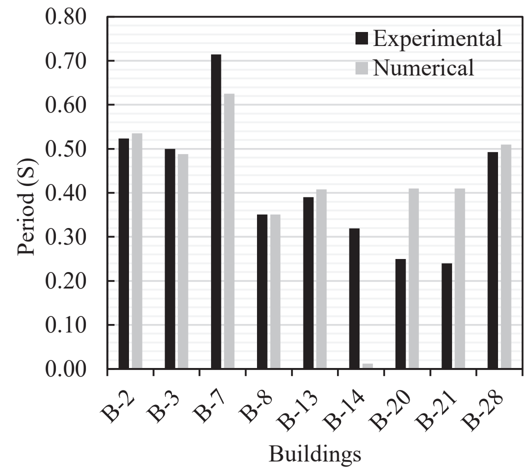

Figure 4. Difference between numerical modelling and test period

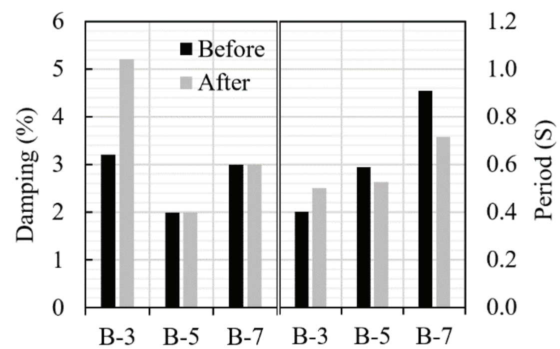

Figure 5. Effect of non-structural elements on dynamic properties of timber buildings

which can be attributed to a 57% increase in mass after the addition of non-structural elements. In this case, the mass increase dominated over the stiffening effect, leading to a longer period. The damping ratio in B-3 increased by 63% after installation of non-structural elements while it remained constant in B-5 and B-7. Further research is needed to better understand the influence of non-structural elements on the dynamic properties of mass timber buildings.

4 – CONCLUSIONS AND RECOMMENDATIONS

In recent years, the construction of tall timber buildings has increased significantly. According to NRC [38], more than 750 tall mass timber and hybrid mass timber projects were completed, designed, or under construction between 2007 and 2022 in Canada alone. However, only a limited number of mass timber buildings worldwide have been tested for their dynamic properties, including fundamental period and damping ratio. This paper presents the available experimental dynamic properties of 32 timber buildings based on laboratory and field vibration tests. The following results are found based on the survey on available data:

- The fundamental period of mass timber buildings shows a clear correlation with building height. However, existing empirical formulas tend to overestimate the period of timber buildings with RC cores. In contrast, the fundamental periods of CLT shear wall and braced frame buildings exhibit a scattered distribution across various empirical formulas from different sources, without consistently matching a specific one.
- Mass timber buildings of the same height, but different structural systems do not have equal fundamental period, which indicated the necessity of deriving specific empirical formulas for the buildings with different LFRS. More data is needed in this area to develop a specific empirical formula to calculate the fundamental period of multi-story timber buildings with different LFRSs.
- Damping ratios vary with building height. The average damping ratio for buildings shorter than 20 m is greater than 2%, whereas for taller mass timber buildings, it is generally below 2%.
- It is recommended that further study be conducted on the effect of non-structural elements on the dynamic properties of mass timber buildings. Additionally, calibration of finite element models using test results is essential for validating modeling assumptions in mass timber buildings.

5 – ACKNOWLEDGMENTS

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