

Advancing Timber for the Future Built Environment

MODAL CHARACTERISTICS OF TWO MID-RISE MASS TIMBER-STEEL HYBRID BUILDINGS UTILIZING AMBIENT VIBRATION TESTS

Samira Mohammadyzadeh¹, Jianhui Zhou²

ABSTRACT: Modal characteristics of buildings are fundamental properties for their seismic and wind design. In this study, ambient vibration tests (AVTs) were conducted to measure the dynamic properties, including natural frequencies, mode shapes, and damping ratios, of two hybrid mass timber buildings in Canada. The structural system of both the 12-storey (the Vue) and 5-storey (Terminus) timber buildings consists of mass timber elements and steel braces for gravity and lateral force-resisting systems, respectively. The modal characteristics of the buildings were extracted using operational modal analysis (OMA) with the Stochastic Subspace Identification (SSI) and Frequency Domain Decomposition (FDD) techniques. The measured fundamental periods and the ranges of damping ratios were compared with the values recommended in the 2020 National Building Code of Canada (NBCC) and the 2019 Canadian CLT Handbook. The differences in the measured frequencies by SSI and FDD were less than 3%, while greater discrepancies were observed in damping ratios. The result of the study showed a discrepancy of up to 37% between the experimental fundamental period and the design values. Up to eight frequencies were obtained for the buildings, providing a more comprehensive understanding of the buildings' dynamic behavior, including higher modes. This information can be used for improving numerical structural analysis in future studies.

KEYWORDS: ambient vibration test, mass timber buildings, dynamic properties, timber-steel hybrid, operational modal analysis

1 – INTRODUCTION

The construction of mid-to-high-rise timber buildings has increased in recent years. Integrating timber with steel or concrete improves the lateral performance of timber buildings. However, there is still a lack of knowledge concerning the dynamic behaviour of timber-based structures [1], and no specific formula is provided in the building codes for evaluating the dynamic behaviour of these buildings in the design stage [2]. Conducting ambient vibration testing (AVT) on constructed timber buildings to measure their dynamic properties provides a database for deriving a fundamental period empirical formula and recommendations for accurate numerical modelling of future timber buildings [3].

Hu et al. conducted AVT on an 18-storey wood-concrete hybrid building, comprised cross-laminated timber (CLT) floors and point supported glulam columns for gravity system with two concrete stair cores as the lateral forceresisting system. They reported that the first three natural frequencies of the building were 1.0 Hz, 1.2 Hz, and 4.0 Hz, respectively, and the damping ratio was 1% [4]. In another study, Hu et al. conducted AVT on an 8-storey building with a concrete podium, CLT shear walls, and glulam posts and beams both before and after the installation of non-structural elements. They reported the first three natural frequencies and damping ratios of the building and showed 12% increase in natural frequency after the addition of non-structural elements, while the damping ratio remained constant [5]. Reynolds et al. conducted AVT on a 7-storey CLT building and found that the damping ratio was amplitude-dependent, ranging from 5.2 to 9.1% [6]. Tulebekova et al. conducted dynamic identification of an 18-storey glulam braced frame building by both long-term AVT and forced vibration test (FVT). The study found that natural frequencies identified from AVT were in good agreement with FVT results, and damping ratios from both AVTs and FVTs exhibited amplitude-dependent behaviour [7].

Timber-steel hybrid buildings are becoming increasingly popular in North America due to the combined benefits of prefabricated wood and steel. The main objectives of the present study are to: 1) measure the dynamic properties, namely natural frequencies, damping ratios, and mode shapes of the 12-story (the Vue) and 5-story (Terminus) mass hybrid timber buildings located in Langford, Canada, by AVTs; 2) compare two different Stochastic Subspace Identification (SSI) and Frequency Domain Decomposition (FDD) techniques in operational modal analysis (OMA); 3) and compare the measured

¹ Samira Mohammadyzadeh, University of Northern British Columbia, Canada, mohammady@unbc.ca

² Jianhui Zhou, University of Northern British Columbia, Canada, jianhui.zhou@unbc.ca

fundamental periods and ranges of damping ratios with the values recommended in the 2020 NBCC [8] and the 2019 Canadian CLT Handbook [9].

2 – METHODOLOGY

2.1 BUILDINGS DESCRIPTION

The Vue Building

The Vue (previously called Tallwood 1, located in Langford, Canada) is a 12-storey mass timber-steel hybrid building rising from level 2 to 12 over a concrete foundation. The Vue includes eleven stories of residential rental units over a 1-storey concrete podium of commercial units and two levels of underground parking. The total height of the building is 39.9 m, with plan dimensions of 57.6 m by 23.6 m, as shown in Fig. 1.

The structural elements of the building include two-way spanning 5-ply 175 mm CLT panels as the floors, point supported glulam (16c-E) columns (Fig. 2a). The lateral force-resisting system of the building consists of an eccentrically braced steel frame in a chevron configuration (Fig. 2b). Mass timber elements are encapsulated for fire protection from level 2 to 11, while at level 12 (penthouse), all timber elements are exposed.



Figure 1. The Vue building: (a) east view; (b) 3D-view; (c) plan of the building.



Figure 2. (a) Point supported CLT panels; (b) building under construction with the eccentrically braced steel frame [10]

Terminus Building

Terminus (located in Langford, Canada) is a 5-storey mass timber office and commercial building. The building consists of four upper mass timber levels built on two levels of underground parking and a ground floor of poured-in-place concrete as shown in Fig. 3. The building is 19.7 m tall, with the plan dimensions shown in Fig. 3c.

The floors consist of 5-ply 175 mm CLT, graded V2 and E1. The gravity system of the building comprises exposed glulam Douglas Fir-Larch (D. FIR-L) 24f-E, EX beam, and D.FIR-L 16c-E columns as shown in Fig. 4a. The lateral force-resisting system of the building includes high-strength, ductile steel braces designed to prevent brittle failure of timber elements during earthquakes as shown in Fig. 4b. CLT staircases and elevator shafts are not part of the lateral force-resisting system, and are structurally isolated from surrounding elements to prevent them from being affected by the movement of other components during an earthquake [11].

2.2 AMBIENT VIBRATION TEST

Ambient vibration testing is conducted by installing accelerometers at multiple locations in the building to measure low-amplitude vibrations induced by environmental sources such as wind and human activity. A set of reference sensors is placed at a fixed level, while other sensors are moved to different levels throughout the structure to capture vibration response. The recorded signals are processed to extract the system's natural frequencies, mode shapes, and damping ratios. Sensor placement is guided by the expected mode shapes, similar to a cantilever beam or initial finite element model [12].



Figure 3. Terminus building: (a) east view; (b) 3D-view; (c) plan of the building.

Ambient Vibration Test of the Vue

The ambient vibration test on the Vue building was carried out on Monday, March 18, 2024. At the time of testing, the building was occupied, and residents were engaged in their daily activities. Additionally, the maximum and average wind speeds on the test day were recorded at 13 km/h and 7 km/h, respectively, in Victoria [13]. For the AVT protocol, three triaxial wireless Sensequake Larzé sensors with 2.4 GHz antennas were used. These sensors feature tuneable sampling rates from 15 Hz to 3906 Hz and utilize GPS or radio beacons for accurate network synchronization down to the microsecond level [14]. Sensor 1 functioned as the reference sensor, while sensors 2 and 3 were roving sensors.

The time history of acceleration and velocity was recorded at a total of 45 points in the building across 25 setups. At each point, three acceleration and three velocity components, namely X (north-west), Y (west-east), and Z (vertical), were recorded, resulting in a total of 270 timehistory datasets. Each setup had a duration of 480 seconds, with a sampling rate of 488 Hz.



Figure 4. Structural elements of Terminus, (a) CLT floor and Glulam beams and columns; (b) Steel brace

As the building is a rental residential property, access to all units was not possible. Therefore, measurement points were placed around the northern and southern staircases from levels 2 to 11, as well as at the corner points of the penthouse level (level 12). Four setups were conducted on level 12, while two setups were performed on each of levels 2 through 11. The locations of the measured points are shown in Fig. 5, where S2 and S3 denote sensors 2 and 3, respectively. The reference sensor (shown as Ref-S1 in Fig. 5) was positioned at the southern staircase on level 12. Fig. 6 shows the sensors placement during data collection, with sensors positioned to the west and east of the northern staircase.



Figure 5. AVT setup details of the Vue



Figure 6. Sensors during the test: (a) west of the northern staircase; (b) east of the northern staircase

Ambient Vibration Test of Terminus

The ambient vibration test on the Terminus building was conducted on Tuesday, March 19, 2024, under normal operating conditions. The recorded maximum and average wind speeds in Victoria on the test day were 16 km/h and 8.5 km/h, respectively [13]. For the AVT protocol, two triaxial wireless Sensequake Larzé sensors were used [14]. Sensor 1 served as the reference sensor, while sensor 2 was the only roving sensor. Sensor 3 was excluded from the test due to a malfunction.

Time-history acceleration and velocity measurements were taken at 30 points in the building across 30 setups. At each point, three acceleration and three velocity components, namely X (north-west), Y (west-east), and Z (vertical), were recorded, resulting in a total of 180 time-history datasets. Each setup lasted 240 seconds, with a sampling rate of 488 Hz. Sensor locations are shown in Fig. 7.

Due to limited access to an east-side unit on level 3, the sensor was placed at the nearest accessible location (Fig. 8a). The reference sensor was positioned at the roof level (Fig. 8b) and shown as Ref-S1 in Fig. 7.



Figure 7. AVT setup details of Terminus



Figure 8. Sensors during the test, (a) alternative point at level 3; (b) reference sensor

Data Processing

SSI and FDD techniques were used to analyze the captured time-history data for modal identification. The Sensquake online dashboard was utilized to implement these algorithms [15].

SSI is a time-domain technique in which data is analyzed directly without conversion to correlation functions or spectra, using singular value decomposition (SVD) [16]. During preprocessing, a time lag of 2 seconds and 1 second was applied for the Vue and Terminus, respectively, to ensure sufficient information on the lowest vibrational modes was included in the analysis. The sampling frequency was reduced using a decimation factor of 20, and an 8th-order bandpass filter was applied to identify mode shapes between 1 Hz and 25 Hz for both buildings. The highest model order was set to 50, corresponding to 25 structural vibration modes.

FDD is a frequency-domain method that utilizes SVD of the spectral density [16]. The frequency resolution was set to 0.1 Hz, based on the data measurement time. During preprocessing, the sampling frequency was reduced with a decimation factor of 20 for both buildings. The minimum modal assurance criterion (MAC) was set to 0.9 for both case-study buildings.

2.3 NBCC AND CLT HANDBOOK DESIGN EQUATIONS

The NBCC provides empirical formula, (1), for estimating the fundamental periods of buildings, including those with braced frames, which applies to both the Vue and Terminus buildings,

$$T = 0.025 h$$
 (1)

where T and h refer to the first period (s) and the height of the building (m), respectively [8]. These formulas have been derived based on regression analysis using the fundamental periods measured for several buildings in California during the 1971 San Fernando earthquake, which may not be applicable to timber structures [2]. Therefore, the Canadian CLT handbook recommends modified empirical formula, (2), to calculate the first transverse period of timber buildings,

$$T = 0.035 \, h^{0.8} \tag{2}$$

In addition, the Canadian CLT handbook recommends 2% and 3% of the damping ratios for wood buildings without and with finishings, respectively [9].

3 – RESULTS

3.1 EXPERIMENTAL DYNAMIC PROPERTIES OF THE VUE

The first eight measured natural frequencies and damping ratios of the Vue building, obtained using the SSI and FDD algorithms, are presented in Table 1. In most mode shapes, the measured damping ratios are below 2%, which is lower than the values specified in the Canadian CLT Handbook for timber buildings with finishings. The frequencies measured by SSI and FDD show close agreement, with differences of less than 3%. However, a greater discrepancy is observed in damping ratios, highlighting the high uncertainty associated with damping estimation. The first eight extracted mode shapes of the Vue are shown in Fig. 9, in which directions X and Y are in correspondence to the north-south and east-west directions of the building respectively.

The first measured fundamental period using the SSI technique is 0.75 s, while the fundamental periods estimated by the 2020 NBCC and the Canadian CLT Handbook are 1.00 s and 0.67 s, respectively. The results indicate that the fundamental period estimated by the NBCC is 33% higher, whereas the value from the CLT Handbook is 11% lower than the experimentally measured fundamental period.

3.2 EXPERIMENTAL DYNAMIC PROPERTIES OF TERMINUS

The first seven measured natural frequencies and damping ratios of Terminus are presented in Table 2. The frequencies obtained using SSI and FDD show close agreement, with differences of less than 3% in most mode shapes. The measured damping ratios range from 1% to 3%; however, a greater discrepancy is observed between the values estimated by SSI and FDD. The extracted mode shapes of Terminus are illustrated in Fig. 10, where the X and Y directions represent the north-south and east-west orientations of the building, respectively.

The first measured fundamental period of Terminus using the SSI technique is 0.36 s, while the fundamental periods estimated by the 2020 NBCC and the Canadian CLT Handbook are 0.49 s and 0.38 s, respectively. The results show that the fundamental periods estimated by the NBCC and the Canadian CLT Handbook are 37% and 6% higher than the experimental fundamental period, respectively.



Figure 9. First eight modes of the Vue



Figure 10. First seven modes of Terminus

Mode Number	Mode Type	Frequency (Hz) SSI	Frequency (Hz) FDD	Damping R. (%) SSI	Damping R. (%) FDD
1	First bending: east-west	1.33	1.36	1.7	2.2
2	First torsion	1.55	1.60	1.4	1.1
3	First bending: north-south	1.85	1.90	4.5	0.5
4	Second bending: east-west	4.06	3.97	2.2	1.6
5	Second bending: north-south	4.19	4.28	1.5	1.3
6	Third bending: north-south	4.94	4.87	2.0	0.6
7	Third bending: east-west	6.16	6.21	0.5	0.3
8	Second torsion	8.44	8.29	0.5	0.4

Table 1: Measured frequency and damping ratios of the Vue.

Table 2: Measured frequency and damping ratios of Terminus.

Mode Number	Mode Type	Frequency (Hz) SSI	Frequency (Hz) FDD	Damping R. (%) SSI	Damping R. (%) FDD
1	First bending: east-west	2.78	2.81	2.4	1.5
2	First bending: north-south	2.96	2.95	2.9	1.8
3	First torsion	3.29	3.4	2.4	1.55
4	Second torsion	5.75	5.73	1.1	3.0
5	Second bending: east-west	6.94	6.5	1.4	0.4
6	Second bending: north-south	7.76	8.85	0.5	0.3
7	Third bending: north-south	9.10	9.33	1.2	0.3

4 – CONCLUSIONS

This study investigated the dynamic characteristics of two mass timber hybrid buildings using ambient vibration testing. The modal properties were identified through SSI and FDD techniques, and the experimental results were compared with empirical values estimated using the 2020 NBCC and the Canadian CLT Handbook formulas. The key findings of this study are summarized as follows:

- The measured fundamental frequencies using SSI are 1.33 Hz (east-west) and 1.85 Hz (north-south) for the Vue, and 2.78 Hz (east-west) and 2.96 Hz (north-south) for Terminus. The measured damping ratios of both buildings range from 1% to 3%.
- Up to eight modes were identified for the buildings. These findings provide a more comprehensive understanding of the buildings' dynamic behavior, including the higher mode effects, and can be used to improve numerical structural analysis in the future.
- The measured frequencies by SSI and FDD are close, with a difference of less than 3%; however, greater discrepancies are observed in the damping ratios, which show higher uncertainty of damping ratio parameter.
- The fundamental period calculated using NBCC and the Canadian CLT Handbook is 33% higher and

11% lower than the experimental fundamental period of the Vue, respectively. For Terminus building, the fundamental periods of the NBCC and the Canadian CLT Handbook are 37% and 6% higher than the experimental values, respectively.

5 – ACKNOWLEDGMENTS

This work is financially supported by BC Forestry Innovation Investment -Wood First program, and the Natural Sciences and Engineering Research Council of Canada (NSERC). We thank Brendan Fitzgerald from ASPECT Structural Engineers company for their valuable assistance in providing information and Rebecca McKay and Matthew McKay from Victoria's Design Build Services (DBS) company for allowing access to the buildings for data collection.

6 – REFERENCES

[1] S. Pastori, E.S. Mazzucchelli, and M. Wallhagen. "Hybrid timber-based structures: A state of the art review." In: Journal of construction and building materials 359 (2022), pp. 129505.

[2] P. Alto. "Tentative provisions for the development of seismic regulations for buildings." Applied Technology Council California, U.S.A, 1978.

[3] B. Kurent, B. Brank, and W.K. Ao. "Model updating of seven-storey cross-laminated timber building designed on frequency-response-functions-based modal testing." In: Journal of structure and infrastructure engineering 19 (2021), pp. 1–19.

[4] L. HU, and S.C. Auclair. "Advanced wood-based solutions for mid-rise and high-rise construction: in-situ testing of the Origine 13-storey building for vibration and acoustic performances." FBInnovations, 2018.

[5] L. Hu, and S.C. Auclair. "Advanced wood-based solutions for mid-rise and high-rise construction: in-situ testing of the Arbora building for vibration and acoustic performances." FPInnovations, 2018.

[6] T. Reynolds, R. Harris, W.S. Chang, J. Bregulla, and J. Bawcombe. "Ambient vibration tests of a crosslaminated timber building." In: Journal of proceedings of the institution of civil engineers-construction materials 168 (2015), pp. 121–131.

[7] T. Saule, A.W. Kei, P. Aleksandar, M. K. Arne, and R. Anders. "Identification of modal properties of a tall glue-laminated timber frame building under long-term ambient vibrations and forced vibrations." In: Journal of structural engineering 150 (2024), pp. 04024125.

[8] Canadian commission on building and fire codes. "National building code of Canada (NBCC)." National Research Council of Canada, 2020.

[9] E. Karacabeyli, and S. Gagnon. "Canadian CLT handbook." FPInnovations, 2019.

[10] Tallwood 1 at district 56 Langford. "Website: Naturally Wood." Available at: https://www.naturally wood.com/projects/tallwood-1-at-district-56/, 2021.

[11] Terminus at district 56, Langford. "Website: Naturally Wood." Available at: https://www.naturally wood.com/projects/terminus-at-district-56/, 2021.

[12] R. Brincker, and C. Ventura. "Introduction to operational modal analysis." WILEY, 2015.

[13] Daily wind speed chart. "Website: Victoria weather stats." Available at: https://victoria.weatherstats.ca/ charts/wind speed-daily.html, 2024.

[14] Sensequake company. "Larze' vibration monitoring system - user manual." 2020.

[15] Sensequake company. "Online dashboard of Sensquake Larzé." https://cloud.sensequake.com/, 2024

[16] M.S. Rahman. "Comparison of System Identification Techniques with Field Vibration Data for Structural Health Monitoring of Bridges." Master's thesis. Carleton University, 2012.