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SYSTEM IDENTIFICATION OF TALL MASS TIMBER STRUCTURES EMPLOYING AMBIENT VIBRATION TEST AND FE MODELLING

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ABSTRACT: Despite the recent rapid development in dynamic characteristics identification of structures, lack of knowledge in dynamic properties of tall mass timber buildings is still an open issue for researchers and designers. There are ongoing international efforts to develop a comprehensive database for predicting the vibration performance of timber structures for serviceability and seismic design. This paper discusses an ambient vibration test (AVT) that was conducted on a six-storey mass timber building known as Wood Innovation and Design Centre (WIDC) located in Prince George, Canada. The test results including the experimental natural frequencies and damping ratios were compared with a three-phase test program undertaken in 2014, 2015, and 2017 by FPInnovations. In addition, a numerical modal analysis was conducted on the same building, using both simplified and complex finite element (FE) models. A sensitivity analysis was carried out considering various assumptions of connection types to investigate its effect on the natural frequencies of the structure. The results of current AVT showed minor changes in frequencies over the service time in comparison to previous tests. According to the numerical results, the simplified FE model poorly matched with the results from AVT, while the complex model showed a better agreement with the measured fundamental frequency; however, significant discrepancies were observed in the second and third modes. The sensitivity analysis indicated low impact of different connection type assumptions on the natural frequencies of the case building obtained from the FE models.

KEYWORDS: System identification, Timber buildings, Dynamic properties, Ambient vibration test, Numerical modelling

1 INTRODUCTION

With the use of mass timber products, interest in constructing more high-rise timber buildings has increased recently. However, due to the lightweight and high flexibility of tall timber buildings, they are susceptible to dynamic lateral loads that are induced by wind and earthquakes [1]. To understand their structural behaviour under lateral loads, prediction of the building dynamic properties is of great importance in the design stage. The National Building Code of Canada (NBCC) allows designers to estimate the fundamental period of timber buildings by an empirical formula which was not developed specifically for timber buildings [2].

To address the lack of data, there is an ongoing research campaign on vibration testing of timber buildings to extract the dynamic properties of these structures to form a database [3-6]. Feldmann et.al studied nine timber towers and three tall timber buildings by ambient vibration testing. The results verified the efficiency of this type of experiments and contributed test data on low-amplitude wind vibration of tall timber structures [1]. Reynolds et al. investigated the difference in dynamic properties between two similar 5-storey timber buildings with the same layout and a concrete core. The difference was in walls and floors, the first was made of a light wood frame and the second was made of cross laminate timber (CLT). The results showed high similarity between the dynamic properties of these two buildings [7]. Hafeez et al. studied dynamic properties of 32 light wood frame buildings and concluded that it was inaccurate to take the height of structures as the sole variable in determining the fundamental period of timber structures [8]. Recently, more mass timber buildings in Canada [3-5] and Europe [9] have been tested under dynamic loads at the serviceability level.

Having an experimental database of modal parameters, FE models with increased accuracy can be developed by engineers in practical design [10]. However, certain details of modelling such as connection types and material properties are still open issues in frequency calculations

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and overall dynamic behaviour of timber building. Reynolds et al. reported, for the two 5-storey buildings, that the FE modelling of just concrete core provided lower fundamental natural frequencies than the measured values [7]. Larsson et al. investigated a nine-storey concrete-timber hybrid building and found that dynamic properties were highly sensitive to the selected elastic properties of CLT walls, but insensitive to the connection properties [10]. Aloisio et al. modelled eight-storey CLT student apartments building located in Norway. The calibration of their model based on AVT results indicated that the impact of connectors under serviceability conditions is negligible [11]. In this regard, Tulebekova et al. had different findings that the stiffness of connections of the glulam frame in modelling the Mjosa tower were a governing parameter [12]. Kurent et al. updated FE model of a seven-storey CLT building based on an input-output vibration test result. Good agreement was observed between the numerical and experimental frequencies in the first six modes. However, the results showed that frequencies matched better in lower modes than in higher modes. [13].

In this study, an AVT was conducted on Wood Innovation and Design Centre (WIDC) building located in Prince George, Canada, to determine its experimental natural frequencies, damping ratios, and mode shapes. The test results were compared with the existed three-phase test program undertaken in 2014, 2015, and 2017 by FPInnovations [5]. The present study contributes to the assessment of dynamic properties change of a mass timber building during different time of its service life. Furthermore, to investigate the efficacy of commercial structural analysis FE software for modal analysis of tall mass timber buildings, two simplified and complex FE models were developed respectively for sensitivity analysis of different connection properties assumptions, and the results were compared with the experimental data. The test results were compared with predicted fundamental frequency from the NBCC equation.

2 MATERIALS AND METHODS

2.1 BUILDING DESCRIPTION

WIDC is a 29.5-meter tall, six-storey (with a mezzanine and a penthouse) mass timber building located in Prince George, British Colombia, Canada (Figure 1). The main structure consists of an innovative combination of post-and-beam construction and built-up cross-laminated timber floor panels. A balloon-type CLT core around the staircase and elevator shaft serves as the lateral load resisting system. WIDC was built in 2014 and was the tallest modern timber structure in Canada at the time of its construction.

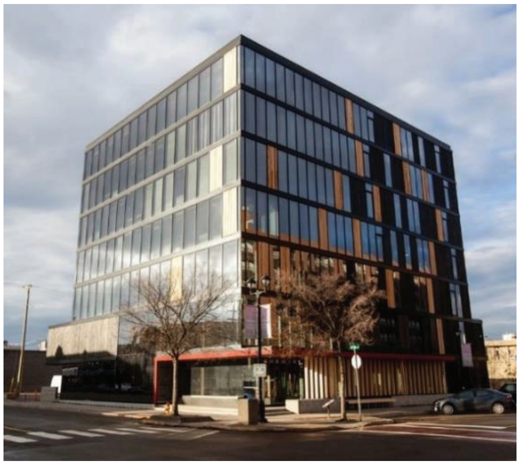

Figure 1: *Wood Innovation and Design Centre [14].*

2.2 AMBIENT VIBRATION TESTS

In 2014, while the building was about to complete with only the structural components and no enclosures, an AVT was conducted to determine its natural frequencies and damping ratios. After the building was completed with all non-structure components and fully occupied in 2015, Phase-II AVT was carried out.

Phase-III AVT was conducted in 2017, to check if the natural frequencies and damping ratios changed from the values measured in 2015. In these three phases, two reference sensors were fixed in the 5th floor level (Phases I and II) and the 6th floor level (in Phase-III). Six sensors with 500 mV/g sensitivity were roved between stories 2-6, 4-6, and 5 to 6 in the three tests, respectively. The location of the sensors is shown in Figure 2.

The results of these previous tests are listed in Table 1 [5]. The first and second vibration modes of the building are the first translational modes along the principal directions, X and Y, respectively, as shown in Figure 2, while the third mode is the first torsional mode.

Table 1: *Frequency and damping ratios of previous phases [5]*

Modes	Natural Frequency (Hz)			Modal Damping Ratio (%)		
	Phase I	Phase II	Phase III	Phase I	Phase II	Phase III
Translation in X	1.1	1.4	1.4	3.0	3.0	2.0
Translation in Y	1.3	1.6	1.6	2.0	2.0	2.0
Torsion	1.5	1.9	1.9	2.0	2.0	3.0

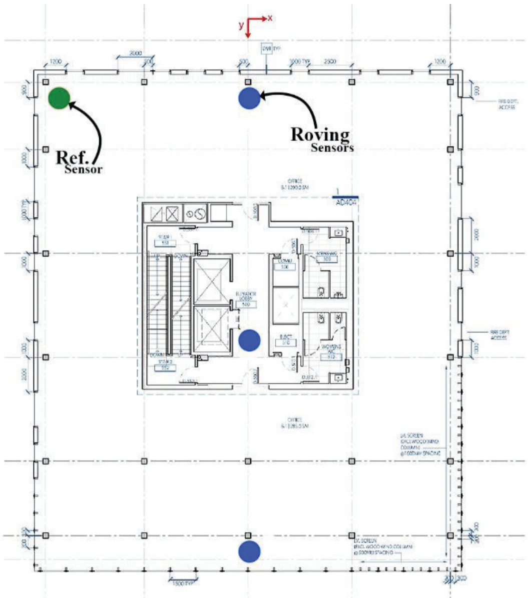

***Figure 2**: Location of the sensors (privious study [5])*

Aiming to monitor the dynamic properties of WIDC at the 9th year of its service life, Phase-IV tests were conducted in January 2023, as discussed subsequently. For the current AVT protocol, a 24-channel SEIMENS SCADAS dynamic data analyser with 10 uniaxial PCB accelerometers of 100 mV/g sensitivity and a sampling frequency of 200 Hz is used for data collection. The time duration for each setup was considered 240 sec. Two accelerometers were mounted on the roof level as the reference accelerometers in X and Y directions of the building and 8 accelerometers were roved between storeys 2-6 for measuring natural frequencies, mode shapes, and damping ratios. The second-floor plan is different from the above floors. However, the sensors were installed at all the floor levels at the same location in plan. No measurements were conducted at the mezzanine floor, which was anticipated not to affect the expected first three mode shapes. Figures 3 and 4 illustrate the locations of the sensors in the building and the overall view of test setup, respectively.

Post-processing of the operational modal analysis (OMA) was carried out using Simcenter Testlab using the OMA add-in. After correlation of time domain measurements, PolyMAX option, which is a curve fitter or modal parameter analyser, was used for producing cross power spectra to estimate the dynamic parameters of the desired system. In this process, all the cross powers functions were visualized along with their sum. Using the sum which is a complex average of all the included cross powers allows the identification of amplitude peaks [15].

2.3 NUMERICALL MODELLING

The experimental results were used to verify the FE model that was developed for modal analysis. For this purpose, the structure was modelled using RFEM 5.25 software in two stages. In the first stage, only the CLT core walls were modelled with lumped seismic inertia assigned at floor levels. The lumped mass was determined based on the actual mass of the materials and effective floor loads of the building. In the second stage, a complex model was developed including glulam beams and columns, CLT shear walls, and CLT floors. The details of modelling (the used material, structural element size, and layout of the elements) is according to the existing technical drawing of the building.

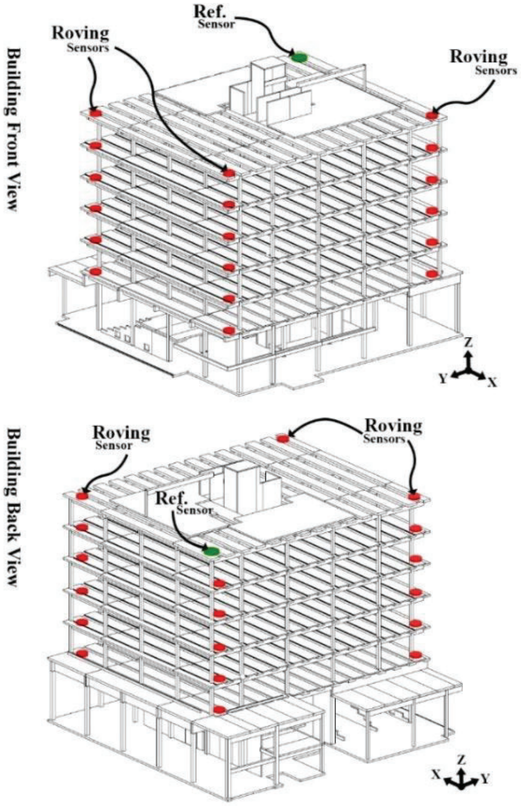

***Figure 3**: Locations of the sensors (phase IV)*

According to available information, the CLT panels used in wall construction are E1 grade 5-ply (175mm) sprue-pine-fir (SPF), and the staggered CLT floors were constructed with E1 grade 5-ply (175mm) and 7-ply (245mm) SFP CLT panels. These floors were modelled as an equivalent 6-ply CLT panel in the complex model. The 24f-EX Douglas Fir glulam beams and 16c-E Douglas Fir glulam columns were used throughout the building. Non-structural elements such as partition walls, façade, claddings, etc were not included in the complex model. The CLT walls and floors were modelled using the RF-Laminate add-on module in RFEM.

A pinned condition was assumed at the base of the columns and walls. As the post and beam were not designed to carry moments, beam-to-post connections were assumed as being pinned. The connections of floor-to-wall and wall-to-wall panels were considered as being fixed. Figures 5 and 6 show the simplified and complex FE models, respectively.

For the sensitivity analysis, floor-to-walls and wall-to-wall panels connection type assumptions were changed to pinned condition while columns and walls connections to the foundation were switched to fixed. This was to investigate the impact of various joint conditions on natural frequencies of the building.

Figure 4*: Overall view of test setup*

2.4 NBCC PERIOD EQUATION

NBCC (2020) provides empirical equations to estimate the fundamental period of buildings. These equations are applicable to structures with various lateral resistance systems such as reinforced concrete moment resisting frames, steel moment resisting frames, for shear walls, etc.

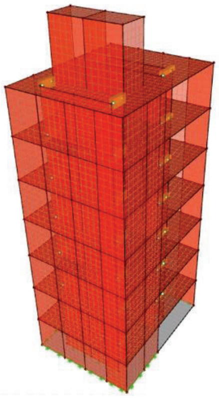

Figure 5*: Simplified FE model*

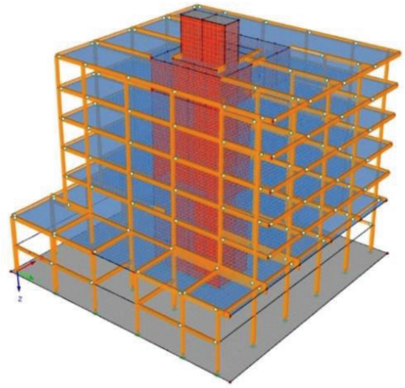

Figure 6*: Complex FE model*

However, no equation is provided specifically for timber structures. In this paper, the equation for 'shear wall buildings and other structures' was adopted, as follows:

$$T_S = 0.05(h_n)^{3/4} \qquad (1)$$

where, T_S and h_n are the fundamental period and the height of structure, respectively [2].

3 RESULTS AND DISCUSSION

3.1 EXPERIMENTAL TEST RESULTS

As listed in Table 2, the results indicate minor changes in the fundamental frequencies of the building over time. Figure 7 shows the cross-power function obtained from OMA. Comparing the test results of Phase III and IV, only 7.1% and 5.2% increase can be seen in the first and third natural frequencies, respectively, while the natural frequency of the second mode remains nearly the same. The relatively small discrepancy in the first and third mode frequencies may result from the differences in test setups used in Phase III and IV. Though accelerometers with different sensitivity (500 mV/g and 100 mV/g respectively) were used in the previous and present study tests, respectively, the sensors' sensitivity in both tests are adequate enough for capturing low frequencies required for this case study.

The consistency of natural frequencies during the time indicates no stiffness degradation in both connections and elements of the building. It should be mentioned that the occupancy of the building is still the same as the previous test, meaning negligible changes of the total mass of WDIC. Damping ratios of the first three modes of the structure at serviceability load level are listed in Table 2. It is well known that the measurement of damping ratios could have high degree uncertainty. Although, some changes can be seen between the values of damping ratios in this study and phase III of the previous study, rounding of the measured damping ratios in phase IV to the integer leads to the same results as previous phase test.

Table 2: *Comparison of natural frequencies (Hz) and damping ratios (%) of the first three modes*

Index	Modes	Values		
		Phase III [5]	Phase IV	Change (%)
Natural Frequencies (Hz)	Translation in X	1.4	1.5	7.1
	Translation in Y	1.6	1.6	0.0
	Torsion	1.9	2.0	5.2
Damping Ratios (%)	Translation in X	2.0	1.5	-25.0
	Translation in Y	2.0	2.0	0.0
	Torsion	3.0	1.5	-50.0

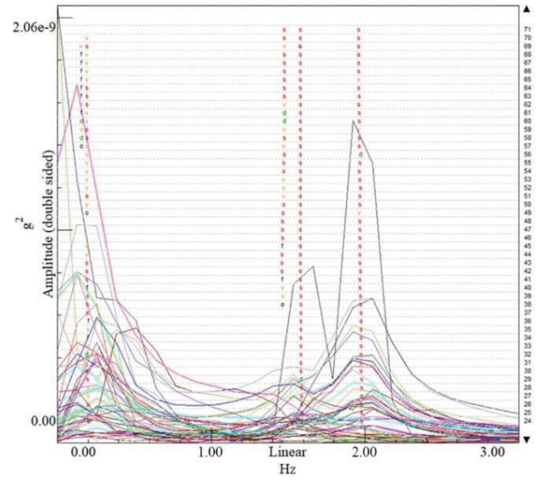

Figure 7*: Typical cross-power function obtianed from phase-IV test*

3.2 FE Modelling Results

The other dynamic property investigated in this study is the mode shapes. As mentioned before, in AVT's the first three mode shapes are the first bending in X direction, the first bending in Y direction, and the torsional mode, respectively. The results of the FE models show good agreement with the finding from AVT. Three first mode shapes of the simplified FE model are shown in Figure 8. Furthermore, the results of the structures mode shapes for phase-IV test and complex numerical FE model are shown in Figure 9.

The comparison between frequency of the first mode in the phase-III AVT, phase-IV AVT, the simplified model, and the complex FE model of the building along with NBCC formulation is shown in Figure 10. As it is clear in Figure 10, there is a significant discrepancy of about 47% between the first natural frequency of the simplified model and the result of Phase-IV AVT. Modelling only CLT core of the building could not predict the building frequencies accurately in this case study, as the first frequency of this model is not well-matched with the measurement. It is worth noting that difference between fundamental natural frequency of the complex model and phase-IVAVT is about 10.8%.

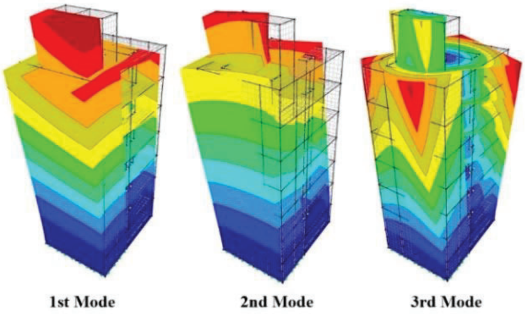

Figure 8*: First three mode shapes of the simlified model*

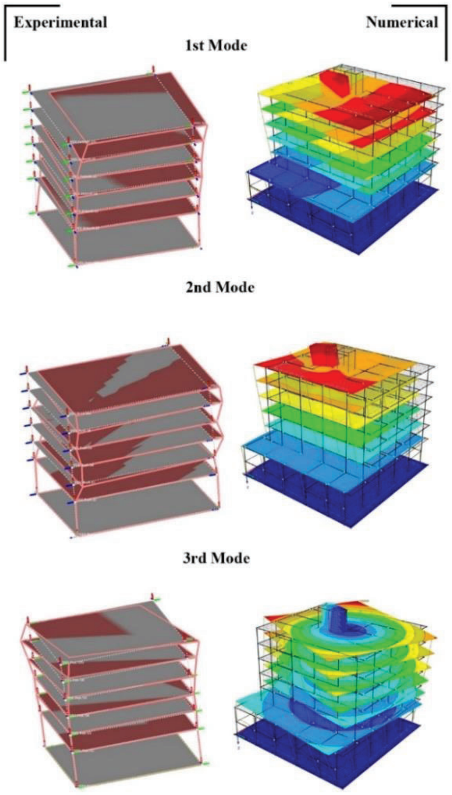

Figure 9*: First three mode shapes of the complex model both numerically and experimentally*

Because the first three measured frequencies of the building are close to each other, the discrepancy of 10.8% between first frequency of the FE model and experiment data cannot be considered as a good match between FE model and test data, though, this discrepancy is lower in comparison with the simplified model. Besides, it is interesting to find that first natural frequency of the building estimated using the NBCC equation matched the measured value reasonably well from designer's point of view based on the data measured on 19 buildings [16] and close the predicted by the complex model. The results of the first three natural frequencies of the simplified and complex model are listed in Table 3. It is clear that the simplified model provided overestimated frequencies for all the three modes. Moreover, the differences between the measured and FE modelled frequencies are larger in higher modes. This finding agrees with the results found in [13] that matching higher modes of the FE modelling with the test results is more difficult than the lower modes.

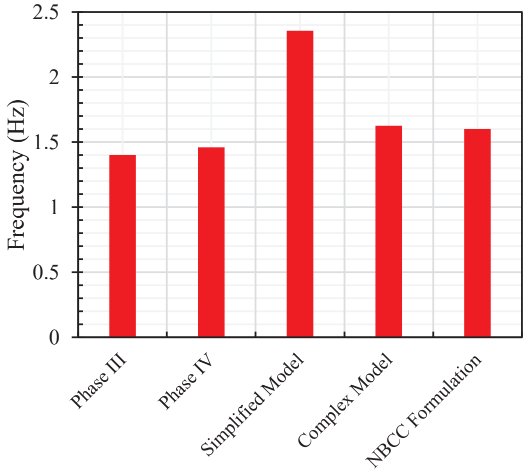

Figure 10: *Comparision between avt, FE modelling, and nbcc equation for prediction of the first natural frequency*

Table 3: *Frequencies of the simplified and complex model*

Modes	Simplified model (Hz)	Complex model (Hz)	Discrepancy (%)
Translation in X	2.3	1.6	35.9
Translation in Y	4.3	2.6	49.3
Torsion	6.0	5.0	18.2

3.3 SENSITIVITY ANALYSIS

A sensitivity analysis was carried on both the simplified and complex numerical models to investigate the sensitivity of the frequencies to different assumptions of connection types. The initial models are based on the assumptions mentioned in section 2.3. As shown in Figure 11, by changing wall and columns base connections from pinned to fixed in simplified model, less than 0.3% soar in all three frequencies is observed. Altering wall-to-wall connections from fixed to hinged leads to a reduction of less than 0.6% in all frequencies. Considering wall-to-floor connections hinged as an alternative for fixed assumption, caused 2.6% decrease in the frequencies.

The sensitivity analysis of the complex model yields similar results to the simplified model. By changing floor-to-wall and panel-to-panel wall connections from fixed to hinged, less than 0.7% reduction is observed. Considering fixed connections instead of pinned in the base supports leads to less than 0.5% increase in all frequencies. Details of the sensitivity analysis of the complex model is shown in Figure 12 for the complex model. The results agree well with the findings in [10,11] that indicates low sensitivity of the FE model developed in RFEM to the different assumptions of connection types in structural elements (fixed, pinned or hinged).

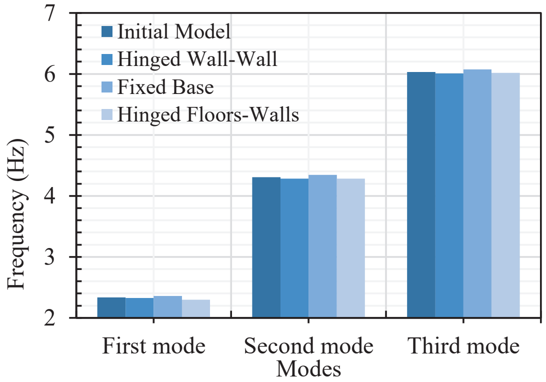

Figure 11: *Details of the sensitivity analysis of the simpified model.*

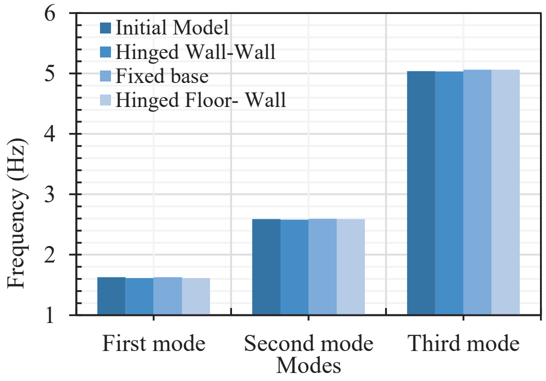

Figure 12: *Details of the sensitivity analysis of the complex model.*

4 CONCLUSIONS

The dynamic properties of a 29.5-m mass timber building was investigated through both AVT and FE modelling. An ambient vibration test was carried out on the building to assess the differences of the dynamic properties after 9 years of its srvice time, as the result of three-phase AVT is already available from the building construction time. Then, two types of FE modelling were developed in RFEM software and the results of both numerical models were compared with the measured frequencies. Finally, a sensitivity analysis was performed to see the effect of different connection type assumptions on the building frequencies.

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A summary of the results and recommendations limited to the current case study can be concluded as follows:

1. According to the experimental test, the first natural frequencies of the structure did not have a significant change in comparison to the last performed AVT in 2017. Frequency change between the first three phase is due to the fact that phase-I testing was performed on the building under construction with only frame and structural components without enclosure. The second phase testing was performed on the finished building with all components that added stiffness and mass, which increased the building frequencies.
2. The results of simplified FE model poorly matched with results of AVT and the complex FE model. Though, the complex model shows a better agreement in the first frequency with the measured frequency values. However, a significant discrepancy can be observed in higher modes. The modal parameters in FE model shows a low sensitivity to the type of connection assumptions (fixed, pinned or hinged), and requires experimental verifications.
3. It is recommended that in the absence of a reasonable reliable FE model, for the design purpose, the NBCC simple equation can be considered to estimate the first natural frequency of mass timber buildings with only shear walls. It is also recommended that for design purpose, for such type of wood construction, 2-3% damping for the occupied building may be used. Besides, if FE modelling is used for design, caution, verification, and calibration is needed.

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