World Conference on
Timber Engineering
Oslo 2023

AMBIENT VIBRATION TESTS AND MODAL ANALYSIS OF A SIX-STORY LIGHTWEIGHT TIMBER FRAME BUILDING

Carmen Amaddeo[1], **Michael Dorn**[2]

ABSTRACT: This paper describes the in-situ ambient vibration tests of a lightweight timber frame building, performed in order to obtain its modal properties. Our case study is a six-story lightweight timber frame building in Varberg, Sweden. Five battery-driven wireless data acquisition units with a total of 14 uni-axial accelerometers were used to perform the in-situ measurements. Accelerations along the two horizontal directions were recorded with a duration of approximately 40 minutes. Two different only-output frequency and time domain Operational Modal Analysis (OMA) methods were used to evaluate the dynamic properties of the building. The modal parameters obtained from the in-situ measurements, such as natural frequencies and mode shapes, were compared with the parameters obtained from the Finite Element (FE) model of the structure. To perform a detailed numerical analysis of the light-frame timber building, all lateral-load resisting system components were modelled. The FE model was calibrated in function of the results obtained from the OMA of the building. Based on the obtained results from the calibrated FE model, it was possible to conclude that the non-structural elements have an influence on the global dynamic response of the building.

KEYWORDS: Timber, multi-story lightweight timber frame building, operational modal analysis, finite element modeling

1 INTRODUCTION

The realization of multi-story residential and commercial timber buildings is rapidly increasing all around the world. Timber structures are, in general, cost efficient, easy to transport, and quickly built on-site due to the high level of prefabrication. Light-frame timber systems have frequently been used to realize multi-story buildings. For this reason, it is important to understand their in-situ dynamic behavior to verify that such a typology of structures meets the design requirements in terms of structural safety as well as serviceability.

Ambient vibration tests are performed in order to obtain the in-situ modal parameters of the building. The results obtained from in-situ measurements can be used to validate and calibrate the Finite Element (FE) model of the building [1]. Calibrated FE models can be used to optimize the design of similar structures under ultimate and serviceability limit state load conditions.

Tests on lightweight timber frame multi-story buildings have not been extensively conducted with the exception of a few cases. The stiffness of a six-story timber frame building, during the construction stages, using dynamic testing has been evaluated by Ellis et al. [2]. Shake table tests on a full-scale two-story lightweight timber frame structure have been conducted by Filiatrault et al. [3, 4], in order to evaluate the dynamic parameters of the building and its seismic performance. In addition, shake table tests on a three-story lightweight timber frame building have been performed by Sartori et al. [5], focusing on the seismic performance of a prefabricated light-frame timber building and on the interaction of structural components.

In our study, to identify the dynamic parameters of the building, the Enhanced Frequency Domain Decomposition (EFDD) [6], and the Stochastic Subspace Identification (SSI) [7] methods have been used. Operational Modal Analysis (OMA) is considered an effective, non-destructive method to assess the actual operational condition of an existing structure.

This paper presents the in-situ dynamics tests carried out at the so-called, Hus 35 in Varberg, Sweden (Figure 1).

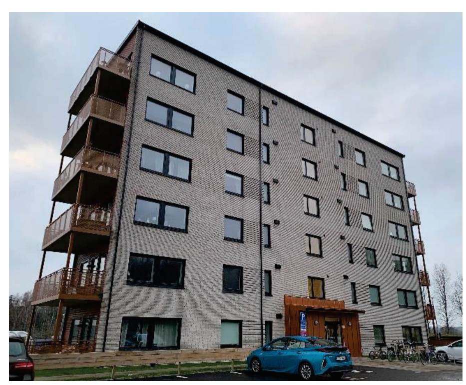

__Figure 1:__ East view of Hus 35 in Varberg, Sweden (picture by the author).

[1] Carmen Amaddeo, Linnaeus University, Sweden, carmen.amaddeo@lnu.se
[2] Michael Dorn, Linnaeus University, Sweden, michael.dorn@lnu.se

https://doi.org/10.52202/069179-0379

The structure was subjected to small ambient vibrations induced by wind. The results obtained in this study will be used as a benchmark for a more extensive test campaign that will be conducted on this building as well as on a second neighboring light-frame timber building in Varberg, Sweden, realized with the exact same design.
The modal parameters obtained from the in-situ test were compared to the one obtained from the FE model of the building. Simplified FE models have been widely used because they are numerically efficient and they demand a low computational effort [8, 9, 10]. Recent studies have focused on developing non-linear FE models including a larger number of deformation mechanisms such as: the detailed modeling of each connection, the individual timber frame stud elements, and the sheathing boards [11]. A detailed modeling strategy was developed by Kuai et al. [12] in order to analyze the deformation behavior of light-frame walls. Due to the high computational demand in modeling all connections, this work will include only the spring connections between different panels in the calibration phase of the FE model of the building. A preliminary study of the same building was developed by Amaddeo and Dorn [13] using a simplified modeling approach.

1.1 BUILDING DESCRIPTION

The Pilgatan block in Varberg consists of four six-story buildings all realized with the same light-frame system and built consecutively from 2020 to 2022. Each building has four apartments at each floor with the staircase and elevator shaft in the middle of the building along the East side (see Figure 2).

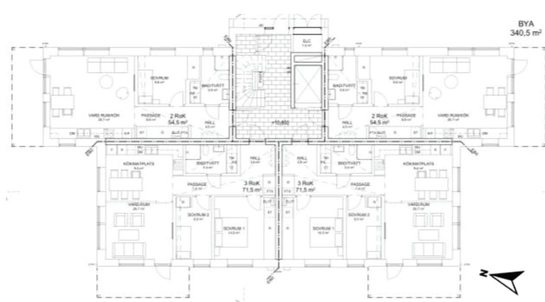

Figure 2: *Plan of a typical story.*

The load bearing system is composed of lightweight timber frames elements. The timber-framed wall panels of the external walls are made of timber studs, 45 mm x 170 mm, and a double layer of Oriented Strand Board (OSB) sheeting panel, 11 mm thick (see Figure 3.a and 3.b). The timber-frame internal walls are made of timber studs, 45 mm x 220 mm and 45 mm x 95 mm, and particle board sheeting panel 38 mm-thick. The elevator shaft and staircase are made with the same system. The load-bearing wall elements are prefabricated and assembled directly on-site. For horizontal stabilization, diagonal steel rods have been used.

This study will focus on the dynamic characterization of one of the buildings in the Pilgatan block, refer to as Hus 35, using ambient vibration tests.

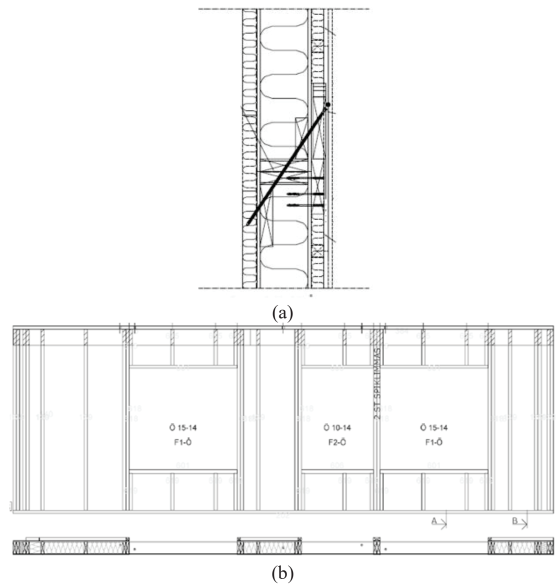

Figure 3: *External wall: (a) Detail of the load-bearing section of a timber-framed wall, (b) Front view of one of the lightweight timber frame panels.*

2 EXPERIMENTAL TESTING PROCEDURE

A first ambient vibration test was carried out in May 2021 [13], using only two data acquisition systems and four accelerometers. During this preliminary test a total of 9 measurements, with a duration of approximately 30 minutes each, were performed. During each measurement, the sensors at the first floor were used as a reference. The extracted natural frequencies of the building were used to validate the sensor layout for the presented study.

Figure 4: *Test setup: two of the total five portable data acquisition systems during the synchronization phase.*

https://doi.org/10.52202/069179-0379

A more extensive ambient vibration test campaign has been conducted starting in October 2022. During this second phase, five wireless data-acquisition systems (see Figure 4) with 14 uni-axial accelerometers, model PCB 393B12 with a sensitivity of 0.5 V/g, were used during the ambient vibration tests.

This type of accelerometers allows us to record low acceleration values also at a low frequency. The sensors were connected to a steel cube element to ensure the orthogonality of the recorded accelerations. The cubes with the accelerometers were connected to a steel plate which secured the placement against sliding, as shown in Figure 5.

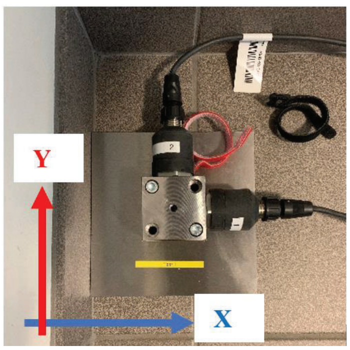

Figure 5: *Detail of the sensors at the first floor, location #1 with the direction of the recorded acceleration.*

Ambient vibration tests are sensitive to the presence of noise, so that both the sensors' location and duration of the test are important parameter during the testing campaign. A thorough placement and proper time synchronization reduces measurement noise and ensures the accuracy of the results.

Three accelerometers were placed on each floor as well as on the roof, except at the third floor where no accelerometers were placed, as shown in Figure 6.

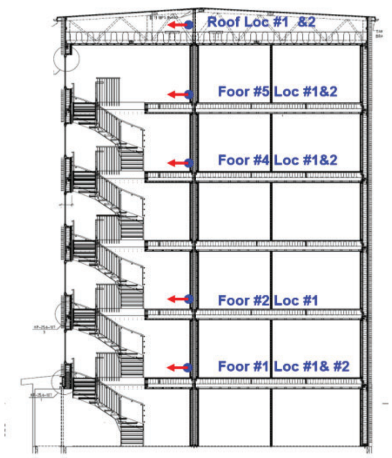

Figure 6: *Building section along the EW direction showing the sensor layout at each level.*

The accelerometers were used to measure the wind and traffic induced ambient vibrations. To minimize the interference with the occupants as well as the input from human induced vibration, the dynamic tests were conducted during the less crowded hours of the day during a work week.

The accelerometers were placed in the area next to the staircase and elevator shaft (see Figure 7). The layout of the sensors for the typical floor level is shown in Figure 7.a, and for the roof level is shown in Figure 7.b, where the sensors are placed farther apart from each other along the longitudinal direction (x-direction).

Measurements were conducted using three accelerometers per floor: one along the longitudinal (x-direction) and two along the transversal (y-direction) direction except at the second floor where only two accelerometers, one along the longitudinal and one along the transversal direction were used (see Figure 6).

The ambient vibration data were recorded for approximately 40 minutes, with a sampling frequency of 120 Hz. The five data-acquisition systems were cable synchronized at the beginning of each test in order to have the same time stamp (see Figure 4). Thereafter, each system was moved to its respective floor and the sensors were connected to each data acquisition system. Actual useable measurement time was reduced by approximately 5 minutes.

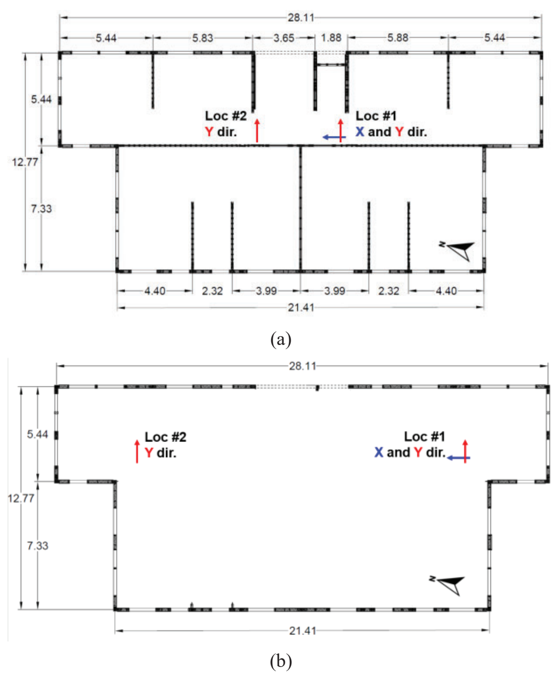

Figure 7: *Sensor layout with the location and direction of the accelerometers. (a) Typical floor level, and (b) Roof level.*

Three different tests were performed on the building in the period between October 2022 and January 2023, to see if any variation of the modal parameters had occurred under different environmental conditions.

The tests were performed respectively on: October 5th, 2021 (Test #1); November 23rd, 2022 (Test #2); and January 10th, 2023 (Test #3). Monthly tests will be performed for a full year in total.

3 EXPERIMENTAL RESULTS

Modal parameters of the building were identified using the EFDD, and SSI methods, respectively a frequency-domain, and a time-domain system identification method. These OMA techniques are available in the software ARTeMIS [14], that was used to analyze the recorded data.

The recorded data were post-processed in order to eliminate corrupted data from the analysis as well as the high-noise signals. A Butterworth filter between 0 and 6 Hz was used to better identify the natural frequencies of the building. This frequency range includes the first three mode shapes of the building in the two translational and torsional directions.

An example of the recorded acceleration at the roof level along the x-direction for a 20 second segment is shown in Figure 8, in which the periodicity of the response can be seen.

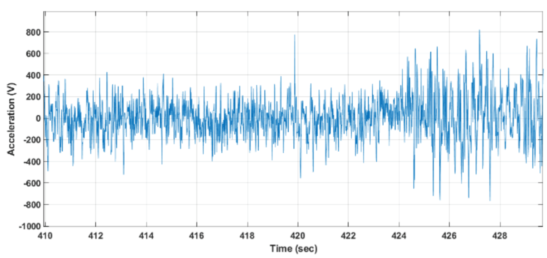

Figure 8: *Acceleration time-history for a 20 second fragment of the 40 minutes data recorded on January 10th, 2023.*

The auto Modal Assurance Criterion (autoMAC) values were calculated [15] and used to measure the degree of correlation and consistency between the mode shape pairs evaluated with one set of collected data. The autoMAC value is defined by Equation (1) as:

$$MAC_{rs} = \frac{|\{\varphi_r\}^T\{\varphi_s^*\}|^2}{\{\varphi_r\}^T\{\varphi_r^*\}\{\varphi_s\}^T\{\varphi_s^*\}} \tag{1}$$

where φ_r and φ_s are the modal vector for the frequency r and s respectively.

3.1 Enhanced Frequency Domain Decomposition (EFDD)

In the EFDD method, in order to evaluate the spectral matrix, the Power Spectral Density (PSD) of a single-degree-of-freedom systems is transformed into the time domain using an inverse discrete Fourier transform [6].

The Singular Value Decomposition (SVD) obtained for the three performed tests is shown in Figure 9. For all measurements, three well defined peaks can be observed at a frequency range between 2 - 4.0 Hz (see Table 1).

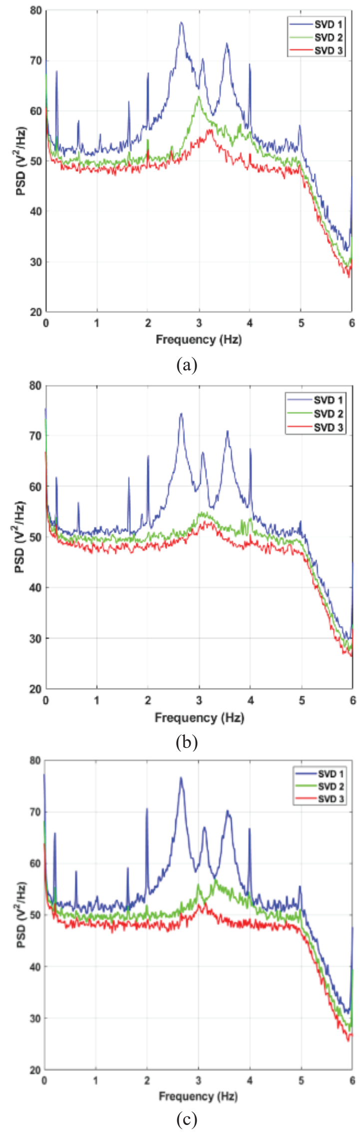

Figure 9: *Singular Value Decomposition (SVD) plot for the EFDD method: (a) Test #1, (b) Test #2, (c) Test #3.*

3.2 Stochastic Subspace Identification (SSI)

The second used system identification method is a time-domain approach. The SSI method is a parametric system identification method that allows the construction of stabilization diagrams. A stabilization diagram is a useful tool for evaluating stable modes and eliminating noise and unstable modes [7, 17].

The state space models' stabilization plots for the three performed tests are shown in Figure 10. The maximum model order is shown by a green horizontal line in Figure 10. In particular, for Test #1, the model order is equal to 23 (see Figure 10a), for Tests #2 and #3 it is equal to 18 (see Figure 10b and 10c).

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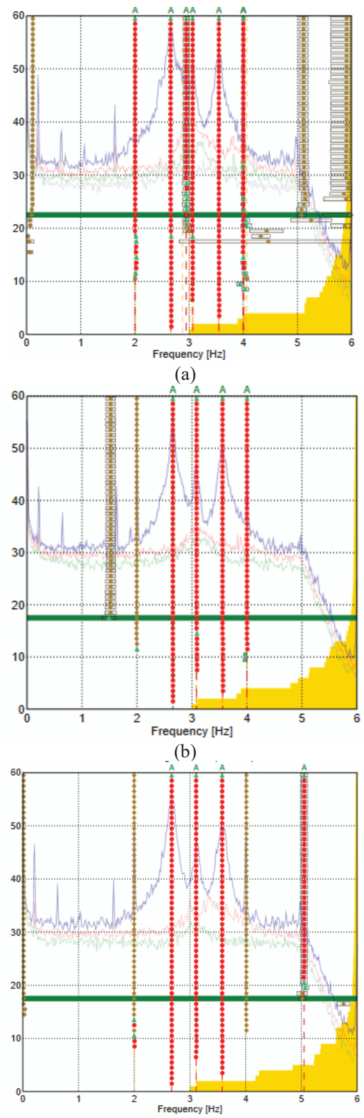

(a) (b) (c)

Figure 10: *State space models for the SSI method: (a) Test #1, (b) Test #2, (c) Test #3.*

The vertical red dots in Figure 10 indicate the stable modes within a frequency range between 0 and 6 Hz. The total number of stable modes is changing between the performed tests. Considering that some of the identified frequency values were very close, only the modes with a low value of complexity were considered as real structural modes (see Table 1).

3.3 Results comparison

Table 1 shows the results obtained from the three tests in terms of natural frequencies and damping ratios using the two OMA method, EFDD and SSI method respectively. Three modes of vibration were identified using both system identification methods.

Table 1: *Natural frequencies and damping ratios identified by the EFDD and SSI methods.*

	EFDD Method		
	Test #1	Test #2	Test #3
Mode 1	f_1 = 2.664 Hz	f_1 = 2.648 Hz	f_1 = 2.673 Hz
	ζ_1 = 2.799 %	ζ_1 = 1.344 %	ζ_1 = 1.549 %
Mode 2	f_2 = 3.072 Hz	f_2 = 3.075 Hz	f_2 = 3.121 Hz
	ζ_2 = 1.143 %	ζ_2 = 0.821 %	ζ_2 = 0.975 %
Mode 3	f_3 = 3.546 Hz	f_3 = 3.551 Hz	f_3 = 3.577 Hz
	ζ_3 = 1.423 %	ζ_3 = 1.707 %	ζ_3 = 1.657 %
	SSI Method		
	Test #1	Test #2	Test #3
Mode 1	f_1 = 2.658 Hz	f_1 = 2.652 Hz	f_1 = 2.671 Hz
	ζ_1 = 2.399 %	ζ_1 = 1.627 %	ζ_1 = 1.375 %
Mode 2	f_2 = 3.064 Hz	f_2 = 3.084 Hz	f_2 = 3.110 Hz
	ζ_2 = 1.754 %	ζ_2 = 1.347 %	ζ_2 = 1.449 %
Mode 3	f_3 = 3.550 Hz	f_3 = 3.557 Hz	f_3 = 3.577 Hz
	ζ_3 = 1.452 %	ζ_3 = 1.522 %	ζ_3 = 1.547 %

It is possible to observe a small variation in terms of natural frequencies identified during the three different tests with both methods. For the natural frequency evaluated with the EFDD method it can be seen a maximum variation equal to 1.5%, for the second identified mode. For the natural frequency evaluated with the SSI method, it can be seen a maximum variation equal to 1.47%, for the second identified mode. Only minor differences in the values of the natural frequencies between both methods are seen.

The SSI method, in general, gives more accurate results while evaluating the damping ratio also for highly complex data, and when there are closely spaced modes as in our case (see Figure 10).
The damping ratio variations between the performed tests are more significative. In particular, it is possible to observe a minimum variation equal to 16.6%, and a maximum variation of 51% for the evaluated damping ratios extracted using the EFDD method. For the SSI method, it can be seen a minimum variation equal to 6.1%, and a maximum variation of 43% for the evaluated damping ratios.
The identified mode shapes, using both OMA methods, for Test #3, performed on January 10th, 2023, are shown in Figure 11.

The first mode shape, shown in Figure 10.a and 10.b, is a translational mode along the transversal direction (y-direction). The second identified mode, shown in Figure 10.c and 10.d, is a torsional mode. The third mode, shown in Figure 10.e and 10.f, is a translational mode along the longitudinal direction (x-direction). Same results in terms of mode shape are visible also for the other performed tests.

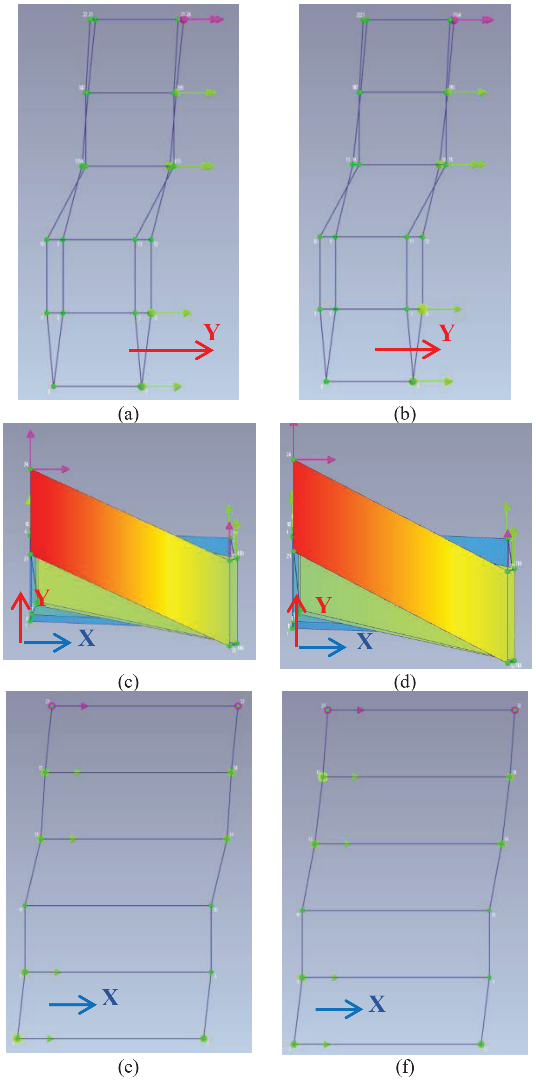

Figure 11: *Identified mode shapes for the Test #3: (a) Mode #1 - EFDD method; (b) Mode #1 - SSI method; (c) Mode #2 - EFDD method; (d) Mode #2 - SSI method; (e) Mode #3 -EFDD method; and (f) Mode #3 - SSI method.*

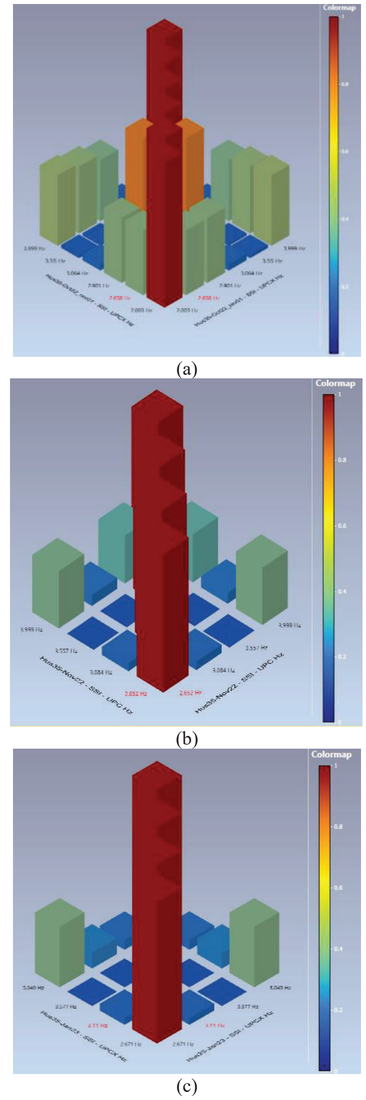

Figure 12: *AutoMAC values for the identified modal parameters with the SSI method: (a) Test #1; (b) Test #2; and (c) Test #3*

The autoMAC values for the three performed tests on Hus 35 are shown in Figure 12. Each bar represents the autoMAC value for a specific mode extracted with the SSI method, the values between 0 and 1.0 are proportional to the degree of correlation. The autoMAC value is equal to 1.0 if the mode shape pairs are exactly a match and equal to 0 if those pairs are completely independent or unrelated. Based on the values of the autoMAC, it can be seen that some of the modes are correlated. For this reason, the closed spaced modes with a low value of complexity were considered to be structural modes (see Table 1).

4 STRUCTURAL MODELLING

In this study, the FE model of the building was developed using SAP2000 [14]. The FE model was developed to validate the results obtained from the in-situ test in terms of modal parameters as well as to understand the role of non-structural elements in the changes of fundamental frequencies for lightweight timber frame structures.

Every component of each lightweight wall was included in the FE model. In particular, beam elements were used for the timber frame members (studs), shell elements were used for the sheeting boards (OBS panel for the external walls and particle boars panel for the internal walls) and two joint link connections were used for the panel's connections. The detail model for one of the wall panels is shown in Figure 13.

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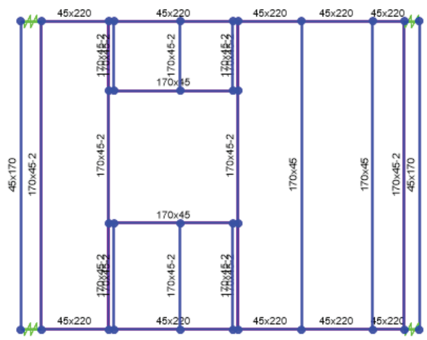


Figure 13: *Lightweight timber frame wall modeled components.*

Table 2 shows the material properties used for the FE model for each different element.

Table 2: *Modeling properties of the elements.*

Element	Characteristics	Properties
Studs (C24 timber)	45 x 170 mm 45 x 220 mm 45 x 95 mm	E = 10200 MPa G = 690 MPa
Sheeting boards	11 mm OSB	E = 6000 MPa G = 1574 MPa
Sheeting boards	38 mm particle board panel	E = 4480 MPa G = 1670 MPa

In order to reduce the computational effort, the floor and roof structural elements, such as joists and floorboards, are not modelled, but only their mass and gravitational loads are included. The FE model developed in SAP2000 is shown in Figure 14.

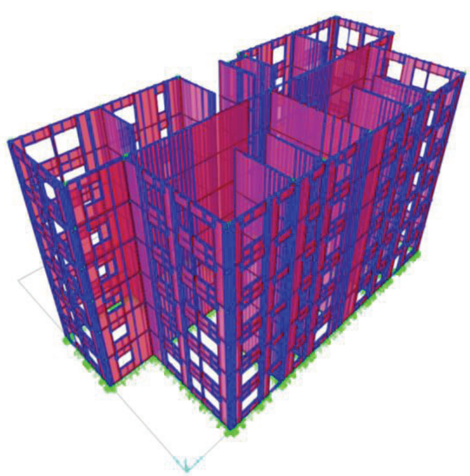
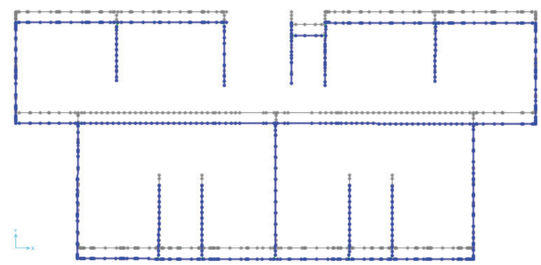


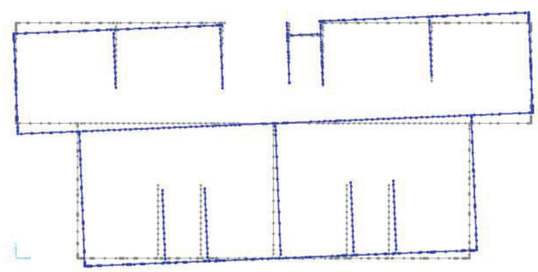
Figure 14: *View of the FE model of the building developed in SAP2000.*

In a first stage, the FE model was developed considering only the gravitational loads from the load bearing system and the slabs (Stage 1). After the ambient vibration tests were performed, in order to calibrate the modal parameters, the load of the non-structural wall components and the façade were added (Stage 2). The façade is a freestanding but horizontally connected to the structure.

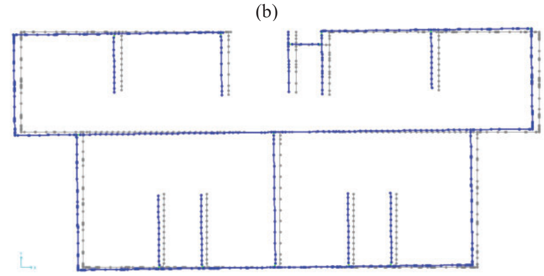
The first three modes of the building obtained from the calibrated FE model are shown in Figure 15.



(a)



(b)



(c)

Figure 15: *Mode shapes obtained with the FE model of the building: (a) 1st Mode: f_1=2.80 Hz; (b) 2nd Mode: f_2=3.38 Hz; and (c) 3rd Mode: f_3=4.732 Hz.*

The frequencies identified in Stage 1 were lower than the ones obtained from the ambient vibration tests. The changes in the computed natural frequencies between Stage 1 and 2 are equal to 16% for the translational mode along y-direction, 13.5% for the rotational mode, and 15% for the translational mode along the x-direction.

Figure 16 shows that the frequencies identified in the first stage where higher than the frequencies identified with the updated FE model (Stage 2). These last ones are consistent with the frequencies identified with the OMA for the three performed tests.

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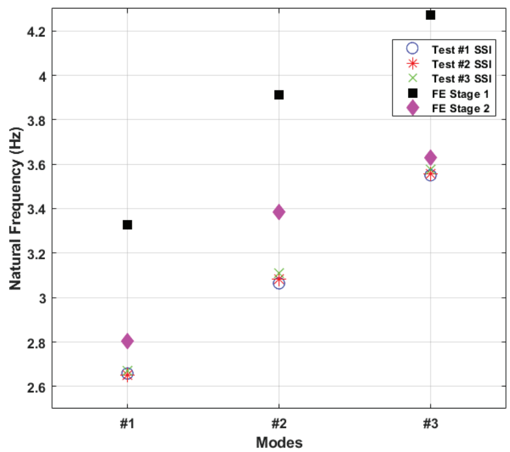

Figure 16: *Comparison between the natural frequencies obtained with the SSI method and the FE model at different stages.*

The higher values of natural frequencies in Stage 1 are compatible with what has been identified in previous studies on a similar building [18]. In particular, for low amplitude wind induced vibrations, ignoring the contributions of non-structural components will lead to an overestimation of the natural frequencies of the building.

5 CONCLUSIONS

The dynamic properties of building Hus 35, part of the Pilgatan block, were identified using frequency and time domain only-output OMA methods. Multiple ambient vibration tests were performed between October 2022 and January 2023. The aim of the testing campaign was to estimate the fundamental natural frequencies, damping ratios and mode shapes of the building and compare them with the one obtained from the FE model.

Three structural modes were identified using the two OMA methods: two translational and one rotational mode. The FE model of the building was developed using elastic beam elements for the studs, elastic isotropic shell elements for the sheeting boards of the external walls and internal walls, and joint link connections for the wall panels connections.

The FE model was calibrated in order to match the results from the in-situ tests in terms of natural frequencies. In particular, the weight on the non-structural elements was added during Stage 2. The mass of the building is a critical parameter while performing the modal analysis of a building. The weight of the exterior wall panels of the façade is an important aspect in calibrating the modal frequencies of the lightweight timber-frame analyzed building.

Further work is necessary in order to develop a more detailed model. In the next stage, the calibrated model should take into account the mechanical behavior of the connections. This will include the sheathing-to-framing connection and the friction and contact interaction between the slabs and the lightweight frame panels. Due to the high computational demand, the implementation and calibration of the mechanical behavior of the connections will be a challenging step.

For low vibrations amplitudes, compatible with the vibrations at the serviceability limit states, the non-structural elements, such as the façade, contribute to the global stiffness of the buildings. For this reason, neglecting the non-structural components in the FE model will overestimate the natural frequencies of the investigated building.

This study is part of a project plan to perform monthly measurements in two identically realized buildings like the one shown in this study. The aim of the project is to relate the possible changes in dynamic properties to the changes in the environmental conditions. Such variations will be implemented also in the FE model of the building to study how such changes can influence the lateral stiffness of the building and its global responce.

Acknowledgements

The authors acknowledge Stiftelsen Nils och Dorthi Troëdssons forskningsfond (project number 1057/22) for the financial support for this project. The authors would like to thank the building owner, Derome, for their interest, easy courteous collaboration, and permission to access the property.

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