Monitoring and modelling of the vibratory behaviour of an 8-storey timber building

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Context and objectives

The implementation of long-term monitoring techniques remains relatively limited, and more research is needed to improve long-term serviceability related to vibration-induced criteria, such as the DynaTTB project (Abrahamsen et al 2020) which launched an international project on wind-induced vibrations in tall timber buildings related to comfort criteria for inhabitants. Our understanding of the dynamic response and structural condition of actual high-rise timber buildings currently faces several scientific issues related to:

- the paucity of experimental data for such buildings and in different structural conditions;
- the specific response of the building for nominally equivalent buildings with almost the same designs;
- the operational and environmental long-term effects on building condition.

In the literature, most modal analysis testing concerns mid-rise timber structures, based on single measurements and only a few examples of continuous monitoring, and with partial information (e.g., Feldmann et al 2016, Mugabo et al 2019). For example, Tulebekova et al (2023) showed the 18-month variation of modal parameters (resonance frequencies) caused by environmental conditions in an 18-storey glulam frame building, located in Brumunddal (Norway), without considering wind speed.

Vibration amplitude, resonant frequency and damping are the key dynamic parameters for a design consistent with serviceability limit state (in this study vibrational comfort). In view of the growing number of high-rise timber buildings, Operational Modal Analysis (OMA) techniques are required to analyse the structural response of real buildings, both during different construction phases and their long-term usage.

The aim of this paper is to investigate the dynamic response of the Haut-Bois Grenoble (France) building, an 8-storey Cross Laminated Timber (CLT) shear panel building. The originality of this study is that it monitors over a three-year period the vibrational behaviour of the building and its environmental conditions.

In the following section, this paper describes the building itself, the datasets used for this study, the data processing methods, and some results of the continuous monitoring.

Material and methods

Description of the Haut-Bois

The “Haut-Bois” is a set of two residential timber buildings of 56 apartments, 5 and 8 storeys high (18 m and 28 m respectively) and covered with zinc cladding (Fig. 1). This study focuses on the 8-storey building only. There is no concrete core in the buildings. The height and plan dimensions (HxLxW) are 28x16x21m. Each storey has multiple balconies, from 5 to 9m^2. Access to the building is via an exterior concrete stairwell (Fig. 1a), separated by 14cm wide seismic joints between the timber structures and the concrete stairwell. Each storey is made of CLT for the shear walls. Floors are made by a combination of CLT panels, glulam beams and some I-section steel beams for the large spans (Fig. 1b).

Measurements and dataset

Measurements are based on the OMA technique under Ambient Vibrations (AV). Punctual measurements have been performed several times during the construction phase and the early stages of the occupancy of the building. Permanent monitoring has started towards the end of the construction phase. Construction started in 2020, and the first AV measurement was recorded during construction on March 11, 2021. Continuous monitoring started on January 1, 2022, and the residents move in at the end of March 2022. Fig 1c displays the sensors positions of the different dataset, while Fig. 2 presents the chronology of the different measurements.

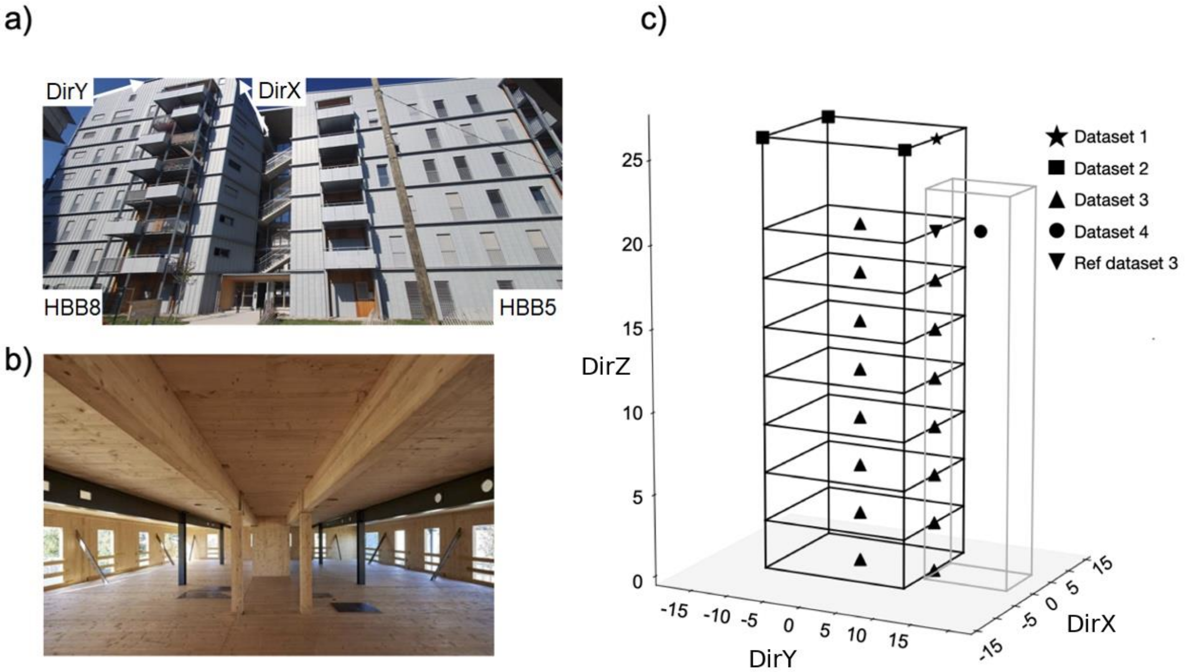

Fig. 1: View of the 8 storey building. a) General view with direction considered for modal analysis. b) Interior view of main structure of a regular storey. c) Experimental setup deployed in the building during the three phases: construction phase (dataset 1), monitoring (dataset 2) and modal analysis (dataset 3). Measurements from the stairwell (dataset 4) are also displayed.

Dataset 1 (construction phase) corresponds to three single AV recordings made during three different construction phases. Ambient vibrations were recorded at one point on the top floor with a Cityshark II 24bits datalogger (Chatelain et al 2012) and one 3-component 3DLite Lennartz velocimeter (cutoff frequency 1Hz). One measurement of 10 minutes at a frequency rate of 200 Hz was recorded on March 11, May 25 and June 3, 2021. On March 11, 2021, most of the vertical and horizontal structural elements and the external framework were complete.

Zinc cladding was being installed at the time. On May 25, 2021, the structural work and exterior framing were complete. On June 3, 2021, plasterboard was being installed as internal finishing.

Dataset 2 (monitoring phase) corresponds to the semi-permanent network installed for SHM. It is part of the National Building Array Program (NBAP) in France, launched in 2004 by the French Accelerometric Network. The dataset in this study used three stations (HB01, HB02, HB03) located in three corners of the building in the attic (Fig. 1c). 24-bit Nanometrics dataloggers, coupled with high-sensitivity 3-component Lennartz 3D-5s velocimeters. The configuration was defined to measure bending, torsion and soil-structure interaction thanks to a fourth station (HB04), installed four months after at the bottom of the building, and not used for this study. An example of one hour of data recordings in the building is given Fig. 3a with the corresponding averaged Fourier spectra in Fig. 3b. The horizontal channels are oriented North-South and East-West (EHE, EHN, EHZ), which correspond to the main direction of the building (i.e., DirX and DirY, and DirZ, respectively). All data are open and available (Guéguen and Vieux-Champagne 2023).

Dataset 3 (OMA phase) corresponds to the full-scale operational modal analysis carried out on June 13, 2022, once all the residents had moved in. Five datasets were recorded for 10 minutes at a frequency rate of 200Hz. One reference sensor was left on the top floor, but the other sensors were mobile, roaming the hallway of each storey. The reference sensor is needed to normalize the recordings before applying Frequency Domain Decomposition for OMA. Finally, two recordings per floor were obtained in the building (Fig. 1c).

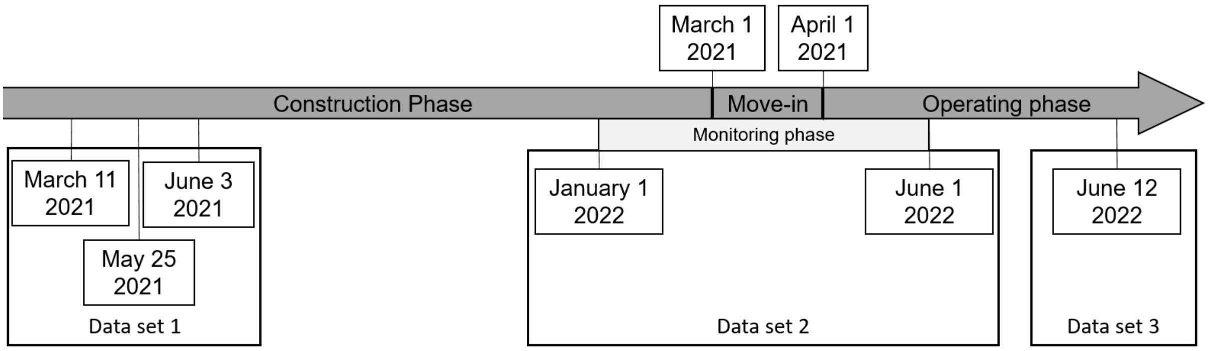

Fig. 2: Timeline description of the different HBB8 data sets during the different phases of the CLT building

Data processing method

For dataset 1, the resonance frequency analysis was performed using a Fast-Fourier Transform computed on overlapping Hanning windows (1 minute in length) and averaged over the 10 min recordings. The resonance frequencies were then picked from the averaged spectrum considering a parametric approach assuming that the highest amplitude peak corresponds to the fundamental resonance frequency in both translation directions (DirX and DirY) and the third peak corresponds to the torsion mode (rotation around the vertical axis DirZ). These three peaks, interpreted as translation and torsion, were validated a posteriori by the OMA phase (dataset 3). An example of such processing is presented Fig 3b.

Two more advanced OMA methods were applied to datasets 2 and 3. The choice of RDT (Ibrahim, 1977) for dataset 2 and FDD (Brincker et al 2001) for dataset 3 results from the long experience acquired by the authors on operational application of these methods: for OMA (Michel et al 2010) and for the monitoring of resonance frequencies and damping values (Guéguen et al 2016).

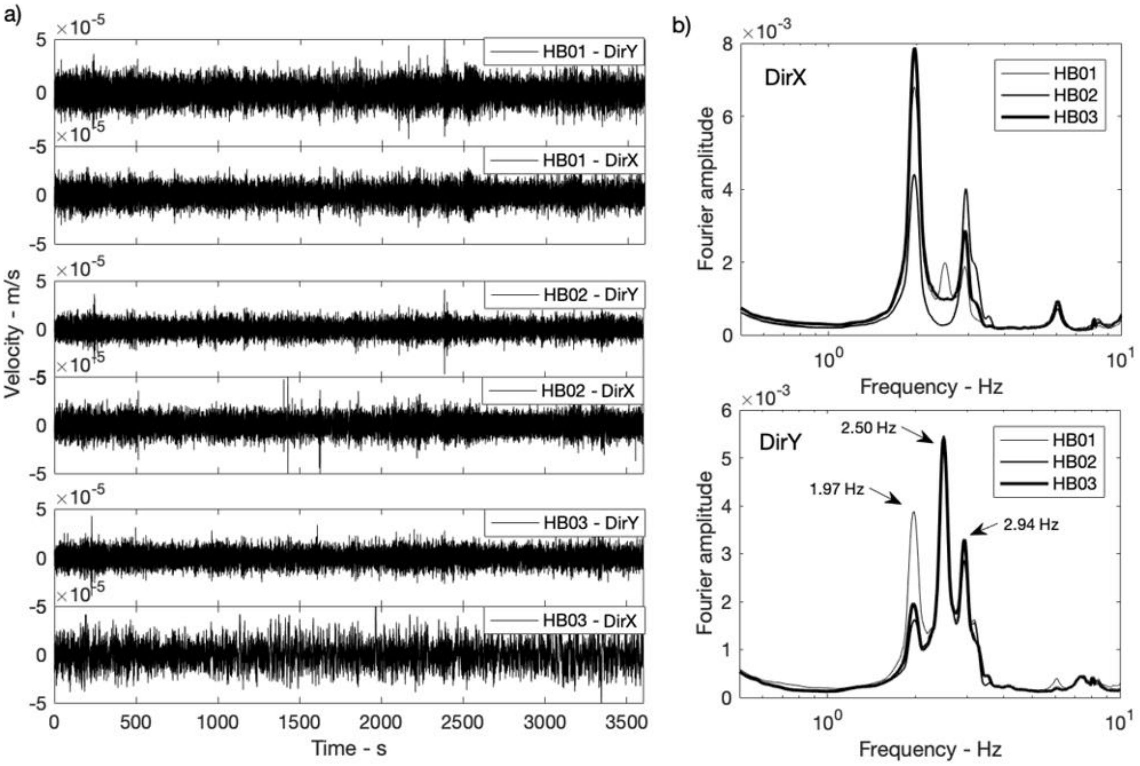

Fig. 3: Examples of dataset 2 (2022/02/01-12:00:00 - 2022/02/01-13:00:00), corresponding to the semi-permanent stations HB01, HB02 and HB03 in both horizontal direction (DirX and Dir Y), in time (a) and frequency (b) domain. The Fourier spectra are averaged Fourier spectra 1 minute long. The peak values indicated correspond to the first resonance modes in DirX (1.97Hz), DirY (2.50Hz) and DirZ (2.94Hz).

Results and discussion

Code provisions versus measured modal parameters

The empirical value of fundamental frequency (Fr) is given as a function of building height, i.e., Fr=46/H according to EC1 Part 1-4 (Eurocode 1 2007) specifically for cantilever structures over 28m and $Fr=20\cdot H^{-0.75}$ according to EC8 (Eurocode 8 2013), which corresponds to 1.64Hz in both cases (H=28m). This value can be compared to 1.85Hz, which is measured on April 1st, 2022, when all residents are installed.

For damping, more variability is expected due to the timber building population considered (Eurocode 5 2014), EC1 suggests an empirical damping value of about 1% for sizing under wind loads, and EC8 suggests 5% for seismic loads. This value can be compared to 1.95%, which is measured in February 2022.

Evolution of modal parameters (construction phase and early operating phase)

Using datasets 1 and 2, the modal parameter variations are assessed during the construction phase, the residents' moving-in phase, and the early operating phase of the building. These variations result from modifications to the structure during the construction phase, occupancy and weather conditions. During the monitoring phase, only the modal parameters (frequency and damping) from one station (HB02) are considered because of their similitude (Fig. 3b).

Fig. 4 shows the variations of the resonance frequencies during the construction and operating phases (dataset 1 and 2). The first value on March 11, 2021, corresponds to the installation of the battens in the roof structures. Two months later (i.e., the May 25, 2021 - 75 days), a drop to

2.18 Hz (-15%), 2.83 Hz (-12%) and 3.44 Hz (-21%) is observed in X, Y and Z direction, respectively, due to the end of the structural elements and exterior carpentry.

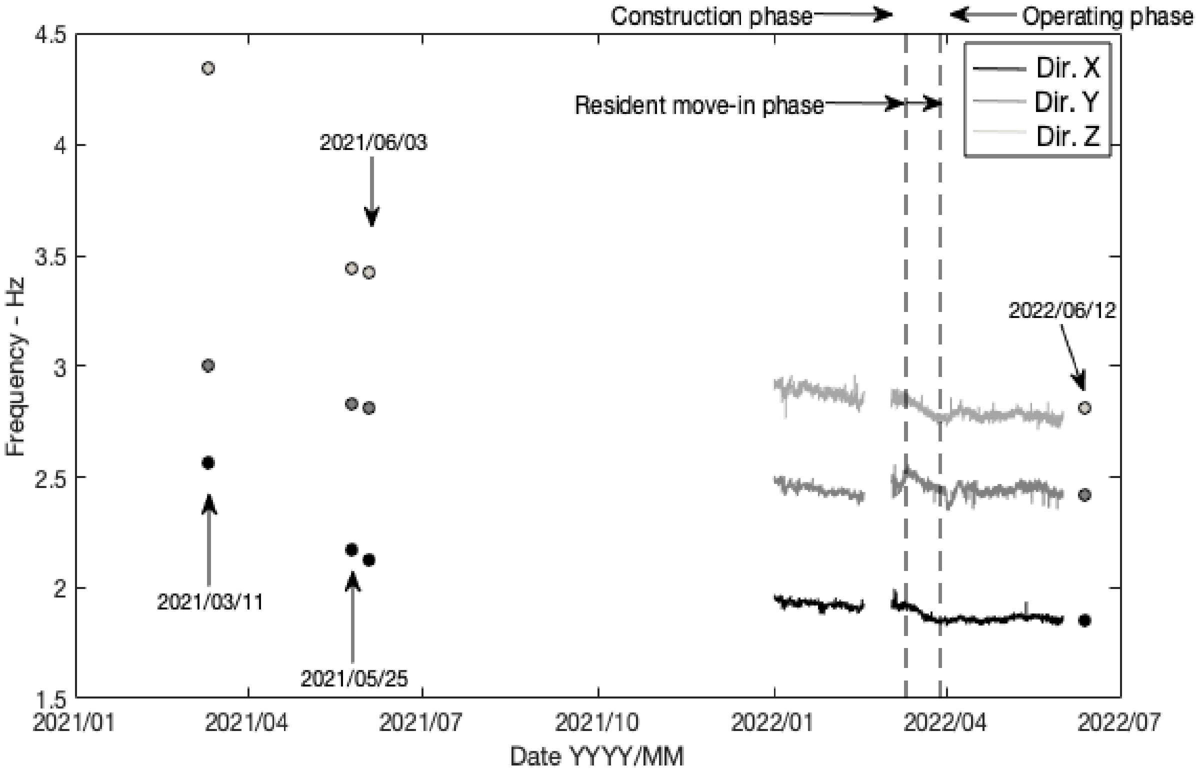

Fig. 4: Variations of the resonance frequency in DirX, DirY and DirZ with the different phases of the OMA and the SHM.

If we assume that the drop of frequency during the resident move-in phase is only due to mass addition, it corresponds to a total mass of 87 tons. If uniformely distruibuted along all the floors, it corresponds to a 30daN/m² load, which seem coherent.

Conclusion

Further analysis will combine evolution of modal and environnemental parameters. Search for correlations will try to identify the environnemental parameters having the most significant effect on modal paramaters. Measured horizontal accelerations, especially during high wind speed episodes, will be compared to confort threshold for residents' confort.

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