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Vibration analyses of an hybrid concrete and cross-laminated timber building case study

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Abstract. Nowadays, some innovative spatial structural typologies among others rely on timber-concrete hybrid solutions for designing modern buildings. However, the dynamic identification analysis may be more elaborate, and sometimes troublesome, due to the coupling effects of the different dynamic nature of cross-laminated timber and reinforced concrete members. In the current manuscript, the authors explore some preliminary results of the dynamic analysis of a hybrid timber concrete building case study. The operational modal analysis (OMA) based on output-only techniques has been employed, referring specifically to enhanced frequency-domain decomposition (EFDD) and the stochastic subspace identification (SSI) methods. The authors compared several ambient vibration OMA results with forced shaker-induced vibration responses highlighting the absence of nonlinearities during in-service operational conditions in two different moments.

Keywords: Timber Structure · Finite Element · Model Updating · Hybrid Timber Concrete Structures · Operational Modal Analysis

1 Introduction

The dynamic behaviour of timber buildings under service loads is a recently debated topic in the scientific literature, primarily thanks to the application of vibration-based identification methods. The growing interest in timber structures is confirmed by multiple initiatives and financed research projects involving the dynamic investigation of timber structures. Cross-laminated timber (CLT) structures are widespread among timber structures, especially tall buildings, due to their satisfactory structural performance and reduced environmental footprint. In detail, various building typologies have been introduced, with CLT as the central part of the load-bearing structure. A leading typology is represented by the timber-concrete hybrid buildings, where concrete elements are used in addition to the timber ones, e.g., for shear walls and elevator shafts. There is a lot of uncertainty in the as-built dynamic response of these buildings. Therefore, experimental vibration tests on timber buildings are precious since they provide insight into the as-built stiffness of different structural components, like shear walls and floors. As remarked by [21], in tall CLT buildings, the stiffness is not merely related to the properties of the CLT panels, but it is also affected by the connection system. Moreover, since timber structures are often lightweight and highly flexible, they may be more prone and susceptible to excessive vibrations [10].

Therefore, compared to other structural materials, many aspects of the dynamic response of timber buildings under service loads are still unknown. In particular, there are two important aspects which still deserve experimental investigations: the long-term dynamic performance of timber structures and the amplitude-dependent behaviour. Concerning the first aspect, as highlighted by Riggio and Dilmaghani [28], most of the recent investigations on the dynamic behaviour in timber structures have been conducted over a short monitoring period [25,2], and few studies hitherto involved long-term monitoring, e.g. Larsson et al. [22]. Regarding amplitude-dependent behaviour, most studies deal with laboratory tests, where structural assemblies or full-scale buildings are evaluated from shake table tests [9]. To the author's knowledge, no research attempts to detect possible amplitude-dependent phenomena in timber buildings from forced vibration tests on actual case structures nor by comparing forced and ambient vibration tests. Forced vibration tests were widespread in past years [5,14], when they were sole for reliably estimatng the modal parameters [33,4]. However, since the pioneering studies of Trifunac in 1972 [30], the comparison of ambient and forced vibration proved that it is possible to determine with adequate accuracy natural frequencies, mode shapes and damping values from both data. Nonetheless, in forced vibration tests, the whipping of the floors might lead to modal interference, a consequence of the concentrated force excitation at a frequency only slightly different from the resonant frequency. This phenomenon may lead to discrepancies between the ambient and forced vibration tests predominantly at the top levels of a structure. Compared to ambient vibration tests, where stationary operational modal analysis can be used, input-output or nonstationary operational modal analyses must be carried out to correctly analyze the outcomes of forced vibration tests' results.

In this paper, the authors compare the stationary and nonstationary operational modal analysis results of an hybrid timber building located in Slovenia based on both ambient and forced vibration tests. The ambient vibration tests led to estimating the modal parameters using the classical stochastic subspace identification and enhanced frequency domain decomposition. The forced vibration tests were used to estimate the intrinsic modes using the Hilbert-Huang Transform (HHT). Several methods have been proposed for estimating the time-varying natural frequencies of engineering structures based on measurements under ambient and forced vibrations [23,35,11]. Among these methods, the Hilbert transform (HT) technique, Teager energy operation (TEO) method, and their variants have been widely used, despite several drawbacks such as negative frequencies, ending effects, and fluctuations [6,34,36]. Besides, these two approaches are noise-sensitive, which will further cause distorted natural frequency estimation [34]. Recently, time-frequency representation (TFR) techniques have drawn increasing attention in field measurements of civil structures due to their advantage in concentrating signal energy along the instantaneous frequency curve while spreading the noise in the time-frequency plane [20,19,13]. Several time-frequency representation methods, including the short-time Fourier transform (STFT) [31,24], the wavelet transform (WT) [15], and the Wigner Ville distribution (WVD) [26], have been applied to analyze measured signals to obtain the instantaneous description of dynamic properties of civil structures. Still, the HHT [18] remains the most used algorithm among recent attempts. It is considered the most appropriate tool to deal with nonlinear and nonstationary signals since the uncertainty principle does not limit it, and its basis is adaptive [29].

This document has the following structure. Section 2 describes the case study under investigation, whereas section 3 presents two subsections dedicated to ambient vibration tests and forced vibration tests respectively.

2 Case study description

The current case study building is an hybrid structure presented in Fig.1 (a) with plan dimensions of 30m×20m approximately, made of CLT, steel and concrete elements located in Slovenia. The main structural elements of the building's second, third and fourth floors are CLT shear walls, while the walls on the first floor are made of concrete. A concrete slab is placed between the first and second floor, while the rest of the floors consists of CLT panels. In the core of the building, there is a steel frame to support the floors. A concrete shaft is placed in one of the corners of the building. Additionally, some timber frame elements around the perimeter of the building support the CLT floor elements between the column-like structure of the outer walls.

The dynamic identification of the building is based on ambient and forced vibration tests, whose experimental accelerometers layout is depicted in Fig.1 (b). The authors monitored only the third floor and the roof level to explore the dynamic behavior of the freely vibrating part of the structure, i.e. above the second floor, and disregarding the stiffening adjacent buildings effects. The experimental campaigns were executed in two different moments for the sake of comparisons, i.e. March 2021 and August 2021. The forced vibration tests were carried out using a shaker sweeping between frequencies from 2 to 22 Hz, at a rate of 5 Hz/h. Fig.2 shows the experimental setup with the shaker and acquisition system.

(a) (b)

Fig. 1. View of the hybrid timber building (a) and sensor placement (b).

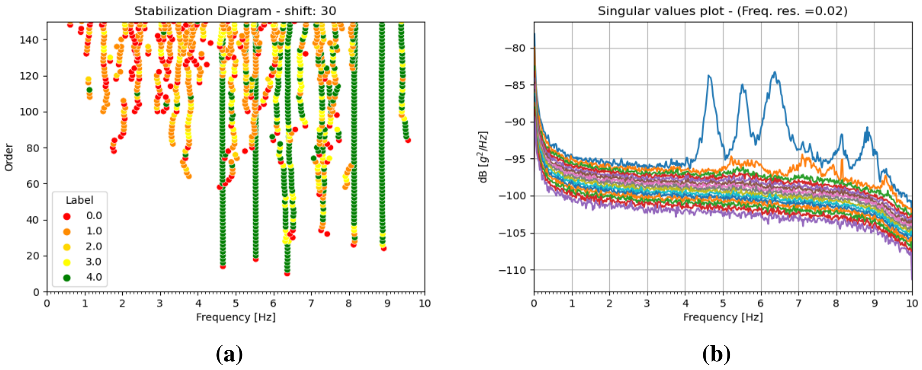
(a) (b)

Fig. 2. Forced vibration test's acquisition system (a) and the adotped shaker (b).

3 Dynamic Identification

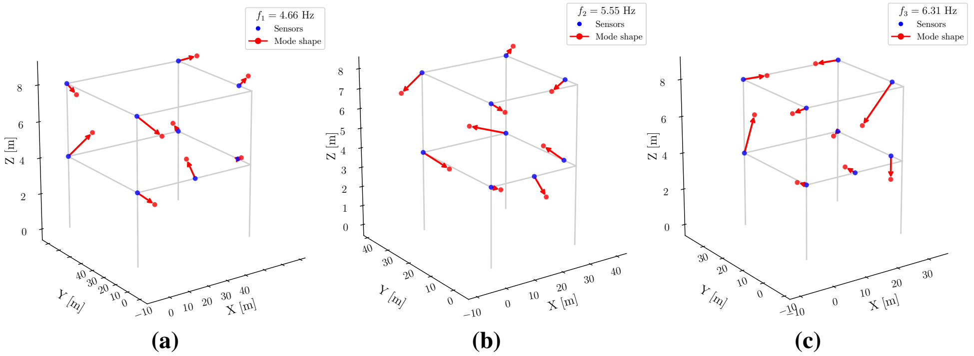
3.1 Ambient vibration tests

The building was tested through two different moment in 2021 for the sake of comparison. The modal parameters are estimated with the covariance-based stochastic subspace identification (SSI-cov) [27] and the enhanced frequency domain decomposition (EFDD) [8]. Fig.3 reports the obtained stabilization diagram from SSI-cov (a) and the singular value decomposition (SVD) of the power spectral density (PSD) from EFDD. The best stabilization diagram, obtained by varying the time shift and the maximum model order, only shows three stable modes in the frequency range 0-25Hz. The three modes at approximately 4.81, 6.27, and 7.08Hz have been plotted in Fig.4. The spatial discretization of the mode shapes does not allow a clear interpretation and distinction between translation and rotational modes. Each mode does not exhibit a prevailing direction of deformation. The mean of the root means square of the signals is approximate. 3.13×10^{-4}g, while the peak acceleration is 0.001g.



(a) **(b)**

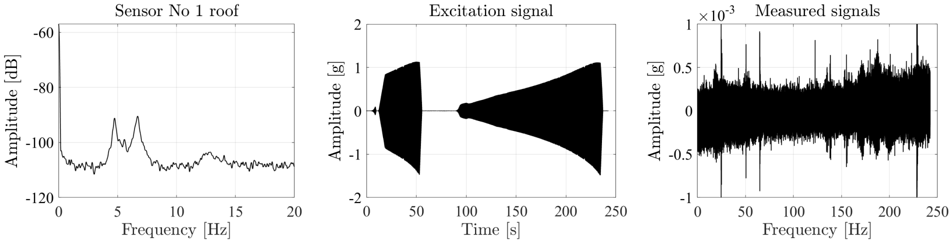
Fig. 3. Ambient vibration. SSI-cov stabilization diagram (a) and SVD of PSD for EFDD (b).



(a) **(b)** **(c)**

Fig. 4. Mode shapes for ambient vibrations, evidencing high vertical components.

These values are essential to understand the variation of the excitation level between ambient and forced vibration tests. Interestingly, there is a high modal component in the vertical direction compared to the translational ones. Although this fact is quite unusual, it may appear as measurement error. Nonetheless, this outcome is conformed to a finite element model that the authors implemented for the sake of comparison, thus evidencing the existance of important modal components along the z axis.



(a) **(b)** **(c)**

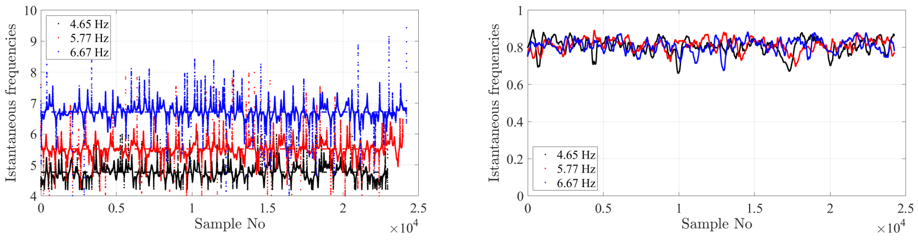
Fig. 5. (a) Power spectrum of a reference sensor, (b) excitation signal and (c) superposition of the post-processed measured signals.

3.2 Forced-vibration tests

The data were processed using the HHT to deal with non-stationary signals. The HHT was proposed by Norden E. Huang and initially published as a patent [16], and paper [18]. It consists of two steps, first the signal is decomposed by empirical mode decomposition (EMD), designed to decompose non-linear and non-stationary signals into a set of spectrally in-dependent oscillatory components, the intrinsic mode shapes (IMFs). Then, the IMFs are processed through the Hilbert Spectral Analysis (HSA) [32,12], resulting in the Hilbert spectrum, which preserves local properties in the time domain and provides information in the amplitude and frequency domain, favouring the identification of hidden local characteristics in the original signal [17]. The Hilbert spectrum is three-dimensional (time-frequency-energy) and can be represented in graphs, similar to the wavelet spectrum. The EMD operates in sequences of local extremes, being performed by direct extraction of local energy associated with the intrinsic time scales of the signal itself, thus, the method is similar to the traditional decompositions of Fourier or Wavelet [1] and can be interpreted as a type of wavelet decomposition with sub-bands produced as needed during the extraction process of the IMFs, which represents the details of the signals on a given scale or frequency range [7]. Fig.5(a) shows the power spectrum of a reference sensor. The peaks revealed by the spectral analysis of the measured signals correspond to those identified from ambient vibration tests. Fig.5(b) shows the excitation signal used as input in the shaker, while Fig.5(d) displays the superposed measured signals from all channels. The mean of the root mean square error is $1.15\times10^{-}4$g, close to those measured during the ambient vibration tests. The maximum acceleration is 0.011g, approximately ten times the peak observed during the operational response. The modes obtained from the HHT correspond to those estimated from ambient vibration tests, as reported in Tab.1. Fig.6 plots the instantaneous frequencies and MAC between each mode estimate with the averaged mode shapes. The MAC plot proves that the averaged mode shapes cannot be considered physical modes, yielding a value close to 0.8 for

Table 1. Comparison between the ambient and forced vibration tests.

Mode	Ambient (March 2021)	Ambient (August 2021)	Forced vibration (August 2021)
1	4.81 Hz	4.58 Hz	4.65 Hz
2	6.27 Hz	5.80 Hz	5.77 Hz
3	7.08 Hz	6.71 Hz	6.67 Hz



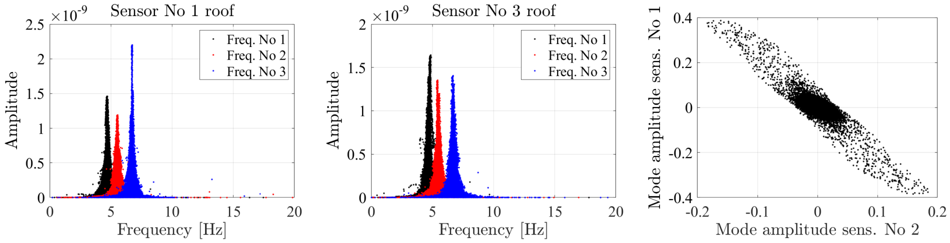
(a) **(b)**

Fig. 6. (a) Instantaneous frequency values for the first three modes (b) MAC between the intrinsic modes and the averaged ones.

all modes. Therefore, the averaged modes cannot be used for model updating. Nonetheless, the MAC variation is minimal, proving that the mode shapes are not very sensitive to the vibration amplitude. Higher sensitivity is shown in the instantaneous frequencies: In particular, the identification leads to higher discrepancies with the averaged ones when the vibration amplitude is lower and the signal is less informative. Nonetheless, the higher excitation level is not enough to activate possible nonlinear phenomena [3], as proven by Fig.7. Fig.7(a)-(b) plots the dependence of the instantaneous frequencies on the response amplitude. The plots exhibit a higher scatter for lower vibration levels. However, increasing vibration levels do not trigger nonlinearities since the estimated values align along a vertical axis. This fact is further proven by cross-plotting the modal components of different sensors. The dots (see Fig.7(c)) align along a line due to an almost linear structural response.

4 Conclusions

Experimental dynamic responses of a hybrid timber-concrete building located in Slovenia have been herein studied. The main objectives, major findings, novelty aspects, and future developments are summarized below:



(a) **(b)** **(c)**

Fig. 7. Amplitude-frequency plots for two sensors and plot of the mode amplitudes between two sample mode components from two modes.

- Comparisons between ambient and forced vibration tests have been conducted evidencing good modal parameters agreement;
- Estimation of the intrinsic modes from forced vibration tests using the Hilbert-Huang Transform (HHT) was employed to detect possible nonlinear phenomena;
- The intrinsic mode shapes (IMFs) obtained with the HHT and the modal components were in good agreement, however, the higher excitation level was not capable of triggering nonlinear phenomena;
- Therefore, in this case, the forced vibration tests are not more informative than the ambient ones.
- Immediate future extensions may involve automatic metaheuristic-based FE model updating and variance-based sensitivity analyses using the results both from forced or ambient vibration tests, comparing the final results to detect possible nonlinearities.

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