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Marija Nefovska-Danilović¹, Vitomir Racić², Marija Milojević², Marko Popović²,
Radovan Cvetković³, Miroslav Marjanović²

MODAL TESTING AND VIBRATION MEASUREMENTS OF A FULL-SCALE CLT FLOOR

Summary: Cross-laminated timber (CLT) floors are increasingly used in long-span buildings as a greener alternative to reinforced concrete, steel and their composites. Despite high stiffness, relatively low mass of CLT makes such floors prone to pedestrian-induced vibrations. While these vibrations do not threaten structural integrity and safety, they often cause vibration serviceability issues. Therefore, vibration serviceability assessment (VSA) regularly governs their structural design. To address a high level of uncertainty pertinent to numerical VSA of CLT floors, in situ vibration measurements of as-built floors are essential. This study presents an experimental investigation of modal properties and pedestrian-induced vibrations of a full-scale CLT floor in an office building in Serbia. The study showed that its vibration behaviour is radically different from what is assumed in leading design guidelines for floor vibrations.

Keywords: cross-laminated timber, pedestrian-induced load, walking, vibration serviceability assessment, human-induced vibration

EKSPERIMENTALNO ODREĐIVANJE DINAMIČKIH KARAKTERISTIKA I ODGOVORA CLT MEĐUSPRATNE KONSTRUKCIJE

Rezime: Međuspratne konstrukcije od unakrsno-lameliranog drveta (CLT) sve se češće primenjuju za savladavanje većih raspona kao ekološki prihvatljivija alternativa armiranom betonu, čeliku i njihovim kompozitnim sistemima. Uprkos velikoj krutosti, zbog relativno male mase, CLT međuspratne konstrukcije osetljive su na vibracije izazvane ljudskim aktivnostima. Iako ove vibracije ne ugrožavaju nosivost konstrukcije, često dovode do prekoračenja graničnog stanja upotrebljivosti, koje najčešće predstavlja merodavan kriterijum za dimenzionisanje. U cilju smanjenja nepouzdanosti numeričke procene vibracija, od posebnog značaja su eksperimentalna merenja na izvedenim objektima. U radu su prikazani rezultati eksperimentalnog određivanja modalnih karakteristika i odgovora CLT međuspratne konstrukcije poslovnog objekta u Srbiji, koji pokazuju značajna odstupanja u odnosu na pretpostavke usvojene u važećim smernicama za projektovanje.

Ključne reči: unakrsno-lamelirano drvo, pešačko opterećenje, hodaње, procena graničnog stanja upotrebljivosti u pogledu vibracija, vibracije usled ljudskih aktivnosti

¹ Faculty of Civil Engineering, University of Belgrade, marija@grf.bg.ac.rs

² Faculty of Civil Engineering, University of Belgrade, Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia

³ Faculty of Civil Engineering and Architecture, University of Niš, Aleksandra Medvedeva 14, 18104 Niš, Serbia

1. INTRODUCTION

Design of long-span and lightweight building floors has increasingly been governed by vibration serviceability criteria, and cross-laminated timber (CLT) floors are no exception [1]. CLT is a lightweight material with a high stiffness-to-mass ratio. This means that stiffness of CLT floors is high enough to span relatively large distances, but due to their low mass they may experience excessive vibrations induced by cyclic human activities such as walking, running or jumping. While these vibrations do not threaten structural integrity and safety, they can cause discomfort for occupants or malfunctions of vibration-sensitive equipment. Therefore, it is very important to assess their vibration performance under human-induced loading at design stage. The assessment of maximum vibration levels of a floor typically requires knowledge about the structural modal properties and walking footfalls, which is commonly regarded as the most relevant load case scenario.

Despite significant advances in numerical modelling techniques, the prediction of vibration response remains affected with considerable uncertainty related to boundary conditions, variability in material properties and presence of non-structural elements [2-5]. Therefore, in situ vibration measurements of as-built floors become a very important aspect in validating and advancing numerical modelling, improving accuracy of vibration serviceability assessment (VSA) and enhancing the reliability of current design frameworks and recommendations.

The experimental testing program presented in this paper was designed to determine in situ the modal properties (natural frequencies, mode shapes and modal damping) and vibration response of a full-scale multi-panel CLT floor under a single pedestrian walking scenario. The tested floor is a part of the annex of the “Kolarević d.o.o.” headquarters building in Pojate, Serbia.

2. EXPERIMENTAL TESTING

The floor consists of 10 CLT panels (S1–S10), as shown in Figure 1a. Each panel consists of five 3 cm-thick layers, resulting in a total thickness of 15 cm. A 5 cm thick cement screed covers the entire floor (Figures 1b and 2). Panels S1–S9 are 130 cm wide, while panel S10 is 109 cm wide, resulting in a total floor length of 1279 cm. The floor width varies between 298 cm and 603 cm. The outer layers of all ten panels are oriented in the direction of the floor’s shorter span.

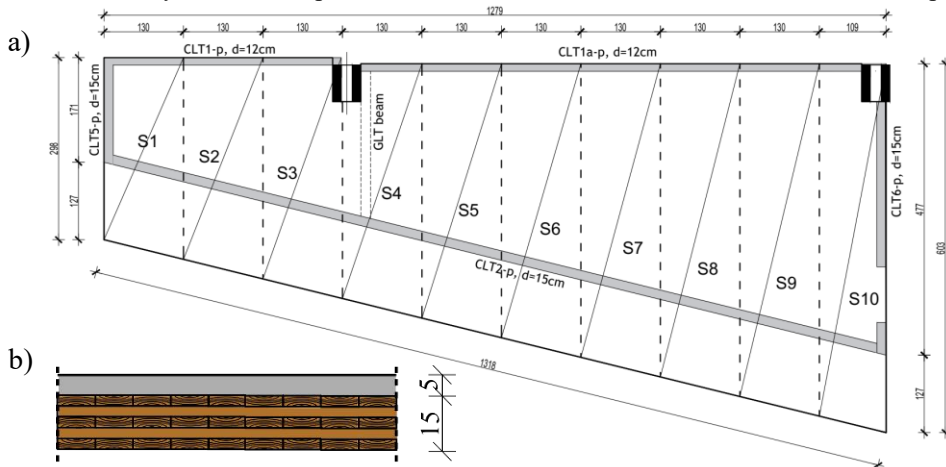


Figure 1: Floor layout (a) with cross-section (b)

The floor is supported by five CLT walls: CLT5-p (15 cm), CLT1-p (12 cm), CLT1a-p (12 cm), CLT2-p (15 cm) and CLT6-p (15 cm), as well as by a GLT beam with cross-section

$b/h=12/36$ cm (Figure 1a). Also, the floor extends outward to form a 127 cm overhang beyond the CLT2-p wall.



Figure 2: Tested full-scale floor

To experimentally determine its modal properties, the floor was excited by gently striking its surface and/or the walls of an adjacent room by three rubber impact hammers, one at a time at different locations (Figure 3a). The resulting vibration response was assumed to originate from ambient vibrations, characterised as a broad-band random noise. The testing grid consisted of 63 measurement points (Figure 4). Acceleration data were recorded using six high-sensitivity SDI 2240-002 accelerometers with a $\pm 2g$ measurement range, connected to a 24-bit HBM QuantumX MX840A data acquisition system operating at a sampling frequency of 600 Hz. The data were measured in swipes, with four accelerometers roving across the grid while two remained stationary at measurement points 8 and 48 as the reference. The recorded acceleration signals were processed in commercial software ARTeMIS [6] to determine the natural frequencies, mode shapes and damping ratios of the floor for the first six modes of vibration.



Figure 3: a) Experimental testing of modal properties and b) an example of a walking test

Walking tests (Figure 3b) proceeded immediately after the modal tests, using the same experimental setup. Four test subjects (TS) were asked to walk along three straight walking

paths (WP1-WP3) shown in Figure 4. Their walking frequency was imposed by constant and evenly spaced metronome beats set at either 1.8 Hz or 2 Hz in a single crossing. The resulting accelerations of the floor were measured simultaneously at six points: 8, 21, 30, 36, 46 and 49.

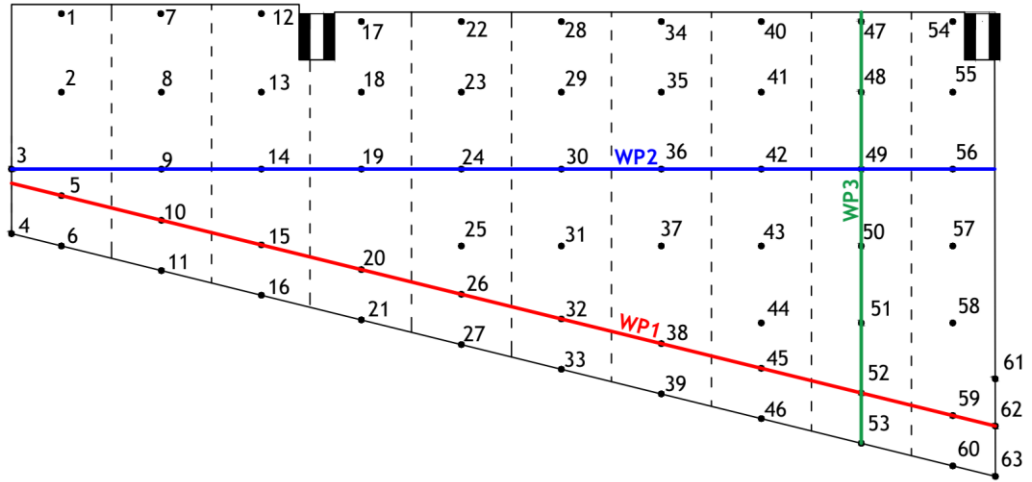


Figure 4: Measurement grid (dots) and three walking paths (lines)

3. RESULTS

Modal properties of the floor are presented in Table 1 and Figure 5. The fundamental natural frequency is below 10 Hz, which classifies the floor as a low-frequency floor (LFF) according to the state-of-the-art design guideline CCIP-016 [7]. Such a floor is supposed to exhibit a steady-state vibration response due to a single pedestrian walking, including the resonance due to the first four harmonics of the walking force. However, the recorded acceleration responses showed that the floor actually behaves as a high-frequency floor (HFF), characterised by transient vibration response due to each footfall. The measured acceleration time histories and the corresponding Fourier amplitude spectra shown in Figure 6 due to TS walking at 1.8 Hz undoubtedly prove the point. There is apparently dominant high-frequency content above 10 Hz, mainly in the range of 15–25 Hz.

The experimentally identified modal damping ratios are significantly higher than the values recommended in the literature [8]. However, given the presence of non-structural elements, partitions and finishes, the measured damping levels can be regarded realistic for the tested floor.

Table 1: Experimentally identified modal properties of the full-scale CLT floor

Mode	Natural frequency (Hz)	Modal damping (%)
1	7.42	7.3
2	9.98	7.8
3	15.10	3.9
4	16.32	3.4
5	19.04	-
6	20.22	-

The highest acceleration response levels were measured when the test subjects walked along WP1 and WP2. Although so called “R factors” (the ratio between the averaged measured RMS acceleration and acceleration threshold to human perception to vibrations [7]) exceeded the permitted limits for office buildings ($R_{\max} = 8$) [9], feedback from the test subjects was that the vibration levels were barely perceptible.

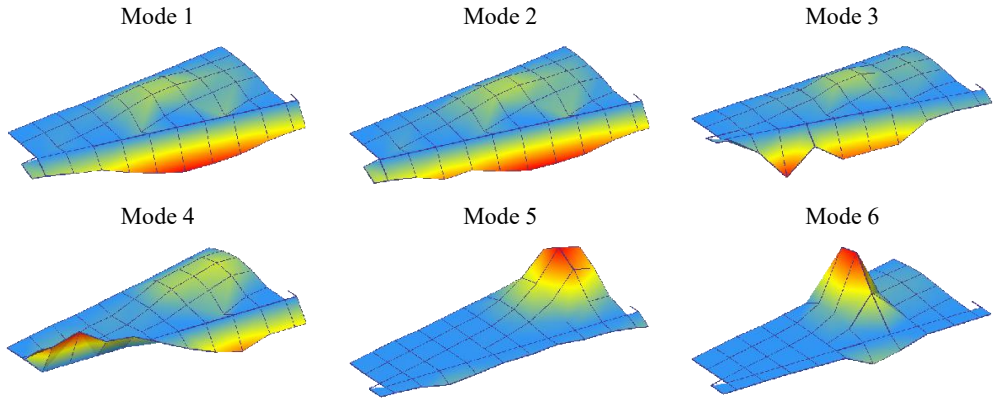


Figure 5: Experimentally identified mode shapes

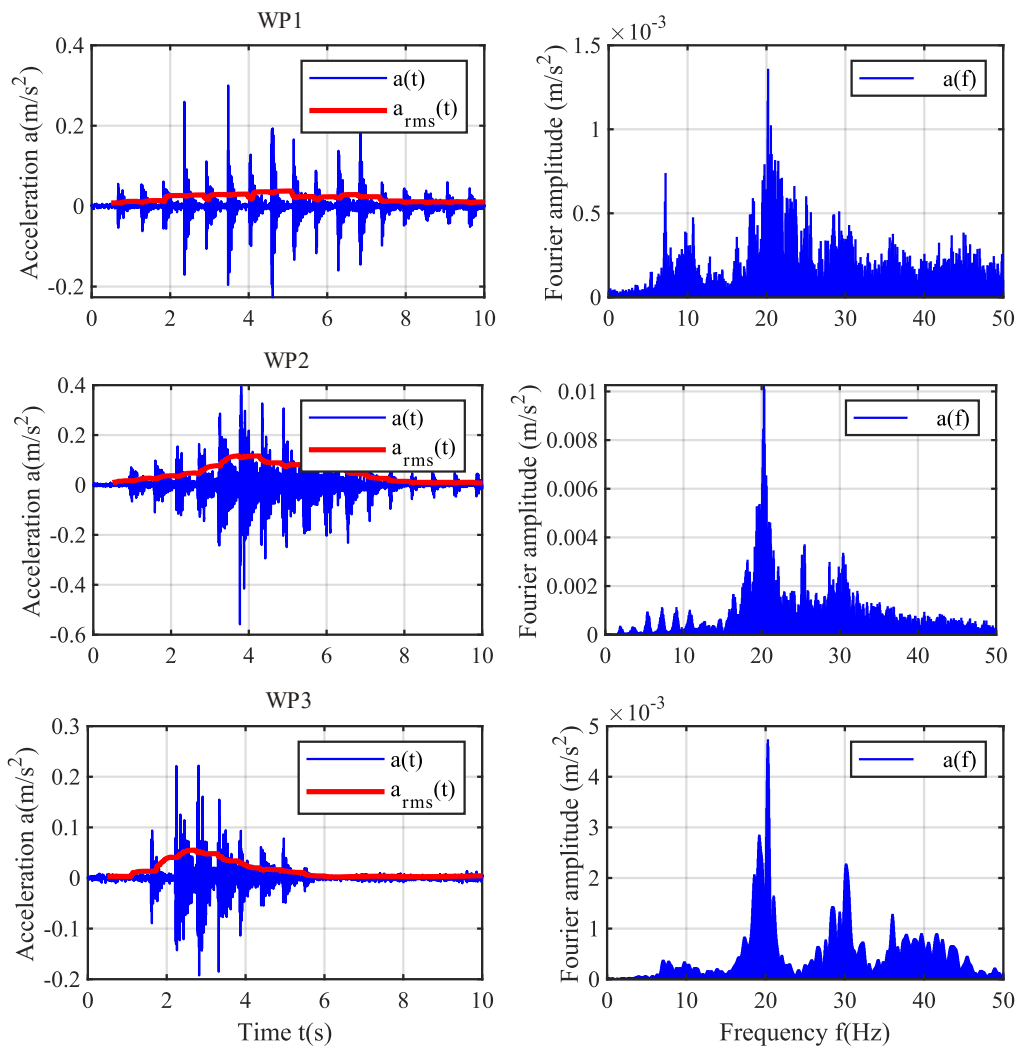


Figure 6: Acceleration time histories (left) and the Fourier amplitude spectra (right) measured at point 30 due to TS walking at 1.8 Hz

4. CONCLUSIONS

The paper presents experimental identification of the modal properties and pedestrian-induced vibration response of a full-scale CLT floor in an office building. Based on its fundamental natural frequency, the floor would be classified as a LFF characterised by steady-state vibration response. However, the measured acceleration responses and their Fourier amplitude spectra showed a fundamentally different transient response typical for HFFs.

The results indicate that classifying a floor solely on the basis of its fundamental natural frequency may yield alarmingly misleading conclusions about the nature of its vibration response when occupied and excited by people walking. Moreover, significant uncertainty still comes from the lack of understanding of how CLT floors actually behave when occupied and dynamically excited by pedestrians. To address this problem, dozens of similar experimental campaigns are needed for developing systematic knowledge about both the dynamic properties of as-built CLT floors and their vibration response under walking loading.

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