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In-Service Performance Assessment of a Traditional Timber House Under Real Environmental Conditions Using Ambient Vibration Measurements

Ponašanje tradicijske drvene kuće u stvarnim uvjetima eksploatacije procijenjeno mjerenjem ambijentalnih vibracija

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ABSTRACT • Timber structures have gained increased attention in recent years due to sustainability-driven construction and the growing demand for reliable performance assessment of wood-based building systems under in-service conditions. Multi-storey bungalow-type timber structures require reliable performance assessment under real environmental conditions. However, such timber structures are continuously exposed to environmental actions that directly influence their stiffness-related dynamic performance. Therefore, the accurate determination of dynamic properties is essential, as these parameters serve as key indicators of the stiffness-related in-service performance and serviceability of timber structures. This study presents an in-service performance assessment of a two-storey traditional timber bungalow house and representative timber elements using a specially developed vibration measurement system, namely the Civil Engineering Vibration System (CEVS) and Civil Engineering Vibration Analysis (CEVA) software. Ambient vibration measurements were conducted under real environmental conditions and three different tension-based stiffening states (tensionless, normally tensioned, and fully tensioned). These states were defined as released, service-level, and fully tightened conditions of the tension-based stiffening elements. Experimental natural frequencies were determined as quantitative indicators of stiffness variation and mechanical performance under different tension-based stiffening levels. The identified natural frequencies ranged from 5.005 Hz to 18.066 Hz, and they consistently increased in the order of tensionless, normally tensioned, and fully tensioned states. The use of ambient vibration measurements enables a realistic evaluation of the in-service mechanical performance of the timber structure under actual environmental conditions. The results contribute to a better understanding of the in-service mechanical performance of timber structures and provide practical guidance for performance evaluation, stiffness assessment and potential strengthening decisions, and sustainable timber construction practices.

KEYWORDS: timber structures; in-service performance assessment; stiffness-related dynamic indicators; ambient vibration measurements; tension-based stiffening systems; traditional timber buildings

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SAŽETAK • Drvene su konstrukcije posljednjih godina privukle veliku pozornost zbog usmjerenosti gradnje prema održivosti te zbog sve veće potrebe za pouzdanom ocjenom stanja i ponašanja drvenih građevinskih sustava u eksploataciji. Višekatne drvene zgrade tipa bungalova zahtijevaju pouzdanu procjenu ponašanja u stvarnim okolišnim uvjetima. Međutim, takve su konstrukcije neprekidno izložene atmosferskim utjecajima koji izravno utječu na njihova dinamička svojstva povezana s krutošću. Stoga je ključno točno određivanje dinamičkih svojstava jer ti parametri služe kao glavni pokazatelji krutosti i uporabljivosti drvenih konstrukcija tijekom njihova korištenja. Ovo istraživanje pokazuje procjenu ponašanja dvokatne tradicijske drvene kuće tipa bungalova te njezinih reprezentativnih elemenata tijekom uporabe. Ispitivanje je provedeno uz pomoć posebno razvijenoga mjernog sustava odnosno računalnih programa Civil Engineering Vibration System (CEVS) i Civil Engineering Vibration Analysis (CEVA). Mjerenja ambijentalnih vibracija provedena su u stvarnim okolišnim uvjetima i pri tri različita stanja napetosti zatega: bez napetosti, pri uobičajenoj napetosti te pri potpunoj napetosti. Ta su stanja definirana kao otpušteno stanje, stanje na razini eksploatacije te potpuno pritegnuto stanje elemenata za ukrućenje. Eksperimentalno određene prirodne frekvencije poslužile su kao kvantitativni pokazatelji promjene krutosti i mehaničkog odziva pri različitim razinama napetosti zatega. Identificirane prirodne frekvencije kretale su se u rasponu od 5005 Hz do 18 066 Hz te su se dosljedno povećavale od stanja bez napetosti, preko uobičajene napetosti do potpune napetosti zatega. Mjerenje ambijentalnih vibracija omogućuje realnu procjenu mehaničkog ponašanja drvene konstrukcije tijekom eksploatacije u stvarnim okolišnim uvjetima. Rezultati pridonose boljem razumijevanju mehaničkog odziva drvenih konstrukcija tijekom njihove uporabe te daju praktične smjernice za procjenu ponašanja, ocjenu krutosti, donošenje odluka o njihovu eventualnom ojačanju, kao i za postizanje održivih praksi u gradnji drvom.

KLJUČNE RIJEČI: drvene konstrukcije; ocjena stanja u eksploataciji; dinamički pokazatelji krutosti; mjerenja ambijentalnih vibracija; sustavi ukrućenja sa zategama; tradicionalne drvene zgrade

1 INTRODUCTION

1. UVOD

Timber structures are increasingly preferred today in terms of aesthetic and environmentally friendly construction techniques. In addition, these structures have a nature compatible architecture and are suitable for sustainable construction techniques.

Wood is considered as a material of use in many buildings according to its place of use and purpose. The use of wood has been seen in most buildings due to wood availability and ease of procurement. These structures are places such as shelters, storages, wooden warehouses, places of worship. Traditional timber structures can be seen in Türkiye in Anatolia as well as in many places in the Eastern Black Sea Region. These structures were built by skilled wood craftsmen of the period, without disturbing the features of the old traditions and in line with the needs of the region, from materials and wood species suitable for the region (Karakul, 2011; Karakul, 2019; Çakiroğlu *et al.*, 2025a). The timber structures in Artvin-Şavşat can be shown as examples of traditional wooden constructions made in traditional architecture.

Multi-storey bungalow-type timber structures are increasingly used in residential and tourism-related applications. These structures are exposed to various environmental conditions and in this context, understanding the dynamic behavior of timber structures is of great importance in terms of both structural safety and comfort. Additionally, these structures may be affected by wind or natural disasters such as floods. However, experimental studies that quantify how tension-based

stiffening systems affect the in-service stiffness-related performance indicators of multi-storey timber houses under real environmental excitation remain limited. This limitation is particularly important for traditional timber houses, where connection details, interlocking members, and tension-based stiffening elements may significantly affect the measured dynamic response. Due to the anisotropic structure of wood, it is highly affected by environmental effects such as humidity and temperature, making it more important to correctly determine the dynamic characteristics of these structures. Since timber is an anisotropic material, its mechanical properties depend on grain direction, loading type, and environmental conditions such as humidity and temperature. (Rahman *et al.*, 2022).

Dynamic properties of structures are of critical importance in determining their resistance and performance against artificial or natural loads. Dynamic characteristics defined as natural frequencies, modal damping ratios and mode shapes play an active role in determining the vibration behavior of structures and obtaining these parameters correctly is necessary for ensuring structural safety. Since timber structures constructed using light and flexible materials are sensitive to environmental vibrations, the behavior of these structures can be examined in detail with experimental methods. Determining the dynamic characteristics of these structures is important for safe structural design and structural health monitoring (SHM). With SHM observations made in recent years, both short-term and long-term natural frequencies, damping ratios and mode shapes of structures can be obtained. In this context, natural fre-

quencies can be used as stiffness-related indicators because changes in boundary conditions, connection stiffness, and tension-based stiffening levels may alter the global dynamic response of the structure.

There are many studies on timber structures and wooden building models in the literature (Ross, 1994; Khoo *et al.*, 2004; Suzuki and Maeno, 2006; Løvholt *et al.*, 2011; Yamada *et al.*, 2012; Li and Xie, 2013; Conde *et al.*, 2014; Lechner *et al.*, 2014; Szafranko and Pawłowicz, 2015; Dai *et al.*, 2016; Altunisik, 2017; Kuo and Sun, 2017; Pawłowicz, 2017; Shimoi and Cuadra, 2018; Achenbach *et al.*, 2018; Toyoda *et al.*, 2019; Yu *et al.*, 2020; Landi *et al.*, 2022; Mackiewicz *et al.*, 2024). When examining timber structures, changes in material condition, connection behavior, moisture content, and boundary conditions may affect the stiffness-related dynamic response of timber structures and even alter its service life. Therefore, proper condition assessment of timber structures can be challenging due to the effects of humidity and corrosion, passage of time, the impact of strength, variable mechanical parameters of the interconnected wooden elements, and the effect of duration of load, etc. (Sørensen *et al.*, 2005; Arya *et al.*, 2010; Branco *et al.*, 2010; Kohler and Svensson, 2011; Unterwieser and Schickhofer, 2011; Lourenço *et al.*, 2013; Faggiano and Marzo, 2015; Cavalli *et al.*, 2016; Branco *et al.*, 2017; Nowogońska, 2019; Poletti *et al.*, 2019; Aydın and Aydın, 2020; Palma and Steiger, 2020; Wu *et al.*, 2020; Nocetti *et al.*, 2021). Catterou *et al.* (2024) studied the dynamics of bracing frames with bolted connections, referred to as frames. Three identical frames on a shaking table were tested, primarily using sine-swept excitation signals. Non-linear modes were identified, and the origins of these phenomena were discussed. Xue *et al.* (2025) studied the dynamic behavior of a multi-storey wooden tower structure with a high stylobate under environmental vibration, and it was stated that frequencies in these types of structures are directly related to the structure geometry. In the scope of the study, natural frequencies, damping ratios and mode shapes were verified by both numerical and experimental modeling. Tulebekova *et al.* (2025) identified the modal parameters by ambient vibration tests on 5 different multi-story timber buildings in Norway and revealed the amplitude dependence of the modes in tall buildings. This study detailed the effects of different building types and heights on the frequency response. Tulebekova *et al.* (2024) investigated the modal parameters of the selected structure and the effect of environmental conditions with long-term monitoring. Amaddeo and Dorn (2024) conducted research on a six-storey light timber framed structure in Norway, where frequency fluctuations (4-7 %) were associated with environmental factors during a four-month moni-

toring period. In a study by Reynolds *et al.* (2016), the dynamic properties of two complete multi-storey timber buildings, identical except for their structural systems, were compared through in-situ testing of the buildings. The natural frequencies, damping ratios and mode shapes of the first three vibration modes of these buildings were determined and compared with those modeled based on the properties of the core and timber walls. In Reynolds *et al.* (2014), simple prediction calculations were performed to estimate the damping in the calculation of wind-induced vibration for multi-storey timber buildings and to evaluate the stiffness of the system by resisting the lateral load.

Timber structures traditionally gave satisfactory seismic performance (Ugalde *et al.*, 2019; Cervio and Muciaccia, 2020). It was thought that their seismic performance was mostly attributed to its structural redundancy, lightweight, elastic deformation capacity, strength and stiffness, and ductility of connections (Ugalde *et al.*, 2019). However, timber structures were not immune to significant damage, especially for homes with structural design deficiencies, as seen in recent earthquakes. Many researchers studied the dynamic behavior of timber structures under seismic loads (Folz and Filiatrault, 2001; Polensek and Schimel, 1991; Filiatrault *et al.*, 2003; Filiatrault *et al.*, 2010). Ductile connections have positive effects on both response and resistance (Ceccotti *et al.*, 2013; Van de Lindt *et al.*, 2010; Tomasi *et al.*, 2015; Flatscher and Schickhofer, 2015).

In this study, the in-service dynamic performance of a two-storey traditional timber bungalow house and representative timber elements was investigated experimentally through ambient vibration measurements. The full-scale structure, located on the Artvin Çoruh University campus and inspired by traditional “Şavşat Houses”, was tested under real environmental conditions using the developed Civil Engineering Vibration System (CEVS) and Civil Engineering Vibration Analysis (CEVA) software. The main objective was to evaluate how tension-based stiffening states influence the natural frequencies and stiffness-related in-service performance of the timber structure.

Ambient vibration measurements were conducted for three different tension-based stiffening states: tensionless, normally tensioned, and fully tensioned. These states represent progressively increasing restraint provided by the tension-based stiffening elements, from released condition to service-level and fully tightened conditions. The identified natural frequencies were used as stiffness-related dynamic indicators; therefore, the study focuses on frequency-based stiffness assessment rather than direct strength evaluation. In addition to the full-scale tests, laboratory measurements on representative timber elements were per-

formed to support the interpretation of the structural-level vibration response.

Unlike many previous studies that evaluate timber structures under fixed structural or boundary conditions, this study experimentally examines the effect of adjustable tension-based stiffening states on the dynamic response of a traditional timber house. The main contributions of the study are the full-scale ambient vibration testing of traditional two-storey timber structure, the comparison of different tension-based stiffening states, the use of the developed CEVS–CEVA system for field-based vibration monitoring, and the interpretation of natural frequency changes as practical indicators of in-service stiffness variation. The findings provide useful experimental evidence for the assessment, monitoring, and potential strengthening decisions of similar traditional timber structures and will also form the basis for future studies.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

This section describes the material characteristics of the timber used in the traditional house, the main construction stages relevant to the structural system, the developed vibration measurement system, and the experimental vibration testing procedure. The methodological workflow consisted of material selection and preparation, documentation of the structural configuration, installation of the Civil Engineering Vibration System (CEVS), data acquisition using Civil Engineering Vibration Analysis (CEVA) software, ambient vibration testing of the full-scale timber house under different tension-based stiffening states, and laboratory vibration measurements on representative timber elements. The experimental data was processed to identify natural frequencies as stiffness-related dynamic indicators.

2.1 Wood material and machining preparation

2.1. Drvni materijal i mehanička obrada

It is known that the construction of Şavşat House in the countryside consists of fir, spruce, pine and chestnut trees in and around the region because they are generally more accessible and easier to obtain. In this study, Scots pine (*Pinus sylvestris* L.) compatible with the region was utilized. The Scots pine wood has a prominent annual ring boundary and yellowish white color. The wood is not shiny and is quite hard, of medium density and has a decorative appearance. When some physical properties of Scots pine wood are examined, full dry density is 0.496 g/cm³, air dry density is 0.526 g/cm³, volume-weight value is 0.426 g/cm³, radial shrinkage is 4.3 %, tangential shrinkage is 8.3 %, volume shrinkage is 12.7 %.

Some mechanical properties are compressive strength of 64 N/mm², flexural strength of 100 N/mm², elasticity modulus of 12000 N/mm², tensile strength of 104 N/mm², shear strength of 10 N/mm², brinell hardness of 40 N/mm² parallel to fibers, brinell hardness of 19 N/mm² perpendicular to fibers (As *et al.*, 2001).

CNC milling was used during the preparation of selected timber components and joint details. Since machining quality may influence the dimensional accuracy of interlocking timber members, the material preparation process was briefly considered in this study. However, CNC-related dust emission was not treated as a vibration parameter; it is mentioned only as a production-related issue associated with the selected Scots pine material.

2.2 Construction stages and structural configuration of the traditional timber house

2.2. Faze gradnje i konstrukcijski sustav tradicijske drvene kuće

The construction process of the two-storey traditional timber house is summarized with emphasis on the structural components relevant to the vibration assessment. Some images of construction stages are shown in Figure 1.

- Design and Planning: Based on research and studies conducted in the district and villages of Şavşat, the design and layout of the timber structure were generated, taking into account the location of the application area. Additionally, some unique additions were made to the structure, which was planned to resemble a traditional Şavşat House, generating a distinct design. The architectural design of the structure, the planning of the load-bearing system and the selection of materials were made at this stage. The selection of the appropriate foundation for the structure was analyzed by taking into account wind and earthquake loads.
- Foundation and Ground Preparation: A reinforced concrete foundation was poured to ensure the stability of the timber structure, and a moisture barrier was installed on top of it. Slope calculations and ground improvement works were carried out at the site.
- Load-bearing system Installation: Wooden columns and beams were joined together to form the structural frame of the structure. Steel connecting elements were used to improve connection stiffness and structural stability. Solid interlocking flooring was used between floors. The upper part between the roof and the second floor was left empty so that it would be visible, and wooden materials were used for support and decorative purposes.
- Interior Applications: Electrical and plumbing installations were completed with decorative pipes, the



Figure 1 Some images of construction stages

Slika 1. Prikaz faza gradnje

floor was laid with interlocking wood material, and the interior decoration was completed.

Before starting the construction of the traditional timber house, production and installation processes were initiated in a suitable location in the laboratory environment in accordance with the existing drawings and designs. First, wooden materials were placed using the “wood interlocking technique” starting from the foundation. As in traditional Şavşat Houses, wooden pieces were joined using a technique similar to “kurtboğaz” (wolf’s throat), with grooved joints (Figure 2). The wooden pieces joined in this way were left in this environment for a certain period of time to allow the grooves to settle. Then, a suitable site was identified, and a soil survey was conducted to verify the suitability of the foundation. High-quality first-class wooden materials were used to ensure the structural integrity of the building.

First, the ground was prepared, and the foundation was laid. Concrete foundation was frequently used. A solid foundation was important for the long life of the traditional timber house. After the foundation

was completed, the structural frame was installed. The main body of the structure was generated by mounting vertical and horizontal supports. Waterproof coatings were applied for the roof to provide protection against external factors such as rain and snow.

Non-structural architectural components, such as doors, windows, interior finishes, and decorative timber elements, were completed after the load-bearing timber frame and floor system were installed. These components were not considered as primary load-bearing elements in the vibration assessment.

In traditional Artvin Şavşat Houses, wooden pieces were joined using a technique with grooved joints and some of 3D images and tension status are shown in Figure 2.

2.3 Vibration measurement system

2.3.1 Sustav za mjerenje vibracija

Vibration tests were performed on the timber structure to identify its dynamic characteristics. To perform measurements, civil engineering vibration system (CEVS) and civil engineering vibration analysis (CEVA)



Figure 2 Some images of 3D views and grooved joints (white rectangular)

Slika 2. Prikaz 3D modela i izlijebljenih spojeva (označeno bijelim pravokutnicima)

were developed. CEVS system and CEVA software were used for data acquisition (Yanik *et al.*, 2022; Aymelek *et al.*, 2023; Yanik *et al.*, 2024; Demirtas *et al.*, 2025). The system consisted of 3-axial accelerometers, arduino, bluetooth, li-ion battery, humidity, temperature, pressure and charge modulus (Figure 3). The software included C# language in visual studio, and arduino programs in order to control the sensor system and to receive data through the sensor system. The properties and equipment of the sensors are given in Table 1.

The other part, i.e. the software part, was developed to command the sensor system. With the software developed, the objectives outlined below have been

achieved. The CEVA software was designed with the help of visual studio (Fig. 4).

The main advantage of the developed CEVS–CEVA system is its suitability for rapid in-service vibration monitoring of timber structures under field conditions. Compared with conventional laboratory-based vibration measurement systems, the proposed system is portable, low-cost, capable of wired or wireless data acquisition, and allows simultaneous recording of tri-axial acceleration and environmental parameters. The CEVA interface also enables real-time signal checking before data storage, which reduces the risk of invalid field measurements. These features make the

Table 1 Properties and equipment of sensors
Tablica 1. Svojstva i oprema mjernih senzora

Parameter / <i>Parametar</i>	CEVS
Multi-axis / <i>Višeosni</i>	Tri-axial
Accelerometer type / <i>Tip akceleratora</i>	Digital
Sensitivity / <i>Osjetljivost</i>	20-bit ADC
Range / <i>Mjerni raspon</i>	Selectable $\pm 2 \text{ g}$ / $\pm 4 \text{ g}$ / $\pm 8 \text{ g}$
Noise density / <i>Gustoća šuma</i>	$25 \mu\text{g}/\sqrt{\text{Hz}}$ for $\pm 2 \text{ g}$
Measuring sensibility / <i>Mjerna osjetljivost</i>	$3.9 \mu\text{g}/\text{LSB}$ for $\pm 2 \text{ g}$, $7.8 \mu\text{g}/\text{LSB}$ for $\pm 4 \text{ g}$, and $15.6 \mu\text{g}/\text{LSB}$ for $\pm 8 \text{ g}$
Sampling frequency / <i>Frekvencija uzorkovanja</i>	Selectable 250 Hz / 500 Hz / 1000 Hz
Content of equipment / <i>Sastav mjerne opreme</i>	Accelerometer, arduino, bluetooth, li-ion battery, humidity, temperature, pressure and charge modulus
Data transfer type / <i>Način prijena podataka</i>	Selectable Wireless or Wired
Baud rate / <i>Brzina prijena podataka</i>	115200 / 500000Baud
Protocol type / <i>Tip komunikacijskog protokola</i>	Between Accelerometer and Arduino is SPI, between Arduino and Bluetooth is UART

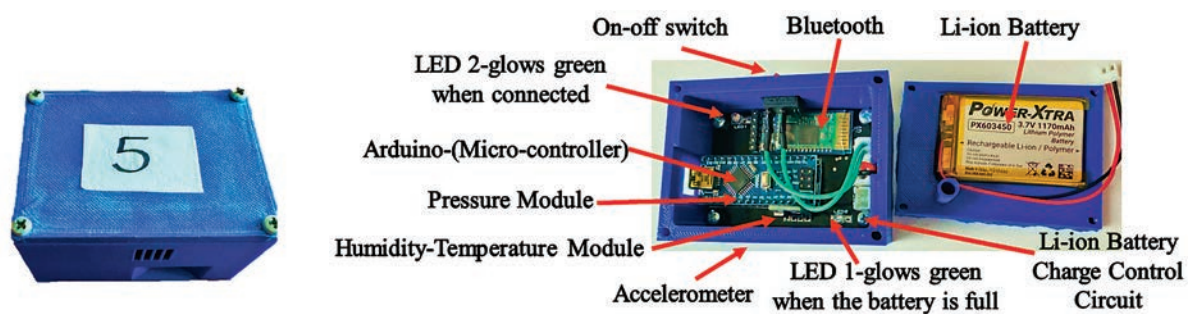


Figure 3 Placement of vibration measurement system elements (CEVS)
Slika 3. Raspored elemenata sustava za mjerenje vibracija (CEVS)

system applicable for preliminary structural health monitoring and comparative stiffness assessment of traditional timber buildings where access, cost, and installation time are important constraints.

The CEVA software was developed in C# using Visual Studio to control the sensor system and manage data acquisition. The software enables sensor connec-

tion control, selection of acceleration range, sampling frequency and measurement duration, real-time preview of signals from the *X*, *Y* and *Z* axes, channel selection, recording time monitoring, and export of measurement data in formats such as .csv and .txt. These functions allowed the recorded signals to be checked in the field before further processing.

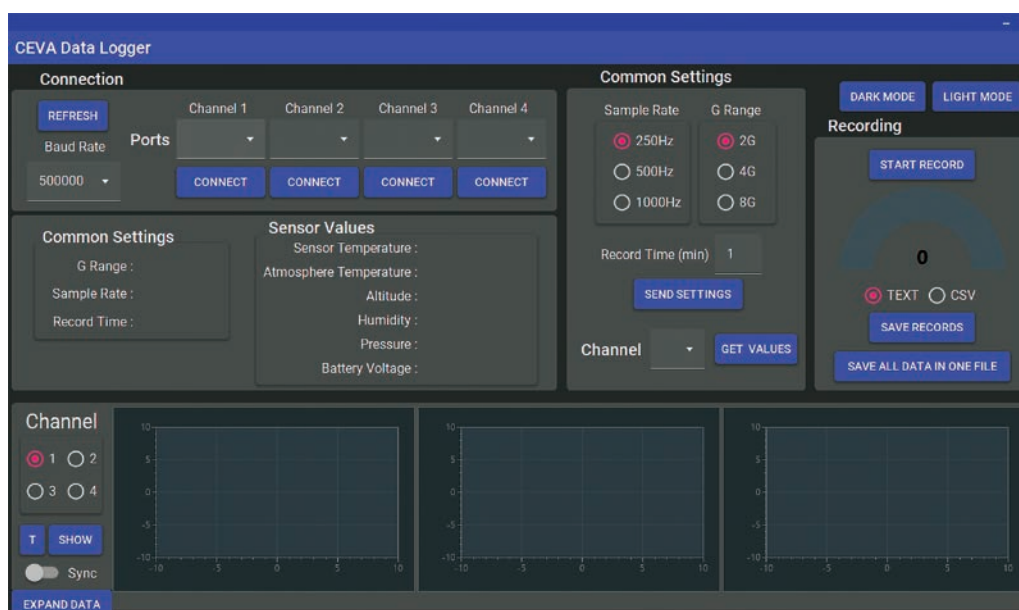


Figure 4 CEVA software interface
Slika 4. Sučelje CEVA softvera

2.4 Full-scale ambient vibration measurements on the traditional timber house

2.4. Terenska mjerenja ambijentalnih vibracija na tradicijskoj drvenoj kući

Measurement setups with different tension-based stiffening states were established for vibration measurements. Vibration measurement system and software were used in these setups. Some of the images of the sensor placement on the structure are given in Figure 5. Some of the images of the data on the CEVA taken from CEVS system are given in Figure 6.

The expression “tensionless < normally tensioned < fully tensioned” refers to the increasing level of initial pre-tension applied to the steel stiffening/tie elements of the timber house, rather than to the tensile strength of the timber material itself. In the tensionless state, the tensioning elements were released so that they did not provide effective axial restraint. The normally tensioned state corresponds to the in-service condition of the house, in which the tensioning elements were tightened to their regular service position. In the fully tensioned state, the same elements were tightened to the maximum practical level allowed by the connection details without causing visible local

damage or deformation. Therefore, the three measurement cases represent progressively increasing restraint and stiffness contribution from the tension-based stiffening system.

In the first measurement setup, 3 CEVS systems were placed in different corners on the 2nd floor. In these tests, the timber house was in the normally tensioned state. In the second measurement setup, the timber house was in the tensionless state, and in the third measurement setup, the timber house was in the fully tensioned state. In the tests, different vibration measurements were made according to the tension status of the traditional timber house.

The 3-axis (X-Y-Z) ambient vibration measurement data obtained from the traditional timber house by using the CEVS system and CEVA Data Logger software were processed in the ARTEMIS software. In the signal processing analyses, frequency and time decomposition domain methods were applied, and singular value graphs were obtained for each analysis. Some of these graphs are given in Figures 7-9 for different measurement setups, where the horizontal axis demonstrates the frequencies and the vertical axis is in decibels (dB). The maximum frequency for signal processing was rearranged as 45 Hz.



Figure 5 Sample images of vibration measurement setups (CEVS)

Slika 5. Primjeri postavljanja sustava za mjerenje vibracija (CEVS)

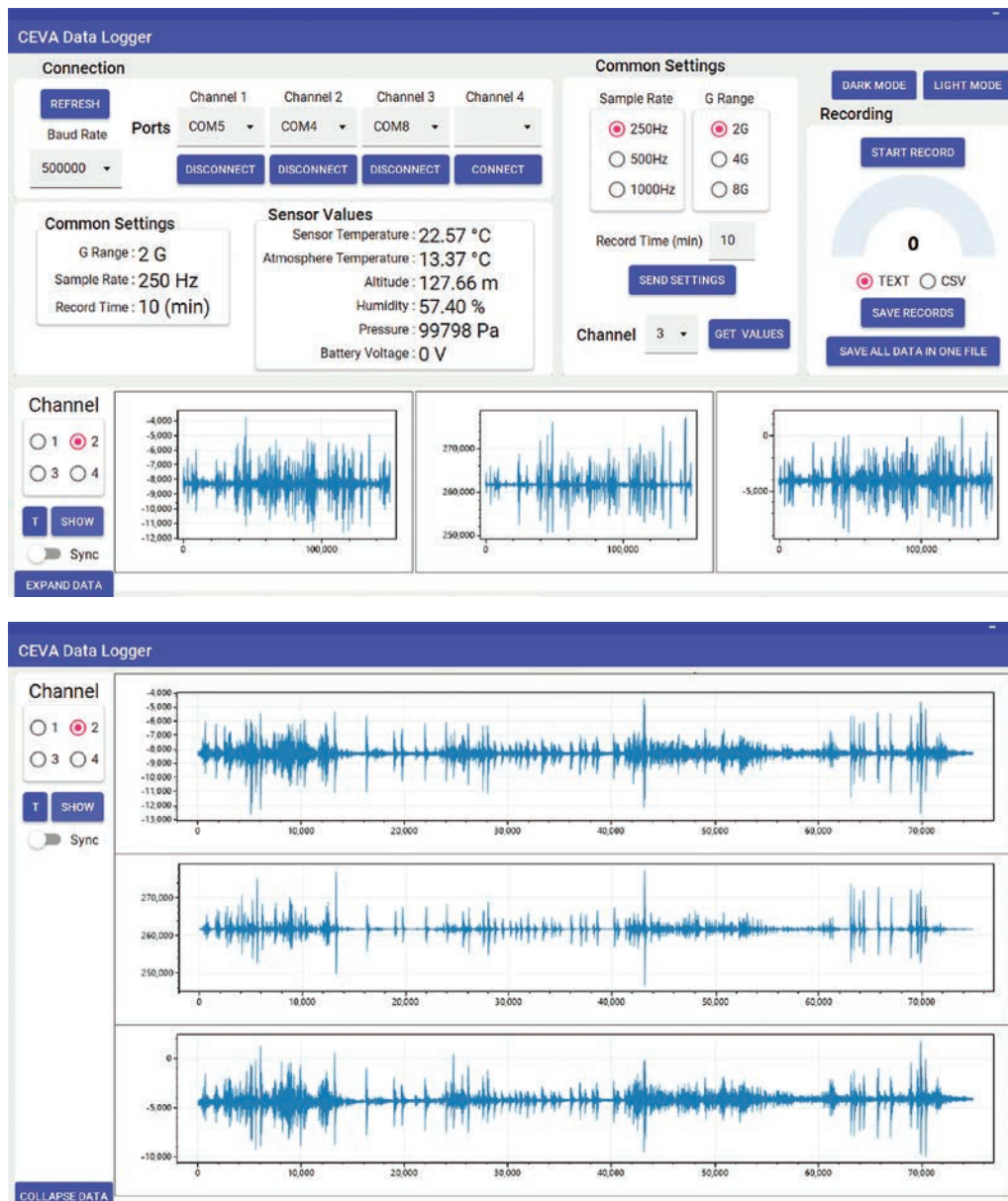


Figure 6 Sample images vibration data (CEVA)
Slika 6. Primjeri zapisa izmjerenih vibracija (CEVA)

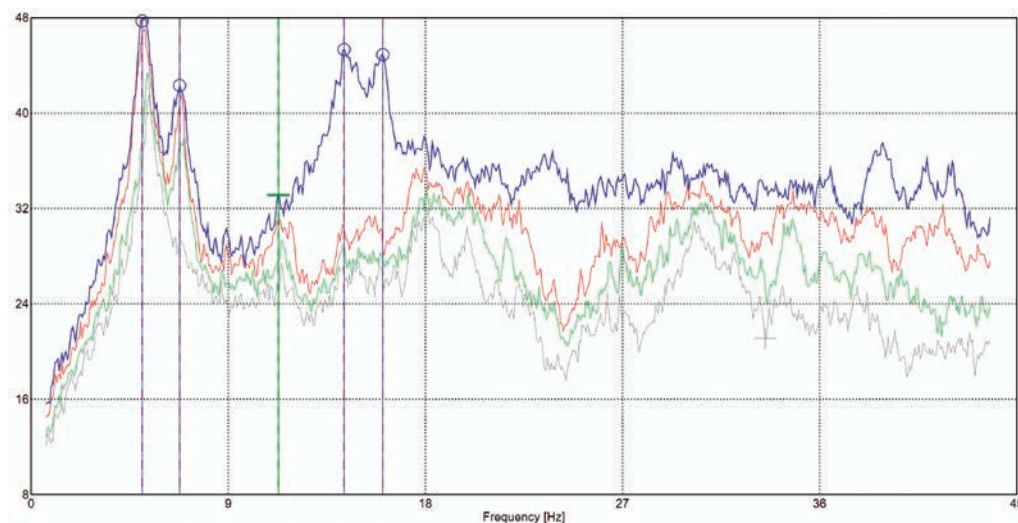


Figure 7 Singular values of spectral densities of normally tensioned state
Slika 7. Singularne vrijednosti gustoće spektra vibracija za uobičajeno napeto stanje

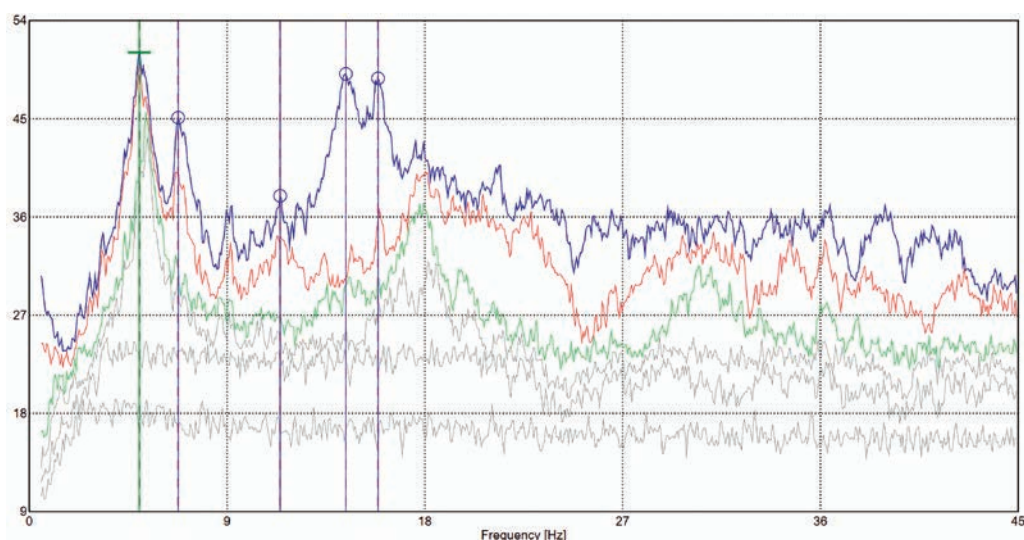


Figure 8 Singular values of spectral densities of tensionless state
Slika 8. Singularne vrijednosti gustoće spektra vibracija za otpušteno stanje

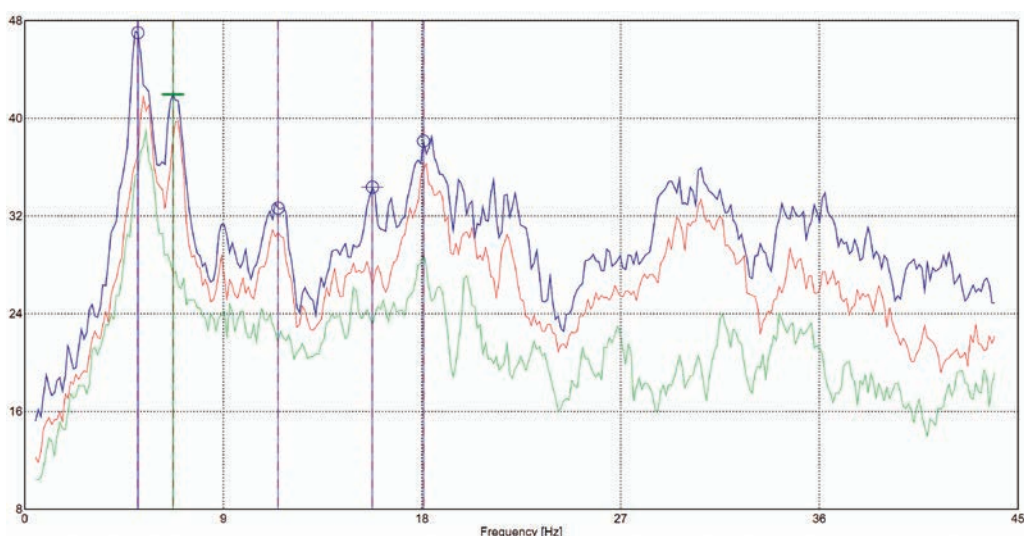


Figure 9 Singular values of spectral densities of fully tensioned state
Slika 9. Singularne vrijednosti gustoće spektra vibracija za napeto stanje

2.5 Laboratory vibration measurements on representative timber elements

2.5. Laboratorijska mjerenja vibracija na reprezentativnim drvenim elementima

Laboratory vibration measurements were performed on representative timber elements to support the interpretation of the stiffness-related dynamic response observed in the full-scale timber house. These tests were not intended to replace the full-scale measurements but to provide complementary information about the vibration characteristics of selected timber components.

Some of the materials used in the timber structure were tested in a laboratory environment. Vibration measurements were collected with the CEVS vibration measurement system on a structure consisting of wooden elements and a cantilever beam, and information about the material properties of the structure was

obtained. The measurement devices established are given in Figures 10-11.



Figure 10 Some images of cantilever vibration measurement setup

Slika 10. Primjeri postavljanja uređaja za mjerenje vibracija na konzolnim elementima



Figure 11 Sample images of individual element vibration measurement setup

Slika 11. Primjeri postavljanja uređaja za mjerenje vibracija pojedinačnih elemenata

The vibration signals received from the cantilever and individual element were manually processed using the ARTEMIS software. The resolution value was selected as 2048. In frequency selection, the enhanced frequency domain decomposition (EFDD) method was used to select the peak. In addition, some of the singular value diagrams were obtained as a result of the processing of the signals given in Figures 12-13. The analysis outputs with different visuals obtained using EFDD are shown in the graphs. The identified frequencies obtained from the laboratory measurements are reported and discussed in the Results and Discussion section.

2.6 Use of artificial intelligence-assisted tools

2.6. Primjena alata utemeljenih na umjetnoj inteligenciji

Artificial intelligence-assisted tools were used only for language editing, improving grammatical clarity, and supporting the organization of the revised manuscript. OpenAI ChatGPT (GPT-5.5 Thinking, ac-

cessed in May 2026) was used during the revision stage to assist with English language refinement and editorial restructuring in response to reviewer comments. No artificial intelligence-assisted tool was used for experimental design, data collection, signal processing, numerical analysis, generation of results, preparation of figures or tables, or interpretation of the experimental findings. All AI-assisted suggestions were critically reviewed, edited, and approved by the authors. The authors take full responsibility for the accuracy, originality, and integrity of the final manuscript.

3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

3.1 Full-scale ambient vibration results of the traditional timber house

3.1. Rezultati terenskih mjerenja ambijentalnih vibracija na tradicijskoj drvenoj kući

Full-scale ambient vibration measurements were conducted on the traditional timber house under three

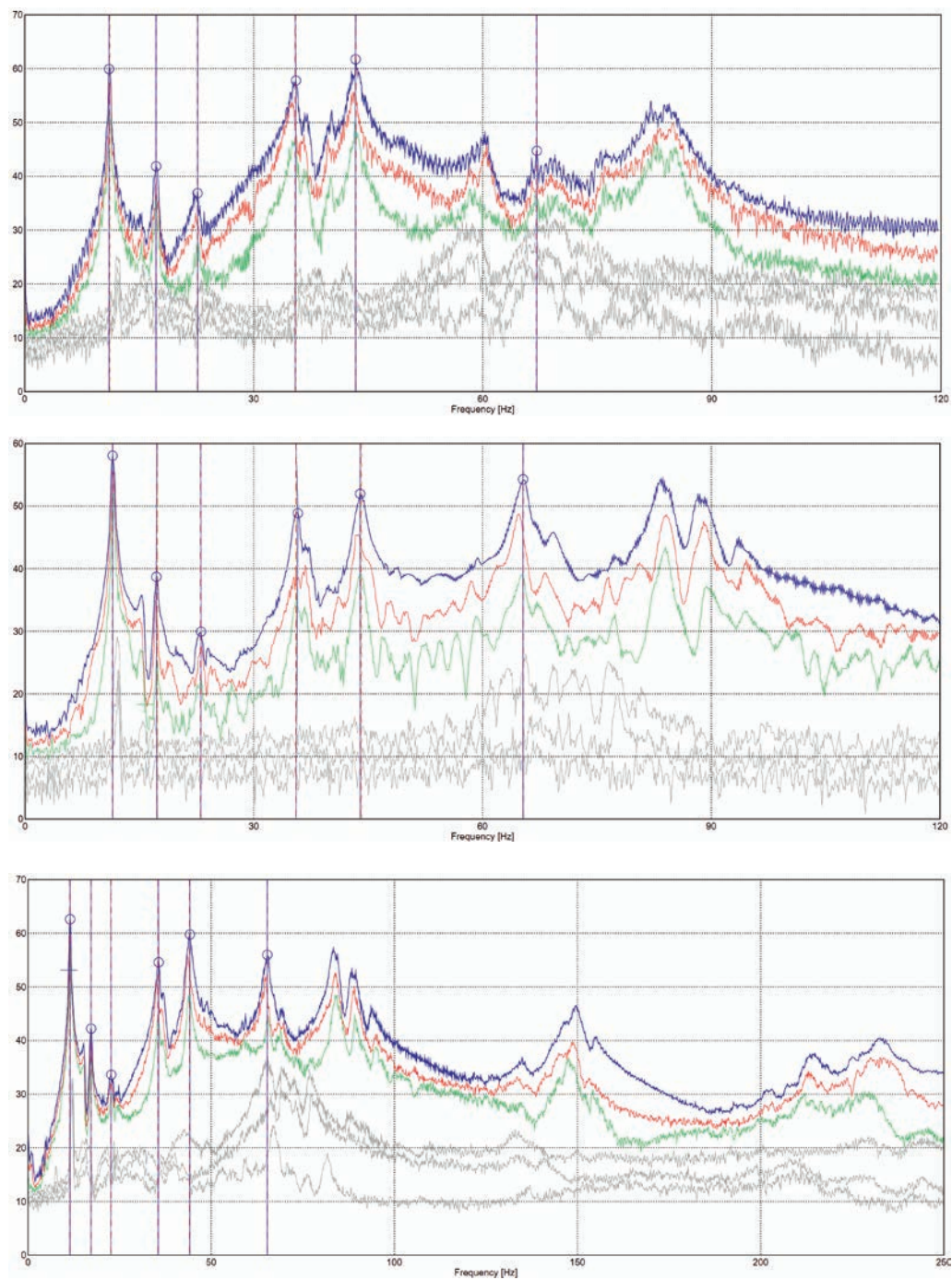


Figure 12 Some singular value graphs of cantilever beam
Slika 12. Primjeri dijagrama singularnih vrijednosti za konzolnu gredu

Table 2 Experimental natural frequencies of traditional timber house
Tablica 2. Eksperimentalne prirodne frekvencije tradicijske drvene kuće

Frequency number <i>Broj frekvencije</i>	Tensionless status, Hz <i>Opušteno stanje, Hz</i>	Normal tension status, Hz <i>Normalno napeto stanje, Hz</i>	Fully tension status, Hz <i>Potpuno napeto stanje, Hz</i>
1	5.005	5.066	5.127
2	6.775	6.897	6.958
3	11.414	11.475	11.597
4	14.494	14.832	15.747
5	15.869	16.052	18.066

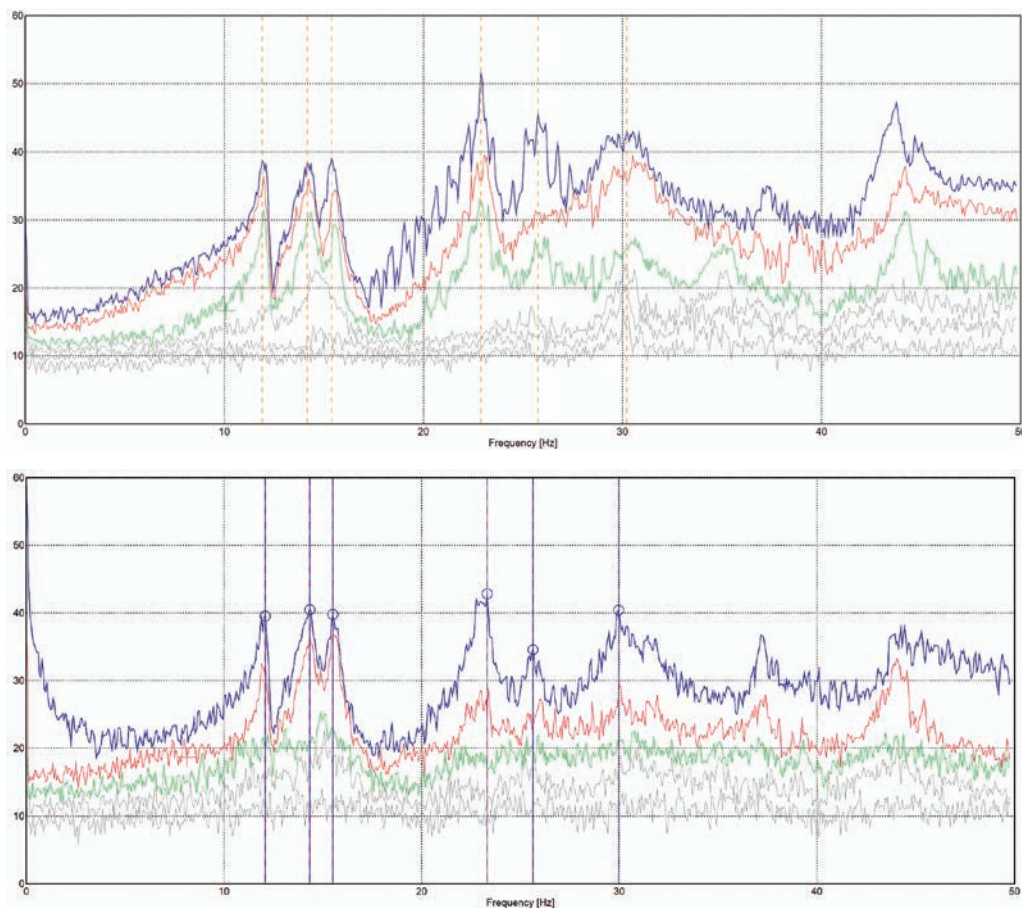


Figure 13 Some singular value graphs of individual elements
Slika 13. Primjeri dijagrama singularnih vrijednosti za pojedinačne elemente

tension-based stiffening states: tensionless, normally tensioned, and fully tensioned. The recorded three-axis acceleration data were processed using ARTeMIS software, and the experimental natural frequencies were identified from the singular value spectra. The first five natural frequencies obtained from the full-scale measurements are presented in Table 2.

Table 2 shows that the identified natural frequencies ranged between 5.005 Hz and 18.066 Hz. For all identified modes, the natural frequencies increased from the tensionless state to the normally tensioned state and then to the fully tensioned state. This trend indicates that the increase in restraint provided by the tension-based stiffening elements resulted in an increase in the effective stiffness of the traditional timber house. Since the mass of the structure was not changed during the measurements, the observed frequency increase can be interpreted as a stiffness-related dynamic response rather than a direct strength increase.

A graphical comparison of the natural frequencies obtained under different tension-based stiffening states is presented in Figure 14. The comparison clearly shows that the frequency values follow the order tensionless < normally tensioned < fully tensioned for each identified mode.

3.2 Effect of tension-based stiffening states on natural frequencies

3.2. Utjecaj stanja napetosti zatega na prirodne frekvencije

The effect of the tension-based stiffening states was more evident in the higher modes than in the lower modes. In the first mode, the natural frequency increased from 5.005 Hz in the tensionless state to 5.127 Hz in the fully tensioned state, corresponding to an increase of approximately 2.44 %. In the second and third mode, the increases were approximately 2.70% and 1.60 %, respectively. However, the fourth mode increased from 14.494 Hz to 15.747 Hz, corresponding to an increase of approximately 8.64 %, while the fifth mode increased from 15.869 Hz to 18.066 Hz, corresponding to an increase of approximately 13.84 %.

The results indicate that the tension-based stiffening system had a measurable influence on the dynamic behavior of the timber house. The relatively small changes in the first three modes suggest that the global low-frequency response was only moderately affected by the tension adjustment. In contrast, the larger increases observed in the fourth and fifth mode indicate that the stiffening contribution of the tensioning elements became more pronounced in higher-frequency

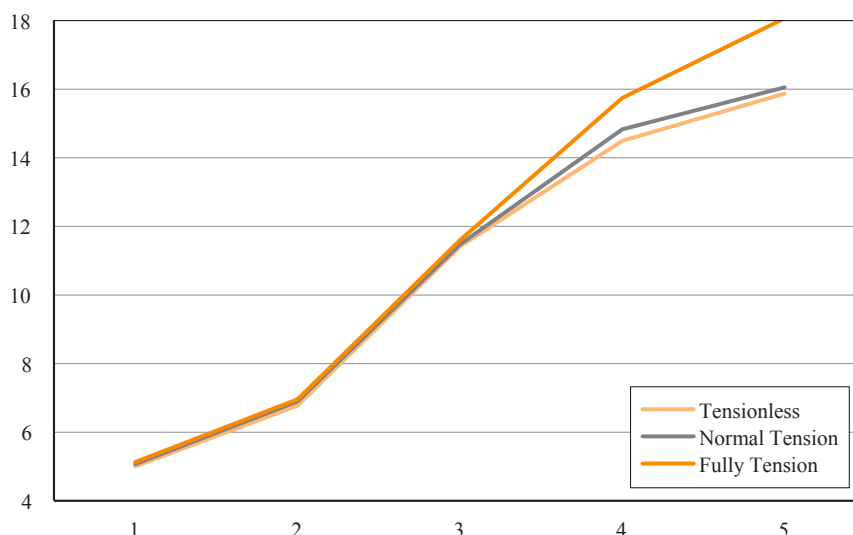


Figure 14 Natural frequencies of the traditional timber house based on tension status
Slika 14. Prirodne frekvencije tradicijske drvene kuće ovisno o stanju napetosti zatega

Table 3 Percentage increase in natural frequencies from tensionless state to fully tensioned state

Tablica 3. Postotni porast prirodnih frekvencija od otpuštene do potpuno pritegnutog stanja

Mode number <i>Broj načina rada</i>	Tensionless state, Hz <i>Opušteno stanje, Hz</i>	Fully tension state, Hz <i>Potpuno napeto stanje, Hz</i>	Increase, % <i>Povećanje, %</i>
1	5.005	5.127	2.44
2	6.775	6.958	2.70
3	11.414	11.597	1.60
4	14.494	15.747	8.64
5	15.869	18.066	13.84

quency vibration modes. This behavior may be associated with the increased local and semi-global restraint provided by the tension-based stiffening elements.

These results should be interpreted as frequency-based stiffness indicators. The measurements do not directly quantify strength or load-carrying capacity. However, under comparable mass and boundary conditions, an increase in natural frequency is generally associated with an increase in effective stiffness. Therefore, the observed frequency trend supports the use of ambient vibration measurements as a practical tool for evaluating stiffness-related in-service performance changes in traditional timber structures.

3.3 Laboratory vibration results of representative timber elements

3.3. Rezultati laboratorijskih mjerenja vibracija na reprezentativnim drvenim elementima

In addition to the full-scale ambient vibration measurements, laboratory vibration measurements were performed on representative timber elements. These measurements were used to support the interpretation of the stiffness-related dynamic response observed at the structural level. The natural frequencies obtained from the cantilever element and the timber element are presented in Table 4.

Table 4 Experimental natural frequencies of the cantilever element and representative timber element

Tablica 4. Eksperimentalne prirodne frekvencije konzolnoga i reprezentativnoga drvenog elementa

Frequency Number <i>Broj frekvencije</i>	Cantilever element's experimental frequencies, Hz <i>Eksperimentalne frekvencije konzolnog elementa, Hz</i>				Wooden element's frequencies, Hz <i>Frekvencije drvenog elementa, Hz</i>	
	M1	M2	M3	M4	M1	M2
1	11.060	11.475	11.432	11.475	12.085	11.902
2	17.215	17.295	17.212	17.090	14.343	14.160
3	22.646	23.015	22.591	22.461	15.503	15.381
4	35.449	35.530	35.536	35.400	23.315	22.888
5	43.369	43.981	44.117	44.189	25.635	25.757
6	67.051	65.329	65.337	65.674	29.968	30.212

The cantilever element was tested in four different measurement sets, while the representative timber element was tested in two measurement sets. For the cantilever element, the average values of the first six natural frequencies were 11.361, 17.203, 22.678, 35.479, 43.914, and 65.848 Hz. For the representative timber element, the average values of the first six natural frequencies were 11.994, 14.252, 15.442, 23.102, 25.696, and 30.090 Hz.

The laboratory results show that the cantilever element exhibited higher frequencies in the upper modes compared with the representative timber element. This difference can be attributed to the different boundary conditions, geometry, and structural configuration of the tested elements. The laboratory measurements do not directly represent the full-scale structural response of the traditional timber house; rather, they provide complementary information on the vibration characteristics of selected timber components. Therefore, these results support the interpretation of the full-scale measurements but should not be treated as a substitute for in-service testing of the complete structure.

4. CONCLUSION

4. ZAKLJUČAK

The full-scale results demonstrate that ambient vibration measurements can be used to detect stiffness-related changes caused by different tension-based stiffening states in a traditional timber house. The consistent increase in natural frequencies from the tensionless state to the fully tensioned state indicates that the developed measurement approach is sensitive to changes in structural restraint and effective stiffness. This finding is practically important for the monitoring, assessment, and potential strengthening decisions of similar traditional timber structures.

The developed CEVS–CEVA system was also shown to be applicable for field-based vibration monitoring. Its portability, ability to record tri-axial acceleration data, and compatibility with subsequent modal identification procedures make it suitable for preliminary in-service assessment of timber structures under real environmental conditions.

However, some limitations should be noted. The tension states were defined according to the adjustment condition of the tensioning elements, and direct axial force measurement was not performed. Therefore, the results should be interpreted as a comparison of operational stiffening states rather than as a force-calibrated pre-tension analysis. In addition, the study focused primarily on natural frequencies as stiffness-related indicators. Future studies should include damping ratios, mode shapes, long-term environmental monitoring, finite element model updating, and the evaluation of

earthquake and wind effects to obtain a more comprehensive assessment of the structural performance of traditional timber houses.

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