

Advancing Timber for the Future Built Environment

# CONTINUOUS MONITORING OF A FIVE-STORY CROSS-LAMINATED TIMBER BUILDING IN A SEISMIC-PRONE REGION

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#### **ABSTRACT:**

The use of cross-laminated timber panels in timber building construction has gained interest in recent years, mainly due to their minimal carbon emissions, construction speed process, and structural performance. Nevertheless, understanding the dynamic properties of Cross-Laminated Timber structures remains a challenge, in particular in countries with seismic hazards. This study aims to determine the dynamic properties of a five-story cross-laminated timber building through vibration-based monitoring. The study case is made of low structural grade radiata pine CLT panels, combines two construction systems, and features irregularly distributed openings. Continuous monitoring measurements with operational modal analysis (OMA) techniques were employed to identify the building's modal properties under operational conditions. The results suggest that the predominant frequencies vary over time due to environmental conditions. In particular, there is a strong correlations ( $R^2 \ge 0.93$ ) between the moisture content and the natural frequency of the building. Another relevant finding is that the frequencies of the fundamental modes vary during a seismic event. These findings contribute valuable data for the development of structural design standards for CLT buildings in seismic regions.

KEYWORDS: Operational Modal Analysis, Cross Laminated Timber, Structural Health Monitoring, Ambient Vibrations

## **1 – INTRODUCTION**

In recent years, the construction of buildings with crosslaminated timber (CLT) panels has attracted increasing interest in countries with high seismicity, thanks to their environmental advantages [1] and good structural performance. CLT material is a composite material capable of forming robust panels that can be used as walls or as slabs. CLT panels are composed of sawn timber, the layers of which are at 90° to each other, giving attributes that confer a quasi-rigid panel capable of resisting in-plane and out-ofplane loads [2]. However, due to the possible occurrence of brittle failures that timber as a material can have under seismic events, this construction system is usually complemented with steel connectors, which are in charge of providing ductility to the structural system [3–5].

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<sup>7</sup>University of Bío-Bío, Chile; Centro Nacional de Excelencia= para la Industria de la Madera (CENAMAD)-ANID BASAL= FB210015, Chile.=aopazove@ubiobio.cl Important efforts have been made to understand the behavior of construction systems based on cross-laminated timber, in this sense, tests have been carried out at the level of connectors [6–10], as well as structural elements such as walls [11–15], and it has also been possible to study at the construction system level by performing static and dynamic tests on prototypes of multi-story buildings (2 to 10 stories) [16–23], all these studies evidence that cross-laminated timber performs well against lateral loads, evidencing good seismic performance of CLT. These international initiatives have reinforced confidence in the use of cross-laminated timber as a construction alternative in seismic zones.

While studies of cross-laminated timber have been carried out, attempts have now been made to understand this structural behavior in real environments, so nondestructive techniques have been used to assess structural behavior. For example, the use of structural health monitoring by means of vibration measurements under operating conditions has been widely used for these purposes. These types of techniques have been widely used in other building systems and have been focused on the determination of dynamic properties over time. From the CLT point of view, studies have been carried out in Canada [24], Sweden [25], the United Kingdom [26], Norway [27, 28] and in Chile [29]. These works highlight the need for more knowledge about the real dynamic response of CLT buildings and underline the importance of continuous monitoring to understand the variation of their properties under different levels of excitation. For example, it has been evidenced that environmental variables influence the dynamic properties of timber buildings [29-31], on the other hand, it has been shown

that seismic excitations can transiently vary the frequency of timber-frame structures [29].

In this context, the present study addresses the long-term monitoring (1 year) of a 5-story building constructed with CLT in an area of high seismicity. The aim is to characterize its dynamic properties by means of the Operational Modal Analysis (OMA) method, as well as to observe the evolution of these properties in response to environmental variables and moderate seismic events. With this, the empirical knowledge necessary for the design of CLT buildings in seismic regions is expanded. Finally, these findings are part of those previously reported by Jara-Cisterna et al. [29], reinforcing the observed trends and highlighting the importance of continuous monitoring.

# 2 – PYMELAB BUILDING

The PymeLab building, located in Concepción, Chile, is located in a highly seismic zone and is constructed entirely of low structural quality (C16) radiata pine CLT panels. This building, is result of a collaborative project with multiple companies, is currently the tallest CLT building in Latin America.

With a floor plan of 4.2 m by 6.6 m and a total height of 14.5 m, the building design considers the alignment of the openings to generate rigid corners. In addition, two construction systems were implemented: the first three levels follow the platform system, while the two upper levels adopt the balloon system. Figure 1 shows a photographic record of the building and Figure 2 shows section views of the building.



*Figure 1: Photographic record of the 5-story cross-laminated timber (CLT) prototype* 

From the structural design point of view, the building was calculated under the method of allowable stresses according to Chilean standards [32, 33], considering a seismic reduction factor of R = 2 and a drift limit of 0.2%. The latter criterion proved to be the most restrictive, conditioning the structure to a large amount of metallic connectors to guarantee its stiffness [29, 34]. The architectural layout and construction details are presented in Figure 3.

As can be seen in Figure 3, there is a large number of metal connectors. On average, in terms of connectors there are 2 connectors/m<sup>2</sup> and 205 fasteners/m<sup>2</sup> (nails + screws).



Figure 2: Sections from outside of the CLT building: a) North, b) South, c) West, d) East.



Figure 3: Model of the CLT tower with some construction details.

#### **3** – EXPERIMENTAL SETUP

To record accelerations induced by environmental vibrations and seismic events, RaspberryShake R4SD [35] sensors, with a sampling rate of 100 Hz, were used. The devices were installed at the northeast corners of the fourth and fifth levels of the building, as shown in Figure 4. The continuous measurement campaign runs from August 1, 2023 to August 1, 2024. This type of sensor has been validated and tested for continuous monitoring of timber structures [29, 31]. The monitoring scheme, together with the position of the RaspberryShake sensors, is shown in Figure 4

Once the signals are measured, post-processing techniques are applied to improve signal quality and reduce computational cost, such as detrending, decimation and low-pass filtering.

The data was collected and processed through Python using the ObsPy library [36]. Once the signals were processed, operational modal analysis (OMA) methods were applied to identify dynamic properties. An OMA technique widely used in the literature, the stochastic subspace identification (SSI) method [37], was used.

During the OMA application, a stabilization diagram is constructed to verify whether the poles are stable. For this purpose, three stability criteria are defined:

$$\frac{|f_k - f_{k-1}|}{|f_k|} < 0.02 \tag{1}$$



Figure 4: Mounting and location of accelerometers for Continuous Monitoring.

$$\frac{|\xi_k - \xi_{k-1}|}{|\xi_k|} < 0.05 \tag{2}$$

$$1 - MAC(\phi_k, \phi_{k-1}) < 0.02$$
 (3)

where  $f_k$  is the identified natural frequency,  $\xi_k$  represents the damping and  $\phi_k$ ) the modal shape associated to the order k). The function MAC (Modal Assurance Criterion) evaluates the similarity between modal shapes. If all three conditions are met simultaneously, the pole is classified as totally stable (label 4), on the contrary, if the pole is unstable, it is assigned the label 0. If it is stable in only the frequency criterion, it is assigned the label 1, if it is stable in frequency and damping the label 2 and if it is stable in frequency and modal shapes the label 3.

For the application of the identification methods, the open-source PyOMA [38] library was used. For the application of OMA, 15-minute windows are selected during a day and the frequencies are determined. Afterwards, a classification process is applied by means of clusters. Once the frequencies are identified, the average of the frequencies identified during a day is calculated.

## 4 – RESULTS

The results associated with the identification of dynamic properties over time will be shown below. Typical accelerograms obtained during a 15-minute window for environmental vibration measurements are shown in the Figure 5 together with their histograms in the Figure 6.

The results shown in Figs. 5 and 6 show that the quality of the signals is good enough to apply the OMA methods, in particular Figure 6 showing how the signals follow a normal distribution, unaffected by clipping, or digital noise.

A typical stabilization diagram for a 15-minute window is shown in the Figure 7.

The results show that in general it is possible to identify two stable frequencies for different orders, these frequencies are associated to translational modes in the x and y direction identified in the work of [29]. This process is performed for a whole day, generating a number of 96 identifications for one day. The Figure 8 shows the dispersion of frequencies identified during one day.



Figure 5: Accelerations recorded in measurement in the 5th story in the: X (top), Y directions (below).



Figure 6: Acceleration histograms with probability density and normal fit.

The results shown in Figure 8 indicate minor variations. In the worst-case scenario, differences of up to 1.62% are observed, suggesting that cross-laminated timber remains relatively stable throughout the day compared to the wood light-frame construction system [31].



Figure 7: Stabilization diagram of estimated state space models for a 15-minute window measurement



Figure 8: Variation of the natural frequencies of the fundamental modes  $f_1$  and  $f_2$  on 1 day

Once the frequencies during a day have been identified, the average frequencies corresponding to the day are calculated. The natural frequencies of the fundamental modes are shown in Figure 9.



Figure 9: Variation of the natural frequencies of the fundamental modes  $f_1$  and  $f_2$ 

The frequencies of the fundamental modes  $f_1$  and  $f_2$  vary by 6% and 8%, respectively. These changes in the frequency is explained by Jara-Cisterna et al. [29] that are associated with the moisture content of the panels that can generate swelling and interlocking between the parts of the structural system, which would increase the lateral stiffness and the natural frequencies. Figure 10 shows the comparison between the moisture content of the CLT panels and the identified frequencies.

Figure 10 indicates that there are higher correlations for both frequencies, showing the correlation ( $R^2 \ge 0.93$ ) between the identified frequencies over time and the moisture content of the CLT panels.

The results on frequency identification and moisture content measurement indicate that there is a clear seasonal trend in the frequencies, with decreases during drier periods (possible shrinkage of the timber in summer months) and partial recoveries in winter, although without reaching the initial value. For example, differences of up to 4% are found when comparing the initial frequencies and those at the end of 1 year. This suggests that, as the panels dry, the timber may undergo changes that prevent it from fully recovering its original stiffness. To assess what is occur-



Figure 10: Variation of the natural frequencies of the fundamental modes f1 (top) and f2 (bottom) and moisture content.

ring, detailed monitoring of the physical and environmental properties is necessary. In addition, something that may be causing the frequency not to be the same as the original could be caused by microvibrations (such as vibrations from ambient or minor to large earthquakes) that could loosen the steel connectors. With that information, changes in frequency could be correlated with environmental and structural factors, and more robust design and maintenance strategies could be defined.

From the point of view of the seismic response, the results of a 5.4  $M_w$  earthquake in the East-West component are shown in the Figure 11.



Figure 11: Seismic Acceleration response in X (top) and Shorttime Fourier Transform (below)

The results shown in the Figure 11 show the seismic response at the 5th floor, it is found that accelerations of 0.074 g are reached at the 5th floor. To analyze what happens with the frequency, the spectrogram is shown. The results indicate that the frequency during the seismic event is reduced by 15.3 % but has been restored once the energy has been dissipated, indicating that there is no structural

damage. During the year of continuous monitoring there are more than 10 earthquakes over 4.5  $M_w$  in a range of radius less than 100 km, it is important to note that the frequency before and after earthquakes remains constant as shown above. Additionally, another raspberryshake was incorporated to measure the excitations at the base level, so it is expected to deeper further research on this phenomenon.

## 5 – CONCLUSIONS

Continuous measurements reveal that environmental factors influence the frequency of the first two vibration modes. Comparing different periods of the year, changes of up to 8% are observed. In addition, it was found that there is a high level of correlation between the moisture content of the panels and the frequencies of the first two vibration modes. Another relevant aspect is that during seismic events, the structure shows changes around the fundamental frequencies, highlighting the need for further studies on this phenomenon. It is important to highlight that more dynamic evaluations are required due to seismic excitations.

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