WCTE Auckland 2012
16 - 19 July
World Conference on Timber Engineering

# VIBRATIONAL PERFORMANCE OF CROSS LAMINATED TIMBER FLOORS

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**ABSTRACT:** This study investigated the vibration behaviour of a cross-laminated timber (CLT) floor plate under various support conditions. CLT floors consisting of up to a total of four CLT panels were tested with two and four sides simply supported. The floor specimens tested included a single CLT panel simply supported at both ends and then with a second, third, and fourth panel progressively added. The same was done with the floor supported on all four sides. Natural frequencies of each floor configuration are presented. The study also included investigating the influence of fastening the CLT panels at the perimeters of the floor with screws when supported on all four sides. The natural frequencies are predicted using a model proposed by Leissa [4]. The predicted frequencies are somewhat different from the measured values. The modulus of elasticity, $E_x$ and $E_y$, and the modulus of rigidity, $G_{xy}$, of an individual panel were measured using a vibration method proposed by Sobue and Katoh [5]. This study also presents the results of vibration tests and predicted natural frequencies of selected floors in a three-storey CLT building.

**KEYWORDS:** Floor vibrations, cross laminated timber, natural frequencies, support condition

## 1 INTRODUCTION

The replacement of concrete slabs with cross laminated timber (CLT) plates leads to lighter floor systems. To prevent disturbing floor vibrations, close attention must be paid to the design of the CLT floor systems and their support characteristics.

Recent design criterion for controlling floor vibration requires the calculation of fundamental natural frequency and the static deflection under a 1 kN load [2]. Fairly accurate predictions of the fundamental natural frequency can be obtained by considering the floor to be a simply supported beam or plate [1].

Typically, the models used in design assume simple support conditions. However, this assumption may not be valid under certain conditions. Jarnerö et al. [3] studied the vibrational behaviour of CLT floors under laboratory conditions and in-situ. They observed that in-situ support conditions have an important effect on damping and natural frequencies of the CLT floor. The researchers also recorded important differences between finite element (FE) analysis results and results obtained from laboratory and in-situ tests. The authors state that the differences were due to the use of incorrect stiffness properties in the FE analysis. Fitz [1] also observed that when the support conditions are more complex, e.g. multiple-span with all edges supported, even relatively sophisticated methods, such as the finite element, produce predictions that can be very different from measured values. Thus, further work should concentrate on understanding how the construction details affect the dynamic characteristics of CLT floors. The information will be useful to produce recommendations on floor vibration serviceability design of CLT floors against excessive floor vibration.

The review of previous research has suggested that there is a need to focus the future research on the effect of support configurations (e.g., multiple-span and support flexibility) on the natural frequencies of CLT floors. Furthermore it is of interest to obtain accurate elastic properties of CLT panels to apply as model input.

## 2 OBJECTIVES

The study's objective is to develop an initial understanding of the influence of support conditions and floor width on natural frequencies of a CLT floor. This was achieved by testing a CLT floor supported on two and all four sides. In each support condition, the floor width was increased progressively from one to four panels. The effect of fastening all four edges of the floor with screws was also studied. The laboratory test results are compared with results from a prediction model proposed by Leissa [4] for orthotropic rectangular plates.

To determine the elastic properties of the CLT plates, the vibration method developed by Sobue and Katoh [5] was used. In this test, the CLT panel is simply supported at the bottom edge while standing vertically on edge with the other three edges free. Three natural frequencies are measured which allow the calculation of two elastic moduli, $E_x$ and $E_y$, and the shear modulus, $G_{xy}$. This would allow a preliminary evaluation of the validity of

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applying this test method to measure elastic properties of CLT panels.

In addition to laboratory tests, in-situ tests have been conducted to determine the fundamental natural frequency of CLT floors within a three-storey building. These measurements were compared with predictions from the Leissa model [4].

# 3 METHODOLOGY

## 3.1 LABORATORY CLT FLOOR STRUCTURE TESTS

The 5-layer CLT panels used in this investigation have the following dimensions: 1.02 m x 4.870 m x 0.132 m. A total of four CLT panels were used to construct a 4.870 m x 4.08 m CLT floor in the laboratory (Figure 1b). Tests were conducted when the floor was supported on two sides and on all four sides. Initially a floor consisting of one CLT panel supported at two ends and then all four sides was tested. The floor width was progressively increased by adding a second, third and a final fourth panel to the floor specimen (Figures 2 and 3). The floor was retested at each floor width. The floor specimens were generally fastened to the supports using wood screws along the perimeter of the floor. A few of the floor specimens were retested without the fastening to the supports (i.e., the CLT panels were simply resting on the supports) in order to observe the difference in natural frequencies.

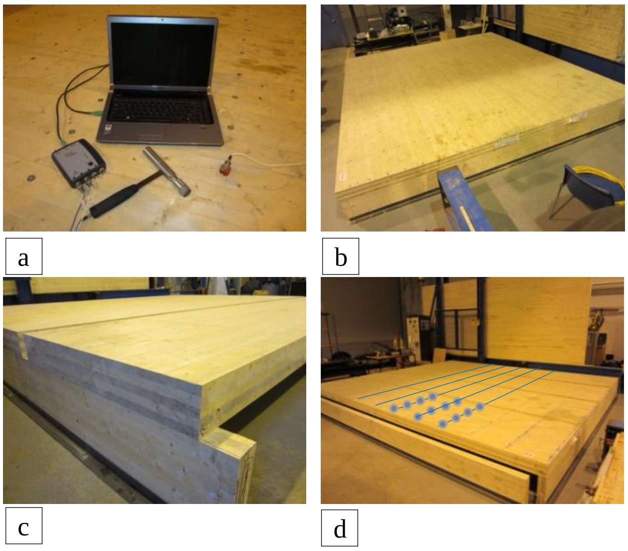

***Figure 1:** Vibration equipment and CLT floor.*

The panels were supported on 3-layer CLT strips 4.265 m x 0.305 m x 0.079 m which were fastened to steel brackets that were in turn bolted to the laboratory concrete slab floor (Figure 1c). The screws used for fastening CLT panels to support were WT-T-8.2mm x 300mm self-tapping screws, and they were spaced at 30 cm apart. Adjacent CLT panels were connected using WT-T-6.5mm x 160mm self-tapping screws. At each connection location, there was a pair of screws inserted at a 45° angle from each connecting panel with a gap of 3.5 cm between them (Figure 2b). The connection spacing was 30cm.

The vibration test was performed by impacting the floor at a location while moving the response sensor (accelerometer) along a constructed grid. The grid was formed with metal washers glued to the floor surface to which the accelerometer could be attached via a magnet (Figure 1d). The grids varied from 12 x 4 to 12 x 8 depending of the size of the floor structure. The vibration equipment used is shown in Figure 1a. It consists of an instrumented impact hammer, accelerometer, a dynamic signal analyser and the modal analysis software installed in a portable computer. The impact hammer kit includes tips with varying hardness and an additional weight attachment to ensure proper excitation force characteristics. A load cell was attached to the hammer which measured the impact force time signal. A ceramic shear accelerometer type 8784A5 produced by Kistler Instrument Corporation was used to measure the acceleration response to an impact caused by the impact hammer. The acceleration and hammer impact force time history signals are connected to a dynamic signal analyser, PHOTON+, which captures and processes these signals. RT Pro 6.33 signal analysis software produced by LSD Dactron converts the time domain signals into frequency domain signals using the Fast Fourier Transform (FFT) algorithm. The RT Pro 6.33 software was set to calculate a total of 800 data points in the frequency range of 0-200 Hz. The frequency domain data permits the identification of natural frequencies and mode shapes.

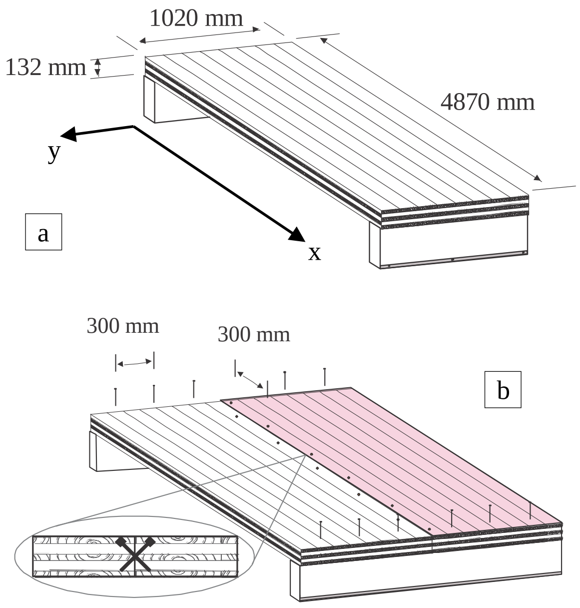

***Figure 2:** CLT floor supported on two sides.*

## 3.2 SOBUE AND KATOH (1982) VIBRATION METHOD

For the Sobue and Katoh [5] non-destructive test method, one of the CLT panels used for test floor construction was chosen for modal testing. The panel was supported on one edge inside a steel frame and clamped with three pairs of steel L-brackets at the bottom to simulate a simple support condition (Figure 4). These three pairs of steel L-brackets were located at the centre and at a distance of 610 mm from each edge of the plate. A 6 x 12 grid was used to capture modal displacements along the plane (x-y) of the panel and be able to construct complete mode shapes of each interested vibration modes of the CLT panel. The panel was tapped with an impact hammer at a location 15 cm in from one of the top corner of the panel. The vibration response was measured using an accelerometer which was moved along the grid sequentially to allow the interested mode shapes to be captured.

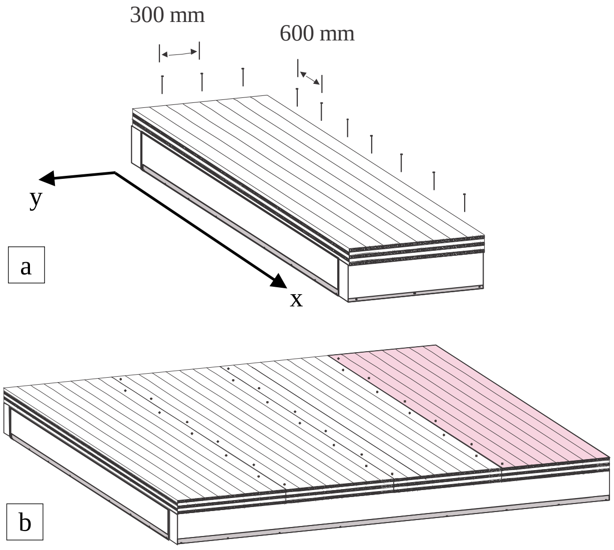

***Figure 3:*** *CLT floor supported on four sides.*

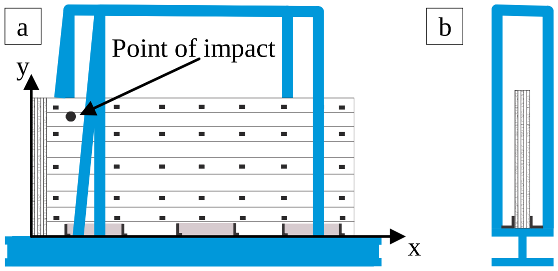

***Figure 4:*** *CLT panel vertically supported on one edge inside a steel frame.*

### 3.3 IN-SITU TESTS OF DOUBLE SPAN CLT FLOOR

In addition to the laboratory test, the results of in-situ vibration test on a three-storey CLT apartment building are presented. The CLT building has double-span CLT floors consisting of four 5-layer CLT panels with dimensions 2299 mm x 12016mm x 184 mm. Two floors in the building were tested, one in the second storey and another in the third storey. A grid was drawn and washers were screwed to the floor (Figure 5a). The same RT Pro 6.33 vibration equipment was used for the test. A larger impact hammer was utilized to excite the floor. The location of impact was held constant for each floor. The accelerometer was moved around the grid to measure and record the vibrations. In one of the floors tested, measurements were made both on the upper and lower (i.e., ceiling of the lower storey) surfaces of the floor. This was necessary because there was an acoustic floor overlay on the top surface, which affected the quality of the measurements.

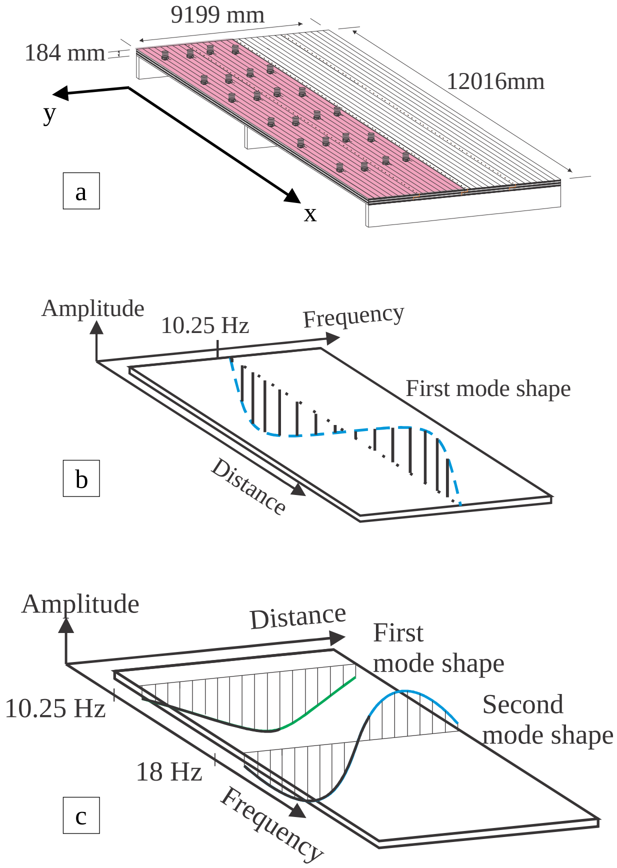

***Figure 5:*** *Double-span in-situ CLT floor.*

## 4 RESULTS AND DISCUSSION

### 4.1 NATURAL FREQUENCIES

The frequency spectra produced by the spectrum analyser software permitted the identification of peaks that corresponded to the natural frequencies of each floor. It was always the case that the first peak corresponded to the first natural frequency. Other frequencies required further analysis to identify. Frequencies that correspond to torsional modes were also detected. The notation $f(m,n)$ defines the frequency, $f$, with mode shape $(m,n)$. For plates supported on two opposite ends, $m$ is the number of half sine waves along the x-axis and $n$ is the number of nodes on the y-axis. For plates supported on four sides, $m$ and $n$ define the number of half sine waves in the x and y directions, respectively.

The frequencies $f(1,0)$, $f(2,0)$ and $f(3,0)$ for the floor supported on two sides are presented in Table 1. It can be observed that both the first and second natural frequencies are consistent as more CLT panels were added to the floor structure. The third natural frequency shows a minor steady decrease as the width of the floor was increased. Their mode shapes are shown in Figure 6, where Figure 6a corresponds to $f(1,0)$, Figure 6b to $f(2,0)$ and Figure 6c to $f(3,0)$. The mode shapes were constructed with the graphing tools provided by Microsoft Office Excel 2007.

***Table 1:*** *Frequencies of CLT floor supported on two opposite sides.*

| Aspect ratio | a/b = 4.8 | a/b = 2.4 | a/b = 1.6 | a/b = 1.2 |
|---|---|---|---|---|
| Mode | 1 panel | 2 panels | 3 panels | 4 panels |
| $f(1,0)$ | 11.5 | 11.75 | 11.5 | 11.25 |
| $f(2,0)$ | 42.25 | 42.75 | 42.25 | 42.75 |
| $f(3,0)$ | 87 | 84.25 | 80 | 77.25 |

***Table 2:*** *Frequencies of CLT floor supported on four sides.*

| Aspect ratio | a/b = 4.8 | a/b = 2.4 | a/b = 1.6 | a/b = 1.2 |
|---|---|---|---|---|
| Mode | 1 panel | 2 panels | 3 panels | 4 panels |
| $f(1,1)$ | 79 | 22 | 15.75 | 12 |
| $f(2,1)$ | 102.75 | 47.25 | 42 | 39.5 |
| $f(3,1)$ | 126 | 79.25 | 76.25 | 74 |

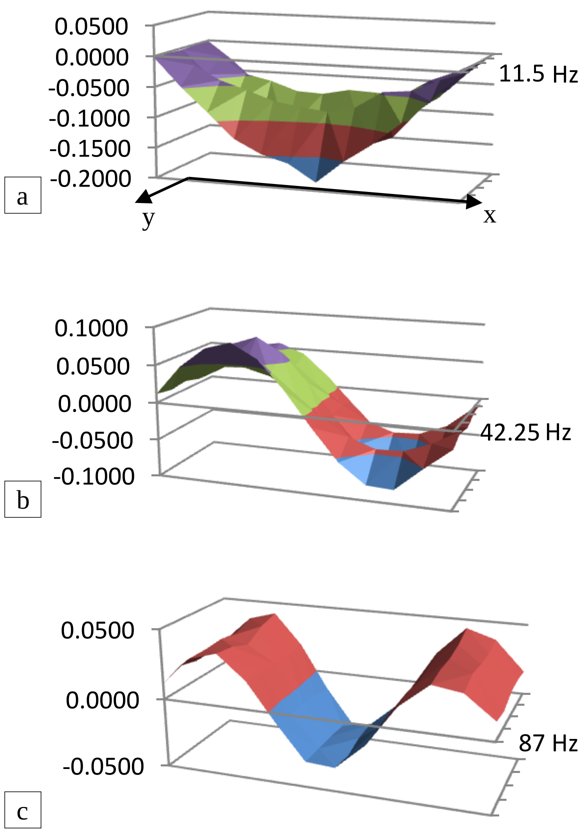

***Figure 6:*** *Mode shapes for the frequencies* $f(1,0)$, $f(2,0)$ *and* $f(3,0)$ *of a single CLT panel supported on two sides.*

Bending mode shapes for the CLT floors supported on four sides are presented in Figure 7. Other modes shapes are detected, torsional ones are present in wider CLT floor systems with three and four panels. Figures 7a, 7b and 7c correspond to the frequencies $f(1,1)$, $f(2,1)$ and $f(3,1)$, respectively, of the floor built with four CLT panels supported on four sides. Their natural frequencies are presented in Table 2. The results show a decrease for each of the frequencies as the floor width increases. The single CLT panel has very high frequency values when compared to values with connected panels. This is a result of having a truly continuous plate and not a discontinuous one. Clearly, the results presented here demonstrate that the floor aspect ratio plays a key part in dictating the natural frequencies of CLT floor systems with all four sides supported. It is noted that as the floor width increases, with four sides supported, the frequency $f(1,1)$ approaches the first natural frequency, $f(1,0)$, observed with panels supported on two sides.

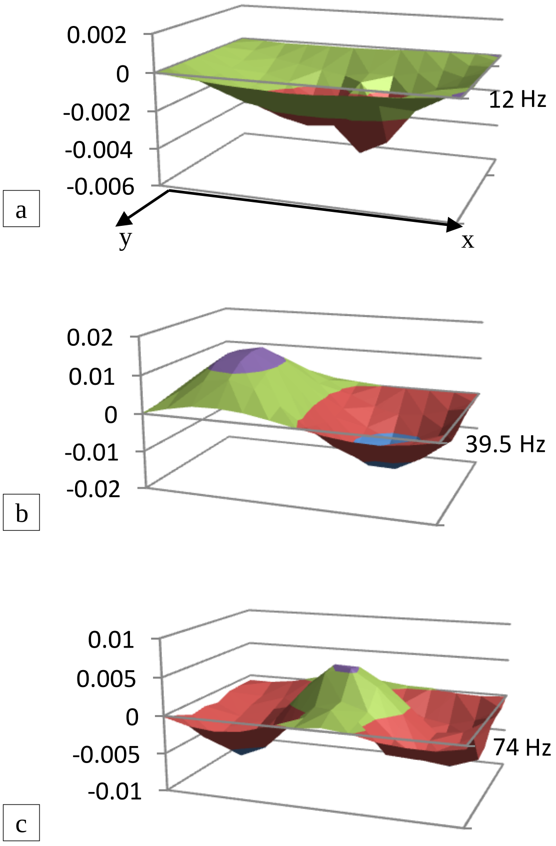

***Figure 7:*** *Mode shapes of frequencies* $f(1,1)$, $f(2,1)$ *and* $f(3,1)$ *of CLT floor (four panels) supported on four sides.*

***Table 3:*** *Frequencies of CLT floor supported on four sides after removing perimeter screws.*

| Aspect ratio | a/b = 4.8 | a/b = 2.4 | a/b = 1.6 | a/b = 1.2 |
|---|---|---|---|---|
| Mode | 1 panel | 2 panels | 3 panels | 4 panels |
| $f(1,1)$ | - | 19.75 | 14.5 | 11.5 |
| $f(2,1)$ | - | 47.5 | 39.5 | 37 |
| $f(3,1)$ | - | 76.25 | 71.25 | 69 |

Table 3 presents the natural frequencies of the floor with all four sides supported after the removal of perimeter screws. The decrease in frequency as the floor width increases is consistent with the results shown in Table 2.

It is noted that consistently natural frequency decreases after the removal of screws. The reduction on average is about 5%. This observation was to be expected because the removal of screws led to a reduction in support stiffness, making the floor system more flexible. Although the discrepancy was small, the type of support detail may explain some of the differences between measured and calculated natural frequencies in various studies because in practice the assumption of simple support is not always achieved.

## 4.2 PREDICTION MODEL

Leissa [4] presents a model to predict the fundamental natural frequency, $f_0$, of orthotropic rectangular plates simply supported on two, three and four sides, Equation 1. The equation is used to predict the frequencies of the floors supported on two and four sides in this work. It is of interest to assess the validity of the model in predicting natural frequencies of the CLT floor systems in this study built with one, two, three and four CLT panels and compare them with the experimental results.

$$f_0 = \frac{1}{2 \cdot \pi \cdot l^2} \cdot \sqrt{\frac{D_y}{g}} \quad \cdots$$
$$\cdot \sqrt{\pi^4 \cdot \left(\frac{D_x}{D_y}\right) + J \cdot \left(\frac{a}{b}\right)^4 + 2 \cdot \left(\frac{a}{b}\right)^2 \cdot \left[K \cdot \left(\frac{D_x \cdot \nu_y}{D_y}\right) + 2 \cdot L \cdot \left(\frac{H}{D_y}\right)\right]} \qquad (1)$$

where:

$$D_x = \frac{E_x \cdot h^3}{12 \cdot (1 - \nu_x \cdot \nu_y)} \qquad (2)$$

$$D_y = \frac{E_y \cdot h^3}{12 \cdot (1 - \nu_x \cdot \nu_y)} \qquad (3)$$

and,

$$H = \nu_y \cdot D_x + 2 \cdot D_{xy} \qquad (4)$$

$$D_{xy} = \frac{G_{xy} \cdot h^3}{12} \qquad (5)$$

with:

$D_x$ = plate flexural rigidity in the x-axis
$D_y$ = plate flexural rigidity in the y-axis
$D_{xy}$ = plate torsional rigidity
$E_x$ = elastic modulus in the x direction
$E_y$ = elastic modulus in the y direction
$g$ = mass per unit area of the plate (kg/m$^2$)
$h$ = thickness of the plate
$a$ = length of the plate
$b$ = width of the plate
$\nu$ = Poisson's ratio
$J$, $K$, $L$ = constants

***Table 4:*** *Leissa [4] constant values for plates supported on two, three and four sides.*

| Support condition | $J$ | $K$ | $L$ |
|---|---|---|---|
| SFSF | 0 | 0 | 0 |
| SSSF | 0 | 0 | 29.61 |
| SSSS | 97.41 | 97.41 | 97.41 |

S = simply supported edge, F = free edge

The material and mechanical properties assumed for the CLT panels are those presented in Table 5. The density was measured, while the elastic properties were partly confirmed from the plate vibration test discussed later in this paper, based on the method developed by Sobue and Katoh [5]. In this study Poisson's ratios $\nu_x$ and $\nu_y$ are assumed to be equal and are represented by $\nu$. It is of interest to see the effect that Poisson's ratio has on the predictions of natural frequencies. Therefore, predictions were calculated with $\nu$ = 0.30 and $\nu$ = 0.

***Table 5:*** *Mechanical properties assumed for CLT panels.*

| Property | Symbol | Mean value | Units |
|---|---|---|---|
| Elastic modulus parallel to face laminates | $E_x$ | 11700 | MPa |
| Elastic modulus perpendicular to face laminates | $E_y$ | 9000 | MPa |
| Shear modulus | $G_{xy}$ | 731 | MPa |
| Density | ρ | 560.0 | kg/m$^3$ |
| Poisson's ratio | $\nu$ | 0.0 - 0.30 | |

Table 6 presents the predictions of natural frequencies for CLT floors simply supported on two sides and on four sides assuming $\nu$ = 0.30. For the floor supported on two sides, it can be observed that the increment of width along the supporting sides has zero effect on the first natural frequency $f_0 = f(1,0)$. This is consistent with the values obtained from experimentation shown in Table 1, in which minimal change between frequencies was observed as additional CLT panels were connected. On the other hand, large differences are seen with predictions for plates supported on four sides and the laboratory results.

***Table 6:*** *Predicted natural frequencies of floor systems supported on two and four sides using Leissa [4] model assuming $\nu$ = 0.30.*

| Aspect ratio<br>Mode | a/b = 4.8<br>1 panel | a/b = 2.4<br>2 panels | a/b = 1.6<br>3 panels | a/b = 1.2<br>4 panels |
|---|---|---|---|---|
| Predictions for plates simply supported on two sides | | | | |
| $f_0 = f(1,0)$ | 12.09 | 12.09 | 12.09 | 12.09 |
| Predictions for plates simply supported on four sides | | | | |
| $f_0 = f(1,1)$ | 257.14 | 75.36 | 41.27 | 29.06 |

Likewise, Table 7 presents the predictions with the model proposed for orthotropic rectangular plates supported on two and four sides, assuming $\nu = 0$. The predictions make it evident that as Poisson's ratio decreases, the fundamental natural frequency decreases slightly. Overall it can be seen that the results are not sensitive to changes in Poisson's ratio for plates supported on 2 sides, with the difference generally is about 5%.

***Table 7:*** *Predicted natural frequencies of floor systems supported on two and four sides using Leissa [4] model assuming* $\nu = 0$.

| Aspect ratio<br>Mode | a/b = 4.8<br>1 panel | a/b = 2.4<br>2 panels | a/b = 1.6<br>3 panels | a/b = 1.2<br>4 panels |
|---|---|---|---|---|
| Prediction for panels supported on two sides | | | | |
| $f_0 = f(1,0)$ | 11.54 | 11.54 | 11.54 | 11.54 |
| Prediction for panels supported on four sides | | | | |
| $f_0 = f(1,1)$ | 234.19 | 61.94 | 30.96 | 20.87 |

Leissa [4] also proposes a general model to predict natural frequencies for orthotropic plates simply supported on four sides, Equation (6). The model proposed by Leissa [4] permits the identification of natural frequencies for different modes, denoted by $f(m,n)$, where $m$ and $n$ are the number of half sine waves of a mode shape in the x and y directions, respectively in Equation (6). The equation for $f(1,0)$ reduces to that of $f_0$ shown in Equation (1).

$$f_{mn} = \frac{\pi}{2 \cdot l^2} \cdot \sqrt{\frac{1}{g}} \quad \cdots$$

$$\cdot \sqrt{D_x \cdot m^4 + 2 \cdot H \cdot m^2 \cdot n^2 \cdot \left(\frac{a}{b}\right)^2 + D_y \cdot n^4 \left(\frac{a}{b}\right)^4} \tag{6}$$

where:

$m$ = number of half sine waves in the x direction
$n$ = number of half sine waves in the y direction

The predicted values for natural frequencies $f(1,1)$, $f(2,1)$ and $f(3,1)$ are presented in Table 8 assuming $\nu = 0.30$. The difference between the predicted and experimental values is evident. The frequency predictions with the general model proposed by Leissa [4] are for continuous plates. It is possible for the CLT floor to have lower frequency values due to the discontinuities at the panel to panel connections, creating a rectangular plate structure with a lower stiffness than a continuous one. The predicted natural frequencies show a decreasing trend as the width of the floor is increased, simulating the addition of another CLT panel. This trend is consistent with that observed in the laboratory tests (Tables 2 and 3). The predictions differ substantially from the experimental results for floors with one, two and three CLT panels. The predicted natural frequencies for the floor with four panels are closer to the measured values but the differences are still significant. It is observed that as the aspect ratio decreases the predictions are closer to the laboratory results.

***Table 8:*** *Predicted natural frequencies for floor systems supported on four sides using Leissa [4] model assuming* $\nu = 0.30$.

| Aspect ratio<br>Mode | a/b = 4.8<br>1 panel | a/b = 2.4<br>2 panels | a/b = 1.6<br>3 panels | a/b = 1.2<br>4 panels |
|---|---|---|---|---|
| $f(1,1)$ | 247.71 | 67.00 | 34.27 | 23.39 |
| $f(2,1)$ | 268.01 | 93.55 | 65.48 | 57.08 |
| $f(3,1)$ | 308.43 | 147.33 | 123.79 | 116.73 |

Predictions using $\nu = 0$ with the general model for orthotropic rectangular plates are presented in Table 9. As observed before, comparing frequency predictions with plates supported on two sides, the predictions are lower with $\nu = 0$. The difference on average is about 10%, which means that for plates supported on four sides the predicted frequencies are more sensitive to Poisson's ratio. Since Poisson's ratio for a material such as CLT is difficult to measure, therefore this issue needs to be taken into perspective when comparing predicted with measured results.

***Table 9:*** *Predicted natural frequencies for floor systems supported on four sides using Leissa [4] model assuming* $\nu = 0$.

| Aspect ratio<br>Mode | a/b = 4.8<br>1 panel | a/b = 2.4<br>2 panels | a/b = 1.6<br>3 panels | a/b = 1.2<br>4 panels |
|---|---|---|---|---|
| $f(1,1)$ | 232.56 | 60.39 | 29.56 | 19.70 |
| $f(2,1)$ | 241.57 | 78.82 | 55.88 | 50.26 |
| $f(3,1)$ | 266.08 | 125.74 | 110.43 | 106.83 |

### 4.3 MEARUREMENT OF MECHANICAL PROPERTIES OF CLT PANEL

A non-destructive vibration test method was proposed by Sobue and Katoh [5] to measure elastic properties of plywood panels, namely the two elastic moduli ($E_x$ and $E_y$) and in-plane shear modulus ($G_{xy}$). It is of interest to determine if the method can also be utilized to measure the elastic properties of CLT panels.

The test method requires the identification of three natural frequencies from modal testing. Sobue and Katoh [5] provide frequency equations that are a function of the three elastic properties, density and Poisson's ratio of the plate material. By assuming a value for the Poisson's ratio, and since density can be measured, the three elastic properties can be calculated from three frequency equations.

Sobue and Katoh [5] provide equations for various combinations of three natural frequencies. This is necessary since the calculated properties can be sensitive to certain natural frequencies. In this study the vibration modes that were used in the calculation were: $f(1,1)$, $f(2,1)$, $f(1,2)$ and $f(3,1)$. In the modal tests performed, only *f*(1,1), *f*(2,1) and *f*(3,1) were successfully identified (Table 10). The value for *f*(1,2) was estimated to be 375.34 Hz.

***Table 10:*** *Measured natural frequencies from CLT panel test. (*value predicted using Sobue and Kato [5]).*

| Mode | Frequency (Hz) |
|---|---|
| *f*(1,1) | 17.75 |
| *f*(2,1) | 41.25 |
| *f*(3,1) | 89.25 |
| *f*(1,2) | 375.34* |

The elastic properties obtained using method [5] and the natural frequencies shown in Table 10 are presented in Table 11.

***Table 11:*** *Calculated elastic properties with vibration method proposed by Sobue and Katoh [5] assuming f(3,1) = 89.25Hz.*

| Property | Value (MPa) |
|---|---|
| $E_x$ | 12622 |
| $E_y$ | 9028 |
| $G_{xy}$ | 601 |

Examination of the spectra revealed that similar mode shapes for *f*(2,1) and *f*(3,1) respectively were noted. Peaks at 40.25Hz, 41.25Hz and 44.75Hz were detected for mode *f*(2,1). Similarly for *f*(3,1), three peaks were noted at 84.74Hz, 89.25Hz and 90.5Hz. For both modes the highest peak was assumed to be the true mode. For mode *f*(2,1) it was clearly 41.25 Hz. For *f*(3,1), the peaks at 84.74 Hz and 89.25 Hz were greater than at 90.5 Hz and similar. A question arises as to which one to employ. If 89.25 Hz is chosen then the elastic properties predicted are those presented in Table 11. Conversely if 84.74 Hz is used, the predicted elastic properties are those presented in Table 12.

***Table 12:*** *Calculated elastic properties with vibration method proposed by Sobue and Katoh [5] assuming f(3,1) = 84.75Hz.*

| Property | Value (MPa) |
|---|---|
| $E_x$ | 10282 |
| $E_y$ | 9007 |
| $G_{xy}$ | 696 |

The results shown in Table 11 are consistent with the assumption that CLT is an orthotropic material. The predictions seen in Table 12 suggest a more isotropic material. Considering the configuration of CLT panels, and how $E_x$ and $E_y$ are being interchanged with every additional layer, it is logical to assume that a more isotropic material is being formed as the number of layers increases.

The elastic properties measured with the vibration method proposed by Sobue and Katoh [5] cannot be confirmed reliably. Further research is necessary to evaluate this method.

## 4.4 IN-SITU VIBRATION TESTS

In-situ tests were performed on a three-storey apartment building constructed entirely of CLT panels in Desbiens, Quebec. The floor construction utilized 5-layer CLT panels, similar to the panels tested in the laboratory. In each apartment, the floor was a double-span system (6 m each). The width of each floor was 9.2 m for the first floor and 9.173 m for the second. Two floors were tested. A first frequency peak of 9.88 Hz for the first floor and 10.25 Hz for the second floor was identified from the measured spectra. Modal displacements were recorded for these two frequencies. The mode shape for the frequencies of 9.88 Hz and 10.25 Hz is a sinusoidal wave in the longitudinal direction, confirming them to be the first natural frequency of the CLT floors. The second natural frequency for the first floor was 18 Hz, showing two half sine waves in the y-direction. For the second floor, two frequencies with similar mode shapes were identified at 13.54 Hz and 17.21 Hz, having two half sine waves in the y-direction.

Using Leissa's model [4] for orthotropic rectangular plates simply supported on two and four sides; the first frequency is calculated for a plate with the in-situ test dimensions 6m x 9.2m x 0.184m, i.e., the double-span floor was treated as two separate simply supported single-span floors.

***Table 13:*** *Comparison between predicted and measured frequency of in-situ floors.*

| Floor | Frequency | in-situ | SFSF | SSSS |
|---|---|---|---|---|
| 1 | *f*(1,0), *f*(1,1) (Hz) | 9.88 | 9.93 | 11.7 |
|  | Percent difference | -- | 0.5% | 18% |
| 2 | *f*(1,0), *f*(1,1) (Hz) | 10.25 | 9.93 | 11.7 |
|  | Percent difference | -- | 3% | 14% |

The predicted first natural frequency for the two in-situ test floors using the Leissa model [4] are presented in Table 13, assuming $\nu = 0$, elastic properties shown in Table 12 and a span of 6 m. Results for SFSF and SSSS systems are presented. The percent differences between the measured and predicted frequencies are also given in Table 13. It can be noticed that based on the assumptions presented, the model provides accurate prediction of the two-span floor using SFSF support condition. A greater percent difference is observed for a prediction using SSSS support condition. In the building, the test floors were supported on all four sides. This may point to the possible use of single-span model to predict the first natural frequency of double-span floor systems. This finding should be treated with caution, however, because of the assumptions made and that only two similar floors were tested. Further work needs to be carried out to provide more evidence.

## 5 CONCLUSIONS

Based on vibration tests conducted in the laboratory on CLT floor systems, the following observations can be made:
- For floor systems with two sides supported, natural frequencies remain fairly constant as the floor width increases.
- For floor systems with four sides supported, natural frequencies decrease as floor width increases.
- The use of screws along the perimeter of the floor structure increases the natural frequencies of the CLT floor structure.
- Torsional modes were detected in wider CLT floor systems.

A model proposed by Leissa [4] to predict natural frequencies of orthotropic rectangular plates supported on two and four sides was evaluated to assess its validity to predict natural frequencies of CLT floor systems. The following conclusions can be made:
- The model is accurate in predicting the first natural frequency of CLT floors supported on two sides.
- For a floor supported on all four sides, the model generally provides poor predictions, with substantial over-estimations of the first natural frequency. However the difference between predicted and measured frequencies decreases as floor width increases. It is possible that for floors with small aspect ratio (span to width), the Leissa model could provide reasonable predictions for a system with all four sides supported.

In addition, a general model for rectangular plates supported on four sides, also proposed by Leissa [4] is considered to predict frequencies for the modes $f(1,1)$ $f(2,1)$ and $f(3,1)$ of the laboratory test CLT floor.
- The model gives poor predictions for all test set ups. It is observed that as the floor size increases the predictions improve for all three modes.

A non-destructive vibration test method proposed by Sobue and Katoh [5] to measure elastic properties of CLT panels was evaluated. Although preliminary results are promising there are test set-up issues that need to be addressed first before the test method can be reliably applied to test CLT panels.

In-situ test permitted the identification of fundamental natural frequencies of two double-span CLT floors in a 3-storey apartment building. It is noted that the Leissa model (1) of single-span orthotropic plate provides reasonable estimate of the first natural frequency.

## ACKNOWLEDGEMENT

This research was supported through funding to the NSERC Strategic Network on Innovative Wood Products and Building Systems.

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