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THE USE OF CROSS LAMINATED TIMBER FOR LONG SPAN FLOORING IN COMMERCIAL BUILDINGS

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ABSTRACT: Long span timber floor solutions have demonstrated their potential to compete with concrete and steel construction for multi-storey commercial buildings. Due to the high strength-to-weight ratio of timber, serviceable vibration performance is a critical structural design issue for long spans. This project investigates the vibration performance of cross laminated timber for long span floors in the Australian and New Zealand building sector. Laboratory experiments and computer analysis are used to study the effect of the increased transverse stiffness, inherent to a cross laminated timber, on the vibration performance of the floor. The effect of boundary conditions, connection and support type, are investigated and quantified where possible. A timber joist floor with a plywood sheath is analysed and tested to validate the methods used in this study.

KEYWORDS: Cross Laminated Timber, Vibration, Plate behaviour, Connections, Numerical analysis

1 INTRODUCTION

In Australia and New Zealand, the cost of multi-storey building construction has remained high, primarily due to the high price of steel, concrete and labour. A number of national studies have indicated the potential for timber to become a structural alternative, particularly for use in mid-rise buildings [1-3]. This can be attributed to the high level of prefabrication possible with timber structures and its low density, both of which contribute to reduced construction time, lower labour and transportation requirements.

Steel and concrete construction allow for large scale column grid floor plans desired for commercial and mid-rise residential buildings. Spans of at least 9m are desired for parking spaces at basement level and open floor office layout on the levels above. For timber to compete with these conventional materials, it is essential to span at least as far while retaining its edge as a light-weight, prefabricated building product. This study is part of a larger project investigating long span timber floor solutions for commercial buildings.

Timber has a high strength-to-weight ratio, higher than both steel and concrete, which means timber floors can span further with reduced weight. Light-weight and long span floors are, however, susceptible to levels of serviceable vibrations that cause annoyance to the building occupants. In fact for spans over 4m, vibration is commonly the critical design parameter for timber floors and therefore is the focus of this study [4].

1.1 CROSS LAMINATED TIMBER

Cross laminated timber (CLT) is now a well-established structural building material in Europe for both single dwelling residential and multi-storey buildings. There is currently limited manufacturing capability in Australia and New Zealand, with the sole CLT plant located in New Zealand. However the method of fabrication of CLT allows large dimensioned panels, whole wall and floor panels, to be manufactured and transported internationally with relative ease. Forte, a 10-storey CLT building located in Melbourne, was constructed from material shipped in from Austria. Despite the transportation distance, the CLT building still displayed an economic advantage compared with concrete and steel construction.
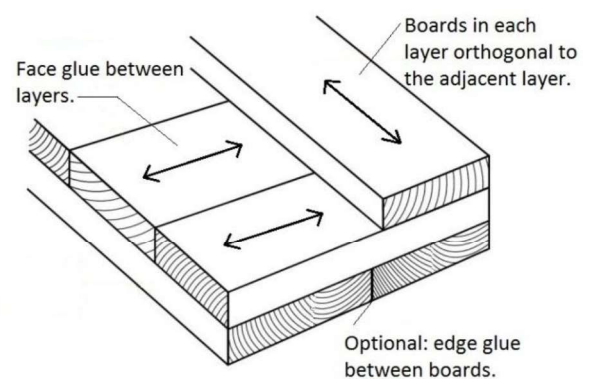

Figure 1: The arrangement of a CLT panel.

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A CLT panel is usually composed of an uneven number of layers, generally 3 or 5 but sometimes more with each layer orientated orthogonal to the adjacent layer, as shown in Figure 1. The outer layers of a CLT floor are generally orientated longitudinal to the primary load path, to provide the required cross-sectional stiffness. The layers orientated in the transverse direction to the load path act as reinforcement to the panel. This arrangement of layers in a CLT floor provides the panel with a larger ratio of transverse-to-longitudinal stiffness than joisted timber floors systems. This means similar to a reinforced concrete slab, CLT is capable of spanning in two directions.

Analytical methods to predict the vibration behaviour of long span timber floors have been developed in Europe and one method specific to CLT in Canada [5].These methods provide calculations and limits for natural frequency, unit deflection, velocity and acceleration of a timber floor. In these methods, CLT is assumed to be a 1-dimensional linear element, which for standard cases can be a valid assumption, however does not fully take into account the two-way spanning nature of CLT. The methods also do not account for the vibration performance being highly sensitive to the load type and boundary conditions. Previous studies have shown that connection type (panel-to-panel and panel-to-supporting element), and loading scenario have a significant effect on the natural frequency and damping characteristics of the floor [6]. Therefore, this study not only focuses on finding long span timber floor solutions that satisfy serviceable vibrations, but also provides boundary condition values for the design analysis procedure.

2 METHODOLOGY

This paper investigates methods used to quantify the vibration characteristics of timber floors. These can be broken down into three methods:

- Current vibration design guidelines.
- Finite element analysis.
- Experimental modal analysis.

Analytical methods that are used to design timber floors are discussed and used to predict the vibration performance of a CLT floor. These methods limit the static deflection, natural frequency, velocity and acceleration of the floor to ensure acceptable vibration performance. A finite element (FE) study is then employed to create a reasonable model to predict the modal characteristics of the floor. This model is then verified using experimental modal analysis. The purpose of verifying and model updating the FE model is to ensure accuracy and to enable parametric studies of the CLT floor. The methodology is verified using a joisted floor with a plywood sheath. The joisted plywood floor has a high span-to-depth ratio and is light in weight. Therefore the floor serves as a good verification of the methodology as it simulates similar conditions of long span floors with low natural frequencies and high accelerations.

2.1 CLT FLOOR PROPERTIES

The CLT floor is sourced from Xlam, which is currently the only CLT manufacturer in Australia and New Zealand, using locally supplied Radiata Pine and Douglas Fir to produce their panels.

The floor is 5.9m in length with a clear span of 5.6m and composed of three adjacent panels, each 2.25m in width as shown in Figure 2. The panels have half lap connections of 50 mm in depth to connect each panel together. The total floor width is therefore 6.65m. The cross section is made up of 5 layers of 35 mm thick lumber.
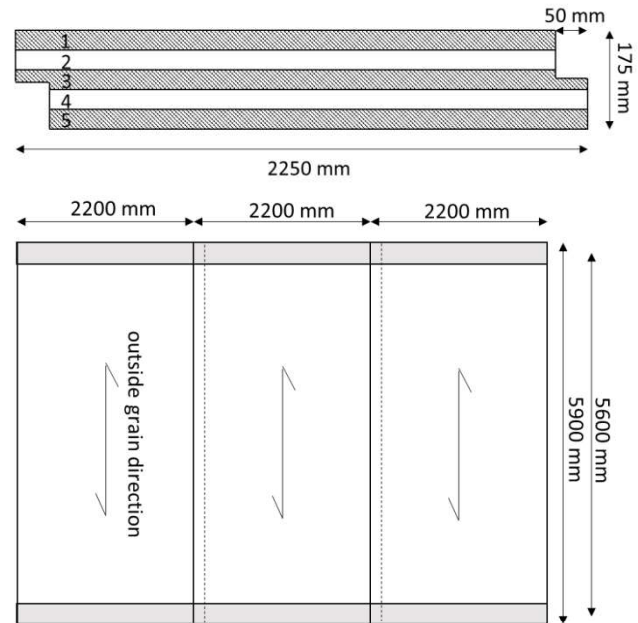

Figure 2: Cross-section of CLT floor plate (top). Plan of CLT floor (bottom).

Due to the cross lamination of the panel the orthotropic material properties of timber become more important than with linear post and beam timber floor systems. The elastic and shear modulus of the strong axis of the timber (along the grain) along with the timber density are supplied by the manufacturer. For the analytical methods discussed in section 3, these values provide enough information to estimate the floor vibration performance. However, for the finite element model, properties in all directions (X,Y & Z) are required. The values used in this study are included in Table 1. These values are based on the manufacturers' guidelines if available and otherwise taken from literature [7].

Table 1: Material properties of CLT.

Layer number	1,5	2,3,4
E_X/ E_Y/ E_Z (GPa)	8.0/ 0.64/ 0.8	6.0/ 0.48/ 0.6
G_{XY}/ G_{YZ}/ G_{XZ} (GPa)	4.0/ 0.4/ 4.0	4.0/ 0.4/ 4.0
μ_{XY}/ μ_{YZ}/ μ_{XZ}	0.3/0.45/0.35	0.3/0.45/0.35
ρ (kg/m^3)	460	460

2.2 PLYWOOD FLOOR PROPERTIES

To verify the procedure of the study a timber joisted floor is investigated. The floor (shown in Figure 3) is composed of laminated veneer lumber (LVL) joists at 600 centres, compositely attached to 21 mm thick F11 plywood. A total of 4 joists, each 90 mm deep and 45 mm wide, span the floor. The floor is 4800 mm in length with a clear span between supports of 4500 mm. Screws at 125 mm spacing connect the timber joist to the plywood floor.
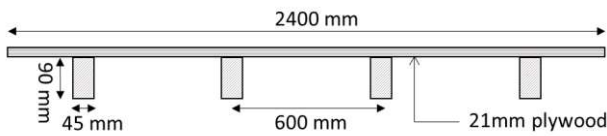

Figure 3: *Cross-section of plywood joisted floor.*

The elastic modulus, Poisson's ratio and density of the timber are taken from the manufacturer's specifications and are shown in Table 2. Both the LVL and the plywood are orthotropic materials. However since the floor system is one-way spanning and arranged linearly, for simplicity the material properties are treated as isotropic.

Table 2: *Material properties of plywood joisted floor.*

Material	E_x (GPa)	μ_{XY}	ρ (kg/m^3)
LVL	13.2	0.3	650
Plywood	10.5	0.3	690

3 VIBRATION DESIGN GUIDELINES

To provide vibration design criteria to structural designers there has been a significant amount of international research on design guidelines that require little to no advanced computing methods. The current vibration design guidelines from Australian timber standards and codes are limited. The standard for Structural Design Actions [8], provides a static unit deflection limit of 1-2 mm under a mid-span unit point load. Specifically for timber structures the standard draws attention to the fact that "deflection limits do not necessarily ensure satisfactory dynamic performance", however no other guidelines are given [9]. Reference is made to AS 2670 [10] which provides acceptability limits in the form of root mean square (RMS) accelerations, however this does not provide a method to calculate the vibration performance of the floor.

Therefore this paper looks at methods that have been developed in other regions of the world, specifically Europe and North America. These methods provide calculations and limits for one or more of the following floor properties; natural frequency, deflection, velocity and acceleration. Limits for frequency are based on avoiding resonance with the 1st harmonic of walking frequency (around 1.5 – 2.5 Hz) plus subsequent harmonics. A method provided by Eurocode 5 limits the

frequency to a minimum of 8Hz [11]. This is due to a study of more than 100 problematic floors that were found to have a fundamental frequency range of 5-8 Hz [12]. However, further studies by Hamm et al. [13] on floors of 50 existing buildings found some floors with natural frequencies over 8 Hz, particularly the lighter floors, did not satisfy acceptable vibrations while a number of floors with natural frequencies between 5-8 Hz had acceptable vibration performance. The study concluded that the stiffness and the acceleration of the floor were also important parameters and provided an extension to the Eurocode 5 method that allowed floor natural frequencies below 8 Hz for heavier floors. Another method developed for the UK Timber Research and Development Association, provides vibration design for joisted timber floors and is reported to be widely employed in Australia and New Zealand [14]. It also limits floor frequency to 8Hz under dead load only and provides a limit of 0.45 m/s^2 to the RMS acceleration caused by a human with a mass of 70 kg performing a heel drop [15].

There have been a number of reviews of these various design guidelines and methods developed internationally [14]. Therefore this paper considers only the static unit deflection suggested by Australian code and compares it with the more comprehensive method provided by Eurocode 5.

3.1 STATIC DEFLECTION LIMIT

Both floors are assessed with a simple static unit load deflection limit of 1-2 mm given by:

$$\Delta = \frac{1000 l^3}{48 E I_{eff}} \geq 1 - 2 mm \qquad (1)$$

where Δ = deflection, l = floor length and EI_{eff} = the effective stiffness of the floor.

For a joisted floor with no composite action between the sheathing and joist, the effective stiffness (EI_{eff}) can simply be calculated using the properties of the joist only. However the plywood floor in this study is compositely connected to the joist with screws at 125 mm centres and therefore the contributing effective width (b_{eff}) of the floor cross-section, contributes to the floors stiffness.

The effective stiffness (EI_{eff}) for both the CLT floor and the plywood floor is calculated using Equation (2), by multiplying the longitudinal stiffness for a 1 m cross section of floor (EI_l), with an effective width factor b_{eff}. The effective width given by Equation (3) is a ratio of the 4th root of the floors transverse stiffness (EI_t) to its longitudinal stiffness (EI_l) [16].

$$EI_{eff} = b_{eff} \cdot (EI_l) \qquad (2)$$

$$b_{eff} = \frac{l}{1.1} \sqrt[4]{\frac{EI_t}{EI_l}} \qquad (3)$$

The CLT floor deflected by 0.41mm while the plywood joisted floor deflected 4.05mm as shown in Table 3. A strict limit of 1mm allowable deflection was applied to both floors to reflect the more stringent criteria of commercial buildings. The CLT floor passed the criteria, while the plywood floor deflected more than 4 times the limit.

Table 3: Results of floor deflection under a static unit point load.

Floor type:	CLT	Plywood
Δ (mm)	0.41	4.05
Δ_{lim} (mm)	1	1

3.2 EUROCODE 5

Eurocode 5 provides acceptable vibration design guidelines for residential timber floors [11]. The code provides equations and limits for the static deflection, fundamental frequency and velocity of the floor. The static deflection is calculated much the same as Equation (1) however Eurocode provides limits between $1 - 4$ mm depending on the design "stringency". For commercial floors a high stringency is required, therefore the results of Table 3 satisfy the deflection criteria for these floors. The fundamental frequency of the floor is calculated using the Equation 4, below:

$$f_1 = \frac{\pi}{2l^2} \sqrt{\frac{EI_l}{m}} \geq 8 \; Hz \qquad (4)$$

where f_l = fundamental frequency, l = floor length, EI_l = longitudinal stiffness and m = static mass per unit floor area (kg/m^2).

The natural frequency of the timber floor is limited to a minimum of 8 Hz, to avoid vibrations caused by resonance. Eurocode states that frequencies of 8 Hz can be acceptable with a "special investigation" required, however, it does not provide guidelines for this investigation. Both the CLT and plywood floor satisfy the frequency limit with fundamental frequencies of 9.05Hz and 9.32Hz respectively (Table 4).

The velocity (v) due to an impulse of 1Ns is calculated using Equation (5), where b is the transverse width of the floor, β is a parameter provided by the code that defines the level of velocity tolerable by human occupants and ζ is the floor damping. The value for β is taken from the code and is equal to 120 for a floor with high stringency.

$$v = \frac{4(0.4 + 0.6n_{40})}{mbl + 200} \leq \beta^{(f_1\zeta-1)} \; m/(Ns^2) \qquad (5)$$

The number of first order modes (n_{40}) with natural frequencies up to 40 Hz is used to calculate the velocity:

$$n_{40} = \left\{ \left(\left(\frac{40}{f_1} \right)^2 - 1 \right) \left(\frac{b}{l} \right)^4 \frac{EI_l}{EI_t} \right\}^{0.25} \qquad (6)$$

A value for damping, is specified by the code as equal to $\zeta = 1\%$. For light weight timber floors the first mode of vibration of damping is generally around 2%, however when considering higher modes, the damping can be as low as 0.8% and therefore the low damping value of 1% is acceptable to use [17]. The results in Table 4 show that the velocity of the plywood floor is above the allowable limit while the CLT provides an acceptable floor design.

Table 4: Results of floor fundamental frequency and velocity using the vibration design method provided by Eurocode 5.

Floor type:	CLT	Plywood
f_1 (Hz)	9.05	9.32
f_{lim} (Hz)	8	8
v (m/Ns^2)	3.24	19.46
v_{lim} (m/Ns^2)	12.85	13.02

4 FINITE ELEMENT ANALYSIS

The cross laminated timber (CLT) floor and the joisted plywood floor are analysed using finite element analysis (FEA) software ANSYS Mechanical APDL 16.0. A sensitivity study is conducted on both floors. The first 5 mode shapes and frequencies are predicted.

4.1 CLT FLOOR

The CLT floor is modelled using SHELL181 laminate elements which are suitable for analysing moderately-thick shell structures. These are four node elements with 6 degrees of freedom at each node as shown in Figure 4. Each laminate represents an individual layer of the CLT panel, the arrangement of the layers is shown in Figure 5. Shell laminate elements provide a computationally efficient and accurate method to model the changing grain direction of the CLT panels.

The floor has been analysed with two different support conditions; two opposite edges supported (one-way span) and with all four edges supported (two-way span). The purpose of changing support condition is to activate the transverse stiffness of the CLT panel and to understand which material properties and boundary conditions govern the vibration performance of the floor.
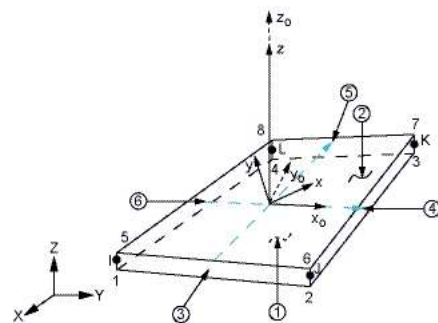

Figure 4: The geometric properties and local axis reference of SHELL181 elements [18].
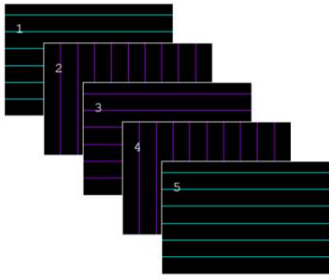
Figure 5: The laminate orientation of the CLT floor plate.

The boundary conditions of the CLT slab have to be carefully considered. There are a number of methods to connect CLT floor plates to the supporting structure (beam or wall element) [19]. These include a single screw connection as shown in Figure 6, a double screw connection, a ledger support and the use of a T-plate or threaded rod. To simplify and accurately capture the support condition a MATRIX27 element was selected. This element represents an arbitrary element with undefined geometry and is specified by its stiffness, damping and mass coefficients. Therefore the element allows the connection to be specified by its values of stiffness without modelling the complexity of its geometry. The half-lap connection is modelled using the same technique. For the preliminary model only the translational stiffness of each connection is activated as there is unlikely to be any rotational capacity in a simple screwed connection.
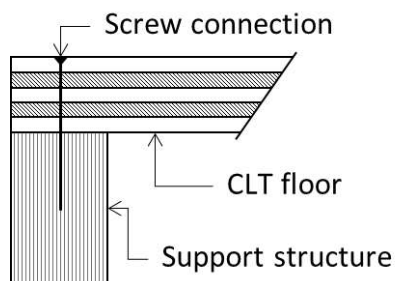

Figure 6: Example of support condition of CLT floor plate.

The first 5 natural frequencies and mode shapes are shown in Table 5. Despite the increased stiffness of the two-way floor due to the additional supports, there is less than a 1Hz difference between the fundamental frequency of the one-way and two-way slab. This is due to no rotational continuity between the half-lap connections, which decreases the influence of the edge supports on the middle panel. However, the benefit of the extra stiffness of the two-way slab is demonstrated in the separation of the lower modes. Closer modes can have a negative effect on vibrational response since they interact to produce motions with relatively high amplitudes [20]. The increased transverse stiffness of the two-way floor increases the modal separation and therefore is likely to improve the dynamic performance.

A sensitivity study was conducted on the elastic modulus, shear modulus, Poisson's ratio and the stiffness of both the support connection and the half-lap

connection. For the material properties specified by the manufacturer, the model was iterated between +/- 20% and the results recorded in Table 6. The results report the percentage change of the frequencies of the first 5 modes when the property is varied. Only the shear and elastic modulus are reported as the Poisson's ratio had no significant effect on the results. The results show that the elastic modulus of the transverse layers (layer numbers 2,4) of the one-way spanning CLT have no significant effect on the model with a 0.1-0.3% change in results. This implies that a lower quality of timber can be utilised for the middle layers. However attention should be given to what is known as the rolling shear modulus ($G_{YZ,T}$) of these layers. While the elastic modulus causes little effect on results, the rolling shear reports a $2.0 - 6.1\%$ change in results. The rolling shear is based on a number of factors including the quality of the material.

Table 5: Mode shapes of one-way and two-way spanning CLT floors.

Mode	One-way	Two-way
1		
f_1 (Hz)	9.0	9.7
2		
f_2 (Hz)	9.6	12.0
3		
f_3 (Hz)	11.8	32.1
4		
f_4 (Hz)	14.2	32.5
5		
f_5 (Hz)	31.4	34.3

For the two-way floor, the elastic modulus along the grain ($E_{X,T}$) of the transverse layers causes a larger sensitivity towards results than for the one-way floor. The two-way sensitivity of $E_{X,T}$ is 0-5.3% while for the one-way floor it is 0.1-0.2%. The other material property that is also activated in the two-way floor is the elastic modulus orthogonal to the grain direction ($E_{Y,L}$) in the longitudinal layers (number 1,3,5). This property affects the results by $0.1 - 3.8\%$. This result, however, assumes edge gluing between individual board layers to achieve

the cross grain continuity. This is not commonly the case with manufacturing CLT panels and so it is unlikely this material property will be activated. This is dealt with by lowering the value for modelling purposes.

Table 6: Sensitivity study on the material properties of the one-way spanning and two-way spanning CLT floor.

Component	Direction	Effect % One-way	Effect % Two-way
Longitudinal layers (1,3,5) Modulus of elasticity	$E_{X,L}$	6-19.4	4.9-15.9
	$E_{Y,L}$	0.1-0.3	0.1-3.8
	$E_{Z,L}$	No effect	No effect
Longitudinal layers (1,3,5) Shear modulus	$G_{XY,L}$	0-9	0.6-6.4
	$G_{YZ,L}$	No effect	No effect
	$G_{XZ,L}$	0.1-0.2	0-0.2
Transverse layers (2,4) Modulus of elasticity	$E_{X,T}$	0.1-0.2	0-5.3
	$E_{Y,T}$	0.1-0.3	0.1-0.2
	$E_{Z,T}$	No effect	No effect
Transverse layers (2,4) Shear modulus	$G_{XY,T}$	0-1.8	0.1-1.3
	$G_{YZ,T}$	2.0-6.1	2.3-6.2
	$G_{XZ,T}$	0.1-0.3	0.1-0.4

The results of a sensitivity study on the rotational and translation stiffness provided by the connections in the FE model are included in Table 7. Only the values that had an effect on the model results are included. All other properties made little to no change to the results when varied. For both connection types (the support connection and the half-lap) the only stiffness properties that had an effect on the results are the translational stiffness in the vertical direction (K_Y) and the rotational stiffness that causes each connection to go from zero fixity to fully rotationally fixed (K_{RX} for the support connection and K_{RZ} for the half-lap connection). The results in Table 7 show that it would be beneficial to experimentally determine the pull-out and rotational stiffness of the connection as they cause a significant change to the results ($0.1 - 60\%$). A single screw is unlikely to provide any rotational stiffness, however results indicate that an increase in rotational stiffness provides a large change in results, up to 60%, and therefore it is worth investigating using additional screws or alternative connection arrangements to improve the rigidity of the connection.

Table 7: Sensitivity study on the connection stiffness of the one-way spanning and two-way spanning CLT floor.

Component	One-way	Two-way
Support K_X	Small effect	Small effect
Support K_Y	Effect: 3.2-11%	Effect: 1.2-3.7%
Support K_Z	Small effect	Small effect
Support K_{RX}	Effect: 14 - 60%	Effect: 7 - 53%
Half-lap K_Y	Small effect	Small effect
Half-lap K_{RZ}	Effect: 15 - 60%	Effect: 0.1 - 42%

4.2 PLYWOOD FLOOR

A timber joisted floor with plywood sheathing has been analysed using FEA and experimental modal analysis to verify the methodology for the CLT floor plate. The plywood floor is modelled in ANSYS 16.0 as SHELL181 elements for both the LVL joists and the plywood sheath. The joists are connected to the plywood with screws at 125 mm centres. These connection points are modelled using MATRIX27 elements with translational stiffness active but no rotational stiffness.

The support connections of the joists were specially manufactured to represent an idealised pin as shown in Figure 7. The preliminary FE model is built to represent the pin-pin support condition, which can be idealised as the beam in Figure 8. The idealised model assumes there is no translational movement in the connection, but rotation is allowed. However supports rarely behave as perfect pins or perfect rigid joints. Therefore an advanced model was also built that contains MATRIX27 elements at the supports to account for any variations in rotational and translational stiffness. The purpose of the advanced model is to allow for the degrees of freedom inherent in the actual floor system. The advanced model can be represented diagrammatically as shown in Figure 8.

Figure 7: Photo of the pin support of the ribbed deck floor.

The first 5 mode shapes and the natural frequencies of the plywood floor are recorded in Table 8. The first two modes have only a 0.3 Hz difference and represent the 1st flexural mode and the 1st torsional mode. The FE model calculated a fundamental frequency (f_1) 1.7 times the value calculated by analytical methods in section 3.2 with a fundamental frequency of 9.32Hz. This is due to the pin-pin assumption of the preliminary FE model compared with the simply supported assumption of the analytical methods.
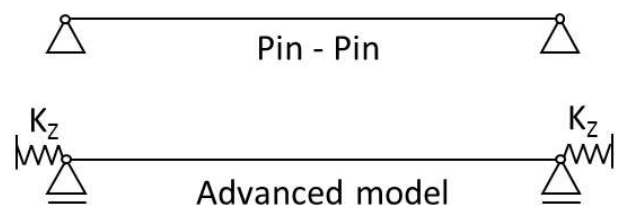

Figure 8: Preliminary model of the plywood deck floor (top), advanced model which represents the actual system (lower).

Table 8: *Frequency and mode shapes for the first 5 vibration modes of the plywood floor using FEA.*

Frequency	Mode Shape
$f_1 = 15.9$ Hz	
$f_2 = 16.2$ Hz	
$f_3 = 24.1$ Hz	
$f_4 = 34.1$ Hz	
$f_5 = 40.8$ Hz	

Figure 9: *Floor plan of plywood experimental modal analysis setup.*

Table 9: *Frequency and mode shapes for the first 5 vibration modes of the plywood floor from experimental results.*

Frequency	Mode Shape
$f_1 = 9.5$ Hz	
$f_2 = 10.2$ Hz	
$f_3 = 19.0$ Hz	
$f_4 = 28.9$ Hz	
$f_5 = 35.8$ Hz	

5 EXPERIMENTAL MODAL ANALYSIS

Experimental modal analysis was conducted on the plywood joist floor. This study reports on the mode shapes and natural frequencies of the structure and compares them with the numerical model in the previous section.

An impact hammer with a tip stiffness that results in exciting the lower spectrum of frequencies of the floor was used to impart an impulse excitation force. The sampling frequency was taken as 1 kHz for a time frame of 20 seconds. The floor was excited in 2 different locations as shown in Figure 9; location 1 was selected to excite more modes simultaneously while location 2 caused excitation of predominately the flexural modes. Each location was hit 30 times and the resulting signals averaged. Twelve accelerometer locations were selected to capture at least the first 5 modes of vibration of the floor. The experimental set up with the impact hammer is shown in Figure 10.
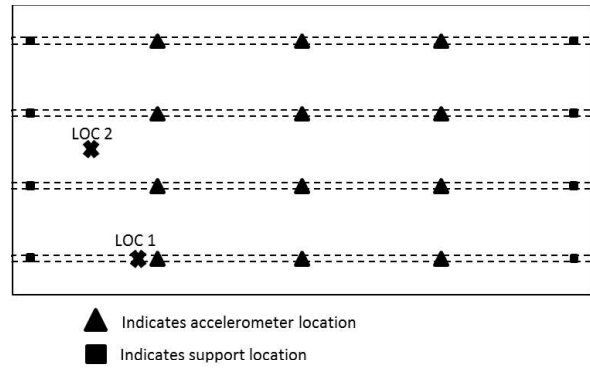
Figure 10: *Photo of the experimental arrangement with the 12 sensors and impact hammer.*

The time domain data is converted to the frequency domain using a Fast Fourier Transform (FFT). To account for any distortion or leakage in the data an exponential window is applied to the FFT. The frequency response function (FRF) which is a ratio of the FFT of the response and the excitation force was calculated to determine the natural frequencies of the floor. Operational modal analysis software, DIAMOND, is used to extract the mode shapes, mode shape vectors and natural frequencies of the floor, which are shown in Table 9.

6   MODEL UPDATING

Using the experimental modal data obtained from the laboratory experiments on the plywood joist floor, the FE model for the floor is updated. The accuracy of the FE model without experimental results to validate the model is limited. The FE model is reliant on a number of degrees of freedom including the support conditions and the material properties. An incorrect assumption in the model can cause results that differ widely from the actual performance of the floor. Experimental testing is essential to validate and update the FE model. Proceeding model updating the model then provides a powerful tool to perform a parametric study that predicts the performance of longer spans of the floor.

It is clear from simple visualisation that the first 5 modes of the experimental data (Table 9) are the same mode shapes as the numerical analysis (Table 8). To quantify the correlation between the mode shapes the modal assurance criteria (MAC) is used [21]. The MAC criterion provides a measure of the least-squares deviation of the mode vector points from a straight-line correlation. The MAC value is recorded as a MAC_{ERROR} (Eq. 7) which gives a percentage error between the mode shapes. A value of close to 0% means good correlation between shapes.

$$MAC_{ERROR} = \left[1 - \frac{\left| \{\varphi_{EXP}\}^T \{\varphi_{FEA}\} \right|^2}{\{\varphi_{EXP}\}^T \{\varphi_{EXP}\} \{\varphi_{FEA}\}^T \{\varphi_{FEA}\}} \right] \cdot 100 \quad (7)$$

While the MAC value provides an assessment of how well the geometric properties of the FE model replicate the real situation, the value is not dependent on the magnitude of the mode shape vector and therefore an additional assessment is required [22]. The natural frequency relative error (Eq. 8) compares the percentage difference between the natural frequencies of the experimental data and the FE model. This study compares the error of the first 5 vibration modes to validate the of the FE model results.

$$NF_{ERROR} = \frac{\left| \omega_{Exp} - \omega_{FE} \right|}{\omega_{Exp}} 100 \quad (8)$$

Comparison between the preliminary FE model and the experimental results reveal that the mode shape vectors match well, with MAC_{ERROR} values between 3 - 7% as shown in Table 10. The errors between frequencies, however, differ between $12 - 40.1\%$ indicating that the model has one or more degrees of freedom either at the support conditions or the material properties that require investigation. These properties were varied between +/-20% using iterative methods in the FE model. The standard deviation between the numerical results and the experimental results reveal that the system is not behaving as an idealised pin-pin beam. The structure is instead behaving similar to a simply supported beam (pin – roller) or in this case a roller support with a translation stiffness (K_z) activated (Figure 8). This is due to the joists being located 100 mm above the pivot point of the connection, allowing some translational movement between the joists and the pin support. The value of the translational stiffness (K_z) from model updating was found to be 9.41 x 10^5 N/m. As this stiffness increases to 1 x 10^9 N/m the results converge on the pin-pin model.

Table 10: *Comparison of experimental results and preliminary FE model results.*

Mode	f_{EXP} (Hz)	f_{FEA} (Hz)	NF_{ERROR} %	MAC_{ERROR} %
1	9.5	15.9	40.1	5
2	10.2	16.2	36.9	7
3	19.0	24.1	21.0	4
4	28.9	34.1	14.4	4
5	35.8	40.8	12.0	3

Following model updating the results of the advanced FE model are compared with the experimental results in Table 11. The error in the natural frequencies (NF_{ERROR}) has reduced from $12 - 40.1$ % to $0.5 - 3.5\%$ indicating the updated model has a good fit of results to the experimental results. There is no significant change in the value of the MAC_{ERROR}, with a slight increase from 5% to 6% in the 1st mode and a slight decrease from 4% to 2% in the 3rd mode.

Table 11: *Comparison of experimental results and advanced FE model results.*

Mode	f_{EXP} (Hz)	f_{FEA} (Hz)	NF_{ERROR} %	MAC_{ERROR} %
1	9.5	9.3	2.2	6
2	10.2	10.1	1.0	7
3	19.0	18.9	0.5	2
4	28.9	28.5	1.4	4
5	35.8	34.6	3.5	3

7 CONCLUSIONS

Cross laminated timber has demonstrated its potential for use in Australia and New Zealand mid-rise buildings. Serviceable vibration design is a key issue for the use of CLT and other timber floors with long spans. Three methods for calculating the vibration characteristics of long span timber floors have been discussed in this paper. These include analytical methods, finite element analysis and experimental modal analysis.

Australian codes and standards currently provide limited and ambiguous design guidelines for vibration performance. Internationally, a significant amount of research has been conducted to improve vibration design guidelines and implement them into codes. These provide more comprehensive analytical methods that can be adapted for local use.

Finite element (FE) modelling provides a powerful computational tool to predict and analyse the vibration performance of long span timber floors. Sensitivity studies on finite element models indicate that increasing the rotational stiffness of both the support connection and the panel-to-panel connection provides CLT with up to a 60% increase in natural frequencies. This is independent on whether the CLT floor plate is supported on two edges (one-way span) or four edges (two-way span).

Experimental modal analysis was conducted on a joisted floor with a plywood sheathing to verify the computational methods used in this study. Using model updating techniques the FE model was able to replicate the modal properties determined from the experimental testing. This procedure enables a parametric study to be conducted in future, to predict the vibration behaviour of the floor with longer spans.

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