World Conference on Timber Engineering Oslo 2023

IN-PLANE DEFLECTION OF CROSS-LAMINATED TIMBER DIAPHRAGMS

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ABSTRACT: Cross-Laminated Timber (CLT) is a reliable alternative to heavy structural components due to its dimensional stability and environmental benefits. However, there is currently no universally accepted design method for calculating the load-bearing capacity and deformation of a CLT diaphragm. The main objective of this study is to develop an analytical model for diaphragm deflection calculation when the major direction of panels is perpendicular to the load and confirm the results with the Finite Element (FE) analysis. In the absence of an experimental study aligned with the derived formula, an FE model was developed based on a full-scale diaphragm test subjected to loading parallel and perpendicular to the panel length. A parametric study was performed on the influence of the diaphragm length and the panel-to-panel connection stiffness. The contribution of bending, shear, and connection's slip to the total diaphragm deflection was quantified. The study reveals that the flexibility of the floor is primarily influenced by two factors: the shear deformation of the CLT panels when the load is perpendicular to the panel length and the stiffness of the panel-to-panel connection when the load is parallel to the panel length.

KEYWORDS: Cross Laminated Timber (CLT) diaphragms, Lateral load, Connections, In-plane deflection

1 INTRODUCTION

Floor diaphragms play an essential role in distributing the applied lateral load to the vertical elements of the lateral load-resisting systems of buildings. Cross Laminated Timber (CLT) panels have become more prevalent in recent years, such as diaphragm components in mid- to high-rise structures, primarily for sustainability reasons [1]. Several studies have investigated the impact of the rigidity or flexibility of CLT diaphragms on the distribution of lateral forces. A rigid diaphragm transmits loads to supports in proportion to the stiffness of the supports, whereas flexible diaphragms deformed in-plane through bending [2]. The lateral load distribution is influenced by the material properties and the load-slip behaviour of the connections between the adjacent panels (called panel-to-panel connections) and panel-to-beam connections [3]. Beairsto, in 2020 [4], evaluated the ductility of two large CLT diaphragms under monotonic and cyclic loads. The test indicated that the ductile design of the CLT diaphragm depended heavily on the panel-to-panel connections.

Pei et al. [5] conducted a series of experiments on a CLT building that was two-story high and 6.7 meters tall, using a shaking table to simulate seismic motions. The floors in this building were made up of 3-ply CLT panels, which were connected using a plywood surface spline and screws. The study found that the CLT diaphragms were significantly stiffer than wood frame floor diaphragms with wood-based sheathing panels, with satisfactory seismic performance. The researchers concluded that the design of a diaphragm needs to consider various sources of overstrength in the diaphragm components, e.g., the strength of the panel-to-panel connections, the stiffness of the boundary elements, and the strength of the fasteners used. Furthermore, Mohammadi [6] conducted experiments to evaluate the seismic performance of CLT diaphragms with multiple configurations. They found that the panel-to-panel connection stiffness significantly affected the in-plane stiffness of CLT diaphragms and recommended that the connections should be designed carefully.

Ashtari [7] investigated selected configurations of CLT floor diaphragm using a two-dimensional (2-D) FE analysis. The comparison between the FE and test results showed that the in-plane stiffness of CLT floors mainly depends on the panel-to-panel connection stiffness and shear modulus of the panels. It is important to note that CLT diaphragms can be loaded either parallel or perpendicular to the major panel axis, as shown in Figure 1. Spickler et al. [8] have provided a procedure for designing CLT diaphragms based on U.S. standards, assuming that the load is applied perpendicular to the panel length. The procedure covers diaphragm design for wind or seismic loads. However, their design approach has certain drawbacks that require attention, such as the failure to consider the impact of panel-to-panel connections on the overall behaviour of the diaphragm. Additionally, utilizing the chord width to determine the bending deflection of the diaphragm may not be a valid assumption.

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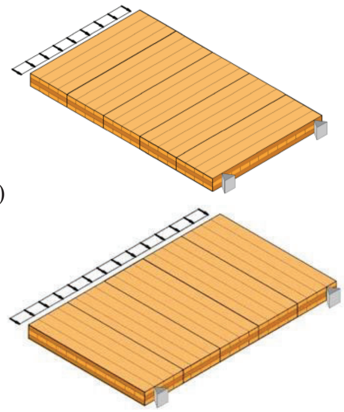
https://doi.org/10.52202/069179-0324



(a)

(b)

Figure 1: *CLT panels subjected to load (a) perpendicular and (b) parallel to the panel direction.*

Wallner-Novak et al. [9] conducted a technical investigation on the design of CLT floor diaphragms according to the Eurocode 5 specifications [10]. The report focused on diaphragms loaded parallel to the panel length and identified panel-to-panel connections that played a significant role in the diaphragm's performance. The study found that the diaphragm's deflection under shear force was primarily caused by the slip in the connections between the CLT panels, while the deflection due to bending resulted from the rotation of the panels. However, the study did not address scenarios where the applied load is perpendicular to the panel length.
Recently, Line et al. [11] conducted an experimental study to evaluate the current design provisions for CLT diaphragms in ANSI/AWC 2021 [12]. The study involved testing two CLT diaphragms that were loaded parallel and perpendicular to the panel length. The CLT panels were connected using plywood surface splines and fastened to glulam beams using self-tapping screws. Following the CLT diaphragm test [11], Line et al. [13] conducted a series of diaphragm connection tests to provide input data for models predicting the load-displacement response of the CLT diaphragms. The objective of the research was to analyse the behaviour of CLT diaphragms when loaded parallel or perpendicular to the panel length. The findings of the study provide helpful information regarding the different sizes and configurations of diaphragms which can contribute to the next edition of the Timber Design Standards in the USA.
This paper studies the effect of connections between CLT panels, assuming a simply supported diaphragm subjected to a uniformly distributed load perpendicular to the panel length. An analytical model is developed and validated using a finite element model. The effect of different connection stiffness values on the diaphragm's behaviour is evaluated.
The researchers also used a similar modelling technique to develop the FE model for CLT diaphragm loading in parallel and perpendicular directions and compared it with the experimental results. The findings show that the FE models agree well with the experimental results, confirming the effectiveness of the models in predicting the behaviour of CLT diaphragms.
This study has practical implications for the design of CLT diaphragms, as it provides a better understanding of the effect of connections on the diaphragm's performance. Additionally, it emphasizes the importance of incorporating different connection stiffness values and the size of the diaphragm length into the design process. Overall, this research contributes to the advancement of CLT diaphragm design and can potentially improve the performance of CLT structures.

2 ANALYTICAL MODEL DEVELOPMENT

When floor diaphragms are considered deep beams, their in-plane deformation can be separated into two components: deformation in the X and Y directions, as shown in Figure 2. The deflection in the X direction is primarily due to the slip between the panels. In the Y direction, deflection is caused by shear and bending in the CLT panels, as well as interlayer slip between the panels. Simple supports are assumed to be located at both ends of the diaphragm. The diaphragm centreline experiences an external in-plane load, q, which is then conveyed to the shear walls below by the CLT panels.

2.1 SLIPPING AMONG THE PANELS

Figure 2 shows an infinitesimal floor segment of finite length dx, the internal forces and moment, and the strain distribution in a typical floor diaphragm system cross-section.

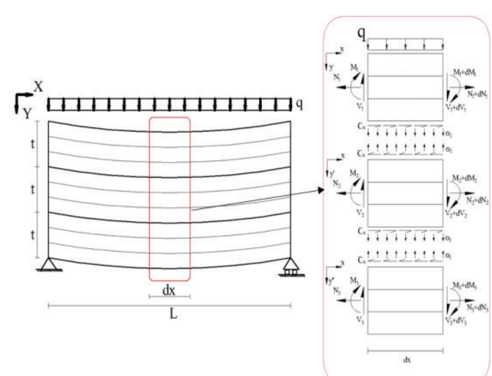


Figure 2: *CLT diaphragm internal force and strain*

The strain in the CLT panel cross-section near the interfaces is caused by the action of the bending moment and displacement in the X direction. First, a longitudinal displacement function (U^N) is assumed for each panel as Equation (1).

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$$U_n^N(x,y) = A_n(x).y_n{}^2 + B_n(x).y_n + C_n(x) \quad (1)$$

The variable n = the panel number and y_n" = the reference point for the local coordinate system upper surface of each panel denoted as. Coefficients named "A_n", "B_n", and "Cn" are determined based on the boundary conditions. With the substitution of a derivative of Equation (1) into the distribution of shear stress throughout the depth of the panels, the shear stress for each panel can be written as:

$$\sigma_{xy(1)} = G_{xy}(2A_1y + B_1) \quad (2)$$

$$\sigma_{xy'(2)} = G_{xy}(2A_2y' + B_2) \quad (3)$$

$$\sigma_{xy''(3)} = G_{xy}(2A_3y'' + B_3) \quad (4)$$

where G_{xy} = the shear modulus, and $\sigma_{xy}(n)$ = shear stress throughout the depth of each panel. It is worth mentioning that, in this study, the analytical model was initially developed for a diaphragm system consisting of three panels. The local coordinates are centred on the upper surface of each panel and are represented as y for the top panel, y' for the middle panel, and y" for the bottom panel. By applying the boundary condition, the shear stresses in the panels can be calculated, and in turn, the shear strain in the panels is obtained as:

$$\gamma_{xy(1)} = \gamma_1 = \frac{\tau(x)}{G_{xy}t}y \quad (5)$$

$$\gamma_{xy(2)} = \gamma_2 = \frac{\tau(x)}{G_{xy}} \quad (6)$$

$$\gamma_{xy(3)} = \gamma_3 = \frac{\tau(x)}{G_{xy}}\left(1 - \frac{y''}{t}\right) \quad (7)$$

γ_{xy} = the shear strain of each panel. The longitudinal displacement function, U_n^N, due to longitudinal forces, is given by:

$$U_n^N = U_n^N(0) + \int_0^y \gamma_n(y)\,dy + U_n^N(t_n) \quad (8)$$

$U_n^N(0)$ and $U_n^N(t_n)$ indicate panel displacement at a panel's top and bottom edges, respectively, and can be calculated by subtracting the panel displacement at each interface from the connection displacement. The longitudinal force acting on each panel is equal to:

$$N_n = Eb\int_0^t \frac{dU_n^N}{dx}dy \quad (9)$$

where t = width (depth) of the panel, b = thickness of the panel, and E = Young's modulus. by substituting a derivative of Equation (8) into Equation (8), the strain at each panel edge is obtained. The shear stress between two adjacent panels can be expressed as Equation (10).

$$\tau(x) = \frac{K_s.n^*}{S}\left(u_{n+1}(x) - u_n(x)\right) \quad (10)$$

K_s = the shear stiffness of a fastener in units of (kN/mm). S = the distance between two fasteners and n* = the number of fasteners per row. The longitudinal displacements are described as $u_{n+1}(x)$ and $u_n(x)$, corresponding to the top of panel n+1 and the bottom of panel n, respectively.

The equations can be supplemented by the equilibrium equations assuming the same deflection for all panels. After some algebraic calculations, Equation (11) can be obtained for panel shear stress, where τ(x) is the shear stress at the interface.

$$\tau(x) = -m\frac{q}{\lambda}\left(\tanh\left(\frac{\lambda L}{2}\right)\cosh(\lambda x) - \sinh(\lambda x)\right) + mq\left(\frac{L}{2} - x\right) \quad (11)$$

Variables m and λ are determined in Equations (12) and (13), respectively. q = uniformly distributed load, and L = length of the CLT diaphragm.

$$m = \frac{1}{\left(\frac{1}{K_s} + \left(\frac{5t}{6G}\right)\right)\lambda^2}\left(\frac{t}{3EI}\right) \quad (12)$$

$$\lambda^2 = \frac{b}{\frac{1}{K_s} + \left(\frac{5t}{6G}\right)}\left(\frac{2t^2}{3EI} + \frac{1}{EA}\right) \quad (13)$$

where A = cross-sectional area of the panel, I = moment of inertia, and G = in-plane shear modulus. After substituting the value of τ(x) into horizontal equilibrium, the maximum amount of axial force can be calculated at the edge of the panels (x= 0 or L):

$$N(x) = \left(-m\frac{q}{\lambda^2}\left(tanh\left(\frac{\lambda l}{2}\right)Sinh(\lambda x) - Cosh(\lambda x) + 1\right) + mq\left(\frac{L}{2}x - \frac{x^2}{2}\right)\right) \quad (14)$$

2.2 DIAPHRAGM DEFORMATION

Diaphragm deformation corresponds to the conventional equation for a deep beam. However, it has an additional term to account for interlayer movement, including the panels' shear deformation. Using Timoshenko's theory [14] to establish the following relationship between the bending moment, shear force, deflection, and rotation of the cross-section:

$$\frac{dw}{dx} = \theta - \frac{EI}{kAG}\left(\frac{d\theta^2}{dx^2}\right) \tag{15}$$

$$\frac{d\theta}{dx} = -\frac{M_T(x) - b\int \tau(x).2t}{3EI} \tag{16}$$

Where w = the deflection of the panels in the *y*-direction and θ = the cross-section angle of rotation and $M_T(x)$ = the applied moment. By substituting Equation (11) into Equation (16) to include the effect of shear stress on the deformation and adding the interlayered movement, we obtain Equation (17), which gives the mid-span deformation of the diaphragm.

$$w(x) = \frac{5qL^4}{384EI_s} + \frac{qL^2}{8kAG} + \frac{mqL^2}{4t}\left(\frac{1}{K_s} + \left(\frac{5t}{6G}\right)\right) \tag{17}$$

3 FE MODEL DEVELOPMENT

A three-dimensional (3D) model was created in Abaqus [15] to calculate the mid-span in-plane deformation of the diaphragm and replicate the layout illustrated in Figure 2. The model comprised a rectangular CLT floor consisting of three 10-meter-long and 2.4-meter-wide panels. Line springs were evenly distributed along the length of the panels to connect them. In addition, butt joint connections were strengthened by using screws oriented at a 45° angle relative to the edge face of the CLT panels to enhance the structure's load-carrying capacity. The comparison of the mid-span deflection of the floor between the FE and analytical models revealed a difference of less than 2%, with the deflection values of 3.3 mm and 3.36 mm, respectively. This indicates that the two models are in agreement with each other and can be relied upon to predict the behaviour of the floor accurately.

3.1 COMPARATIVE ANALYSIS OF CONNECTION STIFFNESS

The stiffness of connectors in the joints of CLT panels was determined through experimental tests from multiple sources, including studies [16-18], where 8mm screws were used. The stiffness values obtained were compared to the analytical model predictions, as shown in Figure 3. The comparison showed that the difference between the experimentally determined stiffness values and the predictions of the analytical model was less than 5%. The finding suggests that the developed formula is accurate for the assumed range of stiffness values. Hence, the analytical model can confidently predict the behaviour of CLT panel joints.

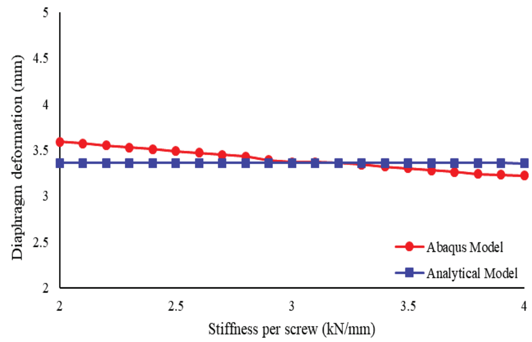


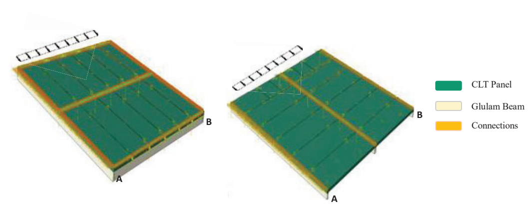
Figure 3: *The diaphragm deformation versus stiffness of the connection*

3.2 FE MODEL VALIDATION THROUGH EXPERIMENTAL STUDY

To the best of the authors' knowledge, no empirical investigations have been conducted to date on the behaviour of a CLT diaphragm subjected to a perpendicular load with the specific boundary conditions assumed in the developed analytical model. Therefore, to validate the modelling approach, the results of full-scale CLT diaphragm tests reported in [11] were compared with the FE model developed to ensure the accuracy of the proposed numerical models.

3.3 FE MODEL SETUP

The experimental study examined the behaviour of two diaphragms, one loaded parallel to the panel length and the other loaded perpendicular to the panel length, as shown in Figure 4.



(a) (b)

Figure 4: *Diaphragm assemblies when the load direction is (a) parallel to the panel length, (b) perpendicular to the panel length.*

For each diaphragm, twelve 1.22 × 3.66 m CLT panels were modelled with a proposed thickness of 105 mm using a three-ply layup. The panel-to-panel spline connection was made using 18.3 mm plywood and 8d common power-driven nails. To establish connections between panels and beams in the FE model, two-point spring elements were utilized. These spring elements were linked to the CLT panel at each fastener point by connector elements that tied the displacement and rotation

https://doi.org/10.52202/069179-0324

of each fastener point to the average displacement and rotation of the neighbouring nodes. As for the experimental study, the diaphragms were pinned at their far corners in the plane of loading (points A and B in Figure 4). The perimeter beams' edges were pinned, allowing the assembly to bend inward while restraining its movement in the direction of loading.

3.4 COMPARING THE RESULTS

The load-displacement curves at the mid-span of the diaphragms subjected to parallel and perpendicular loading to the panel length, obtained from both experimental and numerical analyses, are presented in Figure 5. The results demonstrate a close agreement up to the maximum force, suggesting that the numerical model was successfully validated and can be trusted to predict the behaviour of comparable CLT diaphragms under various loading conditions.

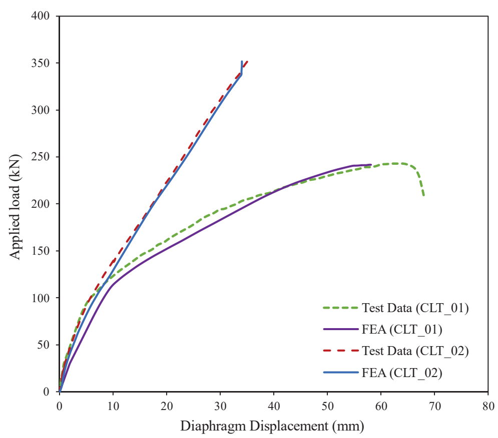


Figure 5: *The mid-span load-displacement curve for diaphragm under in-plane loading; numerical versus experimental.*

The numerical model was based on the assumption of linear-elastic behaviour of the wood components, with the connections exhibiting nonlinear behaviour. Plastic deformation was observed at a load of approximately 100 kN, leading to failure. However, due to numerical instabilities, the simulation was stopped once the load reached its maximum point, and the connections failed. Comparing the experimental and numerical load-displacement curves indicated that the developed numerical model effectively predicted the diaphragms' overall behaviour. These findings suggest that the numerical model can accurately simulate and predict the behaviour of similar CLT diaphragms under varying loading conditions.

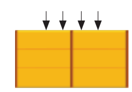
4 THE PARAMETRIC STUDY

A comprehensive parametric study was conducted to augment the database on CLT diaphragms by varying parameters such as panel thicknesses and the Aspect Ratio (AR) of the CLT diaphragms, which is the ratio of the diaphragm length to its depth.

4.1 DIAPHRAGM LOADED PERPENDICULAR TO THE PANEL LENGTH

Table 1 presents six archetypes categorized based on the thickness of the CLT panels, with each group comprising three different panel sizes. Each configuration comprises six panels and three glulam beams placed underneath the panel joints.

Table 1: *Summary of characteristics feature of diaphragm loaded perpendicular to the panel length in FE models.*

Archetype No.	**Diaphragm Size**			Number of layers	**Associated Sketch**
	Length (m)	Depth (m)	Thickness (mm)		
1	9	7.2	175	5	
2	11	7.2	175	5	
3	13	7.2	175	5	
4	9	7.2	245	7	
5	11	7.2	245	7	
6	13	7.2	245	7	

The deformation of the CLT diaphragm under perpendicular loading to the panel length is illustrated in Figure 6. The results indicate an increase in the diaphragm deformation as the length increases. Interestingly, the study found that the thickness of the CLT panels did not significantly impact the deformation of the diaphragm in this configuration.

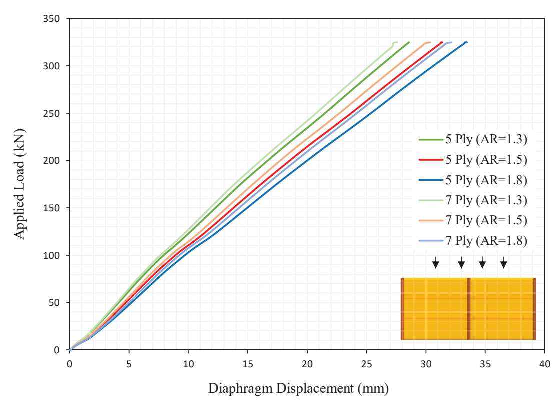


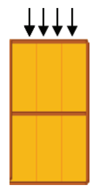
Figure 6: *Load-displacement curves for diaphragm with different diaphragm aspect ratios and thicknesses for loading perpendicular to panel length.*

4.2 DIAPHRAGM LOADED PARALLEL TO THE PANEL LENGTH

Table 2 summarizes the analysis results of six archetypes subjected to in-plane loads parallel to the panel length.

Similar to the analysis of perpendicular loading, the archetypes were divided into two groups based on the thickness of the panels.

Table 2: *Summary of characteristics of a diaphragm loaded parallel to the panel length in FE models.*

Archetype No.	Diaphragm Size			Number of layers	Associated sketch
	Length (m)	Depth (m)	Thickness (mm)		
1	9	7.2	175	5	
2	11	7.2	175	5	
3	13	7.2	175	5	
4	9	7.2	245	7	
5	11	7.2	245	7	
6	13	7.2	245	7	

The results presented in Figure 7 indicate that, for archetypes 1- 6, the diaphragm deflection decreased as the diaphragm length increased under loading parallel to the panel length. The panel thickness did not significantly affect the diaphragm deflection in this configuration. However, it was observed that, for loading parallel to the panel length, the chosen panel depth used in the parametric study, which was twice that of the experimental analysis, resulted in significantly less deformation than the experimental results. These findings highlight the importance of considering the appropriate panel depth to accurately predict the behaviour of CLT diaphragms under in-plane loads parallel to the panel length.

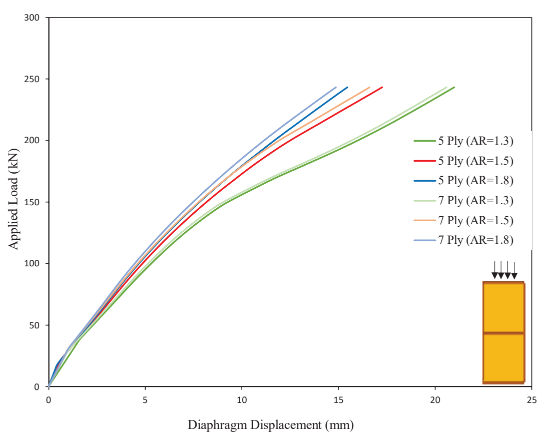


Figure 7: *Load-displacement curves for diaphragm with different diaphragm aspect ratios and thickness for loading parallel to panel length.*

5 DISCUSSION

Figure 8 summarizes the effect of diaphragm length and panel thickness on the behaviour of archetypes 1 to 6 under in-plane loading, both parallel and perpendicular to the panel length. The diaphragms loaded parallel to the panel length are denoted as "parallel," while those loaded perpendicular to the panel length are labelled as "perpendicular." The results reveal that the aspect ratio has the most significant effect on diaphragm deformation, particularly for aspect ratios below 1.5, while panel thickness is not an important parameter. For the diaphragm loaded parallel to the panel length, the stiffness was found to be unaffected by the panel thickness.

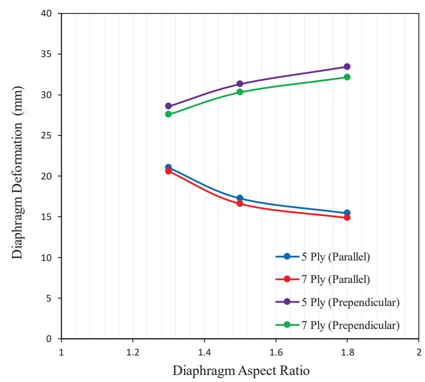


Figure 8: *The effect of the aspect ratio and panel thickness in diaphragm displacement for the archetype 1 to 6.*

6 CONCLUSIONS

This study presents an analytical model to calculate the mid-span deflection of a simply supported diaphragm and predict the force in the connection between adjacent CLT panels when the load is perpendicular to the panel length. The model accounts for the effect of bending and shear deflections of each panel and slip between the panels. To validate the analytical model, a FE model was developed and compared to the behaviour of CLT diaphragms under in-plane loading. The comparison showed good agreement between the predictions of the analytical and FE models, confirming the accuracy of the analytical model.

In addition, proposed FE models were compared to the results of full-scale CLT diaphragm tests to evaluate the modelling approach. A comprehensive parametric study was conducted to identify the most influential parameters contributing to in-plane deformation in CLT floor diaphragms. The behaviour of the employed diaphragm was investigated by varying the aspect ratio and thickness of the CLT diaphragm. It was found that when the load was perpendicular to the panel length, shear deflection in the CLT panels provided the most significant contribution to total diaphragm deflection, while the slip in the connections was the most influential parameter when the load was parallel to the panel length. The study also revealed that the thickness of the panels is not a key parameter in the deformation of the diaphragm under lateral loading.

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The results of this study provide valuable insights into the behaviour of CLT diaphragms under in-plane loading that can be used by practitioners in the design of CLT diaphragms in both loading orientations. The developed analytical model can be applied to predict the mid-span deflection and force in the connections between adjacent CLT panels, enabling the more efficient and accurate design of CLT diaphragms.

ACKNOWLEDGEMENTS

The authors would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) for the financial support of this study under the Industrial Research Chair Program. Financial support was also provided by the Landmark Group of Companies, FPInnovations, Canadian Wood Council, MTC Solutions, Rotho Blaas, Western Archrib, and Alberta Innovates. Their support is gratefully acknowledged.

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