World Conference on Timber Engineering
WCTE 2014 Quebec City Canada August 10-14

# IN-PLANE STIFFNESS OF CROSS-LAMINATED TIMBER FLOORS

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**ABSTRACT:** This study investigates the in-plane behaviour of Cross Laminated Timber (CLT) floor diaphragms and lateral load distribution within buildings containing CLT floors. Detailed 2D finite element models of CLT floors and buildings were generated in ANSYS, to achieve the above objectives. The models were calibrated with test data for a special type of CLT panel-to-panel connection. Furthermore, sensitivity analysis was performed to find the most influential parameters, affecting the in-plane behaviour of CLT floors. It was found that whether CLT floors should be assumed flexible or rigid is predominantly dependent on the relative stiffness of the CLT floor and the attached shearwall system, i.e. shearwalls and shearwall-to-floor connections. For most of the studied cases, CLT floors behaved closer to flexible diaphragms. Other than the stiffness of the attached shearwall system, it was found the in-plane stiffness and thus the in-plane behaviour of CLT floors are primarily dependent on the properties of the panel-to-panel connections and shear modulus of elasticity of CLT panels.

**KEYWORDS:** Cross-laminated timber, In-plane Stiffness, Floor diaphragm, ANSYS

## 1 INTRODUCTION

There are two common design assumptions for the in-plane behaviour of light wood frame floor or roof diaphragms: flexible or rigid diaphragm assumption [1]. Based on the assumption for the flexibility of the diaphragm, designers can utilize simple hand calculation methods to distribute the lateral load to the supporting shearwalls. For flexible diaphragms, the lateral load is distributed according to the tributary area associated with each shearwall. This method of lateral load distribution is referred to as “tributary area” method. In case of a rigid diaphragm, the diaphragm moves as a rigid body and the lateral load is distributed according to the relative stiffness of the shearwalls. Consequently, this method of lateral load distribution is referred to as “wall stiffness” method.

Past studies have addressed the in-plane behaviour of light wood frame diaphragms [2-6]. While in practice, wood diaphragms are generally assumed to be flexible [7], the behaviour of light wood frame diaphragms was found to be semi-rigid [3, 6]. As a result, neither the tributary area nor the wall stiffness method provides an accurate estimate of the lateral load distribution. CLT is a relatively new structural wood product and there is little information on the in-plane stiffness for CLT diaphragms. This study explores the in-plane behaviour of CLT diaphragms and the lateral load distribution in CLT buildings, and examines the most influential parameters.

## 2 CLT PANEL MODEL

A simple CLT floor diaphragm consists of two main components: CLT panels, and CLT panel-to-panel and panel-to-wall connections. The properties and behaviour of the CLT floor depends primarily on the properties and behaviour of these two parts and how they interact within a floor or building assembly.

The properties and dimensions of CLT panels depend on different manufacturers. There are typically 3, 5, 7, or more layers of boards arranged crosswise and symmetric around the mid layer [8, 9]. The width of panels range from 0.6 m up to 4 m, and they could be up to 24 m in length and 0.5 m in thickness. The mechanical properties of CLT panels could be obtained analytically or numerically from the properties of the sub-layers and the adhesive utilized for gluing the layers or from experiments. Gsell et al. [10] concluded that the overall behaviour of CLT panels can be reasonably modelled with orthotropic, homogenous, linear elastic material behaviour. A number of other studies on in-plane behaviour of CLT panels suggest the same conclusion [11-14]. Therefore, the CLT panels in this study were modelled in ANSYS, assuming a linear elastic orthotropic material behaviour.

The values of the nine independent elastic constants of the modelled panels were selected based on the conducted

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tests on the properties of CLT panels manufactured by CST Innovation [15, 16] and reported values from literature. A reference set of values for these constants are tabulated in Table 1. These values were also altered from the reference values for performing sensitivity analysis.

***Table 1:*** *Reference mechanical properties for CLT panels*

| | |
|---|---|
| $E_x$ ($E_{90}$) | 4.0 GPa |
| $E_y$ ($E_0$) | 8.0 GPa |
| $E_z$ | 0.5 GPa |
| $v_{xy}$ | 0.07 |
| $v_{yz}$ | 0.35 |
| $v_{xz}$ | 0.35 |
| $G_{xy}$ | 0.6 GPa |
| $G_{yz}$ | 0.5 GPa |
| $G_{xz}$ | 0.1 GPa |

## 3 PANEL-TO-PANEL CONNECTION MODEL

The second major component of CLT floors are panel-to-panel connections. Modelling the true behaviour of connections in CLT assemblies are of great significance, since they contribute to the stiffness, ductility and energy dissipation in such assemblies [17-19].

Four common types of panel-to-panel connections include single surface spline, half-lapped joint, internal spline, and double surface spline [20]. In this study however, a special type of panel-to-panel connection with self-tapping wood screws, which had been tested at the Department of Wood Science at UBC [21], were utilized for the floor models. A schematic illustration of the connection layout is shown in Figure 1. The screws were installed in pairs, each forming double 45 degree angle incline in 3D. The test specimens were comprised of three CLT cut-outs connected by 8 mm ASSY VG plus self-tapping wood screws. The laminas were Spruce-Pine-Fir grade No. 2 or better material glued by polyurethane adhesive. A total number of 6 specimens were tested under quasi-static loading, for which the load-displacement test results along with the mean curve are demonstrated in Figure 2. The curves were modified to exclude the initial slip in some of the specimens [22]. It can be observed that the initial parts of all of the load-displacement curves are linear with similar slopes. With the onset of nonlinear behaviour, the curves tend to vary considerably in terms of stiffness, capacity, and the ultimate displacement.

To model the connection in ANSYS, the average response curve was approximated with a piecewise-linear fit. For the sake of simplicity and control over the curve defining parameters, the number of segments was reduced to three in the pre-peak region and two in the post-peak region as shown in Figure 3.

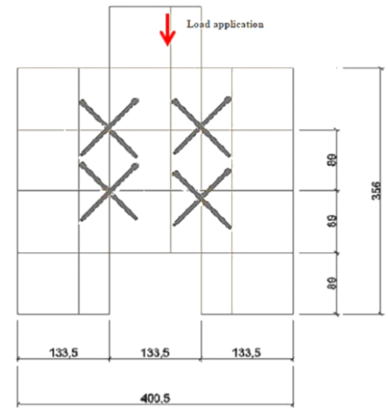



***Figure 1:*** *Panel-to-panel connection tested at UBC [21]*

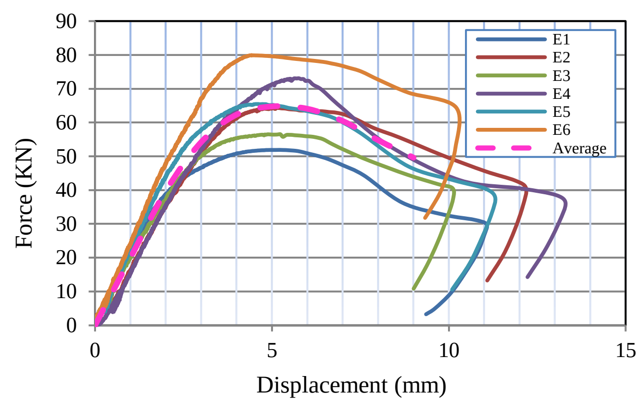



***Figure 2:*** *Tested specimens load-displacement curves*

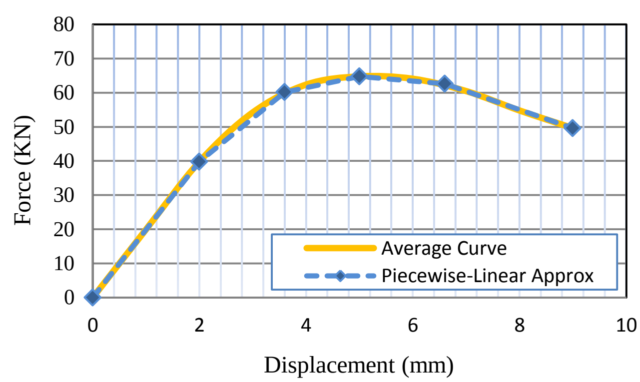



***Figure 3:*** *Piecewise-linear approximate to average load-displacement curve of the tested specimens*

## 4 GENERATING CLT MODELS IN ANSYS

To study the in-plane behaviour of CLT floor diaphragms and the lateral load distribution within CLT buildings, 2D models of CLT floors were generated in ANSYS. The models were created using ANSYS Parametric Design Language (APDL) with direct generation approach. In other words, the coordinates of each node and the connectivity of elements are all defined by the user. This approach of modelling maximizes the control of user and thus allows manoeuvrability in varying different parameters for later on sensitivity analysis.

The CLT panels were meshed with simple 2D membrane element PLANE42. This element has four nodes, with two translational degrees of freedom at each node. The choice of this element is convenient for modelling plane-type members under in-plane loads. The element behaviour was “plane stress with thickness” and linear elastic orthotropic material behaviour was assigned to the elements.

To model the connection, each pair of screws in the connection was replaced with a set of two unidirectional springs, one of which acted in the direction of loading and the other in the perpendicular direction. In fact, the total stiffness of screws was decomposed into two perpendicular components. The approach of replacing fasteners with two unidirectional springs has been exploited by other researchers as well, example of which can be found in Shenton, 2002 [23]. The combined response of the springs under in-plane loads should be the same as the original response of the screws. One way to achieve this was to calibrate the springs in the direction of loading with the average piecewise linear load-displacement curve of the connection (Figure 3). In the perpendicular direction, rigid links were utilized, to ensure that no opening of the connections under in-plane loads was allowed. It was also possible to use linear springs with different stiffness in tension and compression instead of rigid links. However, in practice the existence of chord members, beams, and shearwalls imposes a restraining effect on the floor diaphragm against opening up under in-plane loads. Therefore, incorporating rigid links in the connection model was the preferred choice here.

For developing the connection models in ANSYS, in the direction of loading, nonlinear spring elements COMBIN39 were utilized. The rigid links in the perpendicular direction were modelled with linear COMBIN14 springs with a high stiffness value. Each node on one side of the meshed CLT panels was connected to the adjacent node on the neighbouring panel with a set of COMBIN39 and COMBIN14 springs. In this way, the springs formed an almost parallel system (assuming negligible in-plane deformation in CLT panel edges between the springs). For that reason, the response curve for each of the COMBIN39 springs could be obtained by considering the tributary length along the edge of the CLT panel, over which each COMBIN 39 acted, and multiplying that by the unit length average linear piecewise load-displacement curve. The latter was simply found by dividing the force values of the response curve in Figure 3 by the length of the connection in the test specimens.

The connection model developed in this way was a smeared model, which could readily be calibrated to the response curves of other types of panel-to-panel connections, with various fasteners. Evidently, the model was more accurate for finer mesh along the edges of connected CLT panels. To validate the connection model, a model of the test specimens was generated in ANSYS, and the load-displacement response curve of the model was compared against the actual test results. The comparison demonstrated good agreement between the two responses and thus the connection model was validated (Figure 4).

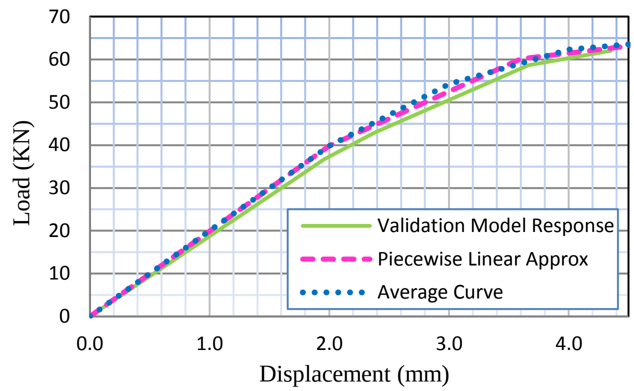



***Figure 4:*** *Comparing validation model response with the actual test average response curve and piecewise linear approximation curve*

## 5 ANALYSIS OF CLT FLOOR MODELS

Four representative floor diaphragm configurations were considered for investigations on the in-plane behaviour of CLT floors (see Figure 5). For comparison purposes, the outer dimensions of all floor configurations were the same, as shown in the figure. The thickness of the CLT floor in all cases was 0.15 m. Configuration 1 constituted a single CLT panel connected to two Shearwalls A and D at the ends. The length of the single CLT panel in this case was not common in practice. Configuration 2 constituted nine much smaller CLT panels connected by the panel-to-panel connection described in the previous sections. It was also bounded by two Shearwalls A and D at the ends. Configuration 3 was essentially Configuration 2 with two additional Shearwalls B and C in the middle that divided the diaphragm into three bays. Finally, Configuration 4 was a Configuration 3 with and opening in the centre bay.

All four floor configurations were modelled in ANSYS. In the first attempt, fixed boundary conditions were imposed at the location of shearwalls. For multi-bay floor models, such as Configuration 3, this condition causes each bay to deform independently of the adjacent bays. The panels were meshed with 40x40 mm PLANE42 elements, and were connected by the connection model described in Section 4. To simulate the seismic load, a static uniform pressure was applied to the lower side of each floor model. The amount of pressure was increased from zero in several small increments, and at each load step the displacements of the diaphragm at the middle of each bay were recorded. The amount of force increased until one of the non-linear COMBIN39 springs reached its capacity, and thus the analysis failed to converge. It was possible to continue the analysis beyond the capacity point by switching the analysis mode to displacement-controlled instead of

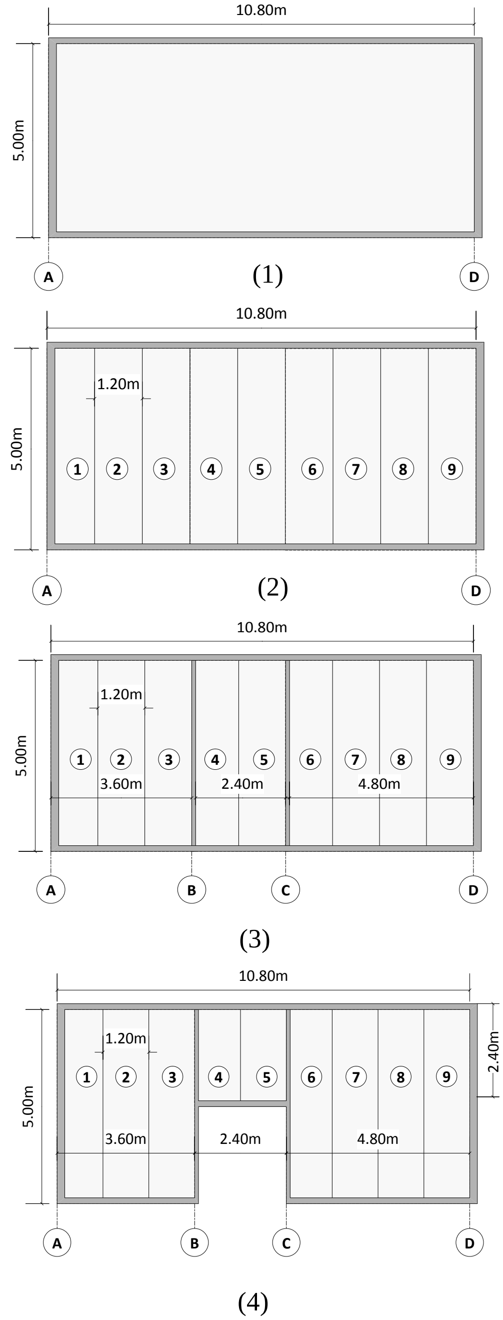



***Figure 5:*** *Analysed CLT floor diaphragm configurations [22]*

force-controlled. However, the in-plane stiffness and lateral force distribution of CLT floors after the capacity point was not an objective for this study. The recorded force-displacement curves were in fact "pushover" curves that reflect the in-plane behaviour of the CLT floor models and provide a measure of their in-plane stiffness. The obtained pushover curves for Configuration 3 floor model are presented in Figure 6. Along with the push over curves are linear trendlines for each curve (shown in dotted lines). These trendlines demonstrate to what extend the assumption of linear in-plane behaviour is credible for CLT diaphragms. Referring to Figure 6, it was clear that for bays BC (2nd bay) and CD (3rd bay) the pushover curve showed noticeable non-linearity and are tri-linear in shape. The latter could be explained considering that the connections were the only source of nonlinearity in the model and had a tri-linear response curve, and they formed an almost parallel spring system. Therefore, assumption of linear in-plane response for CLT diaphragms does not hold in many cases. The amount of non-linearity in the pushover curve depends on the non-linear response of panel-to-panel connections, and the location and number of connections.

By comparing the pushover curves for Configurations 1 and 2, it was observed that the in-plane stiffness of the diaphragm was reduced by 25% and the maximum floor deformation was increased by 40%. This additional deformation occurred in the panel-to-panel connections and was in the form of slip between the adjacent CLT panels.

The slip between the panels was greatest where the shear force was greatest, i.e. in this case closer to the restrained boundaries.

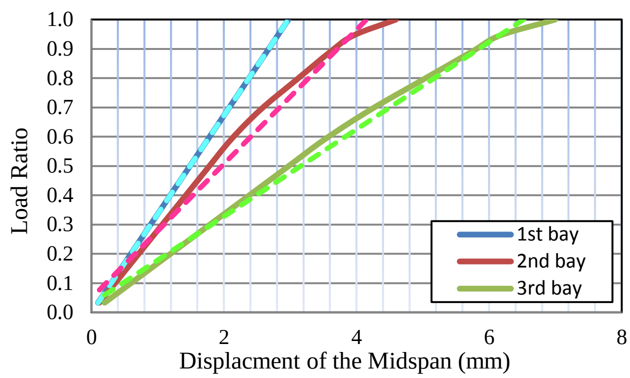



***Figure 6:*** *Pushover curves for Configuration 3 floor model*

## 6 ANALYSIS OF CLT BUILDING MODELS

The main objectives of this section are to determine the lateral load distribution within CLT buildings, and to investigate the suitability of common flexible or rigid diaphragm assumptions for the analysed cases. To do so, a number of building models were modelled and analysed in ANSYS, and the results of lateral force distribution from the analysis were compared to the results of the tributary area and wall stiffness methods applied to the same building.

The CLT building models were created simply by replacing the restrained boundary conditions with shearwall systems in the previously generated floor models. Following the idea incorporated in the connection model, the shearwall systems were also modelled with two sets of parallel zero-length unidirectional springs, one acting along the shearwall (*Y* direction) and the other acting in the orthogonal direction (*X* direction). The springs in both directions were modelled with linear COMBIN14 springs. For each direction, the stiffness of each spring was assigned by dividing the total stiffness of the shearwall in that direction by the number of springs. This stiffness represents the contributions from the shearwall itself, and the shearwall-diaphragm and shearwall-base connection stiffness. Each spring was connected at one end to an adjacent node along the edge of the CLT panel, to which the shearwall was attached, and at the other end, it was restrained in all directions.

The demonstration CLT building considered here was a one story residential dwelling with similar plan to Configuration 3 floor model. The height of the building was 3 m. All shearwalls were 5 m in length. The outer Shearwalls (A and D) and the inner Shearwalls (B and C) were 150 mm and 100 mm thick, respectively. The Young's modulus of elasticity and the Poisson ratio for the shearwalls were assumed to be 10000 MPa and 0.35, respectively. The lateral load distribution within the building was obtained using both the tributary area method (flexible diaphragm assumption) and the wall stiffness method (rigid diaphragm assumption). The details of hand calculations can be found in Ashtari, 2012 [22].

For the building model in ANSYS, four sets of stiffness values were considered for the shearwalls, encompassing a wide range of reasonable values. The four sets included the cases of significantly stiff, moderately stiff, normal, and flexible shearwalls, respectively (the terms are meaningful relative to one another). The 3rd and the 4th set stiffness values were close to in-plane stiffness values of CLT shearwalls reported by Popovski et al. [24-26]. These stiffness values were tabulated for reference in Table 2. Each of the shearwall sets was added to Configuration 3 floor model in a separate analysis to yield four different building models. The share of the lateral load attracted to each shearwall for each set of stiffness values were extracted from ANSYS outputs. The results are compared against the lateral load distribution obtained from hand calculations for the demonstration building in Figure 7. Referring to the figure, it was observed that for the incorporated type of connections and CLT panels, the CLT diaphragm distributes the lateral load almost according to the tributary area method.

***Table 2:*** *Shearwall stiffness values for CLT building models*

| | | Total stiffness of shearwalls (kN/mm) | | Stiffness of COMBIN14 springs (kN/mm) | |
|---|---|---|---|---|---|
| Set | Shearwall | $K_X$ | $K_Y$ | $k_X$ | $k_Y$ |
| 1 | A and D | 1.5 | 1700 | 0.012 | 13.492 |
| | B and C | 0.5 | 1200 | 0.004 | 9.524 |
| 2 | A and D | 0.2 | 450 | 0.002 | 3.571 |
| | B and C | 0.02 | 250 | 0.0002 | 1.984 |
| 3 | A and D | 0.01 | 150 | 0.0001 | 1.190 |
| | B and C | 0.001 | 100 | 0.00001 | 0.794 |
| 4 | A and D | 0.003 | 50 | 0.00002 | 0.367 |
| | B and C | 0.0007 | 30 | 0.00001 | 0.245 |

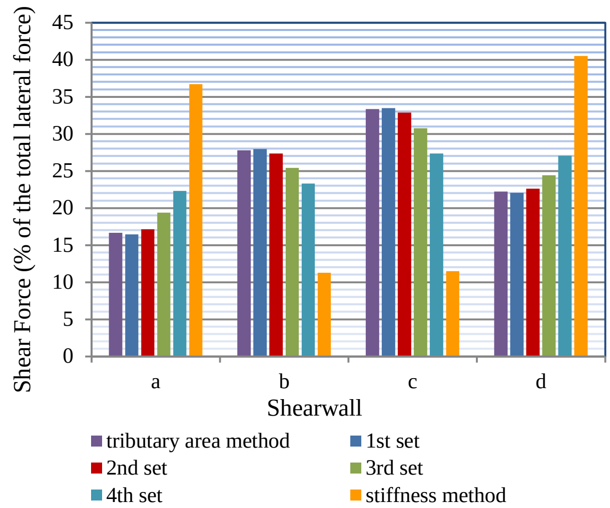



***Figure 7:*** *Lateral load distribution using for Configuration 3 building models with the four sets of shearwalls*

As the shearwalls became more flexible from the 1st set to the 4th set, the discrepancy between the lateral load distribution and the tributary area method results grew. Considering that the floor model in all cases was identical, this observation suggests that whether a floor diaphragm is flexible or rigid depends on the relative stiffness of the floor diaphragm and the shearwall system. In case of stiffer shearwalls, the floor diaphragm is more flexible relative to the shearwalls than when more flexible shearwalls are present.

# 7 SENSITIVITY ANALYSIS

To get a comprehensive understanding of CLT diaphragms in-plane behaviour and lateral load distribution within CLT buildings, it is necessary to identify the most influential parameters by means of parametric study. The studied parameters are categorized in the following two groups:

1. *Material properties*, including mechanical properties of CLT panels, parameters defining the response of CLT panel-to-panel connections, and stiffness of the attached shearwalls.
2. *Geometrical parameters*, including floor diaphragm configuration, number of connected CLT panels, dimensions of the panels.

Each of the above parameters was changed within a reasonable range and their effects on the in-plane behaviour of CLT diaphragms were investigated.

## 7.1 INITIAL STIFFNESS OF THE CONNECTION

The response of the tested panel-to-panel connection was idealized as a piecewise linear curve shown in Figure 3. All the parameters that define this curve affect the in-plane behaviour of the diaphragm. However, only the initial stiffness of the response curve was considered here for sensitivity analysis. This is due to the fact that the initial stiffness of the connection response curve directly affects the initial stiffness of the diaphragm and consequently the lateral load distribution. To study this parameter, Configuration 2 floor model was considered in detail. The initial stiffness of the connection model response curve in Figure 3 is referred to here as *K1*. This stiffness is varied between extreme cases of 0.01*K1* and 1000 *K1* in a number of separate analyses. The change in the initial stiffness of the connection model could be interpreted as the change in the type, size, and density of the connectors (self-tapping wood screws). For each case the pushover analysis was done under uniform pressure load as discussed in Section 5, and the pushover curves were obtained. Figure 8 demonstrates the initial in-plane stiffness of the CLT diaphragm from the pushover curves plotted against the initial stiffness of the panel-to-panel connection in terms of *K1*. Considering the figure, it is evident that the relation of the in-plane stiffness of the CLT diaphragm with the initial stiffness of the connection is not linear. For instance, if the initial stiffness of the connection is doubled by decreasing the spacing of self-tapping screws, the in-plane stiffness of the diaphragm increases only by 35%. Three regions can be recognized in the curve. For practical range of 0.1 *K1* to 10 *K1*, the in-plane stiffness of the CLT diaphragm varies almost logarithmically with the initial stiffness of the connection. For extremely stiff connections with initial stiffness greater than 10 *K1*, most of the diaphragm in-plane deformation takes place in the panels. In other words, the in-plane behaviour of the CLT floor diaphragm with the very stiff connections is controlled by the CLT panels. This explains the plateau in the rightmost region of the curve. On the other hand, for extremely soft connections with initial stiffness value less than 0.1 *K1*, the in-plane deformation of the CLT diaphragm occurs predominantly in the connections. At the very low values of connection stiffness, the integrity of the diaphragm is lost and the in-plane stiffness of the diaphragm tends to become zero. This explains the trend of the curve at left most region.

## 7.2 MECHANICAL PROPERITIES OF CLT PANELS

Mechanical properties of the CLT panels are another set of contributing material properties. Since the overall behaviour of CLT panels was assumed to be linear elastic orthotropic, nine independent engineering constants are in this set of properties. Given that the in-plane behaviour of CLT panels is of interest, only the in-plane shear modulus $G_{xy}$, and the modulus of elasticity in the strong direction of panels $E_y$, and in the weak direction $E_x$ were considered for the sensitivity analysis (Poisson ratios were excluded from this analysis). Configuration 2 floor model was utilized here, again. As before, each of the above three parameters were varied in a reasonable range, keeping the rest of parameters constant. The in-plane behaviour of the CLT diaphragm was monitored by comparing the change in the pushover curves against the change in each parameter. The analysis results suggest that for practical range of elastic

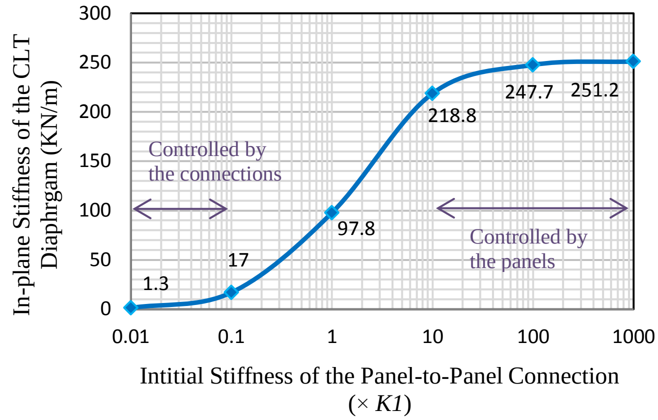
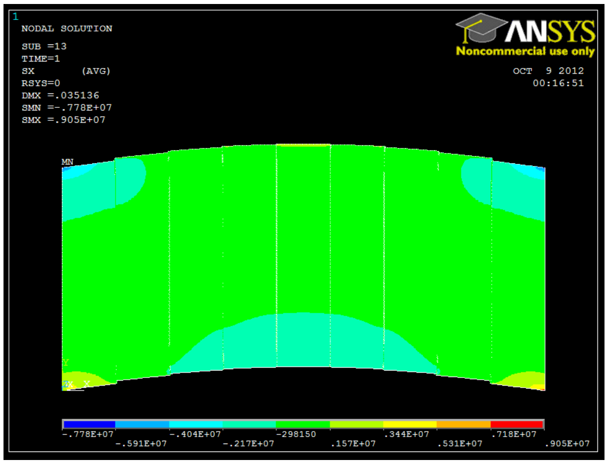



***Figure 8:*** *Effect of the initial stiffness of the panel-to-panel connection on the in-plane stiffness of the CLT diaphragm*

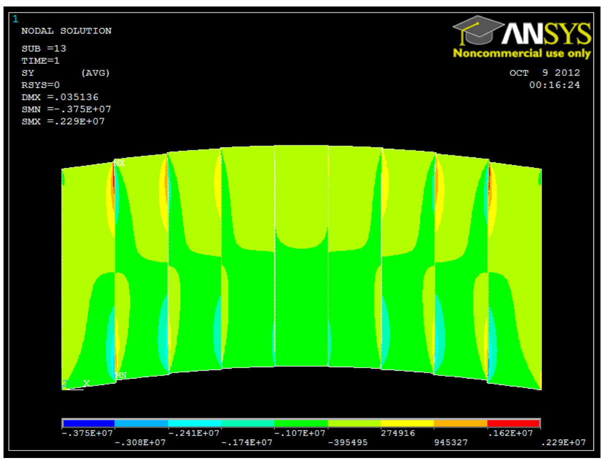
moduli for CLT panels, the in-plane stiffness of the CLT diaphragms is in-sensitive to change in $E_x$ and $E_y$.

In contrast, the in-plane shear modulus $G_{xy}$ seems to be a significantly contributing factor. The above observations can be substantiated further by considering the stress contour plots for the three stress components $\sigma_x$, $\sigma_y$, and $\sigma_{xy}$ in Figure 9 (*Y* is the direction along the shearwalls and *X* is the orthogonal direction). The stress contours were recorded at the capacity point of the CLT diaphragm under uniform in-plane load, before the failure of the first non-linear spring. The applied uniform pressure acting on the lower edge of the diaphragm was 0.8 MPa. The green colour corresponds to very small values of stress, and the red and the blue colour correspond to the extreme stress values of order 10 MPa. Considering the first figure, it is observed that the value of $\sigma_x$ over the entire diaphragm is very small. Since this stress component is an indicator of in-plane bending of the diaphragm, it can be concluded that the share of the flexural deformation in the total in-plane deformation of the CLT diaphragm is negligible. The stress plot for $\sigma_y$ shows that the stress values are insignificant for the upper half of the diaphragm, but gradually increase towards the lower half. It can be deduced that the diaphragm undergoes some extent of axial in-plane deformation. This type of deformation is highest at the lower edge of the diaphragm, where the load was applied. It should be recognized however, that in case of seismic loads, the inertial forces act on the whole body of the diaphragm. In that case, the amount of axial deformation and its distribution is different from the demonstrated case. The third plot shows the distribution of the shear stress $\sigma_{xy}$ over the diaphragm and CLT panels. As expected, the panels experience high shear stress values, most noticeably closer to the boundaries, where the shear force is highest. This in turn demonstrates that the in-plane shear deformation constitutes the largest portion of the total in-plane deformation of the CLT diaphragm.

In another attempt to study the effect of CLT mechanical properties, the in-plane shear modulus $G_{xy}$ was reduced from 600 MPa to an extreme value of 100 MPa in




(a)

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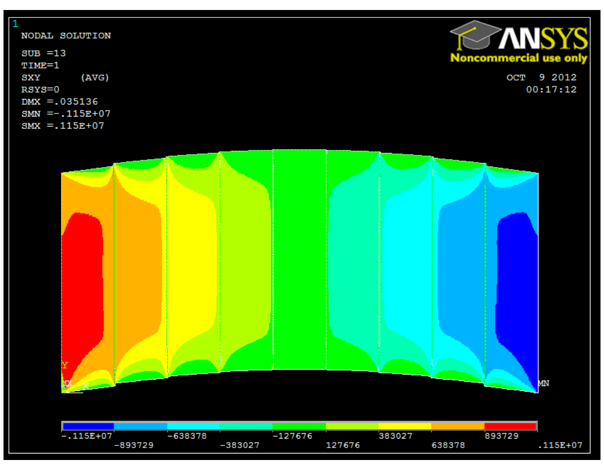



(c)

***Figure 9:*** *Stress contour plots for Configuration 2 floor model (a) normal component $\sigma_x$ (b) normal component $\sigma_y$ (c) shear component $\sigma_{xy}$*

Configuration 2 floor model. The latter case could be interpreted as the in-plane shear modulus of CLT panels, in which the individual layers are connected using mechanical connector such as aluminium nails instead of gluing. Moreover, the number of panels was also reduced to simultaneously study the effect of diaphragm length on the in-plane behaviour. The panels' dimensions and all other parameters were the same in all cases. Figure 10 displays the relation of the diaphragm in-plane stiffness with the number of connected panels for the two shear moduli values. The in-plane stiffness of the diaphragm is the initial stiffness of the pushover curve, as with the previous cases.

The plot demonstrates that as intuitively expected the in-plane stiffness of the CLT diaphragm reduced with reduction in the in-plane shear moduli. Furthermore, the figure highlights that the amount of reduction in the in-plane stiffness is greatest for lower number of connected panels, or alternatively, shorter spans. This can be explained, considering that as the diaphragm span becomes shorter, the share of shear deformation in the in-plane deformation becomes even more significant. Consequently, the change in the in-plane stiffness of the CLT diaphragms due to the change in the in-plane shear modulus becomes more prominent.

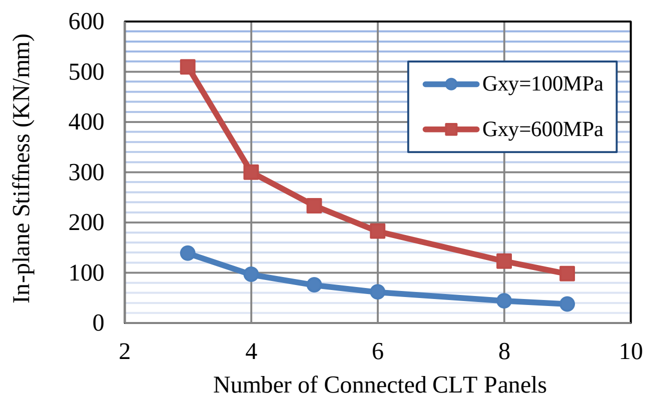



***Figure 10:*** *Lateral load distribution flowchart*

### 7.3 STIFFNESS OF THE ATTACHED SHEARWALLS

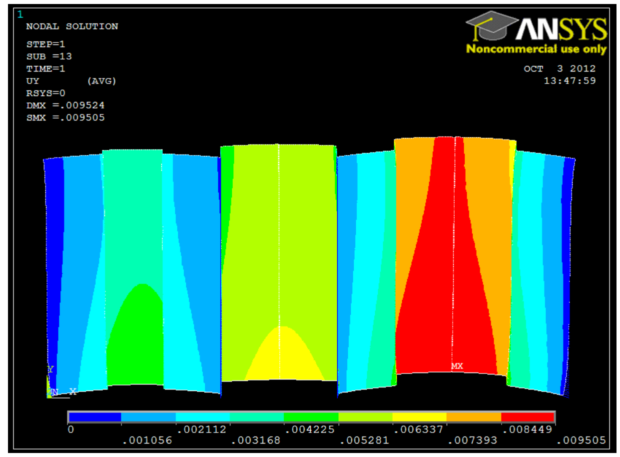
As demonstrated in Section 6, the relative in-plane stiffness of diaphragm and the attached shearwall system is the key factor that determines the lateral load distribution pattern in CLT buildings. A number of additional cases were analysed to further investigate the above statement. The lateral load distribution for these cases is tabulated in Table 1 along with some of the previously analysed cases for comparison. The additional cases included Configuration 3 building model with the 4$^{th}$ set of shearwalls but with rigid panel-to-panel connections instead of the tested connections. By incorporating rigid-panel-to-panel connections, the slip between the panels was excluded from the in-plane deformation of the diaphragm. The other two additional cases were concrete building models. These models were generated using a concrete floor slab in place of the CLT floor in Configuration 3 building model. The concrete material was assumed to be elastic isotropic with modulus of elasticity of 30000 MPa and Poisson`s ratio of 0.25. Concrete floors are typically assumed to be rigid diaphragms and the wall stiffness method is normally utilized for finding the lateral load distribution in the buildings containing this type of floors. Referring to Table 3, the lateral load distribution of the concrete floor with the 4th set of shearwalls is closest to the results of the wall stiffness method. However, the distribution deviates from the results of the wall stiffness method if instead the 1st set of shearwalls, which is much stiffer than the 4th set, is incorporated in the building model. In fact, even in case of concrete floors, if they are attached to shearwalls with relatively high in-plane stiffness, the assumption of rigid diaphragm will not be accurate for predicting the lateral load distribution. The results in the table, also suggest that removing the share of in-plane deformation in the panel-to-panel connections, would make the CLT floor stiffer as expected. The deformation contour plots of CLT floor with the 1st and the 4th set of shearwalls are compared against the concrete floor with the 4th set of shearwalls in Figure 11. The deformation pattern of the CLT floor clearly changes when using different shearwalls with the same floor model. The deformation pattern of the CLT floor with the 4th set of shearwalls is close to the deformation of the concrete floor model. For both cases, the whole floor deforms almost as a single unit, dictating the deformation in the attached shearwalls. However, for the CLT floor with the 1st set of shearwalls, the floor deforms rather independently in each bay. This deformation pattern is characteristic of flexible diaphragms.

***Table 3:*** *Comparison of the lateral load distribution from analysis with hand calculations methods, for a number of CLT buildings*

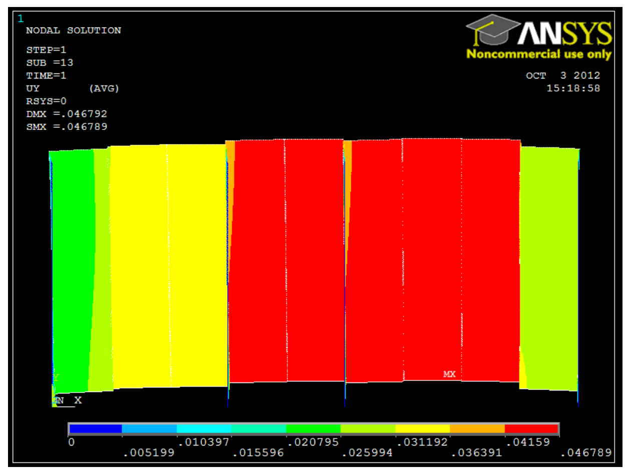
| | Share of the Force in each Shearwall (% of the Total Force) | | | |
|---|---|---|---|---|
| | a | b | c | d |
| Tributary Area Method | 16.7 | 27.8 | 33.3 | 22.2 |
| Wall Stiffness Method | 36.7 | 11.3 | 11.5 | 40.5 |
| Concrete Floor (1st set of shearwalls) | 21.2 | 24.8 | 27.6 | 26.4 |
| Concrete Floor (4th set of shearwalls) | 27.6 | 19.9 | 20.6 | 32.0 |
| CLT Floor (1st set of shearwalls) | 16.5 | 28.0 | 33.5 | 22.1 |
| CLT Floor (4th set of shearwalls) | 22.3 | 23.3 | 27.3 | 27.0 |
| CLT Floor (4th set + rigid panel-to-panel connections) | 24.7 | 22.1 | 23.7 | 29.4 |

### 7.4 GEOMETRICAL PROPERTIES

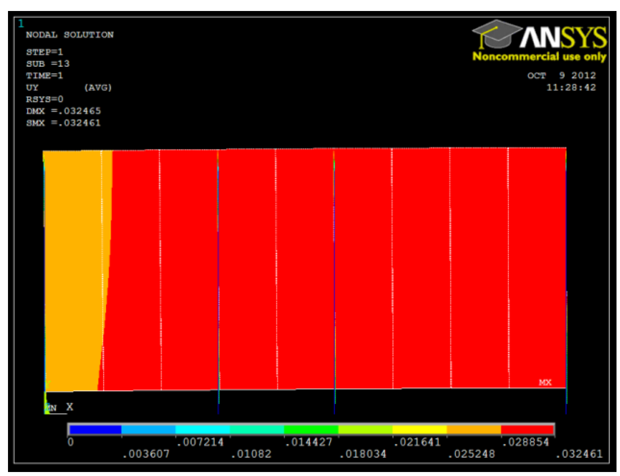
The geometrical properties that affect the in-plane behaviour of CLT floors include dimensions of CLT panels, number of connected panels, and floor diaphragm




(a)




(b)




(c)

***Figure 11:*** *Deformation contour plot for (a) Configuration 3 floor model with the 1st set of shearwalls (b) Configuration 3 floor model with the 4th set of shearwalls (c) Concrete slab floor with the 4th set of shearwalls*

configuration. The effect of the first was addressed along with the effect of in-plane shear modulus of panels in Section 7.2. The dimensions of CLT panels affect the type of in-plane deformations that the panels undergo. For short panels, the panel act as a short deep beam, and thus as demonstrated previously the share of shear deformations is significantly higher than flexural counterpart. However for narrow CLT panels, where the length is much larger than the width of the panel, the opposite holds; i.e. the flexural in-plane deformations within panels dominate the shear deformations.

Lastly, the floor diaphragm configuration affects how the lateral forces are distributed to the shearwalls. In this study a few but representative examples of CLT floor configurations were compared in the previous sections. However, to comprehensively address this item, more research needs to be done in future works.

## 8 CONCLUSIONS

The in-plane behaviour of CLT floor diaphragms has been investigated in this study. A universal approach was taken to study the subject, which can be applied to investigate other types of floor diaphragms as well. Detailed 2D finite element models of selected floor diaphragms were generated in ANSYS to examine various aspects of in-plane behaviour of CLT floors. A simple yet efficient smeared CLT panel-to-panel connection model was developed for the ANSYS floor models. Although this model was calibrated to a specific type of connection with self-tapping wood screws, it can be calibrated to other types of panel-to-panel connections as well.

The in-plane behaviour in this study has been addressed within the context of lateral load distribution to the shearwall system, including the shearwalls and their connections to the floors. The results of the lateral load distribution were compared with the results of the tributary area and wall stiffness methods, the two common hand calculation methods for distributing the lateral load to the shearwalls. Consequently, the in-plane behaviour of CLT floors diaphragms were compared with completely flexible and completely rigid floor diaphragms. The sensitivity analysis provided a deep insight into the importance and effect of each of the various parameters that affects the in-plane behaviour of CLT floors. In particular, the significance of the panel-to-panel connection response on the overall in-plane behaviour of CLT diaphragms was highlighted.

This study explicitly indicated that the in-plane behaviour of a floor diaphragm must be studied in the context of a building system. In other words, whether the floor diaphragm is flexible or rigid depends on the building system and the relative stiffness of the floor diaphragm and the shearwall system.

## ACKNOWLEDGEMENT

The authors gratefully acknowledge the funding for this research project, which was provided by the Strategic Network on Innovative Wood Products and Building Systems (NewBuildS). NewBuildS is a Forest Sector Research & Development Initiative funded by the Natural Sciences and Engineering Research Council of Canada (NSERC), FPInnovations, and Natural Resources Canada (NRCan).

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