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LATERAL DEFORMATION AND KINEMATIC MODES OF MULTI-PANEL BALLOON-TYPE CLT SHEARWALL SYSTEM

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ABSTRACT: Balloon-type Cross-Laminated Timber (CLT) shearwall systems have been widely used as lateral load resisting systems (LLRS) in several mid- and high-rise timber buildings. Contrary to platform-type shearwalls, balloon framing contains continuous panels along multiple storeys in the vertical direction, which helps avoid perpendicular-to-grain compression failure in the floors. Despite some of the advantages associated with this type of construction, design provisions have not yet been introduced to various timber codes and standards, mainly due to the scarcity in research on their behaviours. This paper presents a numerical analysis model with the aim of investigating the lateral deformation and kinematic modes of balloon-type CLT shearwall systems. A finite element (FE) model is proposed, and a discussion on various key parameters affecting the behaviour of the shearwall, including aspect ratios (*h/b*), stiffness of the connectors, vertical loads and the number of panels, is presented.

KEYWORDS: Balloon-type, Cross-laminated timber, Aspect ratio, Multi-panel, Kinematic behaviour

1 INTRODUCTION

Numerous research projects and case studies have highlighted the ability of cross-laminated timber (CLT) shearwalls to resist lateral wind and seismic loads in timber buildings, mainly due to their high in-plane strength and stiffness. When the wall aspect ratio (i.e., height-to-length) is limited between 2:1 to 4:1, it has been demonstrated that CLT shearwalls are capable of dissipating energy through rocking behaviour and engagement of panel-to-panel connections as well as mechanical boundary anchors (hold-downs and angle brackets). This aspect ratio range is usually suitable for platform-type construction, where the wall extends between two consecutive floors. The development of analytical and experimental models for platform-type CLT shearwalls, including establishing the lateral behaviour and kinematic modes of multi-panel shearwall systems, has been undertaken by several researchers [1,2,3,4]. In terms of manufacturing, transportation and installation, it is sometimes desirable to produce longer panels that can extend multiple storeys along the height of the building. Another benefit of this so-called balloon-type construction is the avoidance of having accumulated axial load in the wall that could cause perpendicular-to-grain compression failure in the floors [5].

Balloon-type CLT shearwall systems have already been adopted in several construction projects, such as the Arboratum Project [6], which employs a CLT shearwall core with aspect ratios of the panels ranging from 5:1 to 20:1. Another example is the Arbora Condos in Montreal [7], which contain shearwall panels spanning 7 storeys with aspect ratios between 3:1 and 11:1. Despite the presence of these type of buildings in practice, research activities investigating the performance of balloon-frame CLT shearwalls have been scarce. Some studies have focused on predicting the lateral deformation of a two-panel balloon-type CLT shearwall system [8,9], while others have investigated the impact of ledger beams on the wall performance [10,11].

It is important to note that there are currently no design provisions for balloon-frame CLT shearwalls in various codes and standards (e.g., CSA O86 [12] and Eurocode 5 [13]), mainly due to a lack of fundamental research output involving this system. The review of available research clearly indicates that more research towards developing an understanding of the behaviour of multi-panel balloon-type CLT shearwall systems is necessary.

The current research aims at contributing to the gaps in knowledge in this field by investigating the lateral deflection and kinematic modes of balloon-type multi-panel CLT shearwall systems through a numerical FE approach.

2 SENSITIVITY ANALYSIS

2.1 MODEL DESCRIPTION

A finite numerical element (FE) model has been adopted to conduct sensitivity analyses with the aim of understanding the impact of key parameters governing the

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mechanical behaviour of multi-panel balloon-type shearwall systems subjected to lateral loads. The proposed FE model consists of shearwalls with a total height, a total width and a panel width of h, B and b, respectively, subjected to lateral point force F stemming from wind or seismic loads applied at the diaphragm level of each storey. The panels are assumed to be connected to the foundation by hold-downs with axial stiffness, k_{hd}, along the vertical direction, while the panel sliding along the horizontal direction is restricted. Adjacent panels are connected to each other by means of uniformly placed vertical joints with total shear stiffness k_{vj}. Vertical uniformly distributed gravity loads, q, are assumed to be applied at each floor level. Figure 1 shows a two-panel model with a height representing three storeys.

The numerical analysis is carried out using the commercially available FE software package SAP2000 [14]. A total of 548 different models were developed based on a series of varying parameters, including panel aspect ratio *h/b*, stiffness of hold-down and vertical joints, vertical loads and the number of panels.

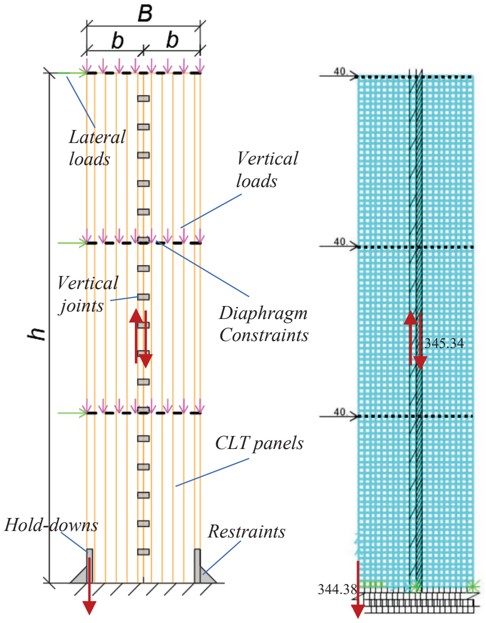

Figure 1: *Two-panel three-storey CLT shearwall model*

2.2 MODEL CONFIGURATION AND PARAMETERS

The FE model adopts thick-shell type elements to simulate the behaviour of the shearwall panels. The mesh size was selected to be 100 mm × 100 mm, based on a mesh sensitivity analysis. It should be noted that when the meshing size was reduced from 100 mm × 100 mm to 10 mm × 10 mm, the difference in the total lateral deformation was within 3%.

Equivalent material properties of the CLT panels were determined using the method proposed by Brandner et al. [15], as presented in Equations (1) and (2) for the effective modulus of elasticity along the vertical, $E_{0,eff}$, and lateral, $E_{90,eff}$, directions, respectively.

$$E_{0,eff} = \frac{E_0 t_0 + E_{90} t_{90}}{t} \tag{1}$$

$$E_{90,eff} = \frac{E_0 t_{90} + E_{90} t_0}{t} \tag{2}$$

where

E_0 is the modulus of elasticity parallel to grain,
E_{90} is the modulus of elasticity perpendicular to grain,
t_0 is the total thickness of vertical layers,
t_{90} is the total thickness of lateral layers,
t is the total thickness of the panel.

For the purpose of the sensitivity analysis, E_{90} is assumed equal to $E_0/30$ [12,16], and E_0 is assumed to be the same in both the longitudinal and transverse layers. The effective in-plane shear modulus, G^*, was estimated according to the method proposed by Bogensperger et al. [17].

Link elements were assumed to simulate the behaviours of hold-downs, vertical joints and foundation supports. Additionally, restraints are applied at the bottom of each panel to restrict their lateral sliding. In order to ensure the same lateral displacements at the top of the panels, a diaphragm constraint at the floor level was imposed.

Table 1 summarises the input parameters used in the sensitivity analysis, while Table 2 indicates the range of aspect ratios investigated.

Table 1: *Values of the basic parameters of models*

Parameter	Symbol	Values
Storey number	n (-)	1; 2; 3; 4
Number of panels	m (-)	1; 2; 3; 4
Lateral load per storey	F (kN/m)	20
Vertical load per storey	q (kN/m)	0; 20
Stiffness of foundation	k_f $^{(1)}$ (kN/m)	1.0×10^6
Panel thickness	t (mm)	175 (5 layers)
Young's modulus and shear modulus	$E_0^{(2)}$, $G_0^{(3)}$ (MPa)	12000; 690
Stiffness of hold-down	k_{hd} (kN/mm)	10; 25; 50; 100
Stiffness of unit vertical-joint	k_{vj}/h (kN/mm/m)	3; 7.5; 15

Note: (1), (2), and (3) refer to the values adopted by [1], [12] and [18], respectively.

Table 2: *Aspect ratio (h/b) matrix in the sensitivity analysis*

	h = 3m	h = 6m	h = 9m	h = 12m
b = 0.25m	12			
b = 0.5m	6	12		
b = 0.75m	4	8	12	
b = 1m	3	6	9	12
b = 2m	1.5	3	4.5	6
b = 3m	1	2	3	4
b = 6m		1	1.5	2
b = 9m			1	1.3
b = 12m				1

The naming convention of the models follows a format where, for example, for "*M12/1 - P3 - VL20 - H10V3*", "*M12/1*" indicates a model (*M*) with a panel aspect ratio of 12 to 1, "*P3*" refers to the number of panels being three, "*VL20*" highlights a value of vertical load (*VL*) equal to 20 kN/m/storey, and "*H10V3"* indicates that the values of the stiffness of hold-downs (H) and the unit stiffness of vertical-joint (V) are 10 kN/mm and 3 kN/mm/m, respectively.

2.3 VALIDATION OF THE MODEL

The methodology proposed in this paper is verified against the shearwall test conducted by Chen and Popovski [8], which consists of a two-panel balloon frame CLT shearwall, as shown in Figure 2. The panels consist of 5-ply CLT (Grade E1) with dimensions of each panel equal to 4125 mm (height) × 420 mm (width). Two sets of hold-downs are placed at both outer corners, and five pairs of panel-to-panel joints (half in the front and half in the back) are used to attach the two panels with an equal spacing distance of 825 mm. Lateral restraints are used to prevent sliding. A uniformly distributed gravity load with a magnitude of 2.1 kN/m is applied on the top of two panels. A concentrated horizontal load is applied at the top of the wall.

Model input parameters were consistent with those used in the study and included modulus of elasticity in the longitudinal layers are E_0 = 11700 MPa and E_{90} = 390 MPa, while the transverse layers were assigned values of E_0 = 9000 MPa and E_{90} = 300 MPa [12]. As a result, the effective moduli of elasticity obtained using Equation (1) and (2) are calculated to be $E_{0,eff}$ = 7140 MPa, and $E_{90,eff}$ = 3834 MPa, respectively. The shear modulus G is assumed equal to 731 MPa, and hence the effective shear modulus G^* is calculated equal to be 380.47 MPa [17].

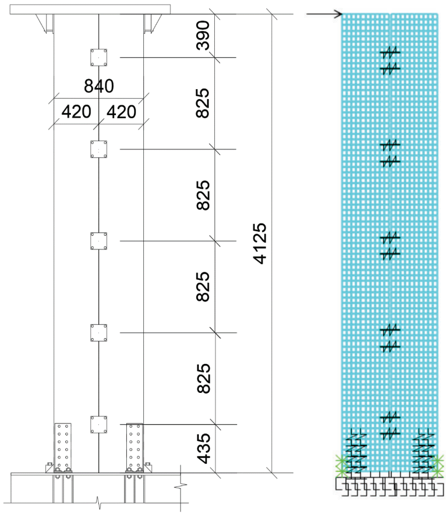

***Figure 2:** Shearwall configuration (left) [8] and FE model (right)*

The results of the comparison (Figure 3) clearly show the ability of the proposed model to mimic the behaviour of the shearwall. Discrepancies are likely related to the values of the assumptions associated with the mechanical properties of the connectors, which have been simplified to bi-linear curves in the FE modelling analysis.

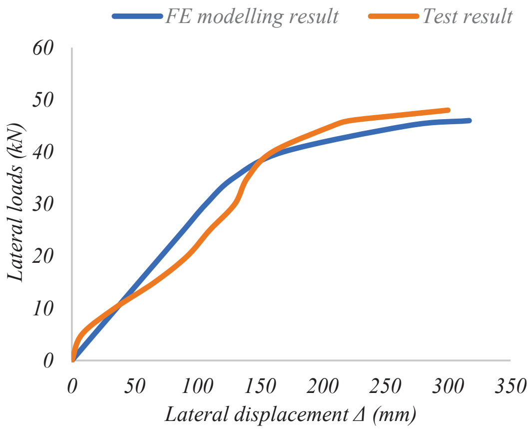

***Figure 3:** Result comparison between FE modelling and test [8]*

3 RESULTS AND DISCUSSION

The results from sensitivity analysis are discussed in the context of the total lateral stiffness, K, defined as the ratio between total lateral loads, ΣF, and the total lateral displacement at the top of the shearwall, Δ_{total}. The relative rocking deformation, r, is defined as a percent ratio that the rocking deformation, $\Delta_{rocking}$, constitutes relative to the total deformation, Δ_{total}, ($r = \Delta_{rocking}/\Delta_{total} \times 100\%$). The discussion also includes the kinematic behaviours that are expressed in terms of coupled-panel (CP) behaviour, which involves rotation of the individual panels about their respective centres of rotation, single-wall (SW) behaviour, where the entire shearwall rotates about one centre of rotation at its end, and intermediate (IN) behaviour that falls between the CP and SW behaviours [1].

3.1 IMPACT OF PANEL ASPECT RATIO

The conducted sensitivity analysis of multi-panel balloon-type CLT shearwall systems shows that aspect ratio h/b significantly impacts the lateral deformation and kinematic modes of the walls. As expected, the results from all cases show that $1/K$ increases with increasing aspect ratio h/b, as shown in Figure 4 for the models *M h/b-P2-VL20-H10V3.*

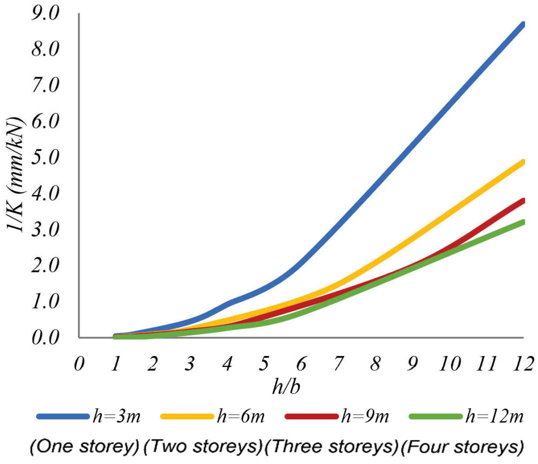

Figure 4: *Relationship between 1/k and h/b for the models M h/b-P2-VL20-H10V3*

Figure 5 shows the relationship between the relative rocking deformation *r* and panel aspect ratio *h/b,* for wall height equal to 6 m. Similar results were also obtained for wall heights equal to 9 m and 12 m. The results reveal consistent tendencies for walls with higher stiffness of hold-downs and vertical-joint to exhibit less rocking. This can be attributed to the restraining effect of the hold-down with higher stiffness, as well as the contribution of the vertical joints with higher stiffness to cause the panels to behave more in SW mode.

It can also be noted that the rocking behaviour is dominant in the range of aspect ratios between 3 and 6, which could be attributed to a largely shear-driven behaviour when the aspect ratio is low (≤ 2), and flexural-driven behaviour for high aspect ratios.

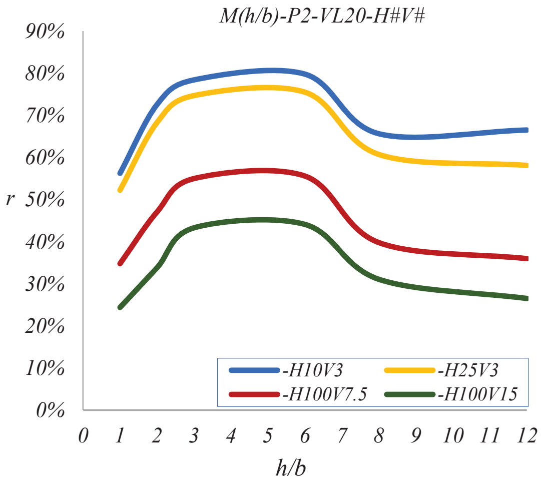

Figure 5: *Relationship between h/b and r when h equals 6 m and vertical load equals 20 kN/m for two-panel models*

3.2 IMPACT OF CONNECTION STIFFNESS

Due to the large range of stiffness values found in the results for connection stiffness, an approach involving normalised lateral stiffness, K_{hd}^* and K_{vj}^*, defined as the ratio between the total lateral stiffness of the wall, *K*, and the value of stiffness related to specific hold-down stiffness, k_{hd}, equals 10 kN/mm in Equation (3), or the specific unit vertical-joint stiffness of k_{vj}/h, equal to 3 kN/mm/m in Equation (4), respectively, is used in this study. The normalised vertical joint stiffness k_{vj} * is defined as a ratio between the value of unit vertical-joint stiffness and the specific value equal to 3 kN/mm/m in Equation (5).

$$K_{hd}^* = \frac{K}{K_{(k_{hd}=10kN/mm)}} \tag{3}$$

$$K_{vj}^* = \frac{K}{K_{(k_{vj}/h=3kN/mm/m)}} \tag{4}$$

$$k_{vj}{}^* = \frac{k_{vj}/h}{3} \tag{5}$$

Figure 6 presents the relationship between the normalised total lateral stiffness K_{hd}^* and hold-down stiffness k_{hd} for $b = 1\,m$, $b = 2\,m$, and $b = 3\,m$, without the application of vertical loads. Generally, it is found that the relationship between K_{hd}^* and k_{hd} is non-linear, and the rate of increase becomes less significant following an increasing hold-down stiffness.

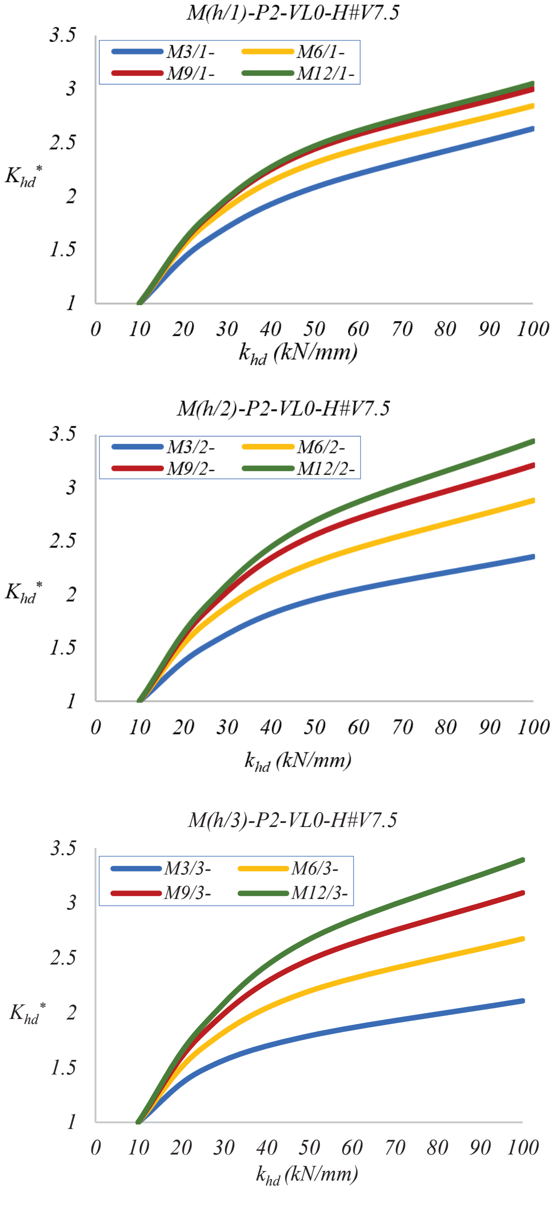

Figure 6*: Relationship between* k_{hd} *and normalised total lateral stiffness* K_{hd}^* *when* k_{vj}/h *equals 7.5 kN/mm/m, and there is no vertical load for two-panel models*

Figure 7 presents the relationship between K_{vj}^* and the normalised vertical-joint stiffness k_{vj}^* for $h = 3\,m$, $h = 6\,m$, $h = 9\,m$ and $h = 12\,m$, including the application of vertical loads. Generally, the trends are consistent with those observed for the hold-down stiffness. When the aspect ratios of panels are low (e.g., 1:1, as in models

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M3/3-, *M6/6-*, *M9/9-* and *M12/12-*), K_{vj}^{*} increases less significantly than those with higher aspect ratios following the growth of the stiffness of vertical joints.

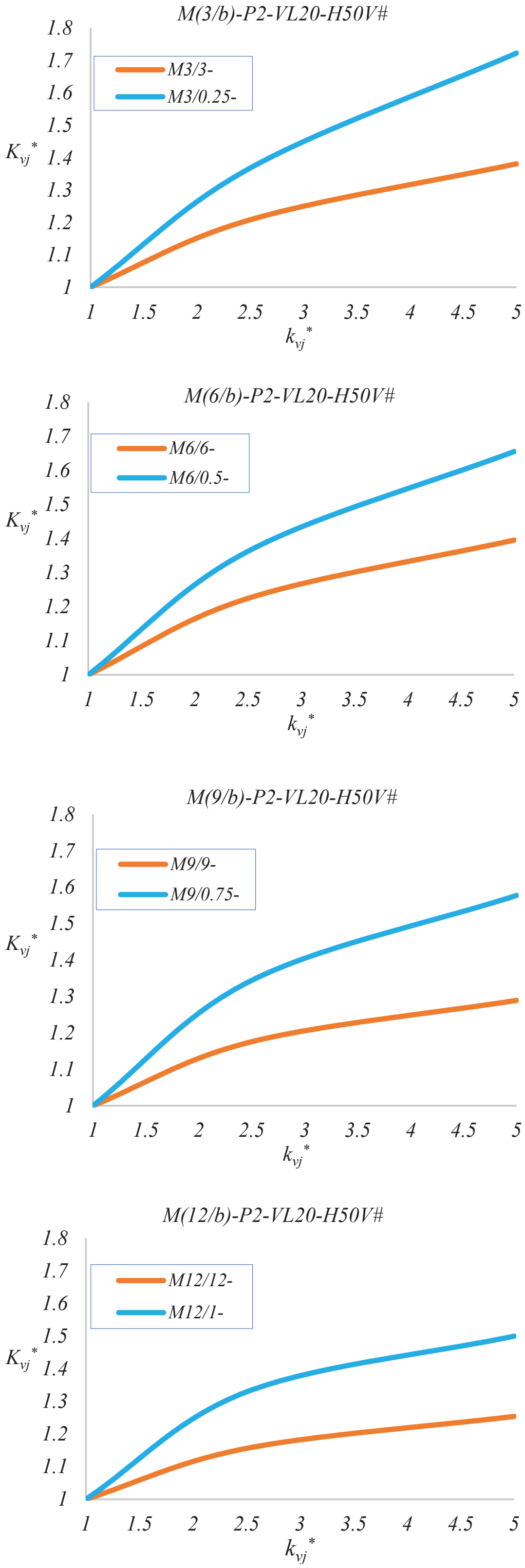


***Figure** 7: Relationship between normalised vertical-joint stiffness k_{vj}^{*} and normalised total lateral stiffness K_{vj}^{*} when k_{hd} equals 50 kN/mm, and vertical loads equal 20 kN/m for two-panel models*

Table 3 illustrates the percentage of two-panel models with CP mode as a function of an increase in hold-down stiffness (includes 72 models), while Table 4 presents the percentage of two-panel models with SW mode when the unit stiffness of vertical joints is varied (includes 96 models). It can be observed that similar to what was found from research on platform-type shearwalls, balloon-type construction tends to be more dominated by CP mode when the stiffness of hold-downs increases, while SW mode is more prevalent when the stiffness of unit vertical-joint increases.

***Table 3:** Percentage of the CP mode using different values of the hold-down stiffness*

k_{hd} (kN/mm)	Percentages of the CP mode#
10	16.7%
25	41.7%
50	68.1%
100	88.9%

#: The percentage of CP mode is calculated by

$$\frac{No.\,of\ the\ models\ shown\ as\ CP\ mode}{No.\,of\ the\ total\ models\ (=72)} \times 100\%.$$

***Table 4:** Percentage of the SW mode using different values of the vertical-joint stiffness*

k_{vj}/h (kN/mm/m)	Percentages of the SW mode#
3	21.9%
7.5	46.9%
15	69.8%

#: The percentage of SW mode is calculated by

$$\frac{No.\,of\ the\ models\ shown\ as\ SW\ mode}{No.\,of\ the\ total\ models\ (=96)} \times 100\%.$$

The relationships between the hold-down or unit vertical-joint stiffness and the percentage of rocking deformation are depicted in Figure 8 and Figure 9, respectively. It can be noted that the shearwalls with higher aspect ratios are more sensitive to hold-down stiffness, while the ones with lower aspect ratios are more sensitive to the unit vertical-joint stiffness. This may be attributed to the fact that when the panel aspect ratio is higher, hold-down stiffness has a more significant influence on the distribution between rocking deformation and flexural deformation, while when the aspect ratio is lower with panels performing more rigidly, vertical-joint stiffness has more impact on the distribution between rocking deformation and shear deformation.

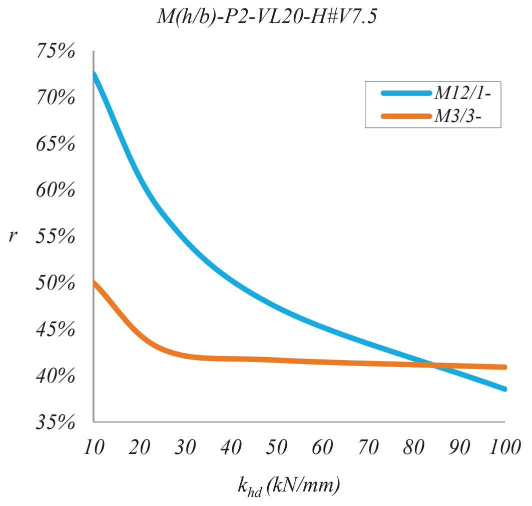


***Figure 8**: Relationship between k_{hd} and r when k_{vj}/h equals 7.5 kN/mm/m, and vertical loads equal 20 kN/m for two-panel models*

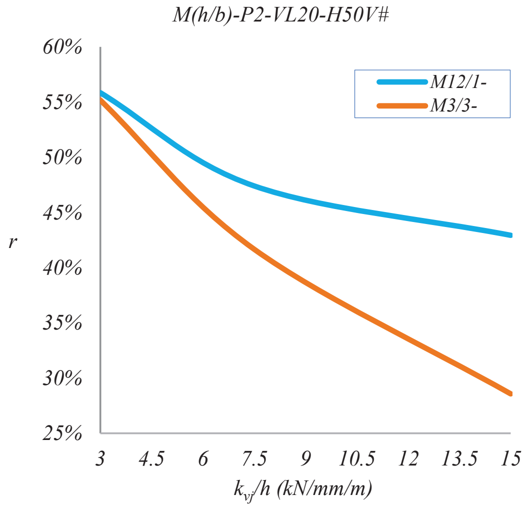


***Figure 9**: Relationship between k_{vj}/h and r when k_{hd} equals 50 kN/mm, and vertical loads equal 20 kN/m for two-panel models*

3.3 THE IMPACT OF VERTICAL LOADS

Models with vertical loads show higher total lateral stiffness *K* compared with those with no vertical loads applied. Figure 10 compares the average total lateral stiffness between the cases that include or exclude the vertical loads when aspect ratios vary from 3 to 12 for two-panel models. It is noted that although the averaged total lateral stiffness is positively affected by the increase in vertical loads, the effect is much less pronounced when the panel aspect ratio increases. It is also found that the presence of vertical loads yields more cases with CP mode. For example, when a vertical load of 20 kN/m/storey is applied, the number of cases with CP mode increases from 130 out of 288 (45.1%) to 180 out of 288 (62.5%).

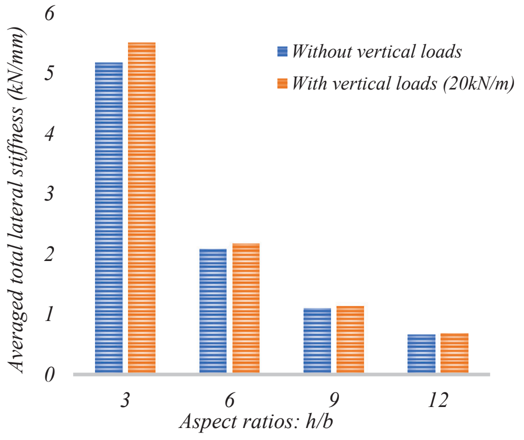
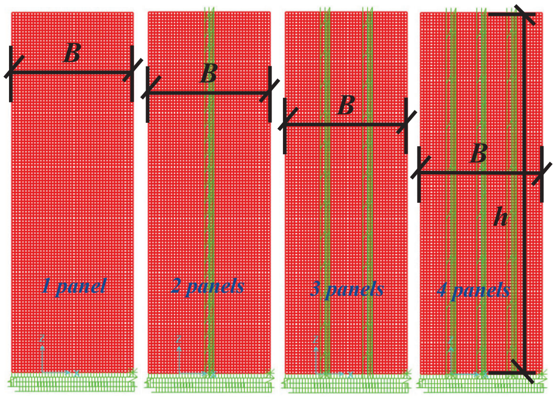


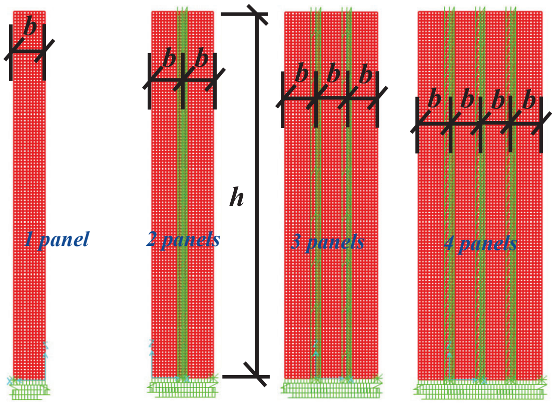
***Figure 10**: Impact of vertical loads on the averaged total lateral stiffness with varying aspect ratios when b equals 1 m for two-panel models*

3.4 THE IMPACT OF THE NUMBER OF PANELS

This part of the analysis considers two conditions, namely a fixed ratio of *h* to *B*, and a fixed ratio of *h* to *b*, as shown in Figure 11.



(a) Varying panel number with fixed h/B (12:4)



(b) Varying panel number with fixed h/b (12:1)

***Figure 11:** Analysis of multi-panel behaviours*

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The analysis for the fixed h/B ratio found that increasing the number of panels resulted in a decrease in the total lateral stiffness of the wall (Figure 12). In comparison, the models with higher relative stiffness $\tilde{k}$ defined as a ratio between k_{hd} and k_{vj} ($\tilde{k} = k_{hd} / k_{vj}$) showed a much larger reduction in stiffness than those with lower relative stiffness values.

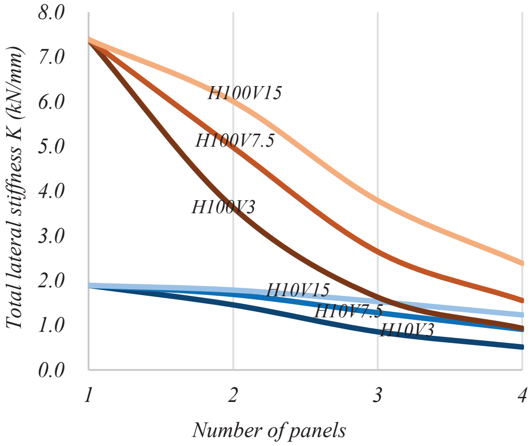


Figure 12: *Relationship between the number of panels and K when h/B is fixed to be 12:4 and vertical loads equal to 20 kN/m*

It can be observed from the results that the number of panels affects the percentage of rocking deformation, with the general tendency for a higher percentage of rocking behaviour when more panels are used, as illustrated in Figure 13.

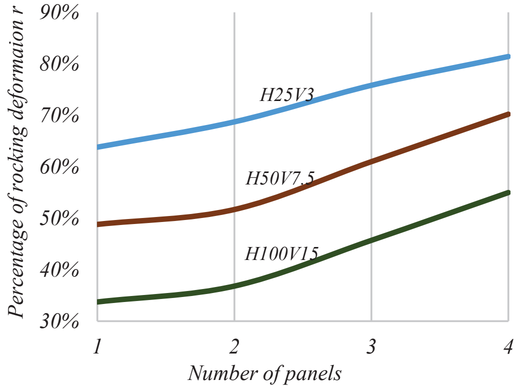
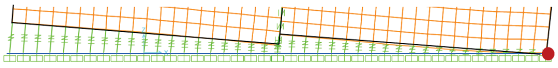
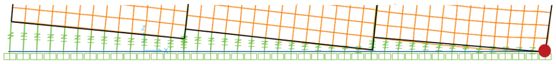


Figure 13: *Relationship between the number of panels and r for the models with CP mode when h/B is fixed to be 12:4 and vertical loads equal to 20 kN/m*

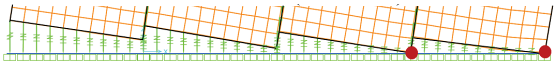
With respect to the kinematic modes, the models with CP mode tend to maintain that behaviour following an increase in the number of panels. However, models with SW mode could shift to IN behaviour when more panels are added. Figure 14 shows an example from model *M h/b -P# - VL20 - H25V15*, where when the number of panels increases from 2 to 4, the kinematic mode changes from SW to IN.



Panel Number = 2 (SW mode)



Panel Number = 3 (SW mode)



Panel Number = 4 (IN mode)

Figure 14: *Kinematic modes of the models with varying panel numbers.*

The analysis found that the total lateral stiffness tends to increase when the number of panels is increased while maintaining a constant ratio of *h/b*.

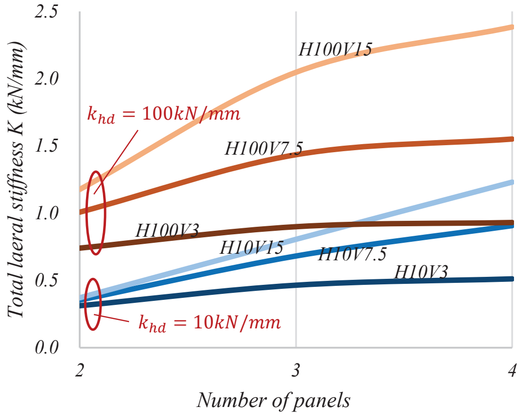


Figure 15: *Relationship between the number of panels and K when h/b is fixed to be 12:1 and vertical loads equal to 20 kN/m*

Similar to the result from the condition with a fixed *h/B* ratio, a higher percentage of rocking deformation is observed for systems using more panels with a fixed *h/b* ratio.

4 CONCLUSIONS

Analysis of the lateral deformation and kinematic modes of multi-panel balloon-type CLT shearwall systems is presented in this paper. A multi-panel shearwall model is proposed, and the effect of key parameters on the behaviour of the shearwall is presented and discussed.

The results highlight the importance of the panel aspect ratio (*h/b*) and the stiffness of connectors. It is found that the total lateral stiffness of the wall is higher when panels with lower aspect ratio, hold-down and vertical joints with higher stiffness and larger vertical loads are adopted. Increasing the number of panels for a shearwall system with a fixed total height-to-width ratio (*h/B*) results in lower total lateral stiffness, while increasing the number of panels with a fixed panel aspect ratio (*h/b*) results in higher total lateral stiffness.

The results also indicate that the lateral flexural deformation for balloon-type shearwalls should not be ignored. In general, a higher aspect ratio, higher stiffness of hold-downs and vertical joints, and fewer number of panels all lead to a higher percentage of flexural deformation.

Finally, it is found that balloon-type CLT system with higher relative stiffness in the connections and higher vertical loads tends to be dominated by CP mode.

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