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AN ANALYTICAL MODEL TO INVESTIGATE THE EFFECT OF DIAPHRAGMS ON THE ELASTIC BEHAVIOUR OF MULTI-STOREY COUPLED-PANEL CLT SHEARWALLS

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ABSTRACT: This study develops an analytical model to describe the behaviour of multi-storey multi-panel CLT shearwalls, specifically accounting for cumulative loads between storeys and the effect of the diaphragm. The analysis considers the contribution of hold-downs, wall-to-floor connections, and panel-to-panel joints, as well as loads transferred from storeys above. The analysis has been developed for shearwalls acting as a series of coupled panels (CP) each individually rotating about a corner. Force transfer between storeys is implemented by distributing reactions through the upper floor diaphragm and a direct force from the upper storey's hold-down. Structuring the equations this way allows for a simplified formulation while including several components of the system's complex behaviour. Two-dimensional finite element modelling is used to verify the accuracy of the developed model.

KEYWORDS: CLT, Lateral Design, Modelling, Earthquake, Mid-rise, Derivation, Diaphragm Effect

1 INTRODUCTION

Lateral Load Resisting Systems (LLRS) in Cross Laminated Timber (CLT) used in platform-type buildings typically consist of two types of shearwalls; namely monolithic shearwalls made with a single panel or multi-panel shearwalls comprised of segments connected with vertical joints. The behaviour of multi-panel CLT shearwalls is primarily related to the properties of the vertical joints and mechanical anchors (e.g., hold-down and angle brackets), while the CLT panels generally behave as rigid bodies [1]. Depending on the relative stiffness between vertical joints and hold-down as well as the magnitude of vertical loads, three kinematic modes may be developed in single-storey multi-panel shearwalls, namely a mode consisting of individual panel rotation (coupled panel, or CP), a mode consisting of a global wall rotation (single wall, or SW) and an intermediate mode (IN) comprised of both CP and SW modes [2,3]. Several analytical methods have been developed to predict the elastic behaviour of single-storey multi-panel CLT shearwalls. Flatscher and Schickhofer [4] developed analytical expressions through displacement-based methods while Masroor et al. [5] proposed an analytical methodology taking into account the bi-directional behaviour of angle-brackets [6,7]. Studies on the mechanical behaviour of multi-storey multi-panel CLT shearwalls, including the structural interaction between floor and wall panels have been limited. D'Arenzo et al. [8] developed an analytical model to investigate the interaction between a two-panel shearwall and the upper floor but such model was limited to single-storey shearwall.

This paper seeks to expand the existing single-storey approach by developing analytical expressions to account for the behaviour of multi-storey multi-panel CLT shearwalls, focusing on the CP kinematic mode. In order to replicate the effects of multi-storey behaviour in a single-storey analysis, the resulting reactions of a storey are used to modify the loads applied to the lower storey. Accordingly, the storeys are analyzed sequentially, beginning from the uppermost storey and transferring reaction forces to the next, lower storey. Due to this transfer of forces between stories, the effect of floor diaphragms between the CLT walls is also investigated and incorporated into the method.

The analytical method incorporates the cumulative effects of force transfer from one storey to another, as well as more flexible formulations to describe the connections between the wall panels and the upper and lower floor diaphragms. The proposed equations are verified against the results of two-dimensional finite element modelling using the Dlubal RFEM software.

2 ANALYTICAL METHODOLOGY

Following the methods developed in [2], analytical equations are developed using the method of virtual work and static equilibrium. Due to the rigid nature of CLT panels, the lateral resistance of the wall is assumed to be

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governed by the properties of the hold-downs, floor to wall connections and vertical joints used to connect the individual panels [5], as illustrated in Figure 1. The connection to the lower floor diaphragm is most commonly provided by angle brackets, while the connection to the upper floor diaphragm is often provided by self-tapping screws or angle brackets.

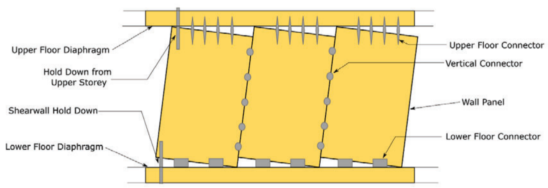


Figure 1*: Displaced CLT shearwall and connection types*

The local stiffness of the connections between the CLT wall panels and the upper or lower floor diaphragms is distributed linearly along the panel edge, in order to broaden the applicability of the analytical method to various connection locations. The distribution of connection stiffness along the edge of CLT panels has been previously investigated in literature as a method to develop elastic analysis and modelling guidelines suitable for practicing engineers, and the method has achieved good agreement with experimental seismic responses [9].

The distributed stiffness of the wall-to-diaphragm connections, k_a when considering the connection to the lower floor or k_t when considering the connection to the upper floor, was calculated for several potential layouts. The equivalent stiffness was determined by equating the sum of work for a layout of connections with an integration of continuous forces representing the distributed stiffness. Illustration of the methodology with an arbitrary connector stiffness k_{br} is presented in Figure 2, with example stiffnesses presented in Table 1.

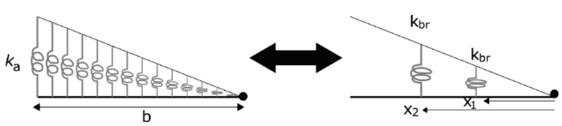
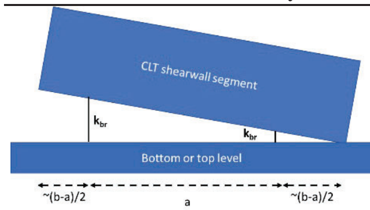
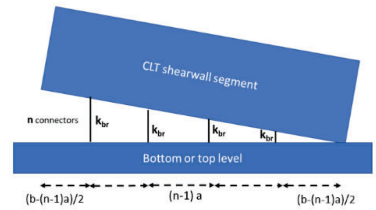


Figure 2: *Equivalency illustration for two point-stiffnesses*

Table 1: *Example distributed stiffness equations*

Bracket or Connector Layout	k_a or k_t
	$\frac{3}{2}k_{br}\frac{b^2+a^2}{b^3}$
	$\frac{n}{4}k_{br}\frac{3b^2+(n^2-1)a^2}{b^3}$

The analytical equations for the CP kinematic mode were determined using the principles of virtual work. The external work acting on the system was contributed to by the applied loads: lateral force F, uplift tension force T and downward vertical loads P_j from the upper floor (Figure 3). The internal work of the system includes contributions from the hold-down, vertical joints, and distributed connections to the upper and lower floor diaphragms. The expressions of external and internal work are presented in Equation (1) and Equation (2), respectively.

$$\sum W_{ex} = Fh\theta + Tb\theta - \sum P_i b\theta \qquad (1)$$

$$\sum W_{int} = \frac{1}{2}k_h b^2\theta^2 + \frac{1}{2}(m-1)(nk_c)b^2\theta^2 + \frac{1}{6}m(k_a+k_t)b^3\theta^2 \qquad (2)$$

where m= number of panels, n= number of connectors in the vertical joints, k_h= hold-down stiffness, k_a= distributed lower floor-to-wall stiffness, k_t= distributed upper floor-to-wall stiffness and k_c= vertical connector stiffness.

The CP kinematic mode is defined by the behaviour during lateral displacement, where each panel within the shearwall rotates about a local corner as shown in Figure 3. Due to the equalized rotation across the panels, it is assumed the upper floor remains horizontal, as does the lower floor. The hold-down tensile force, T, and the vertical point loads P_j provide a different representation of the inter-storey load transfer compared to previous work [2].

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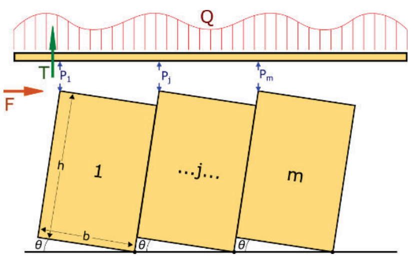

Figure 3: *Illustration of the coupled panel kinematic mode and applied load distribution*

The displacement of the wall causes tension in the hold down of the first panel (j=1), which is transferred as a vertical point load to the storey below. The load is applied upward at the corner of the first panel in the lower storey, as the walls are assumed to be vertically aligned for the transfer of force. The downward vertical load is transferred to the wall through the upper floor diaphragm and applied on the panel corners as point loads P_j. The method utilizes a beam analogy (Figure 4), which includes gravity loads and the net reactions of the storey above in the equivalent vertical load Q. While any pattern of loading can be applied to the beam analogy, the vertical loads and reactions for the panel corners and floor connections above are uniformly distributed along the length of the wall. This distribution of bearing reactions and connection forces is performed according to Equation (3) for storey under consideration (labelled s in the equation), where q_s is the gravity load applied on the floor in kN/m and $R_{cj,(s+1)}$ is the reaction force from the j-th panel of the upper ($s+1$) storey.

$$Q_s \cong q_s + \frac{\sum_1^m R_{cj,(s+1)} - m \times \left(\frac{k_a b^2 \theta}{2}\right)_{(s+1)}}{m \times b} \tag{3}$$

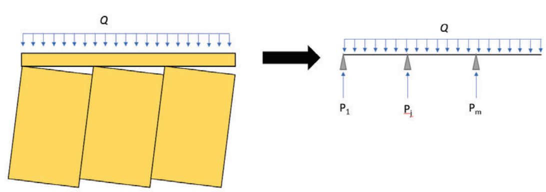

Figure 4: *Illustrated beam analogy for an example isolated shearwall acting in the CP kinematic mode*

Numerical models have shown that distributing the loads uniformly achieves equivalent P_j results as the individually applied reactions for CP analysis, and therefore uniform Q loads are used to simplify the analysis.

Within the analogous system, the contacting point of a panel with the upper floor is treated as a pinned support for a continuous simply-supported beam. This continuous beam represents the upper floor diaphragm above the wall, including an extra length cantilevering over the last supporting panel.

The extent of deflection in a CLT shearwall acting in the CP mode can be described using the angle of rotation θ, as defined in Equation (4), which is also critical in deriving expressions for the connection forces. The connection stiffness to the lower floor k_a, connection stiffness to the upper floor k_t, hold-down stiffness k_h, and the total stiffness of n fasteners in vertical joints nk_c are presented in Equation (5) to describe the combined stiffness k^*.

$$\theta = \frac{1}{k^*}\left(\frac{Fh}{b^2} + \frac{T}{b} - \frac{\sum_1^m P_j}{b}\right) \tag{4}$$

$$k^* = k_h + (m-1) * n * k_c + \frac{mb}{3}(k_a + k_t) \tag{5}$$

The displacement of any point along the wall can be calculated using the angle of rotation. The key displacements to describe the position of the wall panels can generally be defined as the displacement of the panel corners. These displacements include the lateral deflection Δ_h (equal to θ x h) and hold-down elongation v_0 (equal to θ x b).

The elastic resistance of the shearwall is governed by the resistance of the vertical joints and hold-downs, due to the high in-plane rigidity of CLT panels. The equations for the forces in the hold-down and individual vertical connectors, respectively, are presented in Equation (6) and Equation (7). While the stiffness of the connections to the floor diaphragms contributes to the behaviour of the system, they are assumed to not govern the elastic resistance of the wall. The angle of rotation and the location of the wall-to-floor connections can be used with methods of mechanics to calculate the forces in the discrete connectors and ensure adequate capacity.

$$R_h = \frac{k_h}{k^*}\left(\frac{Fh}{b} + T - \sum_1^m P_j\right) \tag{6}$$

$$F_{cy} = \frac{k_c}{k^*}\left(\frac{Fh}{b} + T - \sum_1^m P_j\right) \tag{7}$$

The equations for elastic resistance of the shearwall are derived from Equations (6) and (7), resulting in the set of expressions presented in Equations (8)-(10). Equation (9) provides the wall resistance in the scenario where the hold-down reaches its elastic limit before the connectors in the vertical joint, while Equation (10) provides the resistance where the vertical connectors yield before the hold-down. Due to the nature of the CP kinematic mode, all vertical joints in the wall are exposed to the same magnitude of force.

$$R_w = \min\{R_{wc}, R_{wh}\} \tag{8}$$

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$$R_{wh} = r_h \frac{k^* b}{k_h h} + \frac{\sum_1^m P_i \times b}{h} - \frac{Tb}{h} \quad (9)$$

$$R_{wc} = r_c \frac{k^* b}{k_c h} + \frac{\sum_1^m P_i \times b}{h} - \frac{Tb}{h} \quad (10)$$

The defining boundary for the CP kinematic mode is that all panels remain in contact with the floor surface. As such, the boundary for the validity of the analysis can be defined as when the first panel's reaction force (R_{c1}, as calculated in Equation (11)) is greater than or equal to 0. This results in the condition presented in Equation (12), in terms of the applied uplift tension force T at that storey.

$$R_{c1} = R_h + \frac{b^2\theta}{2}(k_a - k_t) - nF_{cy} + P_1 - T \geq 0 \quad (11)$$

$$T < \frac{k_h - nk_c - \frac{b}{2}(k_a - k_t)}{mnk_c + \frac{mb}{3}(k_a + k_t) - \frac{b}{2}(k_a - k_t)}\left(\frac{Fh}{b} - \sum_1^m P_i\right) + \frac{P_1 k^*}{mnk_c + \frac{mb}{3}(k_a + k_t) - \frac{b}{2}(k_a - k_t)} \quad (12)$$

Equation (12) provides the maximum uplift tension force T a given wall can resist while maintaining CP behaviour, which indicates that the effect of hold-down forces from upper storeys on CP kinematic behaviour is significant. Figure 5 presents the limiting condition for CP behaviour, above which the wall is expected to act in the CP kinematic mode and below which it trends towards the SW kinematic mode. As the ratio of overturning moments changes, which includes uplift tension force T and lateral forces F, the boundary line raises such that a shearwall requires increased hold-down stiffness (or higher counteracting gravity load) to maintain CP behaviour. This is a considerable change from the case without uplift forces from upper storeys, represented by the solid line, where a stiffness ratio of 1 or greater is sufficient to ensure CP behaviour regardless of loading.

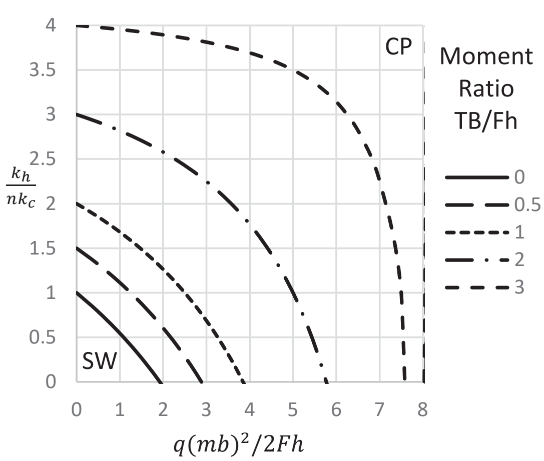

Figure 5: *Effect of uplift tension on behavioural boundary*

3 MODELLING METHODOLODY

Finite element models of both single-storey and stacked multi-storey shearwalls were developed and used to verify the proposed mathematical approaches. The single storey models were used to investigate the assumptions made within the analytical method, as well as verify the accuracy of the final equations. The single-storey models were analyzed sequentially, representing isolated storeys transferring forces to the wall below similarly to the analytical method. The stacked shearwall model is constructed to verify the accuracy of the analyses, as the multi-storey effects would inherently occur during the solution of the model.

The models consist of two-dimensional (i.e. area) rigid elements representing the CLT panels, connected with distributed springs (referred to as linear releases in the software) representing the connections between adjacent CLT panels and between the wall and the upper and lower floors. The floor diaphragms are modelled using properties representing a CLT floor system over an interior wall. Hold-downs are represented by spring elements between the first panels of adjacent storeys (Figure 6), and between the bottom of the lowest first panel and foundation. Dlubal RFEM is used to construct the models and analyze the results.

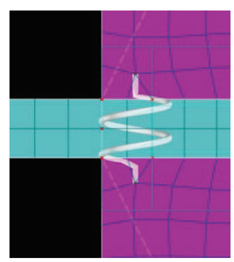

Figure 6: *Modelled hold-down element, in white, between shearwall panels, in purple*

Panel dimensions of 3 m in height and 1.5 m in width are used throughout the modelled walls for consistency. The four-storey model also includes an extended diaphragm, to better represent a shearwall as part of a larger structural system (Figure 7).

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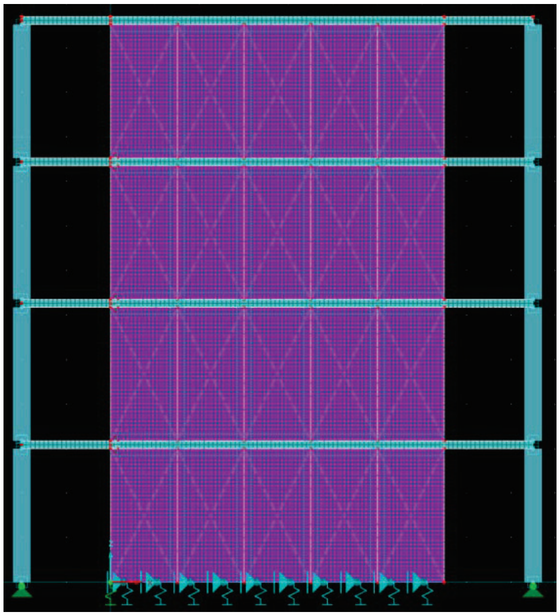

Figure 7: *Four-storey stacked CP model*

The finite element model considers a four-storey stacked five-panel shearwall loaded according to high seismic demands in Victoria (Canada). The load and connection properties are summarized in Table 2. The connection properties are based on manufacturer data for commercial products, and the same stiffnesses are used to connect the wall to both floors.

Table 2: *Coupled Panel modelling properties*

Storey	1	2	3	4
Applied Lateral Load (kN)	42.9	85.7	128.6	96.1
Distributed Gravity Load (kN/m)	20	20	20	10
Number of Vertical Connectors	24	24	15	15
Vertical Connector Stiffness (kN/m)	700	700	700	700
Hold-Down Stiffness (kN/m)	13136	13136	9973	9973
Distributed Floor Connection Stiffness (kN/m/m)	5147	5147	3823	1323

The modelled diaphragm for all cases is 175 mm thick, with an elastic modulus of 9348 MPa and width of 5 m.

4 MODELING RESULTS AND DISCUSSION

The results of the finite element models, as well as the analytical equations, are presented and compared in the following sections. The results of the stacked shearwall model are presented primarily as a target response for the other analyses. The single-storey models are used to investigate the assumptions used in the development of the analytical equations, and the results are compared between assumptions and against the stacked model. The calculated results from the analytical equations are compared against the stacked model result, to evaluate accuracy, as well as the single-storey model results to evaluate consistency.

A sensitivity analysis varying the properties of the floor diaphragm, both within the beam analogy and the finite element modelling, is also presented to investigate the sensitivity of the method.

4.1 STACKED MODEL RESULTS

The stacked shear wall model serves as the target values for verifying the analytical equations and benchmark for the behaviour of the single-storey models used to evaluate the analytical assumptions. The critical results for comparison between the analyses are lateral displacement, panel rotation, and hold-down tension.

The results for the four-storey stacked model indicated a decreasing level of rotation in lower storeys, due to the accumulated gravity load counteracting the lateral forces (Figure 8). While the floor diaphragms between storeys developed curved shapes, the overall surfaces generally remained level between the shearwalls. The results of the analysis are presented in Table 3, indicating inter-storey drift (Δ_h) as well as the total lateral displacement at each floor.

Table 3: *Four-storey stacked model results*

Storey	Δ_h (mm)	Total Lateral Displacement (mm)	θ (mrad)	R_h (kN)
4	3.75	10.37	1.25	15.4
3	3.88	6.56	1.29	19.2
2	1.62	2.64	0.550	16.5
1	0.98	0.98	0.330	6.85

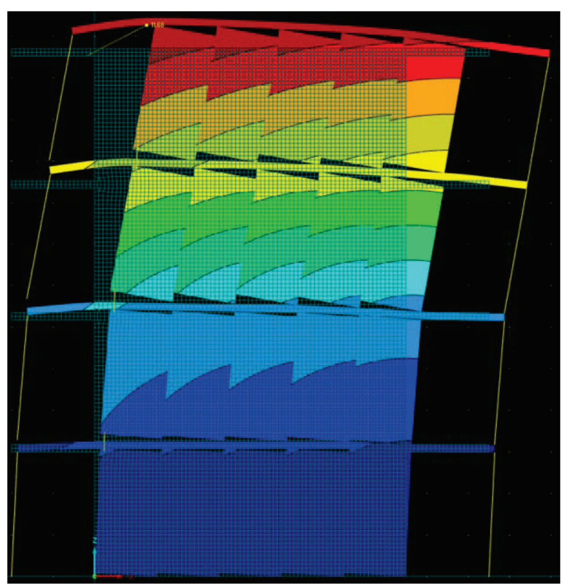

Figure 8: *Displaced shape of four-storey model, 140x deformation*

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4.2 SINGLE-STOREY RESULTS

The single storey-models were analyzed sequentially, as in the approach used in the mathematical analysis. A model of the uppermost storey was analyzed first, and the reaction and hold-down results were used to modify the loads applied to the model of the lower storey.

The properties of the connections to the upper floor will influence the behaviour of the CLT shearwall, similarly to the connections between the wall and the lower floor. However, the inclusion of am upper floor diaphragm into the shearwall analysis does not only alter the system response through the connection to the wall panels. The addition of an upper diaphragm alone will modify how the vertical loads are distributed to the wall panels.

Two sets of single-storey models investigated the load distribution effect of floor diaphragms during CP behaviour. One set applies the vertical loads directly to the wall panels (Figure 9) (i.e. without considering a diaphragm), while the other model includes a modelled upper floor diaphragm which will distribute the applied vertical load to the wall panels (Figure 10).

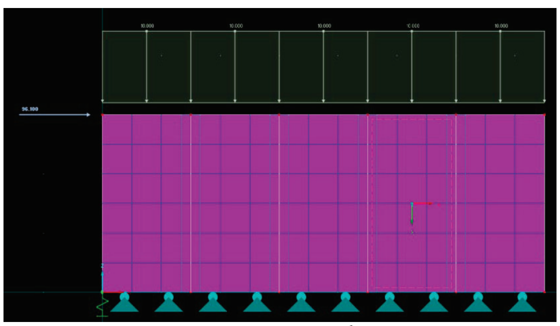

Figure 9: *Single storey model with 4th storey loading, direct panel loading*

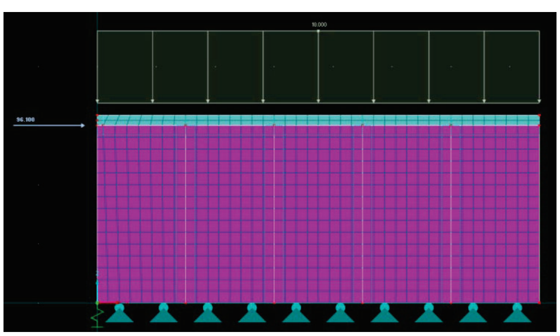

Figure 10: *Single storey model for 4th storey, with diaphragm*

Both models consist of five-panel shearwalls, and as indicated in Table 4, no floor connections were implemented in either model to maintain a valid comparison. Furthermore, the loading was identical between the models, despite differences in reaction values between the analyses which would cause cumulative differences as the forces are transferred to the analysis of the lower storeys. This overall harmonization between the models allows for a direct comparison between the single-storey models and isolates the effect of the floor's distributive properties.

Table 4: *Single storey model information for floor diaphragm comparison*

Storey	1	2	3	4
Lateral Load (kN)	353.3	310.4	224.7	96.1
Gravity Load (kN/m)	95	65	35	10
Uplift Force (kN)	40	35	20	0
Number of Vertical Connectors	24	24	15	15
Vertical Connector Stiffness (kN/m)	700	700	700	700
Hold-Down Stiffness (kN/m)	13136	13136	9973	9973

The model results are presented in Table 5, where it can be observed that the inclusion of the modelled floor diaphragm drastically reduces the lateral deflection for a given loading. This difference can be attributed to the increased moment arm that more directly counteracts the rotation of the panel when the gravity load is applied via a point load on the panel corner rather than distributed over the top edge.

Table 5: *Modelling results for single storey comparison of floor effect*

Storey	Q Loading			Diaphragm Loading		
	Δ_h 1	θ 2	R_h 3	Δ_h 1	θ 2	R_h 3
4	5.96	1.98	29.7	4.52	1.47	22.4
3	13.04	4.33	64.9	7.93	2.58	42.2
2	10.29	3.41	67.4	4.35	1.40	29.4
1	9.76	3.23	63.8	1.64	0.51	10.6

1: mm 2: mrad 3: kN

In order to compare against the four-storey stacked model, and therefore provide storey-be-storey equivalent analysis for comparison with the analytical equations, two additional models were analyzed using the same properties as listed in Table 2. The first set included a floor only above the wall panels, while the second model set extended the upper floor diaphragm to match the construction of the stacked model more closely (Figure 11).

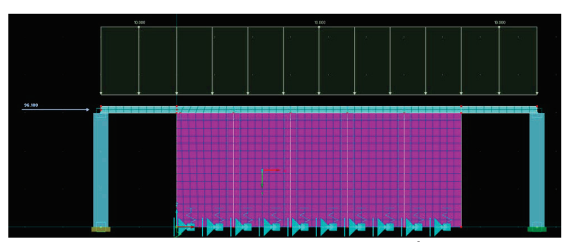

Figure 11: *Extended single storey model for 4th storey*

The accumulated gravity load applied to each single storey model is adjusted by distributing the net reactions from the storey above, using the same methodology presented in Equation (3). The resulting loads applied to each non-extended single storey model are presented in Table 6, and the results of the analysis are shown in Table 7.

Table 6: *Loading cases for non-extended single storey model*

Storey	1	2	3	4
Lateral Load (kN)	353.3	310.4	224.7	96.1
Gravity Load (kN/m)	74.7	54.3	32.3	10
Uplift Force (kN)	33.7	32.3	17.2	0

Table 7: *Non-extended single storey modelling results*

Storey	Δ_h (mm)	θ (mrad)	R_h (kN)
4	3.45	1.12	17.2
3*	6.36	2.05	32.3
2*	4.71	1.51	33.7
1*	3.46	0.99	25.0

*: Uplift observed in first panel

While the single-storey results in Table 7 follow the same general pattern of diminishing rotation in lower storeys as those in the stacked model results (Table 3), several cases of the single storey analysis exit CP mode by exhibiting uplift in the first panel.

The extension of the floor increases the gravity load on each storey, as shown in Table 8. As a result, all extended single storey models remain in the CP kinematic mode. However, the extended model for the lowest storey does not meaningfully display rocking behaviour due to the accumulated gravity load, as shown in Table 9.

Table 8: *Loading cases for extended single storey model*

Storey	1	2	3	4
Lateral Load (kN)	353.3	310.4	224.7	96.1
Gravity Load (kN/m)	108.5	68.4	29.2	10
Uplift Force (kN)	9.23	20.7	16.4	0

Table 9: *Extended single storey modelling results*

Storey	Δ_h (mm)	θ (mrad)	R_h (kN)
4	3.30	1.07	16.4
3	4.18	1.35	20.7
2	1.44	0.44	9.23
1	0	0	0

Comparing the displacement results of both extended and non-extended models to those of the stacked four-storey model, it can be observed that the addition of the extended floor generally improves accuracy to within 10% of the stacked model results (represented by the solid line in Figure 12). As such, the specific distribution of forces from the floor diaphragm has significant influence on the overall behaviour of the shearwall. The tendency for the non-extended model to overestimate displacement is also noteworthy for the purposes of design conservatism and simplicity of implementation. The two primary factors contributing to this are the lesser amount of gravity load within the system as well as an altered load distribution associated with limiting the upper diaphragm length to only remain above the wall panels.

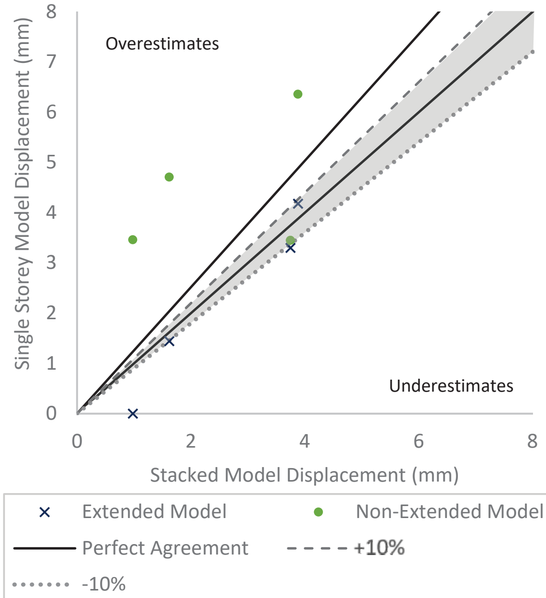

Figure 12: *Lateral displacement comparison between single storey models, against stacked CP models*

4.3 COMPARISON WITH ANALYTICAL RESULTS

The four-storey stacked shearwall was also analyzed using the analytical equations presented section 2. Given the observations regarding the importance of the extended floor diaphragm to the single storey CP models, a beam analogy including extensions equivalent to the stacked model was applied to better reflect the conditions within the stacked model (Figure 13).

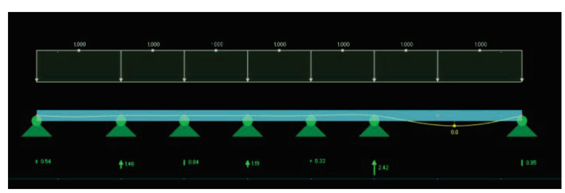

Figure 13: *Extended beam analogy for CP behaviour*

The elastic modulus used within the beam analogy is as presented in Table 2. Table 10 presents the equivalent vertical loads used in combination with the beam analogy, which includes adjustments based on the net reactions from the upper storey (Equation (3)).

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Table 10: Analytical vertical distributed loads

Storey	Q (kN/m)
4	10
3	33.5
2	57.9
1	87.8

The results of the analysis of the four-storey shearwall acting in the CP kinematic mode are presented in Table 11, where similarly to the extended single storey model no rotation was obtained for the bottom storey. The analytical equations performed similarly to the extended single storey model, with overall good agreement with the four-storey stacked model (Figure 14).

Table 11: Analytical results for four-storey CP shearwall

Storey	Δ_h (mm)	θ (mrad)	R_h (kN)	Total Lateral Displacement (mm)
4	3.40	1.13	16.9	9.78
3	4.38	1.46	21.9	6.38
2	2.00	0.67	13.2	2.00
1	0	0	0	0

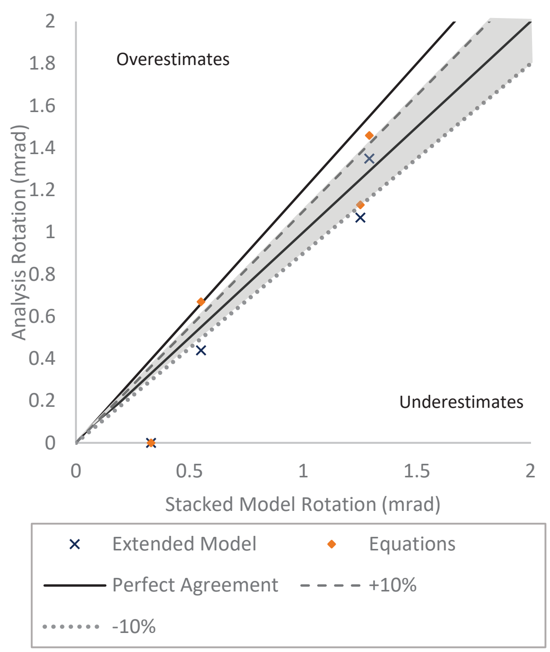

Figure 14: *Rotation angle comparison of proposed analytical expressions and extended model (single-storey), against stacked model*

4.4 FLOOR DIAPHRAGM EFFECT

In order to investigate the sensitivity of the analytical assumptions and finite element model, properties of the diaphragm were varied in both the beam analogy and the finite element model to evaluate the consistency of the results.

The beam analogy, evaluated via one-dimensional modelling, showed no variations in load distribution as elastic modulus of the diaphragm changed. Small variations were observed when changing the depth of diaphragm section, but as shown in Table 12 the discrepancies were minimal within the range of common CLT panel thicknesses. In this analysis, the beam analogy was applied to an isolated five-panel shearwall assumed to have a rotationally fixed boundary condition beyond the last panel, to simulate the effect of continuity on the modelled part (Figure 15).

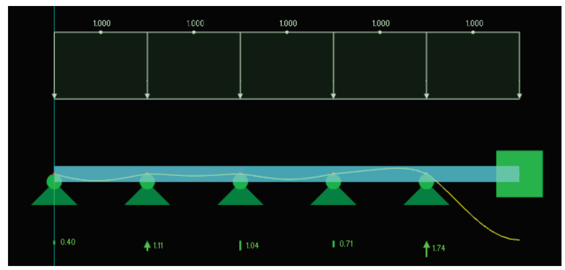

Figure 15: *Beam analogy used in section depth study*

Table 12: *Variation in load factor with diaphragm depth*

Section Depth (mm)	P_1 Factor	P_2 Factor	P_3 Factor	P_4 Factor	P_5 Factor
105	0.40	1.11	1.04	0.70	1.74
175	0.40	1.11	1.04	0.71	1.74
245	0.40	1.11	1.04	0.72	1.73

The sensitivity to floor diaphragm properties was further investigated by varying the effective bending modulus of the modelled floor within the finite element model. As presented in Figure 16, the model results remain consistent until the upper floor bending stiffness is significantly lowered, with only a 3% difference in displacement observed at an 89% reduction. At this point, the diaphragm remains in significant contact with the top surface of the wall panel during displacement and the transfer of forces extends beyond the corner of the modelled panel. As a result, the rotational resistance due to gravity load is reduced by shortening the moment arm and the system displacement begins to increase.

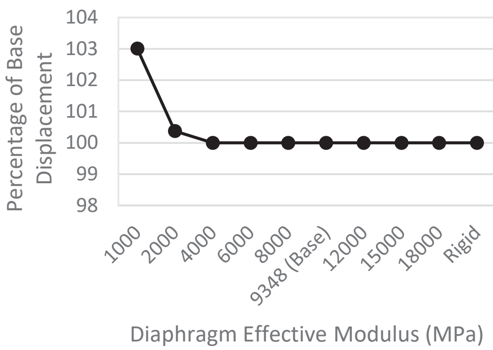

Figure 16: *Variation in model displacement with upper diaphragm stiffness*

While this behaviour contradicts the assumptions of the analytical equations, a floor diaphragm of reasonable stiffness for a CLT panel acting out of plane is expected to be sufficient for the assumed behaviour to remain valid.

These results indicate that the beam analogy for load distribution is reliably applicable to diaphragms in multi-storey platform-type CLT construction, and strengthens the assumptions used in the analytical method for wall behaving in the CP kinematic mode.

5 CONCLUSIONS AND FUTURE WORK

The analytical equations developed in this paper expand upon previous work and provides an approach to calculate displacements and forces in multi-storey CLT shearwall systems while including the effect of floor diaphragms. The results have shown reasonable accuracy when compared against finite element modelling, and the underlying assumptions simplify the individual contributions of the resisting elements while maintaining the complexity of the response. The assumptions regarding the distributive effect of the floor have been shown to be reliable at practical stiffnesses.

Future developments on the topic include expanding the analytical method to include SW kinematic behaviour. Additional modelling analysis can also be used to study and verify equations for more complex systems of shearwalls.

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