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Behaviour of Cross-Laminated Timber Wall Systems under Monotonic Lateral Loading

C. Hughes^{a*}, D. McPolin^a, P. McGetrick^a and D. McCrum^b

^aSchool of Natural and Built Environment, Queen's University Belfast, Belfast, UK;

^bSchool of Civil Engineering, University College Dublin, Dublin, Ireland

* School of Natural and Built Environment, David Keir Building, Stranmillis Road, Belfast, BT9 5AG, United Kingdom

chughes962@qub.ac.uk

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Behaviour of Cross-Laminated Timber Wall Systems under Monotonic Lateral Loading

In response to the global drive towards sustainable construction, cross-laminated timber (CLT) has emerged as a competitive alternative to other construction materials. Despite the construction of CLT buildings up to 10 storeys in areas of low seismicity, few multi-storey CLT buildings have been constructed in areas of moderate to high seismicity due to lack of knowledge regarding their performance under lateral loading. Previous experimental studies of the behaviour of CLT wall systems under lateral loading have been limited to replicating the conditions within multi-storey buildings with approximately three storeys, and most wall systems tested replicated ground floor wall systems. To develop an understanding of how taller CLT buildings would behave under lateral loading, for the first time, testing of CLT wall systems replicating conditions within buildings taller than three storeys was undertaken. In this study, wall systems representative of those within a 10 storey CLT building were experimentally tested; an above ground floor wall system was subjected to monotonic lateral load and constant vertical load, with vertical loads replicating gravity loads at storeys within a 10 storey CLT building. The results obtained suggest variable behaviour of wall systems throughout multi-storey CLT buildings, with lateral movement becoming significant at higher storeys.

Keywords: Cross-laminated timber; wall systems; tall building; lateral load.

Introduction

Over half the world's population are currently living in cities and this number is expected to increase to approximately 68% by 2050 (United Nations, 2018). To facilitate the growing urban housing and infrastructure demands, governments have been required to assess the way in which cities are planned and constructed leading to a global drive towards smart and sustainable future cities. To address some of the sustainability challenges associated with rapid urbanisation, engineers and architects are being encouraged to consider the use of timber before other construction materials; consequently, cross-laminated timber (CLT) has emerged as a competitive alternative to

other construction materials due to its sustainable attributes.

CLT is an engineered wood product formed from layers of timber boards bonded to each other orthogonally, to create large two-way spanning structural panels which can be used to form walls, floors and roofs of buildings. CLT panels are typically connected using metal connectors including hold downs which resist uplift of the walls, angle brackets which resist sliding of the walls and screwed connections which resist shear between adjacent and orthogonal panels. CLT is a prefabricated material which results in reduced on-site construction times, reduced material wastage and therefore reduced costs. Due to its high strength-to-weight ratio, it is fast becoming the solution to constructing high density housing on inner-city sites where underground infrastructure limits foundation loads.

While large scale production of CLT was established in Europe in the early 2000s, Structurlam and Nordic Structures in Canada became the first North American manufacturers of CLT more recently in 2010 (Pei et al., 2016a). As a result, the majority of tall CLT buildings have been constructed in Europe. Hackney, London, is one of several local authorities across the world encouraging engineers and architects to consider timber before other construction materials. This has led to the construction of some of the world's tallest CLT buildings, such as Murray Grove and Bridport House, in Hackney (Pei et al., 2016b). Dalston Lane, a 10 storey residential building located in Hackney is currently the world's tallest, pure CLT, building having been completed in 2017 (Harley et al., 2016).

While CLT buildings up to 10 storeys are being constructed, and taller buildings are being considered, few CLT buildings have been constructed in areas of moderate to high seismicity (Pei et al., 2016b). Timber is a commonly used material in seismically active regions due to its high strength-to-weight ratio, and the ductility and high energy

dissipation capability of its connection systems. However, CLT has not been adopted as a construction material in areas of moderate to high seismicity due to lack of knowledge regarding the performance of CLT buildings under lateral loading and lack of structural codes for the material. Therefore, further research is required to provide the experimental basis necessary to develop such knowledge and so that CLT becomes a competitive construction material for use in mid-rise and high-rise construction in seismically active regions.

Previous Research

As CLT construction has been established in Europe for longer than it has been in other regions, most research into the performance of CLT buildings under lateral loading has been undertaken in Europe, with the first notable project beginning in the early 2000s in Slovenia. Dujic et al. (2004) began by testing CLT wall panels under quasi-static monotonic and cyclic lateral loading. Further experimental investigations were carried out to determine the influence of boundary conditions (Dujic, Aicher, & Zarnic, 2006) and openings within the panel (Dujic, Klobcar, & Zarnic, 2007; Dujic, Klobcar, & Zarnic, 2008) on the behaviour of the wall. The results of experimental investigations were used to verify analytical models developed to undertake a parametric study to evaluate the effect of openings on the shear strength and stiffness of CLT wall panels (Dujic, Klobcar, & Zarnic, 2007; Dujic, Klobcar, & Zarnic, 2008).

To date the most comprehensive project researching the overall seismic performance of low-rise and mid-rise CLT buildings is the SOFIE project which was undertaken in Italy in collaboration with research facilities in Japan. Initially wall configurations with varying connection layouts, vertical loads and openings were tested under in-plane quasi-static monotonic and cyclic loading (Ceccotti, Lauriola, Pinna, & Sandhaas, 2006). Wall configurations were designed to replicate the conditions of walls

within a three storey building later constructed and dynamically tested as part of the SOFIE project (Ceccotti, 2008). The 2D wall system tests found the overall behaviour of the wall system to be dictated by the behaviour of the metal connections; while the CLT panel behaves rigidly, the metal connections provide ductility and energy dissipation within the system.

Following these tests, a full-scale three storey CLT building, approximately 7 x 7 m in plan and 10 m in height, was built and tested on a shake table at the National Institute for Earth Science and Disaster Prevention in Japan (Ceccotti, 2008). The building was tested under various earthquake ground motions until near-collapse was reached, and for these tests near-collapse was defined as the tension failure of one or more hold downs. The building was subjected to 15 earthquakes without significant damage and near-collapse was reached under the Nocera Umbra earthquake record with a peak ground acceleration of 1.2g. Despite reaching near-failure no residual deformations were observed, thus highlighting the potential for CLT construction in highly seismic regions.

Following the successful testing of a three storey CLT building, shake table testing of a full-scale 7 storey building was undertaken in Japan (Ceccotti et al., 2013). The building was 7.5 x 13.5 m in plan and 23.5 m in height. Similar to the three storey building, the seven storey building performed well with no significant damage or residual deformation observed. The CLT panels behaved rigidly and the damage observed was mainly concentrated within the metal connections (hold downs, angle brackets and vertical screwed connections between adjacent CLT panels) which experienced ductile failure and could be easily repaired after the test.

Despite the full-scale shake table testing of two buildings, there was still limited information regarding the mechanical properties of typical connections within CLT

buildings under cyclic loading and therefore the SOFIE project concluded with a thorough investigation of these connections. Gavric et al. (2015b, 2015c) investigated angle brackets, hold downs, vertical connections between adjacent panels and vertical connections between orthogonal panels under quasi-static monotonic and cyclic loading. A total of twenty configurations were tested and these configurations reflected connections used within the three storey CLT building constructed as part of the SOFIE project (Ceccotti, 2008). This study found that despite the use of angle brackets to resist shear forces, these connectors also have significant strength and stiffness axially and therefore will contribute to the overall uplift resistance of a wall system. However, hold downs were found to have significant axial strength and stiffness only and therefore do not contribute to the shear resistance of a wall system.

In addition to the testing of connections, cyclic testing of 2D CLT wall systems comprised of single or coupled CLT wall panels and typical CLT connections (hold downs, angle brackets and screwed vertical connections) was carried out (Gavric, Fragiacom, & Ceccotti, 2013; Gavric, Fragiacom, Popovski, & Ceccotti, 2014; Gavric, Fragiacom, & Ceccotti, 2015a). The kinematic behaviour of multiple wall system configurations was observed and important characteristics of the wall systems, such as strength, stiffness, ductility, energy dissipation capacity and ultimate displacement, were found. The study found that the CLT panels behave rigidly under lateral loading, and any shear or bending deformation of the panel was found to be negligible with the displacement due to sliding or rocking the main components of the overall lateral displacement of the panel. Therefore, it is suggested that there are three predominant types of deformation of the wall system and the deformation type is determined by the capacity of the anchoring connectors (hold downs and angle brackets). The deformation types were noted as; rocking behaviour, sliding behaviour

and rocking-sliding behaviour. The results of the investigation indicate that rocking behaviour leads to greater ductility, energy dissipation and ultimate displacement compared to walls with predominantly sliding behaviour (Gavric, Fragiaco, & Ceccotti, 2013). It was also noted that rocking behaviour resulted in the self-centering of the wall system, unlike sliding behaviour which resulted in a residual lateral displacement of the wall (Gavric, Fragiaco, & Ceccotti, 2015c). Hence it is recommended that the metal connectors remain elastic in shear and yield only in tension to ensure predominantly rocking behaviour with minimal sliding. In addition to the experimental investigation, Gavric et al. developed analytical models to undertake pushover analysis of CLT wall systems (Gavric, Fragiaco, & Ceccotti, 2015c).

Aim of Research

Despite the satisfactory seismic performance observed during full-scale shake table testing of CLT buildings up to 7 storeys, there is insufficient information regarding the performance of building components, such as connections and wall systems, available to inform seismic design guidance for tall CLT buildings. The previous experimental studies of CLT wall systems under lateral loading have been limited to replicating the conditions within multi-storey buildings with approximately three storeys (Dujic, Pucelj, & Zarnic, 2004; Gavric, Fragiaco, & Ceccotti, 2015a; Popovski, Schneider, & Schweinsteiger, 2010). Thus, to develop sufficient understanding of how CLT wall systems in high-rise buildings will behave when subjected to lateral loading, testing of configurations reflecting the conditions of CLT wall systems in taller buildings need to be undertaken.

There has been limited research on performance assessment of CLT wall systems in above ground floor storeys. In most wall configurations tested, the CLT wall panels are anchored to steel or concrete foundations; very limited information has been

published about configurations tested in which the CLT wall panels are fixed to CLT floor panels, as typically found in above ground floor storeys. As tall buildings would have large numbers of CLT wall panel to CLT floor panel connections, the behaviour of these connections must be further investigated in order to evaluate the behaviour of wall systems in above ground floor storeys, and therefore the overall performance of tall CLT buildings.

The aim of this research is to further the understanding of the behaviour of wall systems in multi-storey CLT buildings under lateral loading, focussing particularly on the behaviour of above ground floor storeys in a 10 storey CLT building. Experimental tests have been carried out to evaluate the global behaviour of above ground floor CLT wall systems, representative of those found within a 10 storey CLT building, under repeated monotonic loading. Eight tests have been undertaken on one CLT wall system to understand the effect of varying load on the deformation behaviour and stiffness of the wall system within the elastic region. An additional two tests were undertaken on the same CLT wall system to assess post-yield behaviour. These tests will allow the variation in global behaviour of wall systems at each storey within a multi-storey CLT building to be evaluated and design considerations to be identified.

Test Set Up

A series of ten tests were undertaken on a CLT wall system. During each test a vertical load was applied and maintained, with each vertical load representative of the gravity load experienced by the walls at various storeys within a 10 storey CLT building. The vertical load was applied using a load-controlled hydraulic actuator to the top of the wall panel through a 150x100x10 mm steel rectangular hollow section (RHS) beam to aid the spreading of the load to the ends of the panel. While the steel RHS beam facilitates spreading of the load, it does not provide a perfect redistribution of the point

load to a UDL. A steel plate and two rollers were used beneath the vertical actuator to ensure that the rotation of the wall was not restricted as illustrated in Figure 1. As this study focuses on CLT wall panel to CLT floor panel connections, the ground storey wall system in which the wall panel is fixed to a concrete foundation was not investigated, nor was the top storey in which vertical load is relatively small; thus, the vertical loads were representative of the gravity loads in floors 2-9 of a 10 storey CLT building.

Figure 1. Arrangement at top of wall

The vertical loads applied were calculated assuming all walls and floors within a 10 storey building are constructed using 100 mm thick CLT panels with a density of 470 kg/m^3 , as per the product technical information supplied by Stora Enso (Stora Enso, 2015). By considering the imposed floor load as well as the gravity load of both the floor and wall panels, the vertical loads the wall system was subjected to during the study are representative of realistic loads within a multi-storey CLT building. As CLT buildings are commonly used for residential purposes rather than commercial purposes, an imposed floor load of 1.5 kN/m^2 was selected for a Category A loaded area as per BS EN 1991-1-1:2002, Table 6.2. Partial safety factors of $\gamma_G=1.35$ and $\gamma_Q=1.5$ were considered in the calculation as per BS EN 1990:2002+A1:2005, Table A1.2. Calculations assumed a floor span of 3m between internal CLT walls. The total design

vertical load associated with each storey was calculated to be 10.5 kN/m and this value was used to determine the vertical loads at each storey (e.g. floor 2 in a 10 storey building with 8 storeys above would experience a gravity load of $10.5 \text{ kN/m} \times 8 = 84 \text{ kN/m}$). Figure 2 illustrates the gravity loads calculated at each storey.

Figure 2. Gravity loads at each storey in a 10 storey CLT building

During tests T1-T8, the wall was loaded laterally in increments of 5 kN to a maximum load of 50 kN while a vertical load was maintained throughout the test. The maximum lateral load of 50 kN was selected to ensure the connections behaved elastically. This allowed one wall system to be used for a series of eight tests and the relationship between vertical load and global behaviour to be identified. After these eight tests, an additional two tests were undertaken in which a maximum lateral load of 150 kN was applied to the wall system while a vertical load was maintained to investigate the post-yield behaviour of the wall system. The vertical and lateral loads applied in each of the ten tests are summarised in Table 1.

Table 1. Test loads

Test	Floor	Vertical Load	Maximum Lateral Load
		[kN/m]	[kN]
T1	2	84.0	50
T2	3	73.5	50
T3	4	63.0	50
T4	5	52.5	50
T5	6	42.0	50
T6	7	31.5	50
T7	8	21.0	50
T8	9	10.5	50
T9	2	84.0	150
T10	9	10.5	150

Previous studies have investigated the effect of aspect ratio on the behaviour of CLT wall systems and concluded that wall systems with higher aspect ratios have greater deformation capacity but significantly less strength and stiffness than wall systems with lower aspect ratios (Popovski et al., 2010; Gavric et al., 2015; Amini et al, 2018;). Amini et al. (2018) suggested that an aspect ratio of 2:1 is preferable, however there is a lower bound where the aspect ratio has negligible effect on the behaviour of the wall system, with the aspect ratios of 1:1 and 2:1 exhibiting similar strength and stiffness in their study. Due to the limited clear space under the frame of the vertical actuator the height of the wall panels tested was 1.5 m, approximately half of the typical

height of walls in CLT buildings, and the width of the wall panels was 2.95 m to allow it to be rigidly fixed to the laboratory floor. Therefore, the aspect ratio of the wall system is approximately 0.5 and the findings of this study will be specific to the chosen aspect ratio which is not a variable of this investigation.

The CLT panels used were 100 mm thick and comprised of five 20 mm thick layers. The outer two layers and the centre layer of the panel spanned vertically while the other two layers spanned horizontally. Based on crushing failure, the vertical load capacity of a wall using these panels was calculated to be approximately 605kN/m. As previously mentioned, in a full-scale CLT building the wall height is typically twice the height of the wall used in this test set up and therefore buckling may be the failure mode of these walls which would result in a lower failure load than stated here. Typical CLT connectors were used to fix the wall panel to the floor panel; the wall panel was anchored to the floor panel using two Rothoblaas WHT340 hold downs (Rothoblaas, 2015) partially nailed with twelve 4x60 mm annular ring nails and eight Simpson Strong-Tie ABR105-R angle brackets (Simpson Strong-Tie, 2019) with sixteen 4x60 mm annular ring nails. The floor panel was 1.5x2.95 m; the wall panel was placed centrally on the floor panel. The test set up is shown in Figure 3.

Figure 3. Test set up

To evaluate the global deformation of the wall system, displacements were measured at seventeen locations within the wall system using displacement transducers (Novotechnik TR / TRS Transducer with return spring). The locations of these displacement transducers are given in Table 2 and Figure 4. These measurements allowed the deformation mechanisms contributing to the overall displacements to be assessed. In addition to measuring the lateral displacement of the floor panel at location 11 in Figure 4, the vertical displacement of the floor panel was measured at locations 1 and 2, however they have been omitted from Figure 4 for clarity. These displacement measurements allow the movement of the wall panel relative to the floor panel, rather than the laboratory floor, to be deduced.

Table 2. Displacement measurement locations

Location	Measurement
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1	Uplift of left hand side of wall panel
2	Uplift of right hand side of wall panel
3	Uplift of AB1
4	Uplift of AB2
5	Uplift of AB3
6	Uplift of AB4
7	Uplift of AB5
8	Uplift of AB6
9	Uplift of AB7
10	Uplift of AB8
11	Lateral displacement of floor
12	Lateral displacement of wall
13	Lateral displacement of wall 300 mm from floor
14	Lateral displacement of wall 600 mm from floor
15	Lateral displacement of wall 900 mm from floor
16	Lateral displacement of wall 1200 mm from floor
17	Total lateral displacement at top of wall

Figure 4. Displacement measurement locations

Results & Discussion

The data from the tests was analysed to assess the effect of vertical load on the global behaviour of the wall system, allowing the global behaviour of the wall systems at each storey within a 10 storey CLT building to be inferred. The global behaviour can be summarised by the total vertical and lateral displacement of the wall panel. The total lateral displacement resulting from each loading increment for tests T1-T8 is shown in Figure 5 and the relationship between the vertical load applied and the total lateral displacement is illustrated in Figure 6. The vertical uplift resulting from each loading increment for tests T1-T8 is shown in Figure 7 and the relationship between the vertical load applied and the vertical uplift is illustrated in Figure 8.

Figure 5. Lateral load [kN] vs. total lateral displacement [mm] for T1-T8

Figure 6. Vertical load [kN/m] vs. total lateral displacement/lateral displacement due to sliding [mm] when lateral load is 50 kN for T1-T8

Figure 7. Lateral load [kN] vs. uplift [mm] for T1-T8

Figure 8. Vertical load [kN/m] vs. uplift [mm] when lateral load is 50 kN for T1-T8

Figure 6 and Figure 8 show non-linear relationships between both vertical load and total lateral displacement, and vertical load and uplift. Therefore, there would be different global behaviour of wall systems at each storey within a multi-storey building during the elastic response of the building as the contribution of each deformation mechanism to the global behaviour varies. However, as neither maximum load capacity nor ultimate load capacity of the wall system was reached it is uncertain whether this remains true

for the plastic response of CLT wall systems at different storeys. Nonetheless, the varying contribution of deformation mechanisms to global behaviour within the elastic region reinforces the need to consider connection design at each individual storey. .

Figure 6 shows that the relationship between the lateral displacement due to sliding and the vertical load is also non-linear despite using one wall system with a fixed number of shear connectors for all tests. The increasing lateral displacement due to sliding as vertical load is decreased is likely due to a perceived reduction in stiffness from a combination of reduced frictional force and the reduced shear capacity of the angle brackets due to bidirectional loading of the connection. In this study, and in previous studies (Gavric, Fragiaco, & Ceccotti, 2015), angle brackets have been found to contribute significantly to the overturning resistance, and so as uplift of the panels increases, tensile forces within the brackets increase which is likely to result in reduced shear capacity of the connector due to the bidirectional loading. To fully assess the extent to which bidirectional loading impacts the performance of the shear connector, and its subsequent impact on the global performance of the wall system, testing of typical CLT wall panel to CLT floor panel connections under monotonic loading in both the shear and tension directions will be undertaken.

The results from test T1 are also shown in Figure 9 and Figure 10 to illustrate the minimal difference between the displacements observed during test T9 as lateral load was increased from 0 kN to 50 kN and the displacements observed during test T1 in which the same vertical load was applied and lateral load was increased from 0 kN to 50 kN. Similarly, the results from test T8 are also shown in Figure 9 and Figure 10 to illustrate the minimal difference between the displacement results observed in test T10 in which the applied vertical load was the same. This suggests minimal stiffness degradation due to repeated testing of the wall system under different load scenarios.

While post-yield behaviour was observed during tests T9 and T10, maximum strength and ultimate strength were not yet reached.

Figure 9. Lateral load [kN] vs. total lateral displacement [mm] for T1, T8, T9 and T10

Figure 10. Lateral load [kN] vs. uplift [mm] for T1, T8, T9 and T10

Figure 5 and Figure 7 show that as lateral load is increased from 0 kN to 50 kN, the total lateral displacement and the uplift also increase, with the maximum lateral displacement and uplift occurring at the maximum lateral load. Figure 5 shows non-linear behaviour of the wall system in the lateral direction under all vertical loads as lateral load is increased, while Figure 7 shows linear behaviour of the wall system in the vertical direction during tests T1-T4, and non-linear behaviour during tests T5-T8, as lateral load is increased. Figure 5 indicates that the lateral stiffness of the wall system is reducing as vertical load is reduced, suggesting variable stiffness throughout a multi-storey CLT building. This is likely due to a combination of several factors, including; decreased overturning resistance due to decreased vertical load, decreased frictional resistance due to decreased vertical load and stiffness degradation of the wall system due to the application of repeated monotonic lateral load. The lateral stiffness at both

sections of the bi-linear displacement profile (Figure 11) for tests T1-T8 is given in Table 3.

Figure 11. Bi-linear stiffness profile exhibited in tests T1-T8

The lateral stiffness of the wall system was found by determining the gradient of both sections of the bi-linear trend line for the load-displacement profiles shown in Figure 5.

Figure 12 illustrates how the stiffness was determined using the test T8 load-displacement profile.

Figure 12. Load – displacement profile for test T8 used to determine lateral stiffness

Table 3. Stiffness of wall system in lateral direction

Test	Vertical load	Stiffness, k_1	Stiffness, k_2
	[kN/m]	[kN/mm]	[kN/mm]
T1	84.0	345.3	41.7
T2	73.5	318.3	46.0
T3	63.0	203.8	40.0
T4	52.5	192.5	36.8
T5	42.0	393.0	30.7
T6	31.5	168.9	23.8
T7	21.0	60.6	18.4
T8	10.5	84.0	11.3

While non-linear behaviour of the wall system is evident, residual lateral displacements were negligible for tests T1-T7, suggesting elastic behaviour of the connections during tests T1-T7. More significant residual lateral displacement was observed at the end of test T8, as approximately 18% of the maximum total lateral displacement was remaining after the test suggesting that some connections may have yielded during this test. After test T9, approximately 10% of the maximum total lateral displacement for that test was remaining. After test T10, approximately 42% of the maximum total lateral displacement for that test was remaining and yielding of the angle bracket was visually observed as shown in Figure 13.

Figure 13. Connections after T10

Figure 14 illustrates the loading and unloading displacement profiles for tests T8-T10 in which significant residual lateral displacements were observed. As all tests were carried out on the same wall system, tests T9 and T10 have been influenced by the previous tests with some permanent sliding deformation. Figure 14 shows the

progressive increase in residual lateral displacement across these three inelastic tests to the end of the testing program where a residual lateral displacement of approximately 11.2mm was recorded.

Perhaps a table of % recovery after each test T8 75%, T9 90%, T10 60%. Also what was recovery at end of T1-7?

Figure 14. Lateral load [kN] vs. total lateral displacement [mm] for the lateral loading and unloading of T8-T10

Conclusion

Ten tests were undertaken on a CLT wall system to investigate the behaviour of the wall system under monotonic lateral loading. The wall system was subjected to a constant vertical load during each test, with each load calculated to reflect the gravity load at

floors 2-9 within a 10 storey CLT building. The CLT wall panel was fixed to a CLT floor panel, replicating the configuration of above ground floor wall systems within a multi-storey CLT building. Displacements were measured at seventeen locations within the wall system to determine the global behaviour of the wall system during each loading scenario.

The aim of this study was to further the understanding of the behaviour of wall systems in multi-storey CLT buildings under lateral loading, focussing particularly on the behaviour of above ground floor storeys in a 10 storey CLT building. The study found that connection behaviour alone does not control the behaviour of a wall system, vertical load has a significant influence on the behaviour of CLT wall systems. Non-linear relationships between both vertical load and total lateral displacement, and vertical load and uplift were observed. As a consequence, there is variable global behaviour of wall systems throughout a multi-storey CLT building which confirms the requirement for different connection design at each storey. Significant sliding of the wall was observed in some tests, with a notable residual lateral displacement recorded after test T8 in which the vertical load was lowest and shear force did not exceed the design shear capacity of the wall system. This suggests frictional effects which are dependent on vertical load are highly significant in resisting lateral sliding. Elastic, non-linear, behaviour was observed in the majority of tests, however in instances of low vertical load or high lateral load inelastic behaviour occurred. Stiffness generally decreased as vertical load decreased indicating variable stiffness throughout a multi-storey CLT building. As all other parameters were held constant, it can be stated that the variable stiffness at different storeys of a building is a result of variable vertical load which influences the correcting moment (uplift) and friction (sliding).

While CLT has potential for use in mid-rise and high-rise construction in seismically active regions, more research is necessary to develop the knowledge to predict the behaviour of wall systems within multi-storey CLT buildings. This research has shown the effect of vertical load, which is influenced by building height, on the behaviour of CLT wall systems; it has shown that vertical load effects the contribution of sliding and rocking deformation mechanisms to the global deformation of the wall as it significantly influences both frictional force and overturning moment resistance. In this study, it has been shown with lower vertical loading, wall system will experience greater permanent lateral displacement, due to sliding, relative to those with higher vertical loading.

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