WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA

Advancing Timber for the Future Built Environment

BALLOON-TYPE CLT SHEAR WALL CONSTRUCTION – A REVIEW OF CURRENT PROJECTS AND DESIGN CHALLENGES

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ABSTRACT: With the ever-expanding use of mass timber in buildings, new timber structural systems and typologies are regularly developed and implemented. One such system to resist lateral loads is CLT shear wall construction with a balloon-type framing approach. Designed to achieve structural efficiency and avoid high perpendicular-to-grain compression stresses experienced in the floor panels of traditional platform-type framing, balloon-type CLT shear walls could allow the development of taller CLT buildings. Previous studies have shown that this is a promising solution for the seismic force-resisting system in tall mass timber buildings. However, balloon-framed CLT shear walls are still in their nascency and have only been used in a limited number of projects internationally. This study discusses the technology's value proposition and relevant research, experimental testing projects, and building projects that have used this technology. Finally, current design challenges that hinder more widespread adoption of this system are discussed.

KEYWORDS: cross-laminated timber (CLT), CLT shear walls, balloon-type walls, seismic design

1 – INTRODUCTION

1.1 Mass Timber Design in Canada

Wood construction has grown rapidly over the past twenty years. This rise has been driven largely by the development of engineered wood products. By laminating dimensional lumber into larger engineered wood elements such as cross-laminated timber (CLT) or glued-laminated timber (glulam), the scope of wood use in construction has exploded. Combined with modern timber connections, large-scale engineered wood construction has become achievable.

The 2020 National Building Code (NBC) of Canada permits the design and construction of encapsulated mass timber buildings up to twelve storeys [1]. However, there are no acceptable solutions for using mass timber as the seismic force-resisting system (SFRS) in tall buildings in the 2020 NBC. The NBC provides the needed design seismic force modification factors for two types of mass timber SFRSs: braced or moment-resisting frames with ductile connections and platform-type CLT shear walls. Both systems are limited to 20 m in high seismic zones. Although the height limit is relaxed in other seismic zones, tall platform-type CLT shear wall systems are challenging to design due to the accumulation of perpendicular-to-grain compression stresses [2]. In addition, platform-type CLT shear wall buildings are frequently designed using off-the-shelf steel brackets (hold-downs and angle brackets) originally developed for light wood framed systems. This means that they were not designed to take advantage of the CLT panels' high in-plane strength and stiffness [3]. As a result, the lateral stiffness of platform-type CLT buildings often relies on using many wall lines, making them overly redundant and inefficient. This effectively limits code-compliant mass timber construction to 20 m (~six storeys) in seismically active Canadian regions, unless an "alternative solution" design is pursued [4]. Furthermore, there is a lack of clear design guidance for these mass timber systems in high seismic regions like British Columbia.

1.2 CLT Shear Wall Construction

A promising new alternative to platform-type CLT shear wall construction is balloon-type construction. In balloon-type construction, the wall panels are built continuously along the height of the building (see Figure

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https://doi.org/10.52202/080513-0057

1). This means that the floor panels are attached to the side of the walls using ledgers, instead of interrupting the walls at each floor. As a result, the vertical forces in the wall panels are not transferred perpendicular to the grain through the floor panels [5]. Additionally, using continuous walls reduces the number of connections in the SFRS, which can increase the construction speed and lateral stiffness compared to platform-type systems of a similar height.

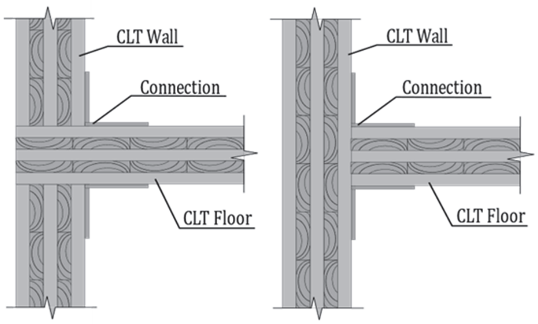

Figure 1 – Left: CLT platform construction. Right: CLT balloon construction

In CLT construction, the connections form a vital part of the system. Because CLT panels are strong and stiff, they are often treated as rigid bodies in platform-type CLT shear walls. They effectively act as big levers, transferring loads to the connectors [6]. The load-deformation behaviour of the CLT material itself is also quite brittle. Therefore, all ductility and energy dissipation must come from the connections. As a result, the performance of balloon-type shear wall systems can be enhanced significantly by using high-performance connection systems, and there has been sustained research interest in these over the past few years. The following section investigates experimental testing projects focused on balloon-type shear walls and their connection systems.

2 – CURRENT RESEARCH

2.1 Experimental Testing

Hold-down connections

Hold-down connections provide overturning moment resistance to CLT shear walls. Ottenhaus et al. [7] and Brown & Li [8] undertook extensive experimental studies on the performance of high-capacity dowelled hold-downs (HDs). They observed that high capacities over 1000 kN can be achieved together with medium to high ductility ratios (5-6). However, in some cases, crossover and brittle failure modes were encountered and these were difficult to predict in CLT [9]. The authors recommended using LVL outer laminations and bolts in the connection end rows to improve the overall connection behaviour.

A wide range of mixed-angle screwed (MAS) HDs was subsequently investigated by Wright et al. [10] and Krauss et al. [11]. These novel connection systems use self-tapping screws (STS) installed at various load-to-screw axis angles to optimize the connection behaviour. It is well established that STS installed at 90° to the loading direction have a high displacement capacity and ductility. If screws are instead inserted at a shallower angle (30-60°), the screws' threads are engaged axially as the connection deforms. This results in much higher loading stiffness and strength, but low ductility. By combining both installation angles in one connection, and optimizing the ratio of the two types of screws, it is possible to design connections with high strength, stiffness, and ductility. Experiments were conducted on small-/ [11], medium-/ [10] and large-scale connections up to 1200 kN [12]. High ductility values (10-20) were achieved using appropriate design. Figure 2 shows the test setup used for these hold-downs.

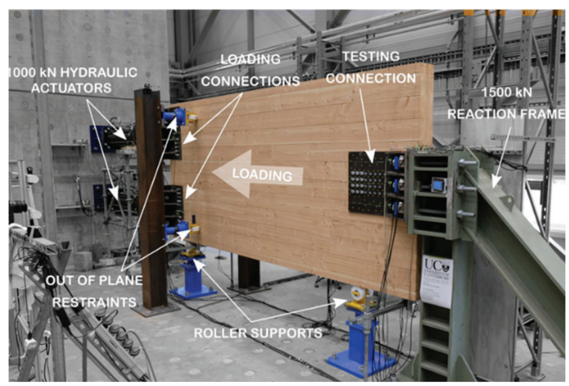

Figure 2 – High-capacity mixed-angle screwed hold-down testing. Photo by Thomas Wright.

Base shear connections

Base shear connections prevent sliding at the wall base and their behaviour has also been investigated by several studies. Steel angle brackets have traditionally been used to prevent base sliding in CLT buildings. However, testing found that castellated shear key joints are much stronger (2.5 to 7 times) [13]. In addition, such castellated shear keys do not contribute significantly to the uplift resistance at the wall base. This makes it simpler to predict the wall's overturning moment capacity analytically.

Hayes et al. [14] tested wall-to-floor connections using metal angle brackets. The authors noted that increasing

https://doi.org/10.52202/080513-0057

the thickness of the angle brackets was the most effective method for achieving larger connection stiffness. Thin angle brackets were very ductile but also deformed significantly.

Panel-to-panel connections

Due to transportation constraints, CLT panels are commercially available in widths up to 3 m. This limits the lever arm that can be developed between HD connections at the wall base. Thus, panel-to-panel coupling joints are required if designers want to construct longer walls or profiled composite walls with C or I-shapes. These joints can be detailed to be ductile and contribute to the system's energy dissipation, or they can be designed to be stiff and increase composite action between adjacent panels. Orthogonal and in-plane panel-to-panel joints were investigated by Brown et al. [15] and Hossain et al. [16], [17]. Tests using mixed-angle screw assemblies achieved reliable energy dissipation and medium to high ductility ratios in the range of 4-8.

Moerman et al. [18] studied the performance of wall-to-beam connections for coupled walls. Coupled walls with link beams have been extensively used in reinforced concrete systems, but have not been applied to mass timber construction. During seismic loading, inelastic behaviour should be concentrated in the ductile steel link beams. The connection between the CLT wall panel and the link beam is critical. In particular, high translational and rotational stiffness must be achieved so that the link beams can contribute to the system's resistance at low drifts. The authors found that using self-drilling dowels in the link beam connection can achieve adequate strength and relatively high stiffness.

Further, Hayes et al. [14] tested a variety of panel-to-panel connections including half-lap and surface spline joints. They found that half-lap connections are significantly stiffer than surface splines and that a combination of inclined and horizontal screws could be used to optimize the stiffness and ductility of the connections.

Proprietary CLT connection systems

Further studies have been conducted on specialized and proprietary connection systems. Examples include the HSK (German "Holz-Stahl-Komposit") system, which consists of thin perforated steel plates that are glued into the CLT and dissipate energy by yielding the steel [19], or the proprietary X-RAD connection system [3] which was designed by RothoBlaas. Self-centering slip-friction devices were developed [20] and have since been applied in buildings in New Zealand and Canada. Special hyper-elastic HDs were introduced specifically for the Canadian regulatory environment by Asgari et al. [21] because a new supplement to the Canadian timber design standard [22] stipulates that the HDs have to be designed as non-dissipative connections which are capacity-protected to remain elastic under earthquake loading.

Full wall testing

Experimental work has also included 2/3-scale wall testing of single, coupled, and post-tensioned balloon-frame systems up to four storeys. Moerman et al. [23] and Krauss et al. [24] applied many of the outcomes from the high-performance component-level testing described above to conventional (without post-tensioning) balloon-type CLT shear walls. Using optimized and well-detailed connections, wall capacities were 163% greater than the strongest previous conventional wall test. Strength utilization was in the region of 60-100%. Damage to the CLT walls was still confined to the connection areas and wall toes, and all connection failure modes were ductile. However, the long (squat) single walls exhibited out-of-plane buckling before reaching their ultimate capacities, and this unexpected failure mode needs to be investigated further as prediction models are still being debated [25]. Coupled walls generally exhibited greater ductility due to the additional contributions from vertical screwed lap joints. The lap joints also impacted the initial stiffness: those using 90° screws had lower stiffness, while those using inclined screws had significantly larger stiffness. An example of a coupled wall test is shown in Figure 3.

Brown et al. [26] focused on the experimental behaviour of single, coupled, and core (flanged) post-tensioned shear wall systems. They found that service and ultimate limit state drifts can be limited effectively to reduce expected structural and non-structural damage during seismic loading. In the coupled and core wall tests, the level of composite action generally reduced with increasing drifts, as the strength and stiffness of the screwed panel-to-panel joints degraded progressively. The authors also compared the performance of coupled wall systems using STS versus UFPs (U-shaped flexural plates). STS joints are much stiffer and thus able to dissipate energy at lower drifts. However, their hysteretic behaviour is very pinched and energy dissipation is minimal at larger drifts compared to UFPs.

Li et al. [5] and Wang et al. [27] further tested two two-storey balloon-type CLT shear wall specimens each (one monolithic and one coupled wall). They found that while the balloon construction typology shows similar strength properties to platform construction, it features a significantly larger initial stiffness and can achieve more energy dissipation.

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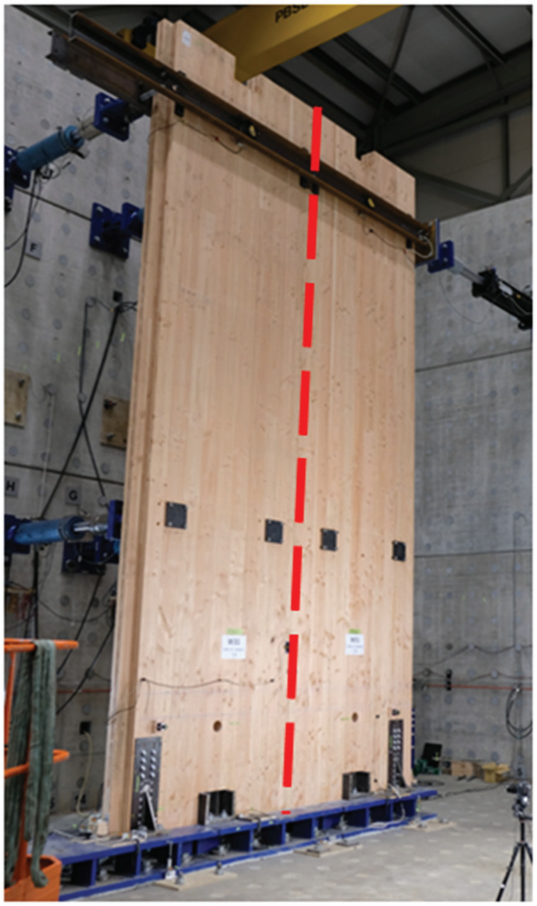

Figure 3 – Three-storey coupled wall test [24]. The vertical panel-to-panel half-lap joint is marked with a red line. Photo by Ben Moerman.

Finally, Hayes et al. [14] tested six balloon-type wall specimens, investigating different connection systems and including a floor diaphragm in three tests. The tests showed significant impacts from torsional forces which limited the outcomes. Wall testing showed the half-lap panel-to-panel connection to be the most desirable due to its quicker construction method and better overall failure mode and performance. The walls with half-lap joints were stiffer and dissipated more energy than those with surface splines.

2.2 Numerical Modelling

Quasi-static wall models

In addition to this large number of experimental studies, several researchers have numerically investigated the performance of balloon-type walls. Detailed 2D static simulations were undertaken by Krauss et al. [28] using CLTWALL2D. This is a 2D finite element analysis (FEA) software written specifically for CLT shear wall structures. It uses plate elements to model the CLT panels and HYST springs for the timber connections. HYST is a mechanics-based connection model that can accurately capture the behaviour of dowel-type timber connections [29]. The authors validated the numerical model using wall test data. Then, they examined the performance of single and coupled wall systems up to twelve storeys using a parametric study. They found that coupled wall systems performed significantly better than single cantilever walls (higher strength, stiffness, and ductility). Using MAS HDs, even tall twelve-storey walls reached peak loads of around 1000 kN.

Chen & Popovski [30] have also completed extensive static modelling of balloon-type shear walls. After developing analytical models that can be used in the design, a parametric study investigated the influence of key factors like panel deformation contribution and vertical joint behaviour on the building height that can be achieved with this system.

Non-linear dynamic modelling

Others have conducted extensive dynamic analyses using more simplified modelling approaches. Moerman et al. [31] developed a numerical model in OpenSees to simulate the behaviour of three-/ to six-storey cantilever CLT shear walls subjected to earthquake ground motions. In this work, the CLT panels were idealized as elastic Timoshenko beam-column elements. The base of the wall was modelled using a fibre section, where the HD connections are captured using Ibarra-Medina-Krawinkler springs and the contact between the CLT and the foundation is modelled using Concrete01 springs. A leaning column with rigid beam-column elements and pinned connections was tied to the wall piers using truss elements to capture any P-δ effects in the structure. The authors reported average peak inter-storey drifts of around 1.5%, with mean ductility demands of 3-5. The model is shown in Figure 4.

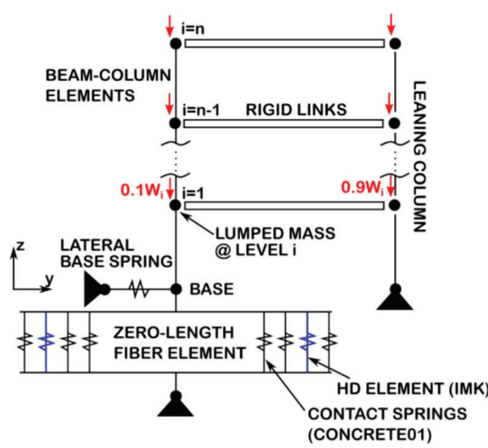

Figure 4 – Non-linear wall model developed by [31]. Image by Ben Moerman.

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Lepine-Lacroix & Yang [32] and Yang et al. [33] used a very similar modelling technique to study the dynamic performance of systems up to twelve storeys, albeit with mini-BRB (buckling-resistant brace) hold-downs and V-shaped truss assemblies with self-centring dampers. The analyzed prototypes were designed and peer-reviewed by practising engineers using the performance-based design guidance published by the National Research Council (NRC) and Canadian Construction Materials Centre (CCMC) [34]. Two yielding mechanisms were considered: single rocking walls with dissipative hold-downs and double rocking walls with both dissipative hold-downs and vertical panel-to-panel joints. Both studies used the FEMA P695 procedure to guide their work. The twelve-storey coupled walls with BRB HDs satisfied the FEMA P695 requirements by providing a sufficient margin of safety (average 3.36). The dual-pinned self-centring walls also met the performance objectives by achieving an adjusted collapse margin ratio of 2.27.

Teweldebrhan & Tesfamariam [35] conducted OpenSees simulations on 20-storey coupled walls with steel link beams and mini-BRB HDs. The modelling approach was similar, although the authors used elastic-isotropic quad elements to capture the CLT panel behaviour instead of Timoshenko beam elements. In addition, no explicit consideration was made for the behaviour of the connection between the CLT wall and the steel link beams, which has a large impact on the system performance [18]. A parametric study was conducted, investigating different levels of coupling, and found that using performance-based design, the maximum inter-storey drift demands could be limited to less than 1.5%, with residual drifts around 0.15%.

Zhang et al. [36] used ETABS to model 12 and 18-storey CLT wall systems and to investigate the impact of the connection stiffness on wall drifts. For this study, the HDs were designed using a modified HSK connection for higher ductility [19]. Unlike previous studies, the model was developed in 3D. With lower connection stiffness, the total reduction in system stiffness was up to 21% for the 12-storey building and 15% for the 18-storey building. This led to drift increases of 49% and 34% respectively. The horizontal (base) shear connections had a larger impact in this context than vertical shear connections (lap or spline joint) and the hold-downs.

Finally, Jafari et al. [37] and Pan et al. [38] conducted more industry-focused studies and looked at the dynamic behaviour of two-storey balloon-type CLT school building projects in Canada. Both studies used conventional light-gauge steel connectors for the hold-downs. Each of these studies found that well-designed and detailed CLT shear wall systems can have very favourable performance under seismic loading with low drifts (less than 1%).

3 – DESIGN & CODIFICATION

Because balloon-type shear walls are still quite new, little work has been done to standardize their design. They are not currently listed in any national building code or design standard. Future design approaches will likely be quite similar to those used for platform-type shear walls. However, their design is simpler because fewer connections are needed. Therefore, simple mechanics-based analytical models are sufficient to predict their performance accurately. Chen & Popovski [2] have published several papers outlining an analytical design model for balloon-type CLT shear walls under lateral loads. It considers wall deflection due to panel bending, shear, and rotation, as well as base sliding, and vertical slip between wall panels. Two different cases are presented: one features a rigid panel base where the CLT rotates freely about its corner; the other model uses an elastic panel base where a certain length of the base forms a compression zone. The authors validated their model using wall test results and recommended the elastic base model for the design of balloon-type shear walls.

Overall, there is currently a concerted effort amongst Canadian research institutions to codify balloon-type CLT shear walls. Studies are ongoing at the National Research Council, the University of British Columbia, the University of Alberta, and FPInnovations, targeting code implementation for the 2030 cycle of the NBC and the 2029 cycle of CSA-O86.

4 – COMPLETED BUILDING PROJECTS

Due to the lack of codification, only a limited number of completed building projects have used balloon-type CLT shear walls. To the best of the authors' knowledge, approximately 30 projects have been built to date. About half of these are low-rise, with three storeys or less. In this section, a selection of the mid-rise and high-rise examples (four storeys or more) is discussed briefly.

The Wood Innovation & Design Centre in Prince George, BC is one of the earliest examples of balloon-type shear wall construction. Completed in 2014, it is a seven-storey (29.5 m) mixed-use facility, with three floors occupied by the University of Northern British Columbia and the rest available to commercial tenants. While the gravity structure is realized using glulam post and beam construction with CLT floors, the lateral system consists of a balloon-type CLT shear wall core. This building is Seismic Category 2 according to the NBC [1].

Another interesting example of balloon-type construction is the Arbora project in Montréal, QC. This development involved three eight-storey residential buildings, with a ground floor concrete podium and seven storeys of mass timber construction. A glulam post and beam gravity structure is combined with load-bearing CLT partition shear walls. Completed in 2019, the shear walls had to be split into three panelized sections vertically to achieve a total length of 23.5 m [39]. This building is Seismic Category 4 according to the NBC.

The Catalyst Building in Spokane, WA, is a five-storey commercial office building completed in 2020. Similar to the previous two examples, this project also features a glulam and CLT gravity system, combined with balloon-type CLT shear wall cores.

The final example discussed here is currently under construction in Vancouver, BC. The Hive is a ten-storey building with a total height of almost 45 m. The bottom storey is a concrete podium with nine storeys of mass timber construction above. The structural design features a post and beam glulam system that is paired with CLT floors to resist gravity loads. Lateral loads are resisted by a perimeter-braced glulam frame combined with four internal balloon-type CLT shear walls (see Figure 5). Tectonus devices are used at the brace ends and in the shear walls to dissipate energy. This building is Seismic Category 4 according to the NBC.

Figure 5 – Shear wall construction in The Hive project. Photo by Ventana Construction Corporation (Matthew Marsolais).

5 – SURVEY

5.1 Survey Design & Questions

To further investigate the current limitations of balloon-type CLT shear wall construction, a survey was designed to capture the point of view of practicing engineers. It can be very easy for academic research to become isolated from engineering practice, and this type of inquiry helps in understanding the opinions of "end users".

The survey contained 21 questions organized into four sections. In the first section, some general information was gathered about the participants and their project experience with balloon-type CLT shear walls:

1. Where are you based?
2. How many balloon-type CLT shear wall projects have you completed?
3. Which building codes/design standards were these designed to?
4. Was a peer review required?
5. Why did you choose balloon-type walls?
6. Was the project funded by additional grants?
7. Were CLT shear walls combined with other lateral force-resisting systems?

In the second survey section, participants were invited to discuss one of their completed projects in more detail:

8. Were the walls post-tensioned?
9. What connection type was used to provide overturning moment resistance?
10. What type of base shear connection was used?
11. What type of panel-to-panel connection was used?
12. Did the building height require tie-downs to connect upper-level CLT panels?
13. How were the walls connected to the diaphragms?
14. Were the walls also designed to resist gravity loads?

The third section of the survey focused on the design and modelling approach chosen by the engineers:

15. How were the walls modelled in design?
16. Did you use a 2D or 3D model?
17. How were connection properties determined?
18. How were CLT stiffness properties determined?
19. Which load case governed the wall design?
20. What drove the wall design? (strength or deflections)

In the final section, participants were invited to share overall reflections on their experience with balloon-type walls and list perceived limitations of the system.

https://doi.org/10.52202/080513-0057

5.2 Sampling

As noted in the previous section, the number of completed buildings with balloon-type walls is very limited. Most of these buildings are known directly to the authors of this study. Therefore, sampling was done exclusively by invitation from the authors and their professional network. No geographical limits were imposed, but only practicing structural engineers were asked to complete the survey. The survey was open for four months, from October 2024 to January 2025.

5.3 Survey Results

Participant and project overview

Eleven engineers completed the survey. This represented an excellent response given the limited number of completed projects. The participants were spread throughout the world, with three engineers from Canada, two from the United States, and six from the rest of the world (including Italy, New Zealand, and the UK).

As expected, the participants demonstrated only a limited level of experience with the system. Most have only been involved in one to three relevant projects, except that one participant has completed five projects already. Collectively, they account for most of the completed projects worldwide with a combined total of 22 projects.

The results showed that in the majority of cases, engineers chose to use balloon-type walls because of the specific performance benefits that they offer. Participants listed the small number of connections, fast construction speed, and high lateral stiffness as the key strengths.

Since the system is still in its early stages, more than seven of the eleven participants indicated that a peer review was necessary to obtain their design approval from the building authorities (see Figure 6). However, only two participants required external grants to construct their projects. This highlights the financial viability of the system. Furthermore, in most cases, the CLT shear walls are the sole required lateral force-resisting system. Only three participants noted that they combined shear walls with other force-resisting systems (e.g., diagonal braces or diagrids) to achieve adequate base shear resistance.

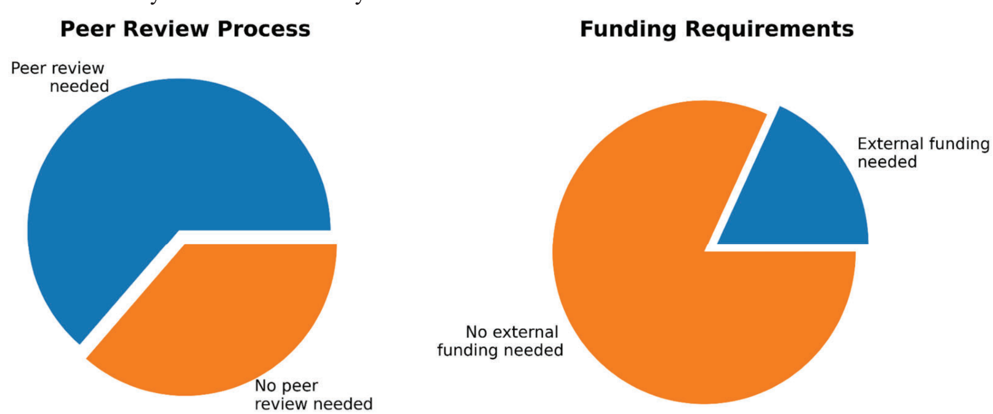

Figure 6 – Survey results: peer review (left) and funding requirements (right).

Design details

Looking more closely at the design details shared by the participants, it is very positive to see that most engineers did not specify off-the-shelf light-gauge brackets but used custom-designed dowelled, bolted, or screwed hold-downs to resist overturning moments (see Figure 7). Similarly, base shear forces are usually resisted by bespoke shear keys or custom brackets rather than light-gauge angle brackets. This is a very positive development, as previous studies have shown that the use of off-the-shelf products can inhibit the performance of high-capacity shear walls due to their limited strength and stiffness [10].

When it comes to multi-panel shear walls, the study participants have used a wide variety of connection details. Half-lap joints with dowel-type fasteners are most common, but surface splines, U-shaped flexural plates, butt joints and steel plates were also utilized. Tie-downs to upper-level CLT panels were generally not required as most projects were limited to four storeys or less. When they were needed, engineers specified glued-in rods or steel hold-down brackets or relied on post-tension clamping.

For the connections between the CLT shear walls and the floor diaphragms participants mostly chose to use steel plates or angles. Beyond this, alternatives included castellated shear keys, steel ties, ledger or stringer beams, screws into the diaphragm concrete and other proprietary connection systems.

Finally, the survey results showed that ten out of eleven engineers used the shear walls to resist both gravity and lateral loads.

Modelling approaches

Participants in the survey provided a fairly even split when it came to modelling approaches. Approximately half chose to use a 2D model, and the other half used a 3D model. However, more variety was seen in the types of elements used to represent the shear walls. No clear consensus was found, with engineers using linear elastic elements such as equivalent beams, as well as 2D shells and more complex laminated elements to study the panel behaviour.

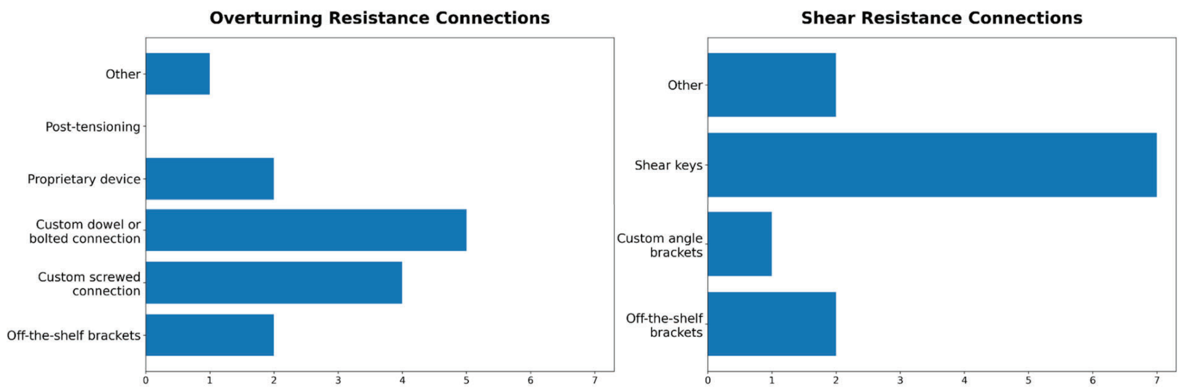

Figure 7 – Survey results: connections used to provide overturning (left) and shear resistance (right).

For the properties that were assigned to the various components in the finite element models, participants mostly used design standards (like Eurocode 5, CSA O86, NZS1720.1) to quantify the stiffness and strength of the connections. In some cases, experimental testing or supplier brochures also provided this information. The CLT stiffness, on the other hand, is not provided by design standards. Here, most participants turned to design guides like ProHolz or used values from the CLT suppliers. Alternatively, finite element modelling or hand calculations were applied. Only rarely participants still used a fully rigid assumption, as this simply doesn't hold for taller walls with high aspect ratios [24].

The seismic load case governed the design according to eight out of eleven survey participants. Only some designs were governed by wind or fire loads. On the side of the shear walls themselves, five responses noted that strength was the limiting factor. In a few cases, deflections at the ultimate and serviceability limit states or connection design also proved critical.

Final reflections

In the final section, participants were invited to share their overall reflections on their experiences with designing balloon-type CLT shear walls. Here, most engineers stated that the system works very well overall. Specifically, they appreciated the system's efficiency through the possible connections optimization, fast construction speed and high lateral stiffness.

However, there are still difficulties in the application of balloon-type CLT shear walls. Participants most lamented the lack of guidance in the building codes. Specifically, there are no prescriptive methods and no specified seismic force modification factors for ductility and overstrength. This means that designers must use alternative, performance-based approaches and it is much more difficult to get these approved by the authorities.

Another point of contention lies in the connections. Participants stated that they have had difficulty with panel-to-panel, diaphragm and hold-down connections. Additionally, there is a lack of information on the stiffness of different connections. This makes the walls difficult to model.

There are also still some problems with the overall implementation of the system. Due to the tall panels that are used, construction sequencing and tolerances are challenging and it can be difficult and/or expensive to prop the walls until the gravity system catches up. One participant also believes that overall, balloon-type walls are more suited to low seismic regions and low-height structures.

https://doi.org/10.52202/080513-0057

6 – CONCLUSION

This study has explored the state-of-the-art of balloon-type CLT shear walls. This novel system has clear benefits compared to platform-type CLT shear walls. This includes the need for fewer connections, leading to faster construction speed, and the elimination of the perpendicular-to-grain stresses that can inhibit the behaviour of platform-type shear walls.

A literature review showed that there has been significant research interest in the system. Most studies have focused on the behaviour of critical connections like hold-downs, shear keys, and panel-to-panel joints. Because most of these researchers are targeting applications in seismic regions, special emphasis has been placed on the ductility and cyclic performance of these connections, but the stiffness has also been a key consideration. Several projects have undertaken full wall testing up to four storeys to validate the system performance.

Complementing the experimental research summarised above, there has also been a concerted effort to study balloon-type shear walls numerically. Here, researchers can push the boundaries due to fewer resource constraints. Published work includes studies on the static and dynamic performance of walls up to 20 storeys which have shown the favourable stiffness and strength of the system.

Codification of balloon-type CLT shear walls in design standards is practically nonexistent. Design models currently exist only in academic literature. However, an increasing number of real-world construction projects have been completed with this technology. Most of these are low-rise (up to three storeys) but some designers have pushed the boundaries by designing up to seven, eight, and even ten storeys with balloon-type walls.

A survey designed to capture the point of view of current working professionals further illustrated the current state of balloon-type wall construction. Only a very limited number of designers have relevant experience with this system, but their overall perspective on the technology is positive. They value the design efficiency that can be achieved with it but are still looking for more design guidance and information to facilitate further uptake.

To summarize, this study showed that while balloon-type CLT shear walls are still a new system in structural design, their application is growing steadily. As researchers continue to investigate their performance at a component and system level, designers are gaining confidence and the needed information for implementation. Future work should focus on further quantifying the performance of key connections and bringing this technology into the building codes and standards so that prescriptive design approaches can be used.

7 – ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of all survey participants. This study would not have been possible without their insights and we thank them all for the time that they spent answering our questions. The UBC Faculty of Forestry Strategic Recruitment Fellowship is also acknowledged to fund the PhD study of the first author.

8 – REFERENCES

[1] NRC, "National Building Code of Canada." Canadian Commission on Building and Fire Codes & National Research Council Canada, 2022.

[2] Z. Chen and M. Popovski, "Mechanics-based analytical models for balloon-type cross-laminated timber (CLT) shear walls under lateral loads," *Eng. Struct.*, vol. 208, p. 109916, Apr. 2020, doi: 10.1016/j.engstruct.2019.109916.

[3] A. Polastri, I. Giongo, and M. Piazza, "An Innovative Connection System for Cross-Laminated Timber Structures," *Struct. Eng. Int.*, vol. 27, no. 4, pp. 502–511, Nov. 2017, doi: 10.2749/222137917X14881937844649.

[4] T. Tannert *et al.*, "Seismic Design of Cross-Laminated Timber Buildings," *Wood Fiber Sci.*, vol. 50, no. Special, pp. 3–26, Aug. 2018, doi: 10.22382/wfs-2018-037.

[5] Z. Li, X. Wang, and M. He, "Experimental and Analytical Investigations into Lateral Performance of Cross-Laminated Timber (CLT) Shear Walls with Different Construction Methods," *J. Earthq. Eng.*, vol. 26, no. 7, pp. 3724–3746, May 2022, doi: 10.1080/13632469.2020.1815609.

[6] A. Aloisio, F. Boggian, R. Tomasi, and M. Fragiacomo, "The role of the hold-down in the capacity model of LTF and CLT shear walls based on the experimental lateral response," *Constr. Build. Mater.*, vol. 289, p. 123046, Jun. 2021, doi: 10.1016/j.conbuildmat.2021.123046.

[7] L.-M. Ottenhaus, M. Li, and T. Smith, "Structural performance of large-scale dowelled CLT connections under monotonic and cyclic loading," *Eng. Struct.*, vol. 176, pp. 41–48, Dec. 2018, doi: 10.1016/j.engstruct.2018.09.002.

[8] J. R. Brown and M. Li, "Structural performance of dowelled cross-laminated timber hold-down connections with increased row spacing and end distance," *Constr. Build. Mater.*, vol. 271, p. 121595, Feb. 2021, doi: 10.1016/j.conbuildmat.2020.121595.

[9] L.-M. Ottenhaus, M. Li, T. Smith, and P. Quenneville, "Mode Cross-Over and Ductility of Dowelled LVL and CLT Connections under Monotonic and Cyclic Loading," *J. Struct. Eng.*, vol. 144, no. 7, p. 04018074, Jul. 2018, doi: 10.1061/(ASCE)ST.1943-541X.0002074.

[10] T. Wright, M. Li, D. Moroder, H. Lim, and D. Carradine, "Cyclic behaviour of CLT shear wall hold-down connections using mixed angle self-tapping screws," *Eng. Struct.*, vol. 286, p. 116123, Jul. 2023, doi: 10.1016/j.engstruct.2023.116123.

[11] K. Krauss, M. Li, and F. Lam, "Influence of mixed-angle screw installations in CLT on the cyclic performance of

commercial hold-down connections," *Constr. Build. Mater.*, vol. 364, Jan. 2023, doi: 10.1016/j.conbuildmat.2022.129918.

[12] T. Wright and M. Li, "Experimental testing of mixed angle screwed hold-down connections for CLT shear walls," in *World Conference on Timber Engineering (WCTE 2023)*, Oslo, Norway: World Conference on Timber Engineering (WCTE 2023), 2023, pp. 2020–2029. doi: 10.52202/069179-0268.

[13] J. R. Brown, M. Li, and F. Sarti, "Structural performance of CLT shear connections with castellations and angle brackets," *Eng. Struct.*, vol. 240, p. 112346, Aug. 2021, doi: 10.1016/j.engstruct.2021.112346.

[14] B. N. Hayes, M. Koliou, and J. W. Van De Lindt, "Seismic Behavior of Balloon Frame Cross-Laminated Timber Connections," *J. Struct. Eng.*, vol. 149, no. 9, p. 04023115, Sep. 2023, doi: 10.1061/JSENDH.STENG-11984.

[15] J. R. Brown, M. Li, T. Tannert, and D. Moroder, "Experimental study on orthogonal joints in cross-laminated timber with self-tapping screws installed with mixed angles," *Eng. Struct.*, vol. 228, p. 111560, Feb. 2021, doi: 10.1016/j.engstruct.2020.111560.

[16] A. Hossain, I. Danzig, and T. Tannert, "Cross-Laminated Timber Shear Connections with Double-Angled Self-Tapping Screw Assemblies," *J. Struct. Eng.*, vol. 142, no. 11, p. 04016099, Nov. 2016, doi: 10.1061/(ASCE)ST.1943-541X.0001572.

[17] A. Hossain, M. Popovski, and T. Tannert, "Cross-laminated timber connections assembled with a combination of screws in withdrawal and screws in shear," *Eng. Struct.*, vol. 168, pp. 1–11, Aug. 2018, doi: 10.1016/j.engstruct.2018.04.052.

[18] B. Moerman, M. Li, T. Smith, and H. Lim, "Design and cyclic testing of bolted end plate connections between steel link beams and cross-laminated timber for coupled shear walls," *Constr. Build. Mater.*, vol. 353, p. 129060, Oct. 2022, doi: 10.1016/j.conbuildmat.2022.129060.

[19] X. Zhang, M. Popovski, and T. Tannert, "High-capacity hold-down for mass-timber buildings," *Constr. Build. Mater.*, vol. 164, pp. 688–703, Mar. 2018, doi: 10.1016/j.conbuildmat.2018.01.019.

[20] W. Y. Loo, P. Quenneville, and N. Chouw, "A numerical study of the seismic behaviour of timber shear walls with slip-friction connectors," *Eng. Struct.*, vol. 34, pp. 233–243, Jan. 2012, doi: 10.1016/j.engstruct.2011.09.016.

[21] H. Asgari, T. Tannert, M. M. Ebadi, C. Loss, and M. Popovski, "Hyperelastic hold-down solution for CLT shear walls," *Constr. Build. Mater.*, vol. 289, p. 123173, Jun. 2021, doi: 10.1016/j.conbuildmat.2021.123173.

[22] CSA, "CSA 086-24: Engineering design in wood," Canadian Standards Organisation, Mississauga, Ontario, Canada, 2024.

[23] B. Moerman, M. Li, T. Smith, and A. Liu, "Cyclic Testing of High-Capacity CLT Shear Walls," *J. Struct. Eng.*, vol. 149, no. 11, 2023, doi: 10.1061/JSENDH.STENG-12188.

[24] K. Krauss, B. Moerman, M. Li, and F. Lam, "Experimental and numerical investigation of the cyclic behaviour of coupled balloon-type CLT shear walls with high-capacity base connections," *Eng. Struct.*, vol. 319, p. 118860, Nov. 2024, doi: 10.1016/j.engstruct.2024.118860.

[25] A. Narcy, D. T. Pham, G. Forêt, and A. Lebee, "Comparison of CLT buckling strength criteria with experimental results," in *International Network on Timber Engineering Research - Meeting 2023*, Biel, Switzerland: KIT, 2023.

[26] J. R. Brown, M. Li, A. Palermo, S. Pampanin, F. Sarti, and R. Nokes, "Experimental testing and analytical modelling of single and double post-tensioned CLT shear walls," *Eng. Struct.*, vol. 256, p. 114065, Apr. 2022, doi: 10.1016/j.engstruct.2022.114065.

[27] X. Wang, M. He, and Z. Li, "Experimental testing of platform-type and balloon-type cross-laminated timber (CLT) shear walls with supplemental energy dissipators," *J. Build. Eng.*, vol. 66, p. 105943, May 2023, doi: 10.1016/j.jobe.2023.105943.

[28] K. Krauss, B. Moerman, T. Wright, F. Lam, and M. Li, "Cyclic performance of balloon-type CLT shear walls with high-capacity hold-downs," in *International Network on Timber Engineering Research - Meeting 2023*, Biel, Switzerland, 2023, p. 17.

[29] M. Li, R. O. Foschi, and F. Lam, "Modeling Hysteretic Behavior of Wood Shear Walls with a Protocol-Independent Nail Connection Algorithm," *J. Struct. Eng.*, vol. 138, no. 1, pp. 99–108, Jan. 2012, doi: 10.1061/(ASCE)ST.1943-541X.0000438.

[30] Z. Chen and M. Popovski, "Theoretical Building Height Limits of Balloon Mass Timber Shear Wall Systems," *J. Struct. Eng.*, vol. 150, no. 1, p. 04023194, Jan. 2024, doi: 10.1061/JSENDH.STENG-12726.

[31] B. Moerman, M. Li, A. Palermo, T. Smith, and A. Liu, "Ductility factor validation for CLT walls with bolted hold-downs: preliminary analyses and observations," in *NZSEE 2022 Annual Conference*, 2022.

[32] S. Lepine-Lacroix and T. Y. Yang, "Seismic design and performance evaluation of novel dual-pinned self-centering coupled CLT shear walls," *Eng. Struct.*, vol. 279, p. 115547, Mar. 2023, doi: 10.1016/j.engstruct.2022.115547.

[33] T. Y. Yang, S. Lepine-Lacroix, J. A. R. Guerrero, J. B. W. McFadden, and M. A. Q. Al-Janabi, "Seismic performance evaluation of innovative balloon type CLT rocking shear walls," *Resilient Cities Struct.*, vol. 1, no. 1, pp. 44–52, Mar. 2022, doi: 10.1016/j.rcns.2022.03.004.

[34] R. DeVall, M. Popovski, and J. B. W. McFadden, "Technical guide for evaluation of seismic force resisting systems and their force modification factors for use in the National Building Code of Canada with concepts illustrated using a cantilevered wood CLT shear wall example," National Research Council of Canada, May 2021. doi: 10.4224/40002658.

[35] B. T. Teweldebrhan and S. Tesfamariam, "Performance-based design of tall-coupled cross-laminated timber wall building," *Earthq. Eng. Struct. Dyn.*, vol. 51, no. 7, pp. 1677–1696, Jun. 2022, doi: 10.1002/eqe.3633.

[36] X. Zhang, Y. Pan, and T. Tannert, "The influence of connection stiffness on the dynamic properties and seismic performance of tall cross-laminated timber buildings," *Eng. Struct.*, vol. 238, p. 112261, Jul. 2021, doi: 10.1016/j.engstruct.2021.112261.

[37] M. Jafari, Y. Pan, M. Shahnewaz, and T. Tannert, "Effects of Ground Motion Duration on the Seismic Performance of a Two-Storey Balloon-Type CLT Building," *Buildings*, vol. 12, no. 7, p. 1022, Jul. 2022, doi: 10.3390/buildings12071022.

[38] Y. Pan, M. Shahnewaz, and T. Tannert, "Seismic Performance and Collapse Fragility of Balloon-Framed CLT School Building," *J. Earthq. Eng.*, pp. 1–21, Sep. 2022, doi: 10.1080/13632469.2022.2123067.

[39] D. Xing, D. Casagrande, and G. Doudak, "Investigating the deformation characteristics of balloon-type CLT shearwall," *Can. J. Civ. Eng.*, p. cjce-2023-0233, Sep. 2023, doi: 10.1139/cjce-2023-0233.

 https://doi.org/10.52202/080513-0057