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DISCRETE VS. CONTINUOUS REINFORCEMENT: A COMPARATIVE STUDY OF CONVENTIONAL AND NOVEL INTERLOCKING CONNECTIONS IN CLT SHEAR WALLS

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ABSTRACT: Cross Laminated Timber (CLT) is an innovative engineered wood product (EWP) increasingly adopted in modular building projects due to its environmental and construction efficiencies. Despite the increasing popularity, the standardised connection methods, such as angle brackets and hold-downs, exhibit limitations in mechanical robustness and require labour-intensive installation. To securely reinforce CLT panels, multiple connectors are typically applied along panel edges. However, the resulting load concentrations can cause permanent damage to the timber over time or even lead to premature failure. To address these issues, a novel interlocking connection system (MOD-IT^{TM}) has been developed, featuring continuous reinforcement and an interlocking mechanism that simplifies both assembly and disassembly in CLT construction. Previous experimental and numerical studies have demonstrated that this system maintains strong mechanical performance while significantly reducing timber damage. Nevertheless, the performance of this system in CLT shear walls has not been extensively studied. This paper presents a comparative analysis of this novel interlocking system against conventional connection methods, specifically focusing on shear wall applications, with the aim of providing comprehensive insights into the effectiveness of interlocking and continuous reinforcement in CLT modular constructions.

KEYWORDS: Self-locking connections, Cross Laminated Timber, Push-over test, Shear wall, Numerical analysis

1 – INTRODUCTION

In CLT structures, shear walls—typically connected with hold-downs and brackets—are essential for lateral stability. Experimental studies, including quasi-static and shake table tests, demonstrate that CLT panels generally remain largely undamaged due to high strength and stiffness, with energy dissipation primarily occurring in the connections. Therefore, connectors have the most significant impact compared to other factors such as friction between structural panels, vertical load and window area on the behaviour of shear wall [1]. However, traditional connection systems face challenges, including low ductility (L or M class per EC8), strength degradation from cyclic loading, and damage accumulation in fasteners and timber, leading to unpredictable cyclic behaviour. These limitations limit the adoption of CLT shear walls in high-performing structures and are crucial for the overall seismic performance of the building.

To enhance construction efficiency and structural performance in CLT buildings, Li and Tsavdaridis [2, 3] recently proposed a novel concept and detailed design of a modular interlocking timber (aka MOD-IT^{TM}) connection that integrates continuous reinforcement and interlocking techniques (Figure 1). MOD-IT^{TM} offers different connector designs for tensile and shear resistance, each consisting of two separate components—a male and a female connector. These components can be directly connected onsite, providing intermediate resistance without the need for additional onsite fastening. This design simplifies both assembly and disassembly processes. simplifying dis/assembly while also. Tests and numerical studies [2] demonstrated its mechanical efficiency and damage-limiting characteristics. The shear connection of MOD-IT^{TM} demonstrated high stiffness and capacity, while the tensile connection had lower capacity with more ductile deformation mode. In addition, deformation was limited within specific connection part even after the failure of specimens. By shifting damage away from the timber and embedded fasteners, this continuous full-length connection can potentially enhance structural integrity by reducing permanent damage to structural materials during service, particularly under unexpected loading events. To advance the understanding of this system's behaviour in reinforcing CLT shear wall systems, a detailed numerical analysis was conducted at meso-scale – modular panelised walls with connections.

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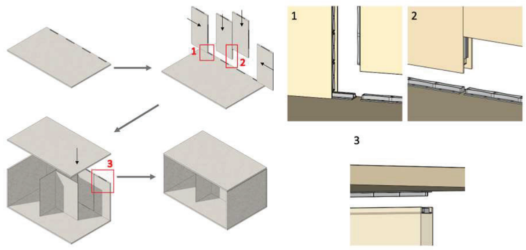


Figure 1. Application overview of the MOD-ITTM connection system for CLT panelised platform-type structures [3]

2 – SHEAR WALL IN TIMBER STRUCTURES

The behaviour of conventional CLT shear wall has been extensively studied to confirm their feasibility in timber structures. Deng et al. [4] conducted parametric experimental studies of single CLT shear walls, examining the influence of connector boundary conditions, aspect ratio, and gravity load on deformation behaviour. The results showed that vertical and shear connector strength has the most significant impact, while friction and gravity load contributions are minimal. Therefore, achieving energy-dissipative kinematic behaviour in CLT shear walls requires careful connector design.

Based on the measurements of vertical and horizontal panel movements in quasi-static test, CLT shear walls' deformation is normally classified as four key components: rocking, sliding, shear, and bending (Figure 2). Their proportions vary depending on connector arrangement and properties [5]. When rocking dominates, panels can revert to their original position upon unloading due to gravitational forces, leading to better ductility, energy dissipation, and ultimate displacement. This behaviour is therefore considered superior to sliding, which causes significant residual lateral displacement [6].

In multi-panel CLT structures, the coupling effect between panels can be classified into three categories (Figure 2): coupled, combined single-coupled, and single-wall behaviour, depending on relative displacement between panels. The coupled wall behaviour parameter κ quantifies this effect:

$$\kappa=\frac{u_2}{u_1+u_3} \quad (1)$$

When the panels behave as a single wall with insignificant relative movement between panels, both u_2 and κ approach '0'. Conversely, when the wall behaves as a coupled wall, κ approaches '1'.

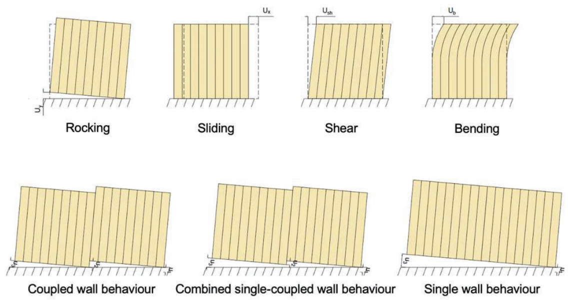


Figure 2. Deformability modes of a single-panel system (top) and a multi-panel system under lateral load (bottom)

3 – NUMERICAL MODELS

3.1 NUMERICAL SHEAR WALL MODEL WITH CONVENTIAON CONNECTIONS

To develop an accurate CLT shear wall model for the analysis in this paper, initial validation was conducted using experimental data from Pozza et al. [7]. The referenced experiment tested a shear wall system comprising two CLT panels (2.95 m × 1.50 m × 85 mm) connected by a half-lap joint with Ø8 × 100 mm self-tapping screws. The panels were anchored using two HTT22 hold-downs (12*Ø4 × 60) and four BMFs105 angle brackets (11*Ø4 × 60) to the steel foundation, following the standard design of the SOFIE project's full-scale CLT building (Figure 3a). The specimens underwent quasi-static cyclic loading per EN 12512 [8], with a reference yielding displacement (Vy) of 20 mm, based on prior IVALSA tests. The panels were loaded onto the top corner in a displacement-controlled manner, with a constant vertical load of 18.5 kN/m on the top of the walls to simulate the load from upper structures in real-world scenarios.

The model's validity was confirmed by adopting validated methodologies from Izzi et al. [9], then comparing results with published experiments. 3D solid elements (C3D8R) were used to model the CLT panels, metal connectors, and steel foundation. Steel grades S250 and S355 were used for the brackets and hold-downs. The CLT panels were modelled as orthotropic elastic materials as outlined in Table 1, without considering the layered properties. This simplified approach was selected because the experiments indicated that deformation in the panels was insignificant. To simplify the complexity of numerous screws in shear walls, screws were represented as bilinear elasto-plastic springs with three degrees of freedom (DOF) for transverse behaviour and as linear springs for axial behaviour (Figure 3b), reflecting their brittle failure in tension.

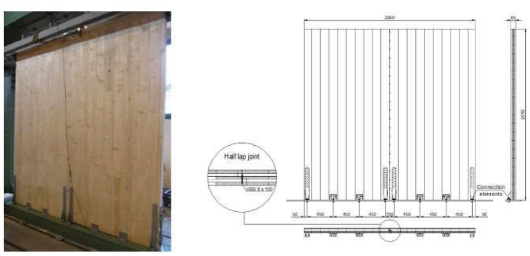
Table 1. Material parameters for CLT panels [9]

ER [MPa]	ET [MPa]	EL [MPa]	RT [–]	TL [–]
600	600	12,000	0.558	0.038
RL [–]	GRT [MPa]	GRL [MPa]	GTL [MPa]	
0.015	40	700	700	

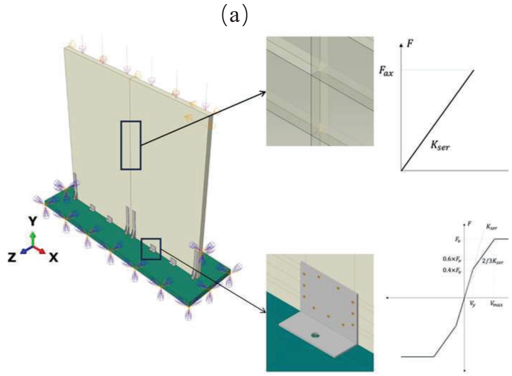
The screw properties input in numerical models were calculated according to EC5 [10]. To account for the interaction effects among screws in angle brackets and hold-downs, the 'effective number of nails in a row' concept was applied, reducing F_{lat} and F_{ax} using the effective factor k_{eff} (Equation 2). This adjustment was not applied to Ø8×100 nails in panel-to-panel connections, as their large spacing eliminate coupling effects. For component interactions, ABAQUS was set with 'Hard Contact' for normal interactions and 'penalty friction formulation' for tangential responses. Friction coefficients were assigned as: 0.4 (Steel-Steel), 0.25 (Steel-CLT), and 0.4 (CLT-CLT).

$$k_{eff} = \frac{n^{0.9}}{n} = n^{-0.1} \qquad (2)$$

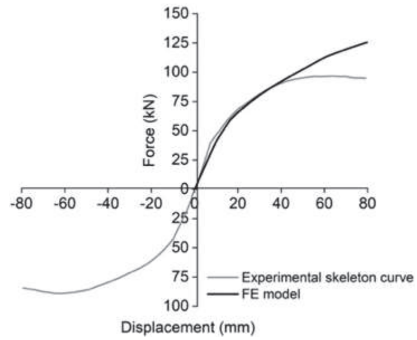
The comparison with experimental results suggest that, the simplifications made in the FE shear wall model do not markedly detract from its predictive accuracy in terms of structural responses (Figure 3c) and deformation. Some overestimations can be observed in the plastic region supporting due to the simplifications in connection properties, while its adoption in further numerical shear wall studies can be confirmed.



(a)



(b)



(c)

Figure 3. Model validation of conventional shear wall: (a) Shear wall testing, (b) Numerical model of the experiment, (c) Force-displacement curves comparison

3.2 NUMERICAL SHEAR WALL MODEL WITH MOD-IT™ CONNECTIONS

The validated modelling methods and boundary conditions were also applied to shear wall models with interlocking connections. Interlocking connectors were modelled using S235 material with detailed 3D geometry, as introduced and validated in previous paper [2]. The tensile connection in the new system was modelled as a continuous element, while the shear connection was represented by repeated unit connectors to improve modelling efficiency. Following the previously validated modelling approach, screws in the MOD-IT™ connections were also simulated using non-linear connector elements. Their influence on overall connection performance was assumed to be minimal, given the damage-controlled design of the MOD-IT™ system, which limits reliance on screw capacity. This was also confirmed by comparing a model with simplified screws and a model with detailed simplified screws (Figure 4).

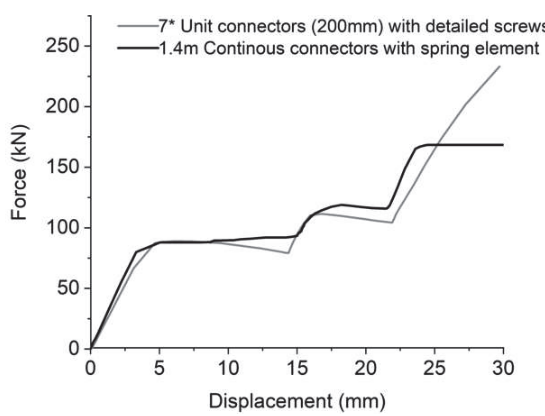


Figure 4. The strength comparison between the detailed and the simplified tensile model

3.3 COMPARATIVE STUDY

After model validation, a numerical parametric study was conducted to compare the lateral behaviour of full-scale CLT shear walls using conventional plate connections

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with those using MOD-IT™ systems. Two wall series were examined: the Wall-P series with conventional connectors (Wall-P-1 following the validated layout and Wall-P-2 with a reduced number of connections), and the Wall-I series using MOD-IT™ connectors (Figure 5). Wall-I-1 and Wall-I-2 employed continuous tensile and shear connections, with Wall-I-2 integrating a 2 m MOD-IT™ tensile connection between panels that enables relative movement. In contrast, Wall-I-3 and Wall-I-4 used 200 mm discrete unit connectors spaced evenly along the wall length. As the goal was to explore the shear-tension interaction of MOD-IT™ shear and tensile connections under monotonic loading conditions, rather than perform a direct comparison, as the two systems reinforce panels in different ways.

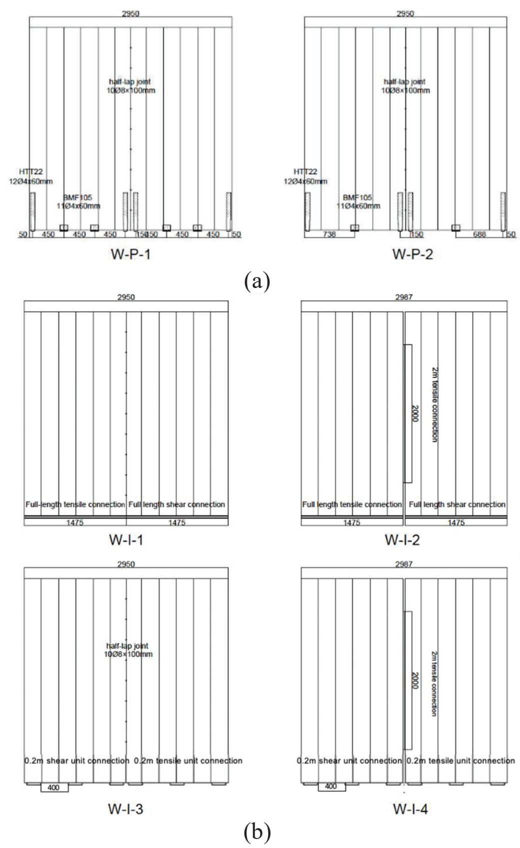

Figure 5. Geometries and connection arrangements of the investigated walls: (a) walls with conventional plate connectors, (b) walls with the MOD-IT connectors

4 – COMPARATIVE NUMEIRCAL SHEAR WALLS MODELS

4.1 DEFORMATION MODE

Figure 6 illustrates the deformation modes across different shear wall models. Shear walls with conventional connections exhibited consistent deformation patterns, with deformation primarily concentrated in the plate connectors (Figure 6a), while the CLT panels remained largely undeformed. Although screw deformation was not explicitly represented by spring elements, the observed plastic deformation in metal plates suggests associated deformation in both the screws and surrounding timber, consistent with the typical behaviour of plate connectors discussed earlier. In these models, angle brackets and hold-downs nearest the load application point showed the greatest deformation. Wall-P-2, which used fewer connectors, exhibited slightly higher peak stress in connectors than Wall-P-1, indicating greater connector deformation and more pronounced panel separation, suggesting a weaker single-wall behaviour compared to Wall-P-1.

Figure 6b shows the deformation behaviour of Wall-I series shear walls with MOD-IT™ interlocking connections at a displacement of 65 mm. Across all models, plastic deformation consistently occurred in the specific part of connection (male connectors), demonstrating the effectiveness of the damage-controlled design achieved through basic capacity-based detailing.

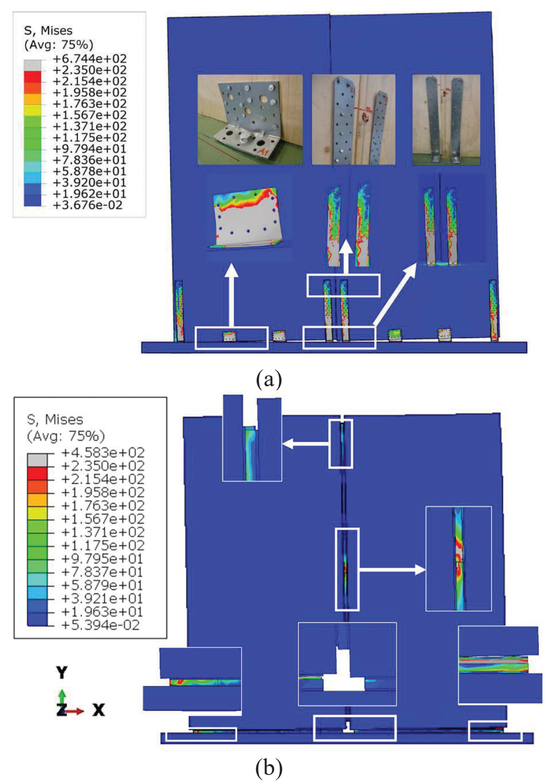

Figure 6. Examples of deformation in (a) Wall-P series and (b) Wall-I series

In MOD-IT's response to lateral load, the bottom part of the connector at the rotation centre experienced localised compression but remained in the elastic range. On the tensile side, more plastic deformation can be observed at the locations that are nearer to the applied load, while the connections near the joint between panels remained largely unaffected. Importantly, minimal stress concentration was observed in the bottom plates of both shear and tensile connections, suggesting that the system, even under large displacements, can limit damage within connectors to protect timber panels, confirming the reliability of the continuous interlocking connection in sustaining large deformations safely.

In Wall-I-1, the load was transmitted smoothly through the continuous shear connections. All shear connections remained below their critical load limits, allowing only minor sliding and preventing the buckling observed in the experimental testing. Slight separation occurred at shear connections farthest from the rotation centre, confirming the rocking mechanism of the shear wall system. The influence of inter-panel connection types was revealed by comparing Wall-I-1 and Wall-I-2. The screwed inter-panel connections in Wall-I-1 promoted strong single-wall behaviour, with the panels rotating together around the bottom left corner, while minimal relative movement observed between them. This is further supported by comparing the results with Wall-I-2, where MOD-IT™ tensile connections were adopted between panels to allow for relative movement, so an increased coupling effect between panels was evident.

In Wall-I-3 and Wall-I-4, which used discontinuous connections at the panel base, higher stress concentrations were observed compared to walls with continuous connections. At a displacement of 65 mm, the tensile male connector near the loading side exhibited significant vertical movement, along with deformation in the part of the connection screwed to the timber panels. This indicates insufficient damage-control capacity in the discontinuous connections and suggests potential force transfer from the MOD-IT™ system to the screws. Due to the lower shear resistance of the discontinuous configuration, the walls exhibited greater sliding, leading to buckling in two shear connectors.

4.2 Structural performance

The structural performance of each shear wall is summarised in Figure 7. Overall, walls with conventional plate connections (Wall-P) demonstrated higher stiffness, ultimate strength, and ductility ratios than those with interlocking connections (Wall-I). The lower initial resistance observed in the Wall-I series can be attributed to the greater degrees of freedom inherent in the interlocking system. Unlike screwed connections with higher rigidity, the interlocking mechanism allows for slight movements between components at the loading direction during the early stages of loading. This flexibility delays the development of full structural engagement, resulting in reduced stiffness and lower load-bearing capacity at the onset of deformation. While this characteristic contributes to the system's energy dissipation potential, it also explains the lower initial resistance compared to more constrained or continuous connection systems.

Wall-P-1 achieved the highest stiffness and ultimate resistance, while Wall-P-2, with fewer connectors, showed slightly reduced performance—consistent with published results [11]. In the Wall-I-1 and Wall-I-2 models, featuring continuous interlocking connections, the force-displacement curves revealed a gradual increase in resistance without a distinct yield plateau, suggesting progressive yielding—likely beginning in the tensile connectors—rather than simultaneous plastic behaviour. This indicates a distributed force transfer along the continuous connection strip, engaging connectors incrementally rather than all at once.

In contrast, Wall-I-3 and Wall-I-4, which used discontinuous interlocking connections, displayed two slight drops in resistance corresponding to buckling in individual shear connectors. However, the smooth strength reduction following buckling—compared to the abrupt failures seen in local-scale tests [2]—suggests that other connectors in the system shared the load, contributing to a subsequent recovery in resistance.

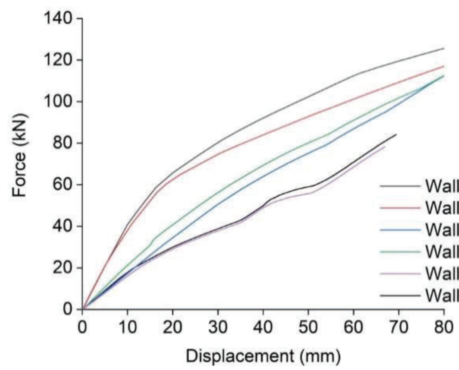

Figure 7. Summary of push-over results of different wall series

4.3 Lateral Behaviours

In terms of the lateral deformation of CLT shear walls, as introduced in Section 2, FE results showed that the shear and bending deformation in panel were negligible, so the analysis focused on rocking and sliding, quantified following [12]. The total displacement at the top of the panel is δ, with the sliding component δ_S measured directly. The rocking contribution δ_r is then calculated as:

$$\delta_r = \delta_S - \delta_S \tag{3}$$

$$\kappa = \frac{u_2}{u_1+u_3} \tag{4}$$

where u_1, u_2, and u_3 represent uplift, relative displacement between panels, and vertical displacement at the rotation center, respectively. A single-wall behaviour is indicated by $\kappa \approx 0$, while coupled-wall behaviour approaches $\kappa \approx 1$

As shown in Figure 8, rocking was the dominant deformation mode in all wall systems. Wall-P-2 showed the highest sliding contribution, which was reduced in Wall-P-1 due to the additional angle brackets. In walls with interlocking connections, sliding was significantly reduced owing to the higher stiffness of shear connectors, which promoted vertical panel movement and increased rocking. Walls with a sliding rail (Wall-I-2 and Wall-I-4) demonstrated greater rocking due to lower panel coupling, allowing more independent rotation. In contrast, Wall-I-3 and Wall-I-4, with discontinuous connections, showed higher sliding from reduced shear resistance. At drifts beyond 1.5%, tensile connections began

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consolidating, increasing stiffness, limiting vertical motion, and causing a shift toward greater horizontal (sliding) displacement.

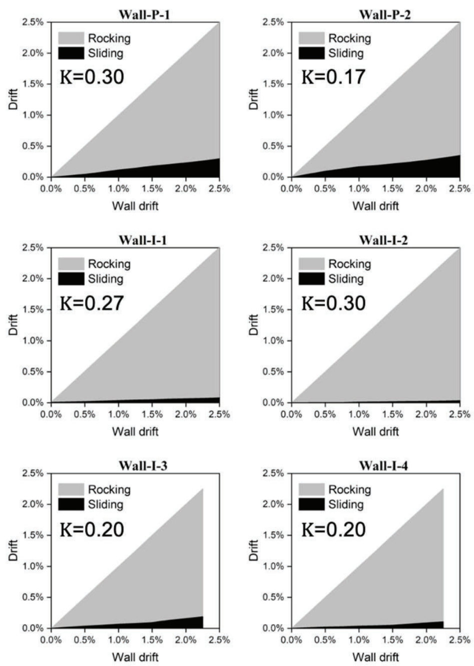

Figure 8. Sliding and rocking drift in shear walls with different connection configurations

6 – CONCLUSION

The parametric study highlights the distinct deformation mechanisms between conventional and MOD-IT™ connections in CLT shear walls. While systems with interlocking feature exhibit lower initial stiffness, they offer a damage-controlled capacity that allows for large deformations without damaging the timber. As a result, these systems can achieve ultimate strengths comparable to conventional connections while enhancing durability and post-event recoverability, even allow for deconstruction and reuse.

A key advantage of interlocking connections lies in the coordinated interaction between strong tensile and weak shear connectors, which, combined with an inter-panel sliding rail, encourages rocking behaviour. This enables each panel to rotate independently, promoting energy dissipation and self-centring under gravity—features highly desirable in seismic design. In contrast, sliding movements often result in residual displacements that require external correction.

The study also demonstrates that continuous connector designs enhance structural performance by minimising load concentration and enabling smooth load transmission along panel edges, which can be a favourable feature in timber panelised structures. With proper detailing, the continuous steel plate provides both structural reinforcement and protection against environmental exposure. Additionally, the integrated sliding rail effectively controls relative panel movement, reducing both in-plane and out-of-plane separation.

Moreover, the interlocking connection design creates a cavity between panels and the foundation, which isolates vertical load transfer during rocking. This feature helps protect floor elements from compression damage, contributing to the system's overall resilience. Collectively, these behaviours make interlocking connections a promising solution for enhancing the ductility, energy dissipation, and post-event serviceability of CLT shear wall systems.

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