WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

Block Tear-Out Resistance of High-Performance Hybrid Grout-Steel-CLT Connections for Balloon-type Shear Walls: Experimental Study

Mohammad Shekarchi[1], Blériot Feujofack[1], Cristiano Loss[2], Tony Yang[3]

ABSTRACT: This study evaluated the performance of a novel hybrid grout-steel-cross laminate timber (CLT) connection when subjected to monotonic loading parallel to the grain. Three different connection configurations with various grout diameters were fabricated and tested. These tests are part of a broader experimental study that has been designed to develop a resilient and reliable connection for employing in mid- to high-rise timber structures. The connection failure modes, ultimate load-carrying capacity, and post-peak behaviour were recorded and discussed in this paper. The research outcomes are expected to provide valuable guidance for structural engineers and architects in designing resilient and sustainable timber buildings.

KEYWORDS: Hybrid Connections, Load-slip diagram, Residual Capacity, Resiliency, Brittle Failure

1 – INTRODUCTION

Timber has several environmental, economic, and aesthetic advantages as a construction material, making timber structures increasingly popular in housing. With emerging advancements and technologies in engineered wood products such as cross-laminated timber (CLT), timber has become a suitable material for even high-rise buildings [1]. CLT panels are composed of multiple layers of lumber boards arranged crosswise, typically at 90-degree angles, and bonded together on their wide faces and, occasionally in Europe, along their edges.

In most modern high-rise mass timber hybrid buildings, CLT panels and glulam members are used to transfer gravity loads to the foundation, while steel or reinforced concrete lateral load resisting systems (LLRS) are employed to withstand the significant applied lateral loads such as wind and seismic loads. Recently, studies have been carried out to find alternative CLT LLRS for high-rise timber structures adopting a balloon-type shear wall architecture [2-4].

The balloon-type construction method involves the implementation of vertical structural elements, such as shear walls, extending from the top of the structure to the foundation without being interrupted by horizontal elements, such as floors or beams. In fact, the horizontal elements are attached to one side of the vertical members. Using this solution, the limitations arising from significant compressive stress perpendicular to the grain in structural members are avoided.

Traditionally, a resistance-only approach was used to design a structure so that the resistance of each structural member must be greater than the stress level experienced by that element. In this framework, if a structural element such as a shear wall fails, the entire element must be replaced, which can be costly. In some cases, the structure may need to be even demolished following a strong earthquake, as it would no longer be safe for occupants. A resilient framework for structures focuses on the ability of structures and systems to withstand against and also recover from various stresses and hazards such as earthquakes and hurricanes. The main goal of a resilient framework is to maintain the functionality of the structure during and after these events by minimizing experienced damage and downtime of the structure [5].

Although implementing traditional shear walls like thick reinforced concrete (RC) shear walls can improve the overall performance of a building during severe earthquakes, the spalling and crushing of the bottom corner of the RC shear walls can happen, which requires significant repair after the seismic event [6]. This would

[1] PhD student, Sustainable Engineered Structural Solutions Laboratory, Department of Wood Science, The University of British Columbia, Vancouver, Canada
[2] Associate Professor, Sustainable Engineered Structural Solutions Laboratory, Department of Wood Science, The University of British Columbia, Vancouver, Canada
[3] Professor, Department of Civil Engineering, The University of British Columbia, Vancouver, Canada

https://doi.org/10.52202/080513-0538

be the same on the compressive side of alternative timber shear walls if used as LLRS. To prevent experiencing these severe damages, the rocking shear wall systems have been introduced and evaluated in several research studies. These rocking shear wall strategies are usually made of engineered timber materials, such as cross-laminated timber (CLT) or laminated veneer lumber (LVL), and are designed to allow controlled rocking movement during a seismic event [7]. In other words, the rocking mechanism enables the shear walls to pivot at their base and return to their original position after an earthquake, minimizing residual displacements and reducing repair costs. In order to control higher displacement demands and cyclic structural stability during severe seismic events, advanced energy dissipation devices are implemented at the base of the shear walls [8], or two shear walls are connected using coupling beams performing like shear fuses to make a coupling shear wall system [9-10]. Also, post-tensioning techniques can be employed to improve the rocking performance of shear walls during an earthquake by anchoring post-tensioned rods or tendons to the foundation and enhancing structural stability and the self-centering ability of the wall [11]. These strategies can dissipate seismic energy efficiently, limiting damage to the main structural elements.

Yang et al. [12] numerically evaluated the seismic performance of a 12-story balloon-type rocking CLT wall prototype based on two metro areas in Canada: the city of Vancouver and Montreal. It was shown that the designed shear walls attained a sufficient and acceptable collapse margin ratio compared to the minimum limit value suggested by FEMA P695 [13].

Connections are key components in a mass timber structural assembly. They allow loads and stresses to be transferred from the horizontal and vertical members to the foundation. Conventional hold-down connections consist of metal brackets attached to at least one side of the walls by nails, screws, or bolts to withstand uplift and overturning forces. Previous research studies [14-15] have shown that these connection technologies can be employed only in low- to mid-rise structures as those are prone to high strength degradation and stiffness loss under cyclic load.

For high-rise timber structures, advanced connection technologies are required to resist the high seismic forces. Various types of connections have been studied experimentally and numerically as potential solutions for mid- to high-rise timber structures. Among them, dowelled slotted-in steel plates hold-down connections, Holz–Stahl–Komposit (HSK) system, pinching-free connectors, and glued-in rod connections have been shown as suitable candidates [16-19]. However, in almost all these systems, the steel components of the connection are designed to yield in order to dissipate seismic energy, which can cause partial or complete damage to the connection and some parts of the CLT walls. These damages make buildings vulnerable after a strong earthquake and repairing them can be costly. To minimize the level of damage a high-performance hybrid connection is needed to act with an energy dissipative device such as resilient slip friction joint device simultaneously. This system allows high-performance connectors to provide the required resistance and stiffness while the energy-dissipative device should dissipate and absorb the energy imposed by the earthquake.

This study presents a high-performance hybrid connector that can be utilized in designing hold-down joints using energy-dissipative devices between the CLT shear walls and the foundation. With specific reference to Fig. 1, the hybrid connector consists of rounded steel elements surrounded by a ring of epoxy-based gout of predetermined thickness based on the rod diameter and expected performance level.

With the thick layer of epoxy-based grout, stresses are transferred from the steel rod to the CLT panel more uniformly, reducing the stress concentration level at the contact surface of the holes [20]. Easy and straightforward assembly and disassembly of this hybrid connection does not need advanced equipment and expertise. By using fully threaded steel rods, the CLT panels can be connected easily to side steel plates or energy-dissipative devices. In addition, the typical large hole gap between the steel rod and CLT panels facilitates the pouring of the grout

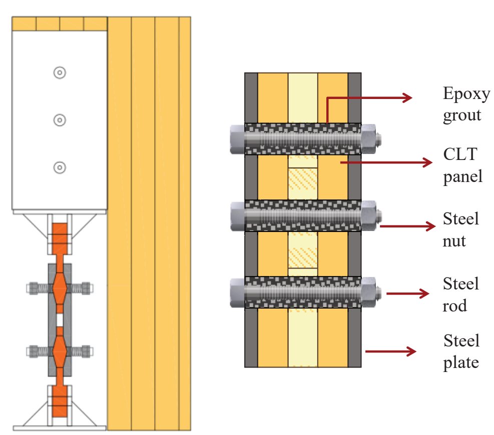

Fig. 1: Proposed hybrid connection (left) proposed connection with an energy dissipative device (right) details of connection.

https://doi.org/10.52202/080513-0538

mixture, which can be readily cast into such space without the need for injections. This simplicity allows multiple connections to be assembled in a short period of time, often within an hour, on-site showing its capability as an efficient solution to be employed in various construction applications. Shulman and Loss [21] and Feujofack and Loss [22] performed several hundred push-out tests on this hybrid connector loaded parallel and perpendicular to the grain. It was concluded that this hybrid connector could exhibit ductile behaviour if specified grout-to-rod diameter minimum requirements are met.

This study aims to contribute to the existing literature by conducting an experimental study on such novel high-performance hybrid grouted connections and exploring their ultimate performance and failure mechanisms under monotonic pull-out loading parallel to the grain. The effect of end distance and grout diameter on the performance of the connection is studied under static loading parallel to the outer layer of the CLT panel.

Table 1: Test variables

Parameters	**Level 1**	**Level 2**	**Level 3**
Grout Diametr(D_g)	48 mm	72 mm	96 mm
End distance (a_l)	$2D_g$	$3D_g$	$4D_g$
Row Spacing (S)	$2D_g$	$3D_g$	$4D_g$
Number of connectors (n)	1	2	3

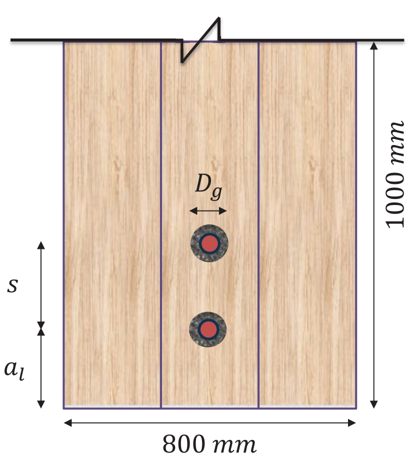

Fig. 2: designation of test variables.

2 – MATERIALS

Timber: 3-layer CLT panels with 35 mm thick lamellas were used in this study. All panels were made of No 2 visually-graded (VG2) lumber and 2100fb 1.8E machine-stress-rated (MSR) lumber boards. The 3-ply CLT panels were selected in this study to analyse the most critical bearing condition in the wood interested by the lateral loads in the shear connectors. In addition, these 3-layer CLT panels can be stacked next to each other and sandwiched by steel plates to make a strong composite section.

Epoxy-based Grout: To bond the steel rods to the CLT elements, a three-component epoxy-based grout [23] was used. This special grout mixture provides boding solutions featuring large gap-filling properties, high compressive strength, and non-shrinking properties. According to the manufacturer's data sheets, the compressive and tensile strength of this epoxy-based grout after 7 days of curing at room temperature attain 103 and 14 MPa, based on ASTM D 695 [24] and ASTM C 307 [25], respectively. Additionally, the high viscosity of this epoxy grout made the fabrication of these connector types reliable since it can prevent leaking into the small internal voids present inside the CLT panels.

Steel: Steel rod diameter and specifications were kept constant for all the specimens of this experimental study. Specifically, zinc-coated fully threaded steel rods respectively 24 in diameter and 250 mm in length in the strength class of 8.8 were used in each connector. An average yield strength of 733.5 MPa with a CoV of 1.82% and an ultimate tensile strength of 878.3 MPa with a CoV of 0.84% were assessed based on material tests conducted by Shulman and Loss [21] on three samples in accordance with the ASTM E8M [26].

3 – EXPERIMENTAL PROGRAM

3.1 TEST VARIABLES

In order to understand the performance of the proposed hybrid steel-grout-CLT connection, several variables were considered in this experimental study. One of the parameters that can affect the ultimate load-carrying capacity of the connector is the grout-to-steel rod diameter ratio. In this paper, the effect of utilizing three grout-to-rod diameter ratios of 2, 3, and 4 representing low, medium, and high ratios were evaluated, respectively. Moreover, three different end distance and row spacing arrangements were chosen to be accessed. These values

https://doi.org/10.52202/080513-0538

were chosen as a coefficient of the grout diameter (D_g). The selected values of end distance and row spacing distance were $2D_g$, $3D_g$, and $4D_g$. Values smaller than these could not be reasonable as it was obvious that connection with an end distance less than $2D_g$ most probably had a really low load-carrying capacity and failed suddenly and in a brittle mode. Additionally, the effect of group action of connectors was of interest in this study. When a group of connectors in a row is subjected to a lateral load, the connection's ultimate load capacity is smaller than the load a single connector is able to withstand times the number of connectors used. Three different numbers of connectors (i.e., 1, 2, and 3 connectors) were considered in the study. Table 1 and Fig. 2 summarize the test variables as well as their respective levels.

With 4 variables and 3 levels for each variable, the factorial method requires the fabrication and testing of 81 specimens. As an alternative method, the L9 orthogonal array Taguchi's design can apply to four variables, each with three levels. It includes 9 unique experimental runs that cover all possible combinations of levels. To make sure that the test results are reliable, a minimum of 5 replicates are required for each connector arrangement. Therefore, the final testing matrix comprised 45 full-scale hybrid connection specimens. Table 2 represents the designed experimental program.

This paper only includes the main results of the pull-out performance of individual hybrid connectors. Test results on group connectors will be published in future reports and manuscripts.

3.2 SPECIMEN FABRICATION

CLT panels were delivered by a local Canadian manufacturer in sizes 6000 mm long and 2400 mm wide. Each CLT panel yielded 9 specimens, each measuring 2000 mm in length and 800 mm in width. Based on the position and number of hybrid connectors in each specimen, the CLT cuts were drilled precisely using CNC-machining via a Hundegger robot-drive machine. The predrilled hole diameter was set to match the grout diameter of the connector. However, the final 9 mm of the drilled hole had a diameter equal to the steel rod, ensuring that the epoxy grout would not leak out while it was still wet and in a plastic form.

After drilling the CLT cuts, these were laid flat, and the inside surface of the predrilled holes was thoroughly cleaned using brushes, a vacuum and an air-blowing gun in order to remove wood splinters, oil, dust or any bond-inhibiting particles. Then, the steel rods were inserted inside the holes in such a way that the middle 105 mm of the steel rods were inside the holes and 72.5 mm of steel rods were out of the CLT panels, symmetrically, from both sides. To fill the gap between the rod and the CLT panel, the 3-component epoxy-based grout was mixed and cast into the hole. The mixing procedure is always important for these types of grouts or epoxies to get the maximum possible compressive, tensile and bond strength. For this specific grout, according to the manufacturer's recommendation, the hardener and the resin were mixed with a slow-speed mixer (between 400 and 600 rpm) for approximately 1 – 2 minutes until the mix showed a uniform dark grey colour. While mixing at low speed, the aggregate, the third component, was slowly added and mixed until thoroughly blended so that there was no dry aggregate inside the mixture and all of them were completely wet. Thereafter, given the working time of the gout, it was cast into the CLT panel holes in three stages until the holes were completely filled. At each stage, one-third of the hole was filled, and the poured epoxy grout was tamped down to minimize air bubbles in the mixture, which could otherwise adversely affect the mechanical properties of the grout.

Table 2: Experimental program

Experiment	**Diameter of grout (D_g)**	**End distance (a_l)**	**Spacing within the row (S)**	**Number of connectors (n)**
1	48 mm	$4D_g$	$2D_g$	1
2	48 mm	$5D_g$	$3D_g$	2
3	48 mm	$6D_g$	$4D_g$	3
4	72 mm	$3D_g$	$3D_g$	3
5	72 mm	$4D_g$	$4D_g$	1
6	72 mm	$5D_g$	$2D_g$	2
7	96 mm	$2D_g$	$4D_g$	2
8	96 mm	$3D_g$	$2D_g$	3
9	96 mm	$4D_g$	$3D_g$	1

Finally, to fix and adjust the position of the steel rods at the centre of the hole, a wooden ring with a thickness of 9 mm, an inner diameter matching the steel rod diameter (24 mm), and an outer diameter matching the grout diameter

https://doi.org/10.52202/080513-0538

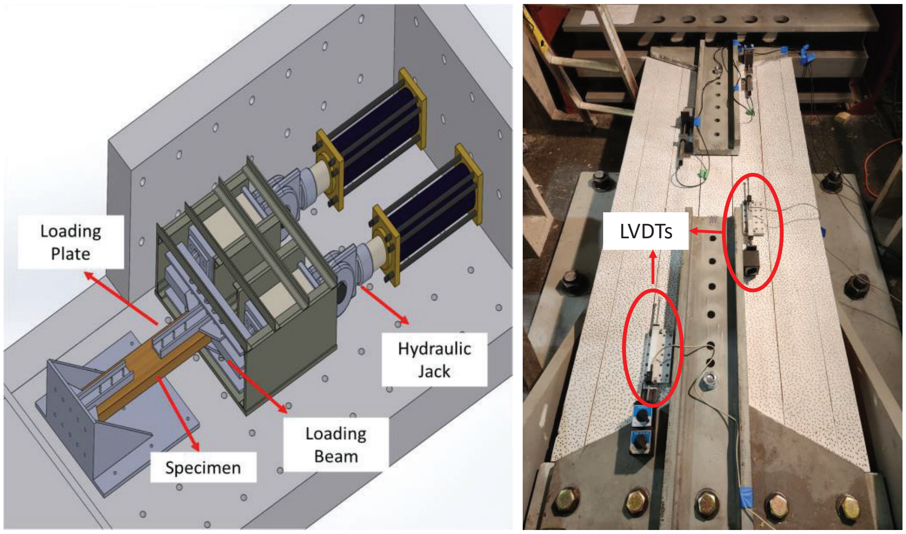

Fig. 3: (left) Schematic view of test set-up and (right) LVDTs positions.

was placed on top of the hole using the gentle impacts of a rubber hammer until its surface was flush with the CLT panel (see Fig. 4). This also further help to remove air bubbles trapped inside the grout mixture. All fabricated specimens were then transferred to a room with standard controlled conditions and stored for at least 14 days to make sure the epoxy-based grout achieved the mechanical properties for which the specimens were designed.

3.3 TEST SET-UP

Quasi-static monotonic pull-out shear tests were conducted using a custom-made test set-up to evaluate the performance of the proposed hybrid shear connectors. One end of the test setup was designed to fix the specimen, while the other end was used to apply the pull-out load to the connectors. A displacement-controlled loading procedure with a constant loading rate of 1.5 mm per minute was selected for this experimental program to guarantee each specimen reached failure within 10 minutes as per ASTM D5764 [27]. Two hydraulic jacks, each with a capacity of 650 kN (a total capacity of 1300 kN), were used to apply the shear pull-out load parallel to the grain direction of outer CLT layers. Both hydraulic jacks were connected to a steel beam and the steel beam itself was attached to two thick steel plates of the specimens. The part of rods extended outside of the panel were used for attaching the thick steel plates to both sides of CLT panels using steel nuts before beginning of the tests.

To measure the slip values of each connector, two Linear Variable Displacement Transducers (LVDTs) were attached to both sides of the specimens. Those LVDTs were positioned to align with the centre of the connector at both the fixed and loaded ends. The load and slip values were recorded using a computer-based data acquisition system.

In this study, each large-scale specimen was loaded until the hydraulic jacks reached a displacement of 50 mm. Hence, not only the ultimate load capacity of the connector

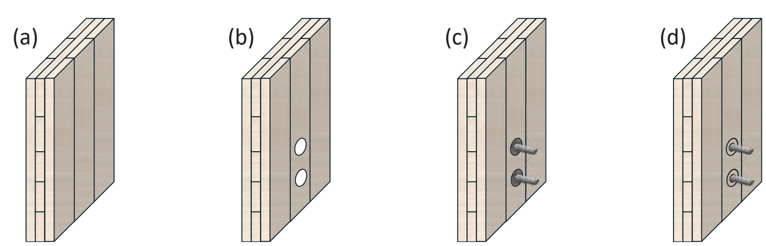

Fig. 4: (a) Cutting specimen, (b) Drilling the panel, (c) Pouring Grout and inserting steel rods and (d) Installing wooden ring.

https://doi.org/10.52202/080513-0538

could be captured but also it was possible to evaluate the post-peak behaviour of the tested specimen. Fig. 3 indicates the location of LVDTs as well as the schematic view of the test set-up used for this experimental study.

4 – RESULTS AND DISCUSSION

4.1 FAILURE MODE

The failure mode of the hybrid connection can be affected by various factors such as the mechanical properties of every material utilized in the connection (e.g., the timber species for the outer and inner layers of the CLT panels, epoxy-based grout, and steel rod). Another important factor influencing the failure mode that a hybrid connector may experience is the geometric properties of its components. Key geometric factors include the thickness of the CLT panels, the number and thickness of CLT layers, the arrangement of CLT layers, the diameter of the epoxy grout and steel rod, as well as the end distance and edge distance of the connector. Additionally, the loading conditions applied to the specimen can affect the failure of the shear connectors. For instance, a connection under push-out loading protocol may exhibit a ductile failure mode. In contrast, the same connection under pull-out loading conditions may experience a brittle failure mode.

In this study, the main failure mode observed was brittle failure due to shear failure of the outer lamellas of the CLT panel. As shown in Fig. 5, the failure of these specimens started with the formation of cracks at both sides of the grout hole. As the pull-out shear load increased, those cracks propagated toward the loaded end of the connection until the entire timber could not resist more load and failed. In addition, the adhesive layer between the outer and inner layers of CLT panels failed due to shear stress. The inner layer of the CLT panels could have experienced failure due to the tensile stress perpendicular to the grain if the edge distance, the distance from the connector to the side edges of the connection, was too low. In this study, since the edge distance was 400 mm, no tensile failure of timber perpendicular to the grain was observed.

Since the stresses are transferred from the steel rod to the epoxy grout and then into the wood, a more uniform stress distribution is applied to the wood-bearing area. Consequently, the stress concentration level at the vicinity of the rod and the resulting wedging force, which generates tensile stress perpendicular to the grain, in the outer CLT layers reduced significantly. Also, the transverse layer of the CLT can resist the generated wedging force due to its favourable mechanical properties in the direction of the applied wedging force. Therefore, it

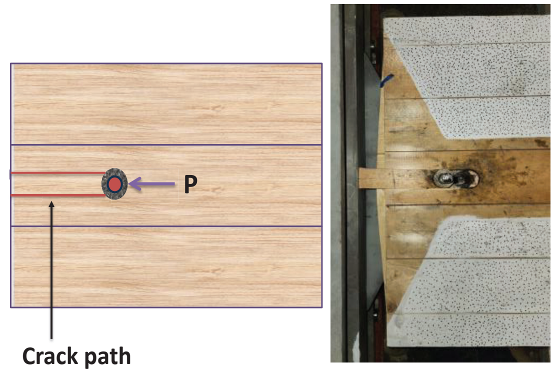

Fig. 5: Failure mode of the connector.

can be concluded that Mode II fracture (sliding mode due to shear stress acting parallel to the plane of the crack) had a substantially higher contribution to the ultimate failure mode of the connection in comparison with Mode I fracture (opening mode due to tensile stress normal to the plane of the crack).

4.2 STRUCTURAL PERFORMACE OF SPECIMENS

Fig. 6 shows the typical load-slip curve of one of the tested connections featuring a 72 mm grout diameter. When loading started, the connections showed an approximate linear response. Once the connection reached its ultimate load-carrying capacity, a brittle failure was observed, and the load-slip curves were dropped suddenly. The test results also showed that connections attained their maximum capacity within a maximum 6 mm slip. However, it should be noted that due to the presence of the inner layer of the CLT panel, the load did not drop to near zero after the failure in the wood outer layers, and a non-negligible residual load capacity was observed. The recorded residual load after the peak load for all of the studied specimens was within the range of 40 to 60% of

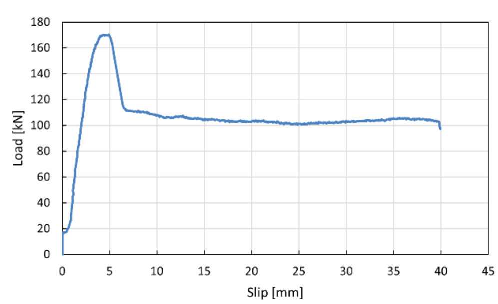

Fig. 6: typical load-slip curve for tested connector.

https://doi.org/10.52202/080513-0538

the corresponding maximum load. An increase in grout diameter resulted in a reduction of the slope of the descending portion of the curve, confirming the sensitivity of the plasticity of materials to their stressed volume.

Table 3 and Fig. 7 summarize the recorded ultimate load of the tested connections with grout-to-steel rod diameter ratios of 3 and 4. Values are normalized with the maximum load obtained by the specimen with a grout-to-steel rod diameter ratio of 2. According to these data, a direct correlation was observed between the ultimate load of the tested specimens and the grout diameter. This direct relationship was shown as nonlinear. A 49% and 75% increase in the ultimate load mean value was shown for grout-to-rod diameter ratio changes from 2 to 3 and 2 to 4, respectively. It should be mentioned that the distance from the nearest lamella edge to the connector hole can considerably affect the ultimate load of the shear connectors. If this distance is too small, such as less than 10 mm, since there are no glue edges among timber lamellas, the gap between the edges could be considered as a failure plane with no resistance against the shear load. Hence, increasing the grout-to-rod diameter ratio can lead to decreasing the ultimate load in some specific scenarios.

The variation in the load-carrying capacity among replicas of each connection configuration emanates from several factors, including material property variations, imperfections in the CLT panel, grain deviations, and finger joints. These factors should be carefully considered in future designs of this type of connection. The ratio of the 95-th percentile to the 5-th percentile ultimate load, based on a Log-Normal distribution for various grout-to-rod diameter ratios, is provided in Table 3. An indirect correlation was observed between the ratio of the 95-th percentile to the 5-th percentile ultimate load and the grout-to-rod diameter ratios of the connections. This is because a lower grout-to-rod diameter ratio increases the contribution of mode I fracture in the ultimate failure of the connection. This combination of fracture modes in connections with the lower grout-to-rod diameter ratios could lead to experiencing a greater variability in their ultimate load capacity values. Applying some modifications to connections, such as increasing the end distance or row spacing, or strengthening the CLT panel with screws, could help change the brittle failure of the connection into a ductile failure. These modifications may also decrease the variability in the ultimate load capacity of the tested hybrid connections.

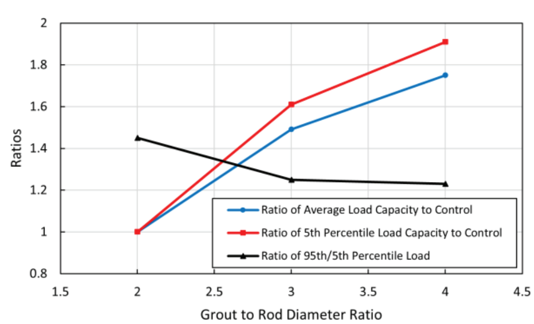

Fig. 7: Effect of grout to rod diameter ratio on the hybrid connection performance.

Table 3: Comparison of test results

Grout to rod dimeter ratio	**Ratio of average load capacity to control**	**Ratio of 5 Percentile load capacity to control (kN)**	**Ratio of 95th/5th percentile load capacity**
2	1	1	1.45
3	1.49	1.61	1.25
4	1.75	1.91	1.23

5– CONCLUSIONS

This study evaluated the structural performance of a novel high-performance hybrid connector. The connector was made of steel rod with strength class 8.8, a thick layer of epoxy-based grout with compressive strength of 103 MPa and 800 mm wide by 2000 mm long E1M5 105 mm thick CLT panel. Based on the test results of this study, the following main conclusions can be drawn:

- An increase in epoxy grout diameter results in a higher ultimate load. The ultimate load of connections with a grout-to-rod diameter ratio of 4 was 75 % higher than the tested connection with a grout-to-rod diameter ratio of 2.
- All specimens developed a brittle failure mode, with the outer CLT layers failing in shear when subjected to pull-out loading. In order to have a ductile failure mode, these findings suggest that the end distance of $4D_g$ should be increased, or the CLT panel should be strengthened using screws to increase the shear capacity of the outer layers.
- Although the connection failed suddenly after reaching its maximum load, the post-peak load did not drop to zero because of the inner CLT layer. The observed value of this residual load capacity was within the range of 40 to 60% of the

corresponding maximum load for tested specimens.

- An increase in the thickness of the epoxy grout results in a decrease in the stress concentration near the rod as the grout uniformizes the stress distribution transferred into the wood. In addition, the epoxy grout decreases the contribution of Mode I fraction and increases the contribution of Mode II fraction in failure of this hybrid connection.
- The variability of load-carrying capacity values between different replicas of the same configuration is due to several factors, including mechanical properties variations of materials, imperfections in the CLT panel, grain deviations, and finger joints. An indirect relationship between the ratio of the 95-th percentile to the 5-th percentile ultimate load and the grout-to-rod diameter ratios of the connectors was observed.

REFERENCES

[1] D. Safarik, J. Elbrecht, and W. Miranda. “State of tall timber 2022.” In: CTBUH Journal (2022), pp. 22–31.

[2] A. Alsamouly, and C. Loss. “High-Performance Steel-Timber Hybrid Rocking Shear Wall System for Mid-Rise to High-Rise Buildings: Preliminary Seismic Study.” In: International Conference on the Behaviour of Steel Structures in Seismic Areas (2024), pp. 818–829.

[3] Z. Chen, and M. Popovski. “Mechanics-based analytical models for balloon-type cross-laminated timber (CLT) shear walls under lateral loads.” In: Engineering Structures (2020), p. 109916.

[4] X. Wang, M. He, H. Dong, and Z. Li. “Numerical modeling strategies and parametric analyses of platform-type and balloon-type cross-laminated timber (CLT) shear walls under lateral loads.” In: Engineering Structures (2023), vol. 295, p. 116857.

[5] P. H. Longstaff, N. J. Armstrong, K. Perrin, W. M. Parker, and M. Hidek. “Building resilient communities: A preliminary framework for assessment.” In: Homeland Security Afairs (2010), vol. 6, pp 1–23.

[6] C. Todut, D. Dan, and V. Stoian. “Theoretical and experimental study on precast reinforced concrete wall panels subjected to shear force.” In: Engineering Structures (2014), vol. 80, pp. 323–338.

[7] D. Ugalde, J. L. Almazán, H. Santa María, and P. Guindos. “Seismic protection technologies for timber structures: a review.” In: European Journal of Wood and Wood Products (2019), vol. 77, pp. 173–194.

[8] A. Hashemi, P. Zarnani, R. Masoudnia, and P. Quenneville. “Experimental testing of rocking cross-laminated timber walls with resilient slip friction joints.” In: Journal of Structural Engineering (2018), vol. 144, no. 1, p. 04017180.

[9] S. Tesfamariam, K. Skandalos, and B. T. Teweldebrhan. “Design of Tall-Coupled-Wall Timber Building: Energy Dissipating Coupling Beams.” In: Engineering Applications of Artificial Intelligence (2024), vol. 136, p. 109055.

[10] B. T. Teweldebrhan, M. Popovski, J. B. McFadden, and S. Tesfamariam. “Development of ductility-related modification factor for CLT-coupled wall buildings with replaceable shear link coupling beams.” In: Canadian Journal of Civil Engineering (2022), vol. 50, no. 5, pp. 362–374.

[11] F. Sarti, A. Palermo, S. Pampanin, and J. Berman. “Determination of the seismic performance factors for post-tensioned rocking timber wall systems.” In: Earthquake Engineering & Structural Dynamics (2017), vol. 46, no. 2, pp. 181–200.

[12] T. Y. Yang, S. Lepine-Lacroix, J. R. Guerrero, J. B. McFadden, and M. A. Al-Janabi. “Seismic performance evaluation of innovative balloon-type CLT rocking shear walls.” In: Resilient Cities and Structures (2022), vol. 1, no. 1, pp. 44–52.

[13] FEMA P695: Quantification of Building Seismic Performance Factors, Washington, DC: FEMA, 2009.

[14] L. Pozza, B. Ferracuti, M. Massari, and M. Savoia. “Axial–Shear interaction on CLT hold-down connections–Experimental investigation.” In: Engineering Structures (2018), vol. 160, pp. 95–110.

[15] F. Benedetti, V. Rosales, A. Opazo-Vega, J. Norambuena-Contreras, and A. Jara-Cisterna. “Experimental and numerical evaluation of hold-down connections on radiata pine Cross-Laminated-Timber shear walls: a case study in Chile.” In: European Journal of Wood and Wood Products (2019), vol. 77, pp. 79–92.

[16] X. Zhang, M. Popovski, and T. Tannert. “High-capacity hold-down for mass-timber buildings.” In:

https://doi.org/10.52202/080513-0538

Construction and Building Materials (2018), vol. 164, pp. 688–703.

[17] N. Chan, A. Hashemi, P. Zarnani, and P. Quenneville. “Pinching-free connector for timber structures.” In: Journal of Structural Engineering (2021), vol. 147, no. 5, p. 04021036.

[18] T. Tannert, and C. Loss. “Contemporary and novel hold-down solutions for mass timber shear walls.” In: Buildings (2022), vol. 12, no. 2, p. 202.

[19] M. Shekarchi, M. Shakiba, M. Yekrangnia, and T. Tannert. “Performance of glued-in rod timber joints under seawater and UV exposure cycles.” In: Construction and Building Materials (2022), vol. 322, p. 126418.

[20] S. Tolotti, T. Tannert, and C. Loss. “Connectors for Hybrid Cross-Laminated Timber Prefabricated Buildings.” In: Proceedings of the 16th World Conference on Timber Engineering (2021), Santiago, Chile.

[21] S. Shulman, and C. Loss. “High-performance grout-reinforced shear connectors for hybrid steel-cross-laminated timber building systems: Experimental study.” In: Journal of Building Engineering (2023), vol. 67, p. 106014.

[22] B. Feujofack, and C. Loss, “Predicting the structural behaviour and failure mechanism of hybrid steel-grout connectors for cross-laminated timber panels using high-fidelity finite-elements modelling.” In: Construction and Building Materials (2024), vol. 447, p. 138121.

[23] Hilti, Inc., Hilti Epoxy Grout (EG) Product Data Sheet, Hilti, Inc., 2011.

[24] ASTM International, ASTM D695-18: Standard Test Method for Compressive Properties of Rigid Plastics, West Conshohocken, PA: ASTM International, 2018.

[25] ASTM International, ASTM C307-18: Standard Test Method for Tensile Strength of Chemical-Resistant Mortar, Grouts, and Monolithic Surfacings, West Conshohocken, PA: ASTM International, 2018.

[26] ASTM International, ASTM E8/E8M-22: Standard Test Methods for Tension Testing of Metallic Materials, West Conshohocken, PA: ASTM International, 2022.

[27] ASTM International, ASTM D5764-23a: Standard Test Method for Evaluating Dowel-Bearing Strength of Wood and Wood-Based Products, West Conshohocken, PA: ASTM International, 2023.