High Performance Glued-in Rod Connections in Cross-Laminated Timber (CLT) Structures

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ABSTRACT

Glued-in rods are efficient and high-capacity connections for achieving high-strength joints in new timber structures and reinforcing existing timber buildings. With the emergence of cross-laminated timber (CLT) and the construction of high-rise buildings, there is a potential for glued-in rods to be adopted in CLT construction. To achieve this goal, the differences between the CLT and the previous engineered wood products and their effect on the strength and the seismic performance of the glued-in rod connections should be investigated. Therefore, this paper investigates the experimental performance of CLT connections with multiple glued-in rods. For this purpose, 42 full-scale tests were conducted, where the specimens were tested under monotonic and cyclic loading by varying embedment lengths of rods and rod to grain angle. The rods were embedded in the parallel to the grain laminations, perpendicular to the grain laminations, and on the boundary of two cross-wised layers. The monotonic tests showed that glued-in rods embedded on the edge of the CLT panel at different angles and locations could provide high-strength connections. Rod to grain angle affected the failure mode and the force vs. displacement curve of the connections. Moreover, the cyclic loadings illustrated that glued-in rod connections keep their elastic properties and initial stiffness until failure. The outcomes of this research demonstrated that glued-in rod connections could offer a reliable and robust connection for CLT construction in seismic active regions.

1 INTRODUCTION

Wood is renewable and sustainable and has the lowest carbon dioxide emissions and energy consumption among many building materials. As a result, it is among the greenest available building materials. The commercial introduction of the novel CLT, which is capable of supporting loads both in-plane and out-ofplane, is one of the reasons for the revival of timber construction. CLT is a quasi-rigid composite, panel-shaped engineered wood product that is typically made of an uneven number of layers (typically three, five, or seven layers), each made of boards placed side by side and arranged cross-wised to other laminations at an angle of 90° (Brandner et al. 2016).

Wood elements behave elastically, so the ductility and energy dissipation behaviour for timber structures typically depend on the connections. Therefore, a critical step in designing a structural timber system is configuring the connections (Falk 2009). Designing ductile connections to disperse energy has a number of advantages, including the potential to be included in earthquake analysis and improve structural resilience (Ottenhaus et al. 2021). Different techniques, such as adhesive bonding, dowel-type fasteners, or direct contact, can be used to connect timber elements (Schober and Tannert 2016). Mechanical fasteners are the most popular connecting technique, and they are extensively described in modern timber design standards such as EN 1995 (2004). As an alternative, adhesive bonding offers an effective solution when combined with proper design, appropriate standards, and rigorous quality control. Due to the possibility of combining joining techniques to create "hybrid" connections, the aforementioned classification of connections is not exclusive (Fricke and Vallée 2021).

Glued-in rods have been utilized successfully for about 30 years for both new buildings and in-situ strengthening and restoration of structures (Serrano 2001). Glued-in rods create rigid, high-capacity connections and are considered a hybrid connection engaging timber, rod, and adhesive. When compared to connections with mechanical dowel fasteners, timber connections with glued-in rods frequently achieve superior capacity and rigidity (Del Senno et al. 2004). As a result, research on this type of connection is becoming more and more prominent, as shown by a steady rise in publications starting in the late 1990s (Madsen. 1998). Phenol-resorcinol, epoxy-based, and polyurethane-based adhesives are frequently utilized for glued-in rod connections (Chans et al. 2010).

Early research on timber connections with glued-in rods began with a single rod under axial tension because it enables a clear separation of characteristics, such as rod diameter d_r, embedment length l_a, and edge distance e, with respect to their influence on the mechanical performance of the connection. Several distinct failure modes were identified based on these preliminary tests: (a) rod tension failure, which could be brittle or ductile depending on the material of the rod; (b) cohesive failure of the adhesive, which is related to its bonding strength; (c) localized timber shear failure near the bond, which involves the timber strength; and (d) failure of the timber member, which is largely dependent on the type of wood and geometrical properties of the connection such as edge distance (Tlustochowicz et al. 2011). In timber connection design, ductile failure of the rod is the preferable failure mechanism, especially when considering steel rods that ensure ductile failure modes. By excluding all of the potential brittle failure mechanisms using the right techniques, such as by oversizing embedment lengths, the mechanical properties of steel rods allow for a precise estimate of connection capacity (Thamboo et al. 2022). However, since glued-in rod connections are designed to resist heavy loads and increase the durability of the constructions, generally, these connections consist of multiple glued-in rods. On the other hand, multiple rods add to the complexity of glued-in rods and cause additional effects, such as the mutual interaction of stress fields produced by individual rods (Gonzalez et al. 2016).

Glued-in rod connections are very efficient when designed as capacity protected members for seismic applications. Therefore, the main goal of this project is to experimentally investigate the behaviour of glued-in rod connections with multiple threaded steel rods embedded in the parallel, perpendicular, and on the boundary of two cross-wised layers in CLT and tested in axial monotonic and cyclic tests. The cyclic tests will present the effect of loading on the stiffness and strength of the glued-in rod connections to be designed in high seismic regions.

2 GLUED-IN RODS FULL SCALE TEST

CLT panels manufactured of Radiata pine laminations with MSG8 grade for longitudinal laminations and MSG6 for transverse laminations bonded using one-component polyurethane adhesive on the surface without edge bond were utilized for the experimental tests. Galvanised threaded rods with 24 mm diameter, and 8.8 grade were used for the steel rods. Prior experiences have demonstrated that the interaction between the threaded rod and the adhesive is primarily mechanical and that chemical treatment of the rod's surface is not a common technical practice in the industry. Therefore, the surface of the rods was only cleaned using a wire brush prior to gluing.

The rods were embedded at the parallel, perpendicular, and on the boundary of two cross-wised layers of CLT on the panel's edge. For this purpose, 5-layer CLT panels were utilized for the glued-in rods placed in the perpendicular laminations and rods embedded on the boundary of two cross-wised layers, whilst 7-layer CLT panels were used for the rods embedded in the parallel to grain direction rods, resulting in the outer layer of the CLT specimens being in the longitudinal direction for all the testing specimens. The top view and cross-sectional view of the CLT specimens are illustrated in Figure 1.

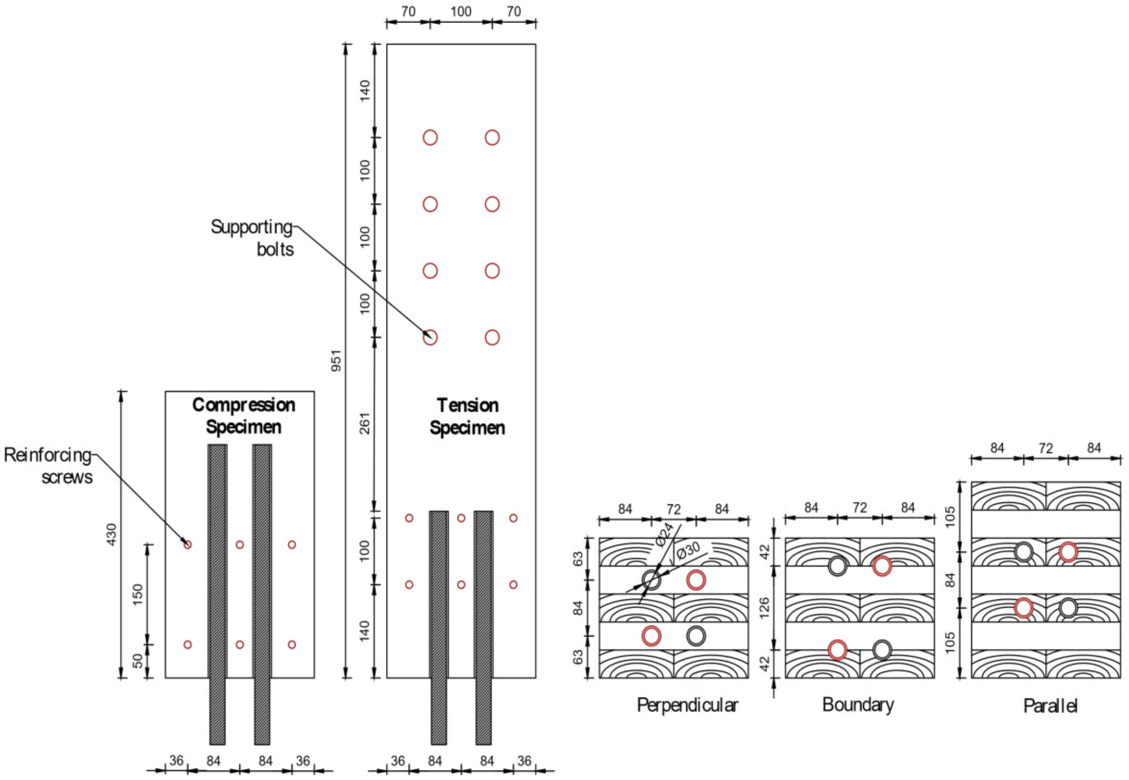


Figure 1. Top view and cross-sectional view of specimens; red holes and rods on the cross sections represent the two diagonally tested rods.

In order to ensure a 3 mm adhesive thickness, holes with 30 mm diameter at two embedment lengths (250 and 350 mm) were drilled in parallel, perpendicular, and on the boundary of two cross-wised layers of the CLT specimens. The holes had a rod distance of 72 mm and an edge distance of 84 mm. Additionally, O-rings were used to retain the rods in the center of the holes throughout the adhesive injection and curing. The 8 mm holes for the injection of the adhesive were drilled on the surface of CLT specimens along the rod's length near the beginning and end of each rod. The rods were secured in the holes using East 221 epoxy adhesive, and during the adhesive injection and curing time, the CLT specimens containing the steel rods were kept horizontal. Prior to the injection of the epoxy adhesive, silicone putty was employed to stop adhesive leakage from the specimen's cross-section. For specimens containing rods with 250 mm embedment length, two knife plates were put into the CLT's pre-cut slots and supported by eight M20 bolts served as the fixation method for the CLT specimens during the tests. At the testing end, a pulling steel member was designed and used to pull out two diagonal glued rods simultaneously. The testing specimen's disassembled components are shown in Figure 2.

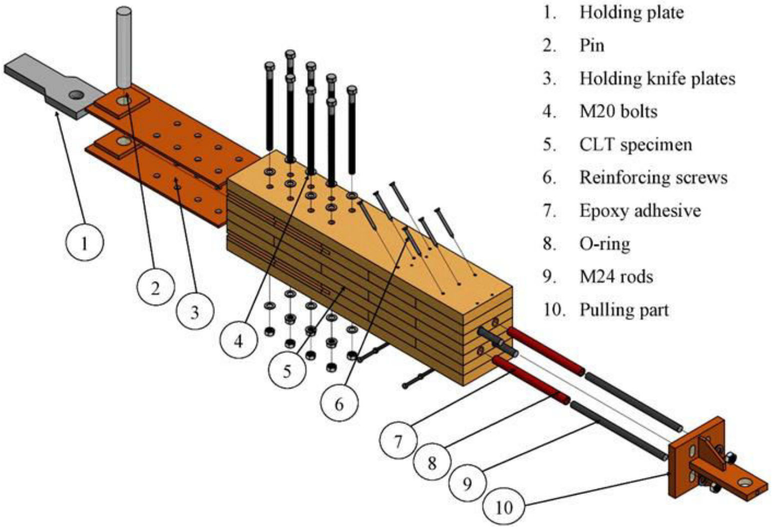


Figure 2. CLT specimen containing rods parallel to the grain with 350 mm embedment length.

2.1 Loading set-up and protocol

The strength of two diagonal rods was examined for the experimental tests. Specimens containing rods with an embedment length of 250 mm were tested in tension, whereas specimens containing rods with an embedment length of 350 mm were tested in compression. For the monotonic test, glued-in rods were loaded with a 1000 kN Avery machine at a constant displacement rate of 2 mm/min throughout the loading operation and conducted in four repetitions. Two LVDTs were used to measure the average displacement/slip of the rods. For cyclic loading, a 500 kN MTS machine was used, and the tests were conducted with three repetitions. Figure 3 illustrates the test setup for the cyclic loading on the glued-in rods.

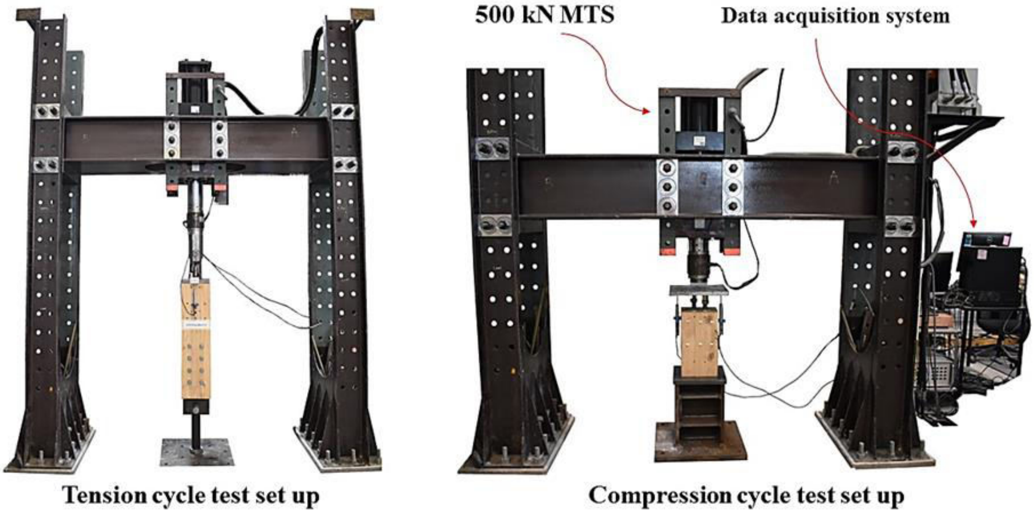


Figure 3. Cyclic loading test-set up component of glued-in rods.

For cyclic tests, a loading technique was adopted and modified from BS EN 12512:2001 (European Committee for Standardization (CEN), EN 12512:2001). From the monotonic loading, the force reference for the cyclic loading was derived. Due to the stiffness of the glued-in rod connections and failure occurring within 1-2 mm displacement of the rods, the loading was carried out in a force-control manner with a 5 kN/s loading rate. For the cyclic loading, CLT specimens containing rods with 250 mm embedment length were tested in tension only cycles, while specimens containing rods with 350 mm embedment length were tested in compression only cycles. In the first cycle, the specimens were subjected to a tension/compression load to impose 25% of the load. The specimens were then unloaded to zero force. In the second cycle, the first cycle was repeated, but this time 50% of the force was applied. Three cycles are performed at 75% of the maximal load in the third round. The load was then increased until failure occurred for the specimens with 250 mm of embedment length, and another three cycles at the maximum load were established for the specimens with 350 mm of embedment length. Glued-in rods with embedment lengths of 250 mm were tested until failure at their last cycle, but specimens with embedment lengths of 350 mm did not show any failure at the tested range by the machine capacity. Figure 4 provides the loading cycles of specimens with 250 and 350 mm embedment lengths.

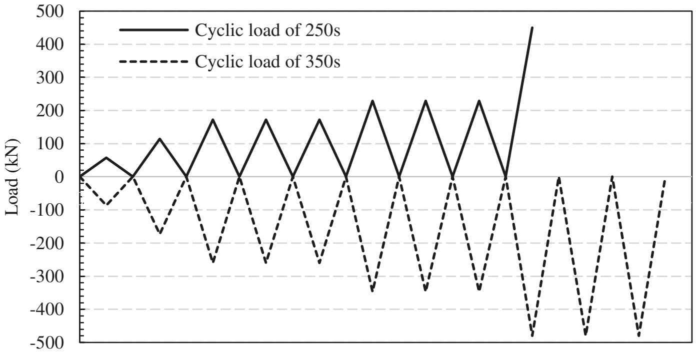


Figure 4. Cyclic loading protocol.

3 RESULTS AND DISCUSSIONS

3.1 Monotonic test results

In glued-in rod connections, the steel rods are designed to yield, resulting in a ductile failure mechanism. Although, this research was designed so that the steel rod's strength was greater than that of the other connection components to get the tolerance threshold of brittle failure and other types of failure of the connection components by using high grade threaded rods. Given the properties of CLT, the specimen's specifications, such as the lamination dimension, grade, bonding, etc., have an impact on the specimen's failure mode. For instance, weak finger joints, knots, and unbonded edges can act as the stress concentration points and cause failure and weaken the connection. Therefore, the failures observed in this study were obtained under the influence of the characteristics of the members and the geometric properties of the designed connection.

The force-displacement curves presented a nearly linear initial relationship between the ultimate load F_u and embedment length after which there is an increasingly nonlinear reaction until the ultimate load F_u. The average pull-out strength of glued-in rods embedded perpendicular, parallel, and on the boundary of two cross-wised layers of the CLT, with 250 mm embedment length, was 343 (CoV 0.03), 333 (CoV 0.06), and 305 kN (CoV 0.06), respectively. The shorter distance between the rods and the CLT surface may be the cause of the reduced pull-out strength of the rods embedded on the boundary of two cross-wised layers of CLT. By stress distribution around the rod's circumference along the length, and stress reaching the surface of the CLT, premature fracture eventually forms and weakens the connection's strength. Figure 5 shows the typical pull-out strength of glued-in rods with 250 mm embedment length. The glued-in rods with 350 mm embedment lengths at the perpendicular, parallel, and boundary of two cross-wised layers of CLT had an average compression strength of 506 kN (CoV 0.02), 493 kN (CoV 0.04), and 482 kN (CoV 0.04), respectively. Similar to rods with 250 mm embedment length, for rods embedded on the boundary of two cross-wised layers, the connection strength decreased due to shorter surface distance and premature crack formation. Figure 5 displays the average compression strength of rods with 350 mm embedment length.

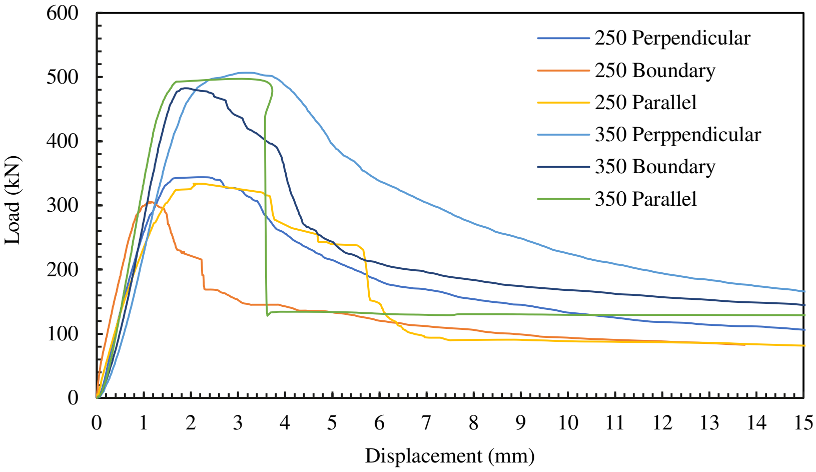


Figure 5. Average of strength for glued-in rods with 250- and 350-mm embedment lengths.

For rods embedded perpendicular to the grain, a variety of probable failure types have been documented in the literature. Separation of the entire transverse layer or rolling shear is among the most frequent failure types for rods embedded perpendicular to the grain (Ayansola et al. 2022; Azinović et al. 2018). Because timber has lower tangential and radial strength, rolling shear failure in the transverse layers was the observed failure mode for the rods embedded perpendicular to the grain, as shown in Figure 6a. The failure in this transverse layer owing to rolling shear can highlight the need for reinforcement of the CLT when glued-in rods are used as a connection method. To prevent the creation and expansion of the rolling shear failure, despite extending the edge distance of the rods, rolling shear still appears to be unavoidable and is unaffected by the glued-in rod connection's geometrical properties. The force-displacement curve was smooth as a result of this progressive rolling shear failure. The stress did not, however, reach the CLT's surface when the rods were inserted perpendicular to the grain. Along the length of the rod, the epoxy adhesive was also damaged and failed. As shown in Figure 6b, the parallel to the grain rods were pulled out in the form of plugs that held parallel lamination segments. Therefore, block shear of wood caused the connections to fail and resulted in a sharp drop in the connection's strength, whether it occurred near the wood-adhesive contact or by removing a block of wood. For the rods embedded parallel to the grain, no damage was observed on the surface and edge CLT specimens. The non-edge bonded laminations could also influence the volume of plugged-out timber near the rods. Rods inserted parallel to the grain have been reported to experience a similar plug-out failure in the literature (Muciaccia 2019).

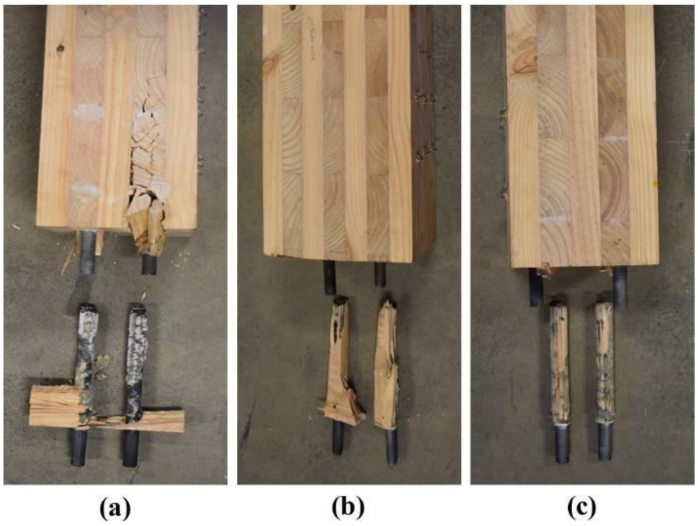


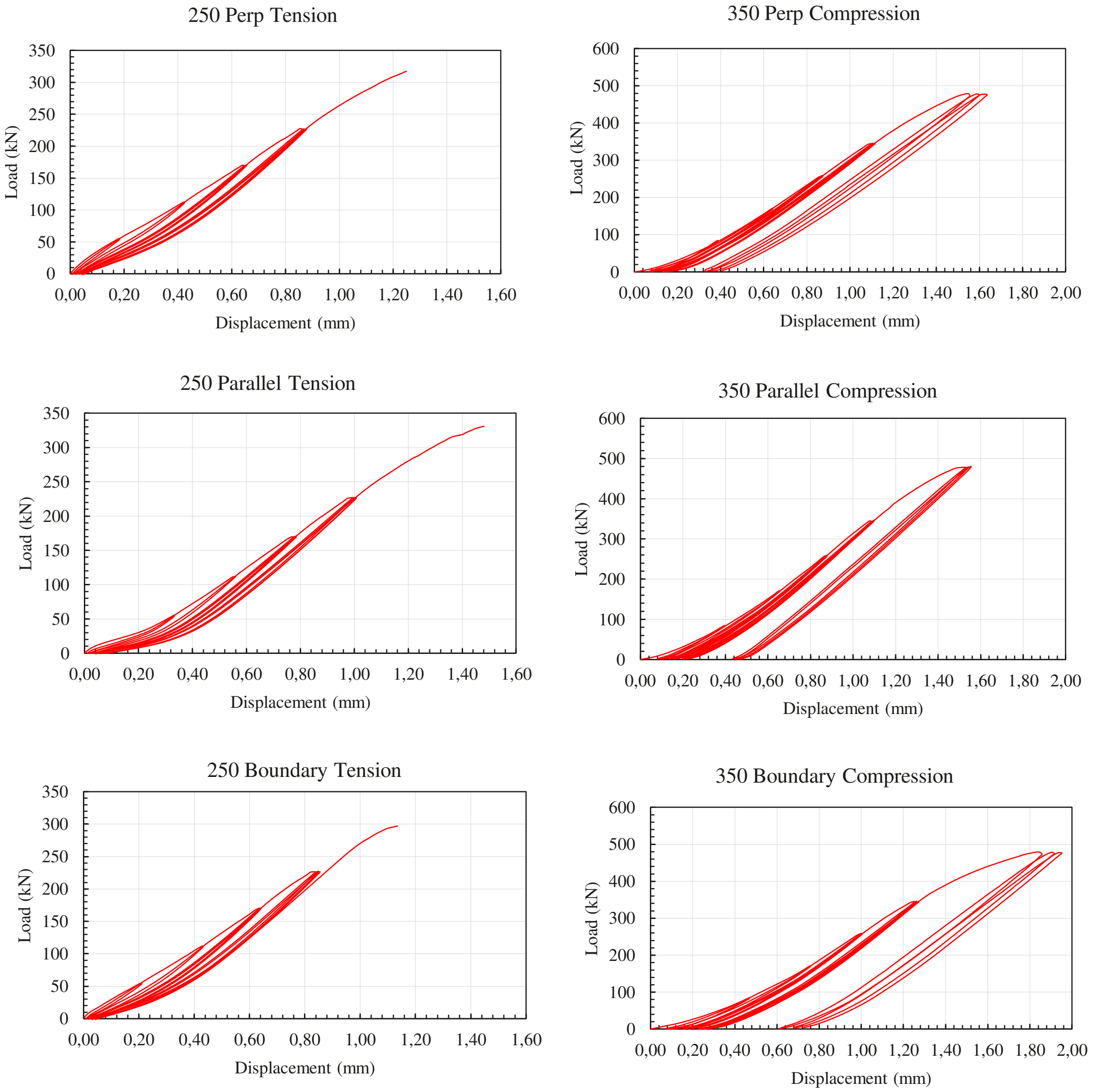
Figure 6. Failure mode on the edge of CLT specimens under tension test, (a) rods perpendicular to the grain, (b) rods parallel to the grain, (c) rods embedded on the boundary of two cross-wised layers.

As presented in Figure 6c, the rods embedded on the boundary of two cross-wised layers were completely pulled out in the shape of a cylinder while holding the epoxy with wood fibers remained on the surface. As shown in Figure 7, the failure of rods embedded on the boundary of two cross-wised layers of CLT reached the specimen's surfaces for both tension and compression tests, demonstrating the impact of the rod's close distance to the CLT surface. This issue gets worse when two lengthwise laminations that are not edge-bonded located near the length of the rod. The edges of the CLT specimens did not demonstrate signs of damage in relashion with the fracture propagating to the CLT's surface. Due to the limited edge distance, this crack formation has also been observed in glulam specimens with glued-in rods, reaching the specimens' surface along the anchorage (Rossignon and Espion 2008).

Figure 7. Surface crack of specimens containing rods on the boundary of two cross-wised layers.

3.2 Cyclic test results

Figure 8 provides an overview of the hysteresis response of the cyclic tests conducted on the glued-in rods embedded in CLT. All curves for the specimens with 250 mm embedment length displayed a nearly linear trend at cycles till failure. Glued-in rods with 250 mm embedment length that were inserted perpendicular, parallel, and on the boundary of two cross-wised layers failed at 331, 317, and 297 kN, respectively. The connections for the rods with 350 mm embedment length demonstrated stiff and elastic performance, but there was a slight plastic deformation at each cycle in the final 3 cycles of the tests. Regarding the machine's capacity, CLT specimens with 250 mm embedment length were tested until failure after the last cycles, while CLT specimens with 350 mm embedment length did not fail in cyclic tests. The specimens with 250 embedment length showed a similar failure mode to monotonic tests. Moreover, CLT specimens containing rods with 350 mm embedment length showed higher displacements at the cyclic loadings which illustrate that by increasing the embedment length of the rods their energy absorption increases.


250 Perp Tension

350 Perp Compression

250 Parallel Tension

350 Parallel Compression

250 Boundary Tension

350 Boundary Compression

Figure 8. Hysteresis loops of glued-in rods under cyclic loading.

As can be seen in the figure, the specimens demonstrated a nearly elastic performance with is a desired stiffness when these connections are designed as capacity-protected members. This means a seismic fuse or similar (e.g. energy dissipation device) can be connected to the CLT using these connections so that the inelasticity (e.g. ductility) is localised in the fuses and the glued-in-rod connections remain elastic. By capacity design, it is determined which elements of a structural system will be allowed to yield (ductile components) and which elements will stay elastic (brittle components). Therefore, glued-in rods illustrate the potential of using these connections in capacity design of the structure in which yielding members can be designed precisely.

CONCLUSIONS

This article investigated the mechanical behaviour of glued-in rods embedded in CLT under monotonic and cyclic loadings. The experimental tests found that the failure mode and failure load of rods are significantly different according to their rod-to-grain angle. The maximum strength was achieved with rolling shear failure in the transverse layers and crushed epoxy adhesive with a smooth force vs. displacement curve with glued-in rods embedded perpendicular to the grain. It is advised to embed rods perpendicular to the grain if employing glued-in rods in CLT connections. In contrast, rods embedded parallel to the grain showed lower strength and sharp strength losses because of the plug-out failure mode. Due to their closer distance to the surface of CLT, rods inserted on the boundary of two cross-wised layers exhibited the lowest strength, and rods retaining epoxy adhesive were pulled out in a cylindrical shape. The outcomes of the monotonic tests showed that glued-in rod connections could only behave ductile and fail as a result of ductility under the proper design circumstances. The cyclic loadings also showed that glued-in rod connections retain their elastic properties until failure. The results of this investigation demonstrated that this connection method could offer a reliable connection for CLT construction especially in capacity design of the buildings. This implies that the CLT can be connected to a seismic fuse such as an energy dissipation devices using glued-in rod connections, allowing the such as ductility to be localised in the fuses while the glued-in-rod connections remain elastic. However, it must be considered that the experimental study only investigated a certain type of timber, adhesive, and rod type. Future research is required to supplement the expanded set of factors, such as employing various glued-in rod connection details (rod sizes, adhesive types, spacings, and edge distance). To better understand the behaviour of glued-in rod connections, a wide range of test data needs to be created with various types of failure modes.

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References

Ayansola, G. S., Tannert, T., & Vallee, T. (2022). Experimental investigations of glued-in rod connections in CLT. Construction and Building Materials, 324, 126680.Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., & Thiel, A. (2016). Cross laminated timber (CLT): overview and development. European Journal of Wood and Wood Products, 74(3), 331-351.

Azinović, B., Serrano, E., Kramar, M., & Pazlar, T. (2018). Experimental investigation of the axial strength of glued-in rods in cross laminated timber. Materials and Structures, 51(6), 1-16.

Chans, D. O., Cimadevila, J. E., & Gutiérrez, E. M. (2010). Model for predicting the axial strength of joints made with glued-in rods in sawn timber. Construction and Building Materials, 24(9), 1773-1778.

CEN. EN-1995-1 European Committee for Standardization, Brussels, Belgium (2004).

Del Senno, M., Piazza, M., & Tomasi, R. (2004). Axial glued-in steel timber joints—experimental and numerical analysis. Holz als Roh-und Werkstoff, 62(2), 137-146.

European Committee for Standardization (CEN), EN 12512:2001, Timber Structures-Test Methods-Cycling Testing of Joints Made with Mechanical Fasteners, CEN, Brusells, 2001.

Falk, R. H. (2009). Wood as a sustainable building material. Forest products journal. Vol. 59, no. 9 (Sept. 2009): pages 6-12., 59(9), 6-12.

Fricke, H., & Vallée, T. (2021). Hybrid joining techniques. In Advanced Joining Processes (pp. 353-381). Elsevier.

Gonzalez, E., Avez, C., & Tannert, T. (2016). Timber joints with multiple glued-in steel rods. The Journal of Adhesion, 92(7-9), 635-651.

Madsen, B. (1998). Reliable timber connections. Progress in Structural Engineering and Materials, 1(3), 245-252.

Muciaccia, G. (2019). An experimental approach to determine pull-out strength of single and multiple axially loaded steel rods bonded in glulam parallel to the grain. Wood Material Science & Engineering, 14(2), 88-98.

Ottenhaus, L. M., Jockwer, R., van Drimmelen, D., & Crews, K. (2021). Designing timber connections for ductility–A review and discussion. Construction and Building Materials, 304, 124621.

Rossignon, A., & Espion, B. (2008). Experimental assessment of the pull-out strength of single rods bonded in glulam parallel to the grain. Holz als Roh-und Werkstoff, 66(6), 419-432.

Schober, K. U., & Tannert, T. (2016). Hybrid connections for timber structures. European Journal of Wood and Wood Products, 74(3), 369-377.

Serrano, E. (2001). Glued-in rods for timber structures—a 3D model and finite element parameter studies. International journal of adhesion and adhesives, 21(2), 115-127.

Thamboo, J., Navaratnam, S., & Ponnampalam, T. (2022). Pull-out resistance of glued in rod connection in timber: Reliability analyses using an experimental database. Construction and Building Materials, 344, 128291.

Tlustochowicz, G., Serrano, E., & Steiger, R. (2011). State-of-the-art review on timber connections with glued-in steel rods. Materials and structures, 44(5), 997-1020.