AN INVESTIGATION OF CROSS LAMINATED TIMBER CONNECTIONS WITH MULTIPLE GLUED-IN RODS

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Keywords: *cross laminated timber, glued-in rods, timber connections, numerical modelling*

ABSTRACT

Wood has been used as a construction material for hundreds of years. New engineered wood products such as Cross-Laminated Timber (CLT) and new connections are investigated over time as a result of resource constraints and rising market demands. Glued-in rods are one of the frequently used connections in new timber construction, as well as reinforcing existing timber buildings. Although numerous studies have investigated these connections, experimental data concerning tests on the glued-in rods embedded in CLT are still lacking, and most of the investigations are conducted on solid timber, glulam, and Laminated Veneer Lumber (LVL). Generally, existing studies have tested this connection as a single rod, while in practice, they are used as a group. Moreover, numerical modelling investigations on the glued-in rods are scarce, especially when they are embedded in CLT. Therefore, a comprehensive study, including experimental tests and numerical modelling was conducted on the axial strength of CLT connections consisting of glued-in rods embedded on the edge of the CLT. In this investigation, the effect of the rod diameter, embedment length, and rods placement on the edge of the CLT was studied. The findings demonstrated that the pull-out strength increases with increasing rod diameter and embedment lengths, with rods embedded perpendicular to the grain exhibiting the highest increase and rods embedded in the middle layers of the CLT exhibiting the lowest increase. Finally, the compatibility of the design equation proposed by the New Zealand Timber Design Guide (NZ TDG) on the average pull-out strength calculation of glued-in rods embedded on the edge of CLT is investigated. According to the findings of this research, NZ TDG can be used conservatively in predicting the average pull-out strength of glued-in rods embedded on the edge of CLT.

1. INTRODUCTION

Wood has been used as a building material since ancient times and is getting more popular due to its sustainability, lightweight, and attractive appearance. To overcome the limitations of traditional construction methods, new engineered wood products such as CLT, glulam, and LVL as well as new connection techniques have been introduced (1). In timber structures, connections are critical design factors, and their strength determines the structure›s strength, and connection stiffness greatly influences the structure›s displacement behaviour (2). Various types of connections in timber construction are used, differing in principles of load transfer and strength.

Glued-in rods are one of the frequently used connections in timber structures due to their high strength and stiffness, which can be used in reinforcing existing timber buildings and constructing new timber structures (3). Being completely embedded in timber, glued-in rods provide good fire, corrosion, and weather resistance and have been widely used in column-base, beam-column, the knee of portal frames, and in connecting timber to other structural materials such as steel or concrete (4). Glued-in rods transfer load to the timber through the fully cured adhesive along the rod›s length, which is a different force-transferring mechanism compared to other types of timber connections, such as bolted connections and screws (5). Generally, glued-in rod connections are used to withstand large tensile, shear, or bending forces;

therefore, this connection mostly consists of multiple rods (6). Moreover, glued-in rods give the opportunity to prepare the connection in the factory resulting in precise connection details. They are considered a hybrid connection, and their performance is influenced by their constituents, including timber (density, moisture content, etc.), rod type (steel threaded rods or rebars, glass, carbon, and basalt-fibre reinforced polymers, or hardwood rods), and adhesive type (7).

Glued-in rods are mainly used with solid wood, glulam, and to a limited degree with LVL members. With the introduction of CLT, there is a potential for glued-in rods to be used in CLT construction. For this purpose, the performance of glued-in rods embedded in CLT needs to be investigated. Therefore, this study focuses on the experimental tests and numerical modelling of CLT joints with multiple glued-in rods. The effect of rod diameter, embedment length, and rod to grain angle on the axial strength and failure mode of connections were investigated.

2. MATERIALS AND METHODS

2.1 Material properties

For the experimental tests, CLT panels made of New Zealand grown Radiata pine with MSG8 grade for longitudinal layers and MSG6 for transverse layers bonded with one-component polyurethane adhesive on the surface and without edge bond were used. The threaded rods with a 24 mm diameter were supplied as galvanized 8.8 grade. Chemical treatment of the rod's surface is not a common technical practice in the industry, and previous experiences have shown that the interaction between the threaded rod and the adhesive is chiefly mechanical (8). Therefore, the surface of the rods was not treated with any chemical material before gluing and cleaned by a wire brush and blow gun to remove any dust and dirt.

The rods were placed on the edge of the CLT panel in the parallel, perpendicular, and middle of two cross-wised layers of CLT. For the threaded rods embedded in the perpendicular and middle layer, 5-layer CLT panels were used, while for the rods embedded in the parallel to the grain direction, 7-layer CLT panels were used so that the outer layer of the CLT specimens was in the longitudinal direction. The East 221 epoxy adhesive was used to hold the rods in the timber. It was injected using adhesive bleeding holes drilled on the length of each rod. Silicone putty was used to prevent adhesion leakage while injecting the epoxy adhesive. The typical properties of the applied epoxy adhesive are provided in Table 1.

Table 1. Typical cured properties of the applied epoxy adhesive.

	Typical cured properties			
Epoxy	Tensile strength (MPa)	Compressive strength (MPa)	Flexural strength (MPa)	Maximum operating temp (°C)
	200-300	300-400	350-450	65-75

Holes with 30 mm diameter and two embedment lengths (250 and 350 mm) were drilled in the parallel, perpendicular, and middle of two cross-wised layers of the CLT specimens guaranteeing an adhesive thickness of 3 mm. The holes had 84 mm edge distance and 72 mm rod distance. The cross-sectional dimensions of the different configurations are provided in Figure 1. Moreover, O-rings were used to keep the rods in the middle of the holes during adhesive injection and curing. Finally, the epoxy adhesive was injected while the specimens and the rods were kept horizontal.

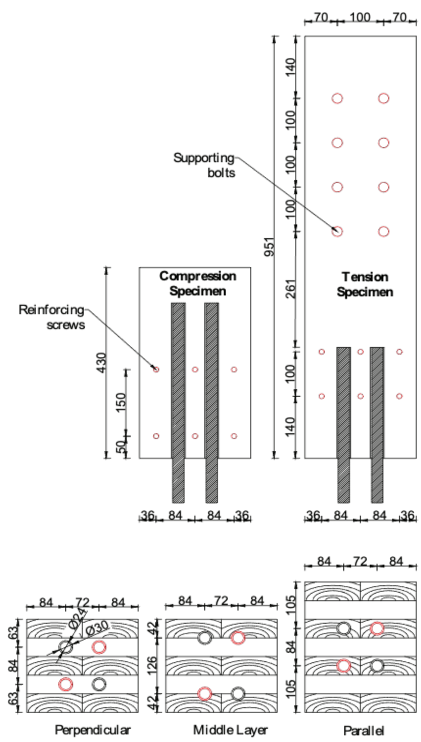

Figure 1. Dimensions of experimental test specimens. Rods in red on the cross section represent two diagonal tested rods in each test.

To prevet the rolling shear in the transverse layers during the test, the CLT specimens were reinforced using twelve 11×150 mm fully threaded high strength steel wood screws. The screws were inserted at 45˚ from the face of the exterior lamination and were exposed to tension forces. After epoxy injection, the specimens were kept in the conditioning room (65%±5 RH and 24±2 ˚C) for at least three weeks so that the epoxy adhesive was completely cured before testing. To hold the CLT at the supporting end during the tension tests, slots were cut at the supporting end of the specimens to be fixed and held using two designed knife plates and eight M20 bolts. A steel pulling fixture was also designed and manufactured to pull out two diagonal rods simultaneously. The exploded drawing of a 5-layer CLT specimen with rods perpendicular to the grain with 250 mm embedment length is shown in Figure 2.

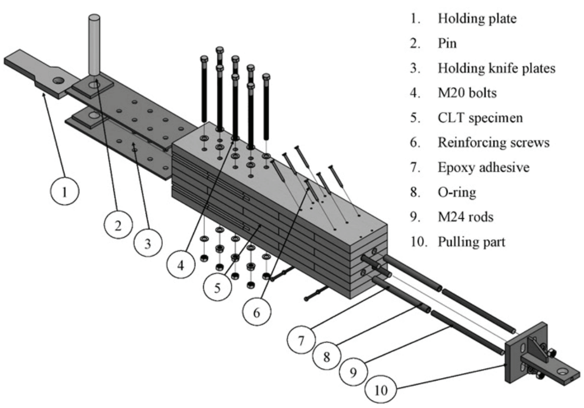

Figure 2. Exploded-view of CLT specimen containing rods with 250 mm embedment length in the parallel to the grain laminations.

2.2 Test set-up

Two diagonal rods were tested for each experimental test; rods with embedment lengths of 250 mm were tested in tension, while rods with embedment lengths of 350 mm were tested in compression. The pull-out and compression strength of rods were measured using a 1000 kN Avery machine under monotonic loading. To measure the rod's relative displacement to the timber during the tests, two LVDTs were utilized, and the tests were conducted with a displacement control scheme with a rate of 2 mm/min. Four identical specimens were tested for each rod placement (parallel, perpendicular, and middle layer) and embedment length (250 and 350 mm). The test set-up of the glued-in rods subjected to tension test is shown in Figure 3.

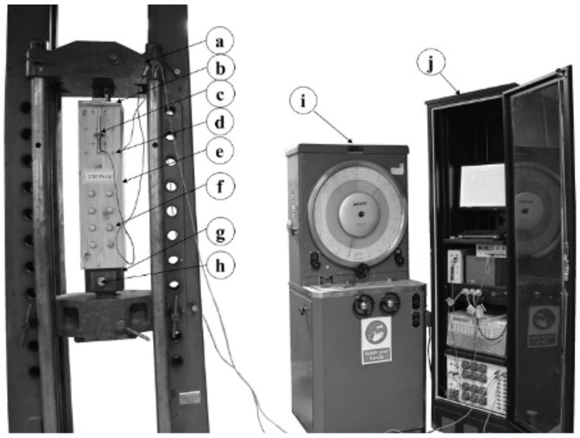

Figure 3. The rod pull-out test set-up: (a) 1000 kN Avery machine, (b) steel pulling part, (c) LVDT, (d) reinforcement screws, (e) CLT specimen, (f) M20 bolts, (g) supporting knife plates, (h) pin, (i) analogue load indicator, (j) data acquisition system.

For the specimens with 350 mm embedment length tested in compression, the specimens were cut to 430 mm lengths, and at the bottom of the specimen, wood at the continuation of the length of the rods was removed using a drill. This eliminated timber along the rod's length and removed the extra compression strength of timber during compression tests, as shown in Figure 4.

Figure 4. bottom view of CLT specimens containing M24 rods with 350mm embedment length in the parallel to the grain lamination tested in compression.

2.3 Numerical modelling

Numerical modelling was performed using Abaqus software (9) to investigate the effect of the rod diameter and embedment length on the pull-out strength of the glued-in rods embedded in the parallel, perpendicular, as well as middle of two cross-wised layers. For the modelling, the components of the glued-in rod connection, including timber, epoxy, and steel rod were defined using linear elastic properties. For this purpose, a set of experimental tests was performed on the epoxy adhesive to obtain its mechanical properties and the properties of the steel rod were obtained from the material data sheet provided by the supplier. The orthotropic mechanical properties of the Radiata pine timber are obtained from a study conducted by Van Le et al. (10), as presented in Table 2.

Table 2. Mechanical properties of steel, epoxy, and timber.

Member	Properties	
Steel	E= 213000 MPa	$V = 0.3$
Epoxy	E= 2193 MPa	$V = 0.3$
Timber	E_1=10400 MPa; E_2=E_3=347 MPa; G_{12}=G_{13}=692 MPa; G_{23}=69 MPa	$V_{12} = V_{13} = V_{23} = 0.2$

E: elastic modulus, V: Poisson's ratio; G: shear moduli.

Moreover, for the interaction along the rods, the cohesive zone method is used, and the interaction properties of rods regarding the embedment location are provided in Table 3. For all the interactions, displacement at failure was kept at 2 mm.

Table 3. Interaction properties of embedded rod regarding the rod to grain angle.

Rod to grain orientation	Knn (N/ mm^3)	Kss (N/ mm^3)	Ktt (N/ mm^3)	Normal (MPa)	Shear-1 (MPa)	Shear-2 (MPa)
Parallel	160	160	160	14.2	14.2	14.2
Perpendicular	225	225	225	14.5	14.5	14.5
Middle layer	**320**	**320**	**320**	**14.7**	**14.7**	**14.7**

Figure 5 illustrates the numerical modelling details of CLT connection containing glued-in rods with 24 mm diameter and 250 embedment length located perpendicular to the grain direction.In the parametric studies, the pull-out strength of rods with 20, 24, and 30 mm diameters and the embedment lengths of 250, 350, and 450 mm anchored in the parallel, perpendicular, and middle layers of CLT were investigated.

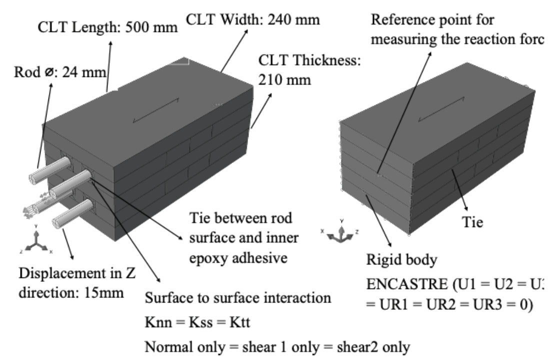

Figure 5. Numerical modelling details of glued-in rods with 24 mm diameter and 250 mm embedment length located in the perpendicular to the grain direction.

3. RESULTS AND DISCUSSIONS

3.1 Failure loads of experimental tests

The average pull-out strength of glued-in rods with 250 mm embedment length located at the perpendicular, parallel, and middle layer of CLT reached 343 (CoV 0.03), 333 (CoV 0.06), and 305 kN (CoV 0.06), respectively. The lower pull-out strength of the rods embedded in the middle of two cross-wise layers of CLT can be due to the lower distance of rods to the CLT surface. This decreased distance causes stress to reach the surface of the CLT, causing cracks to appear and ultimately reducing the strength of the connections. The average pull-out strength of glued-in rods with 250 mm embedment length is presented in Figure 6. The average compression strength of the glued-in rods with 350 mm embedment lengths located at the perpendicular, parallel, and middle layer of CLT reached 506 (CoV 0.02), 493 (CoV 0.04), and 482 kN (CoV 0.04), respectively. Similarly, the lower surface distance of the rods in the middle layers led to a reduction in the connection strength. The mean compression strength of rods with 350 mm embedment length are shown in Figure 6.

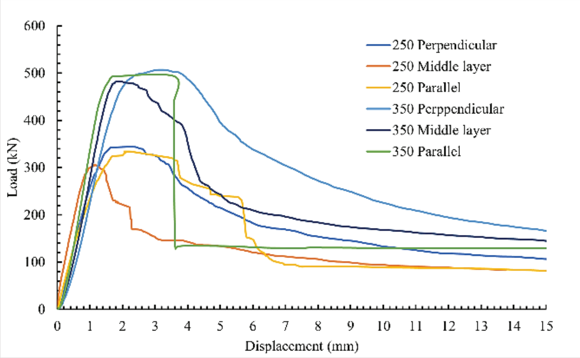

Figure 6. Average of strength for glued-in rods with 250- and 350-mm embedment lengths.

3.2 Failure modes of experimental tests

In practice, glued-in rod connections are designed to obtain ductile failure mode through the yielding of the steel rods. However, this research was designed in such a way that the strength of the steel rods was greater than that of other connection components, so that the tolerance threshold of brittle failure and other types of failure of the connection components could be obtained. Given the nature of the CLT, its specifications, such as lamination dimension, grade, bonding, etc., affect the specimen's failure mode. For instance, unglued edges, defective finger joints, and knots can initiate failure and lead to lower connection strength. Figure 7 illustrates the typical failure mode for specimens with rods at varied embedment positions.

For rods embedded perpendicular to the grain, various type of possible failures were witnessed in the literature. For example, separation of the whole transverse layer or rolling shear are among the mostly witnessed failure modes for rods embedded perpendicular to the grain (11, 12). Due to the lower tangential and radial strength of timber in the transverse layers, rolling shear failure in the transverse layers was the observed mode of failure for the rods embedded perpendicular to the grain, as shown in Figure 7a. This transverse layer›s failure due to rolling shear can emphasize on the need for reinforcement of the CLT, and despite increasing the edge distance, the rolling shear seems inevitable, and it is independent of the CLT›s dimensions. This progressive rolling shear failure led to a smooth force-displacement curve. On the other hand, with the rods inserted perpendicular to the grain, the stress did not reach the CLT›s surface, and there was no visible crack on the surface along the length of the rod. In addition, the epoxy adhesive was also shattered and broken in many places along the rod›s length.

The rods embedded parallel to the grain were pulled out in the form of plugs holding segments of parallel lamination, as illustrated in Figure 7b. Therefore, whether close to the wood-adhesive contact or by the removal of a block of wood, block shear of wood caused the connections to fail and led to a sharp strength reduction of the connection. Due to the larger distance of the rods to the surface of the CLT, no damage was observed on the surface and edge of the CLT. Moreover, epoxy adhesive holding rods parallel to the grain also was not damaged during the tests. Similar plug pull-out failure of rods embedded parallel to the grain has been reported in literature for rods embedded parallel to the grain of glulam (13).

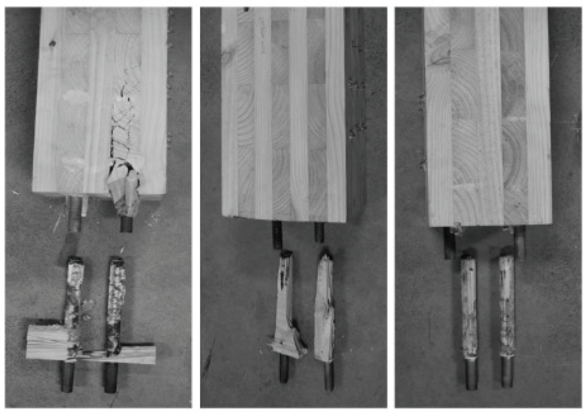

Figure 7 Failure mode on the edge of CLT specimens following tension tests, (a) rods perpendicular to the grain, (b) rods parallel to the grain, (c) rods embedded in the middle layer of two cross-wise layers.

The rods embedded in the middle layer of two cross-wised layers were entirely pulled out in the form of a cylinder while still holding the epoxy with wood fibers on its outer surface, as shown in Figure 7c. For both tension and compression tests, the failure of rods inserted in the middle of two cross-wised layers of CLT reached the specimen's surfaces, illustrating the effect of the lower distance between the rod and the

CLT's surface, as shown in Figure 8. This phenomenon exacerbates in the case of having two laminations not edge-bonded close to the rod's length. Regarding the crack reaching the surface of the CLT, no damage was observed on the edge of the CLT specimens. This type of crack reaching the surface of the specimens along the anchorage due to the low edge distance also has been reported for glulam specimens containing glued-in rods (14).

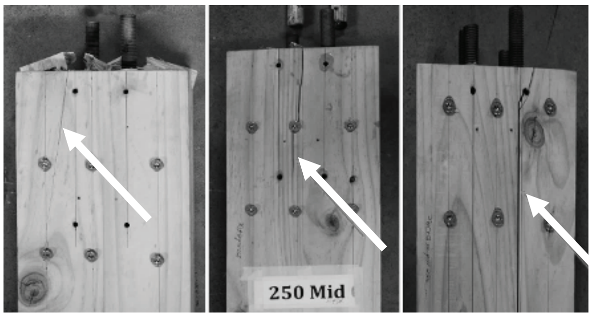

Figure 8. Surface crack of specimens containing rods in the middle of two cross-wised layers.

3.3 Numerical Modelling

3.3.1. Numerical modelling validation

The numerical models were validated using replica experimental tests. The precision of the numerical modelling validations was evaluated based on three parameters, including maximum failure load, connections stiffness, and failure mode. Validations with high precision were prepared for all the parallel, perpendicular, and middle layer embedded rods.

In terms of the maximum loads, the comparison of the maximum predicted loads and experimental test results are provided in Table 4. The numerical models prepared for the rods with 250 mm embedment length evaluated the pull-out strength of the M24 rods with a maximum 2% difference for all the rod placements (parallel, perpendicular, and middle layers of two cross-wised layers).

Subsequently, by having validated models for rods with an embedment length of 250 mm, their prediction accuracy was examined by the experimental test results of rods with an embedment length of 350 mm. The numerical models tested the rods with 350 mm at tension and predicted the pull-out strength of the rods with a maximum 4% difference. In general, numerical models predicted the strength of glued-in rods with a P_{Test}/P_{FE} of 0.992 and a standard deviation of 0.028, as presented in Table 4. Since in experimental tests, rods were tested in compression, while in numerical modelling they were tested in tension, the disparity is greater for the rod's strength prediction. This comparison also showed a minor difference between the compression results of experimental tests and pull-out results of numerical modelling of rods with 350 mm embedment length.

Table 4. Comparison of maximum strength of rods between experimental tests (P_{TEST}) and numerical modelling (P_{FE})

Rod to grain orientation	Embedment length (mm) L_a	P_{Test} (kN)	P_{FE} (kN)	P_{Test}/P_{FE}
Perpendicular	250	344.0	346.7	0.99
Perpendicular	350	506.6	525.8	0.96
Middle layer	250	305.2	310.0	0.98
Middle layer	350	482.5	464.1	1.04
Parallel	250	333.9	331.8	1.01
Parallel	350	493.0	510.3	0.97
Average				0.992
Std Dev				0.028

The numerical models were also validated according to the stiffness of the bonds. Figure 9 demonstrates the high correspondence of stiffness of the connections between the experimental tests and numerical modelling of the M24 rods embedded perpendicular to the grain of CLT. Regarding the defined interaction properties, after following the stiffness and reaching the maximum load, it loses its strength, while for the experimental tests, a gradual reduction in the force was observed, as presented in Figure 9.

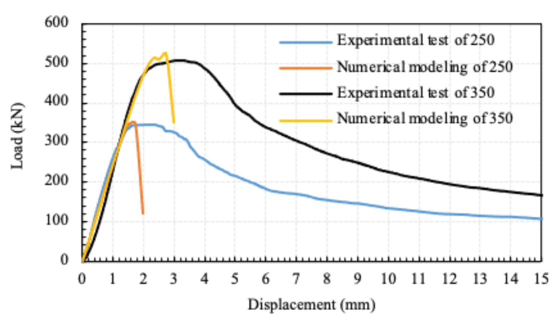

Figure 9. Comparison of force vs. displacement curve for the rods with 24 mm diameter embedded in the perpendicular to the grain direction.

Additionally, during the experimental tests, a crack developed along the length of the rods inserted in the middle of two cross-wised layers, as shown in Figure 8. The same stress distribution reaching the surface of the CLTs was also observed in the numerical modelling of rods embedded in the middle layer of two cross-wised layers, as presented in Figure 10a. Moreover, experimental tests of the rods embedded perpendicular to the grain of the CLT illustrated rolling shear failure in the transverse layer, as shown in Figure 7. The numerical modelling containing rods embedded perpendicular to the grain predicted stress distribution and displacement reaching the edge of the CLT specimen and leading to rolling shear, as shown in Figure 10b.

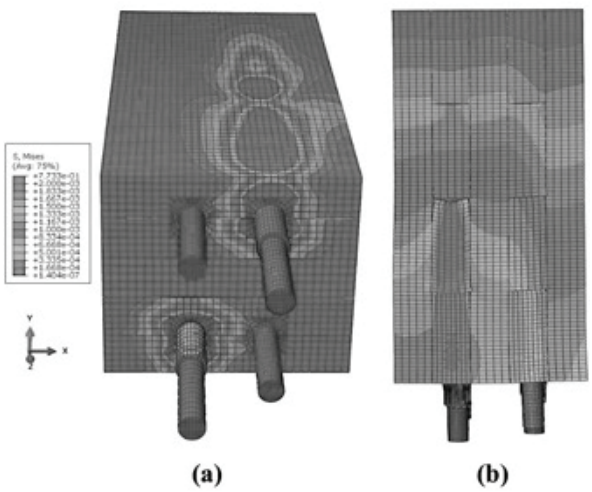

Figure 10. Failure mode and stress distribution in the numerical modelling a) M24 rods with 250 mm embedment length located in the middle of two cross-wised layers; b) side view of CLT containing M24 rods with 250 mm embedment length located perpendicular to the grain lamination.

3.3.2. Parametric investigation

The parametric analysis of two rods embedded perpendicular to the grain and tested diagonally showed that by increasing the rod's diameter and embedment lengths, the pull-out strength increased. Rods with 30 mm diameter and 450 mm embedment lengths reached 961 kN pull-out strength, as shown in as shown in Figure 11.

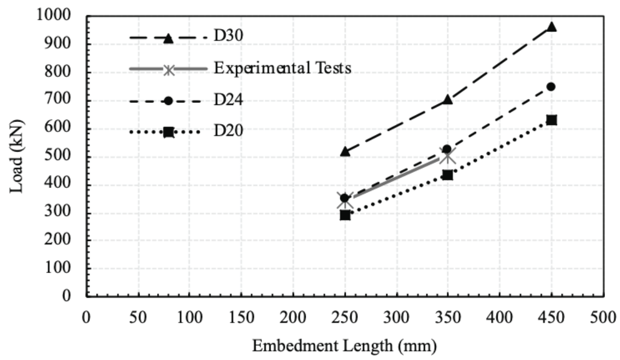

Figure 11. Numerical modelling and experimental test results of rods embedded perpendicular to the grain direction.

For rods embedded parallel to the grain, the pull-out strength of the numerical modelling increased by increasing the diameter and embedment length. The maximum pull-out strength of the rods reached 836 kN for rods with 30 mm diameter and 450 mm embedment length, as illustrated in Figure 12.

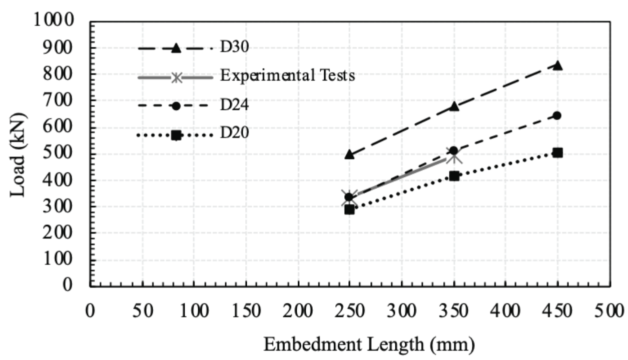

Figure 12. Numerical modelling and experimental test results of rods embedded parallel to the grain direction.

For rods embedded in the middle of two cross-wised layers, rods with 20- and 24-mm diameters showed an increasing trend in the pull-out strength. While by increasing the rod's diameter to 30 mm and embedment length to 450 mm, they did not show a significant increase in the pull-out strength and failed at 647 kN (as illustrated in Figure 13). This can be due to the lowering distance of the rods to the surface, and as shown in the experimental tests and numerical modelling failure modes, this low distance leads to early crack propagation on the surface and early failure.

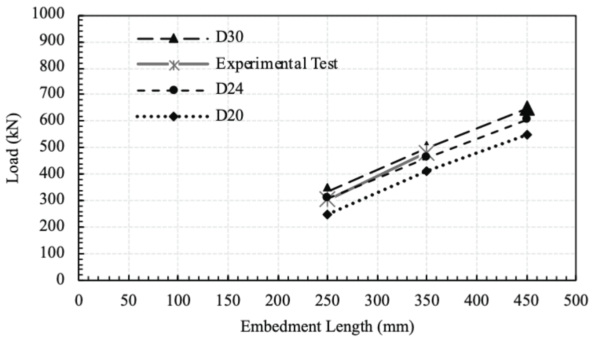

Figure 13. Numerical modelling and experimental test results of rods embedded in the middle of two cross-wised layers.

3.3.3. Compatibility of the results with the design equation proposed by New Zealand Timber Design Guide (NZ TDG)

The NZ TDG (6) has introduced a design equation for epoxied steel rods embedded at the end grain of glulam and LVL as below:

$P_{ult} = 6.73 \times k_b \times k_e \times k_m \times (l/d)^{0.86} \times (d/20)^{1.62} \times (h/d)^{0.5} \times (e/d)^{0.5}$

k_b: Bar type factor

k_m: Moisture factor

k_e: Epoxy factor

l: Embedment length

d: Rod diameter

h: Hole diameter

e: Edge distance

Regardless of the rods angle to embedded glulam or LVL, this equation can predict the axial pull-out strength of epoxied rods for wood with a moisture content of up to 22%, rod diameter of $12 \le d \le 24$ mm, embedment length of $5d \le d \le 20d$, hole diameter of $1.15d \le h \le 1.4d$, and edge distance of more than 1.5d. NZ TDG could conservatively predict the pull-out strength of the glued-in rods with an average difference of 33%. For example, the lowest pull-out strength for rods with 24 mm diameter and 250 embedment length belong to the rods embedded in the middle layer of the two cross-wised layers, which reached 305.2 kN, while the NZ TDG equation predicts the pull-out strength to be 262.7 kN. This equation predicted the pull-out strength of this glued-in rod with a 16% difference. Regarding the fact that this equation is designed for glulam and LVL, its prediction is conservative and can be applied to the glued-in rods embedded in CLT.

It should be noted that the NZ TDG is based on the characteristic strength, while the results of experimental tests are mean values. Moreover, for the experimental test results and comparison, no other factors such as Φ or k_1 (load duration factor) were considered. The comparison of results obtained from experimental tests and design equation of NZ TDG, is presented in Table 5.

Table 5. Comparison of experimental test results with NZ TDG.

Rod location	l (mm)	TDG (kN)	Test results (kN)	DIFF. (%)
Perpendicular	250	262.7	344.0	31
Perpendicular	350	350.9	506.6	44
Middle layer	250	262.7	305.2	16
Middle layer	350	350.9	482.5	38
Parallel	250	262.7	333.9	27
Parallel	350	350.9	493.0	41
Average				33
Std Dev				0.103

l: embedment length

4 CONCLUSIONS

By carrying out experimental tests and numerical modelling on glued-in threaded rods embedded on the edge of CLT, the effect of rod diameter, embedment length, and rod location on the strength of the glued-in rods was investigated. The findings of the experimental tests and numerical modelling demonstrated that by increasing the rod diameter and embedment length, rods inserted perpendicular to the grain led to the highest pull-out strength. CLT specimens containing rods perpendicular to the grain direction showed rolling shear failure and gradual force reduction. By increasing the rod diameter and embedment length of rods located parallel to the grain of the CLT, the pull-out strength of the rods showed a steady increase and failed in the form of plug pull-out with a sharp strength loss after reaching the maximum strength. On the other hand, with rods embedded in the middle of two cross-wise layers, the early failure happened on the surface of the CLT due to the lower distance of the rods to the surface. Even by increasing the rod diameter, the rods did not present a subsequent increase in the pull-out strength, and the crack formation on the surface led to significant strength reduction. Finally, a comparative investigation was conducted on the NZ TDG formula and mean values of experimental tests, to better understand potential differences when predicting the pull-out strength of glued-in rods embedded in CLT regardless of the rod's location on the edge of the CLT.

5 ACKNOWLEDGEMENTS

The authors wish to thank the financial support of the New Zealand Timber Design Society and WIDE Trust for supporting this research.

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