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PERFORMANCE OF GLUED-IN-RODS IN CROSS-LAMINATED TIMBER

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ABSTRACT: Glued-in rods (GiR) are an interesting technical solution for numerous structural applications in timber engineering, and the availability of Cross-laminated timber (CLT) provides opportunities to extend the use of wood beyond traditional low-rise residential construction. Although GiR connections have the potential to be used in CLT, research on this topic is scarce. In this paper, an investigation on the performance of GiR in CLT is presented. Two different 5-ply CLT panel thickness (139 and 175 mm), two different steel rod diameters (d = 12.7 and 19.1 mm) and four different anchorage length (l_a = 6d, 10d, 14d, 18d) were investigated. A total of 180 specimens were fabricated and subsequently tested under uni-axial tension loading in a pull-pull configuration. The governing failure modes as a function of the tested parameters were shear at the interface and wood plug pull out with an increase in capacity with rod diameter and anchorage length.

KEYWORDS: Glued-in rod, CLT, Failure modes, Anchorage length, Pull-pull tests.

1 INTRODUCTION

Innovative structural materials such as Cross-laminated timber (CLT) [1] and high-strength connections such as Glued-in Rods (GiR) [2] provide options to extend the use of wood beyond low-rise residential construction. CLT is a laminated composite with a number of wood lumber layers glued primarily orthogonal to each other. Particularly, due to its planar shape and dimensional stability, the introduction of CLT has been labelled a 'game-changer' in the building industry [3].

GiRs are connectors that are concealed inside the wood member. This is both an architecturally pleasing feature and provides the joint with excellent fire protection when compared to conventional dowel-type timber fasteners. GiR joints in many cases outperform traditional fasteners due to their high strength and stiffness.

GiR connections are composed of a wood product, rod (mostly steel) and adhesive. These three materials transfer loads and equally deform simultaneously [4] and can exhibit different failure modes: i) yielding of the rod (if the rod is made from steel); ii) shear along the rod; iii) glue line failure, iv) tensile failure of the wood member; v) block shear failure in the wood member (for multiple rods); and vi) splitting of the wood member. When designing GiR joints, it is important to avoid the adhesive from being the weakest link in the connection. The preferred failure mode of GiR is ductile yielding of the rod rather than adhesive or wood brittle failure [2,4].

The performance and the failure modes of GiR have been shown to depend on several parameters, including the anchorage length (l_a), rod diameter (d), rod edge distance, number of rods, glueline thickness, type of adhesive, load-to-grain angle, and moisture content of timber [2]. Although not linear, GiR capacity has been shown to increase with an increase in anchorage length [e.g. 5,6]. To increase resistance, Gehri [7] suggested moving the rod anchorage zone away from the surface of timber into the inner part by leaving a gap at the face end of the drilled hole where no adhesive is applied along the anchorage length. It was further proposed to reduce the cross-section of the rod (necking) over a given length to obtain the desirable plastic deformation inside the wood.

Although the use of GiR in solid timber and engineered wood products like glulam is now widely used, GiR can also be effectively used with CLT. One way to achieve this is in panel-to-panel joints in walls and wall-to-floor connection where the rod can be connected parallel or at an angle of inclination to the timber and connection of the panel to other structural elements like concrete and steel. However, information about the behaviour of GiR in CLT is scarce in the literature.

Azinovic et al. [8,9] studied the performance of GiR in CLT and demonstrated that the load-carrying capacity increased with bonded length and rod diameter and the connection stiffness depended mostly on the rod diameter. Based on the installation direction with respect to the CLT strength axis, significantly different failure modes where observed such as the edge lamination tear out, complete tear out of CLT layer, failure along non-glued timber edges and failure of timber next to adhesive, all of which deviate from the regular failure modes seen in other wood products. Further studies were recommended because of the complexity of the observed connection's response.

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2 EXPERIMENTAL INVESTIGATION

2.1 OBJECTIVE

The objective of the research presented herein was to investigate the structural performance of single GiR in CLT under consideration of anchorage length, rod diameter and CLT thickness.

2.2 MATERIALS

Two CLT panel lay-ups were used: 1) 139 mm and 175 mm thick 5-ply panels with lay-ups of 35-17-35-17-35 mm and 35-35-35-35-35 mm, respectively. The material was provided by Structurlam [10] and produced in accordance with ANSI/APA PRG320 [11]. The grade E1M4 panels are made from SPF species with the apparent density (based on the weight and volume of the specimen) of 484 kg/m^3 (coefficient of variation CoV of 2.6%) for 139 mm CLT and 456 kg/m^3 (CoV of 3.2%) for the 175 mm CLT. The moisture content was determined as on average 12.6% (CoV of 2.2%).

ASTM A193 B7 [12] steel rods of diameter 1/2” (12.7 mm) and 3/4" (19.1 mm) were used. The yield strengths were experimentally determined as 657.5 and 681 MPa for the 1/2" and 3/4" rods, respectively, on five samples each. Two-component polyurethane adhesive Loctite CR 821 by Henkel was used. The adhesive shear strength was experimentally determined as 7 MPa following the procedure as outlined in ASTM D1002-10 [23].

2.3 SPECIMEN CONFIGURATIONS

In most test series, the rods were completely glued-in all along the embedment length. In selected test series, the rods were partially left un-glued (l_u = 4d) inside CLT. For the completely glued specimens, most CLT specimens were 200 mm wide and 600 mm but with two different thicknesses (t=139 and 175 mm). Some selected test series consisted of 150 mm wide and 800 mm long CLT panel.

Two different steel rod diameters d = 12.7 mm (1/2") and 19.1 mm (3/4”) and four different anchorage lengths l_a = 6d, 10d, 14d and 18d were used. Holes with diameters d_h = 15.9 and 22.2 mm for the 12.7 and 19.1 mm diameter rods, respectively, were drilled into both ends of the CLT panels to effectively test 2 connections with one specimen. The holes were made to be larger than the rod diameters to create a 1.6 mm thick layer of glue. Figure 1a illustrated all geometry parameters: l is the length of the CLT panel, l_c the clearance between the opposite rods in each specimen, l_r, the rod length, e_d the edge distance and l_u the unglued anchorage length.

Each specimen combination had five replicates. In total, 18 test series for a total of 90 specimens were fabricated and subsequently tested, see Table 1. The series naming consisted of the rod diameter in inches (1/2 or 3/4), followed by anchorage length (6*L,* 10*L,* 14*L or* 18*L*) and the panel thickness (139 or 175). The test series with partially un-glued specimens, see Figure 1b, included two different anchorage lengths (l_a = 6d and 10d) and were labelled as 6*L#* and 10*L#,* respectively.

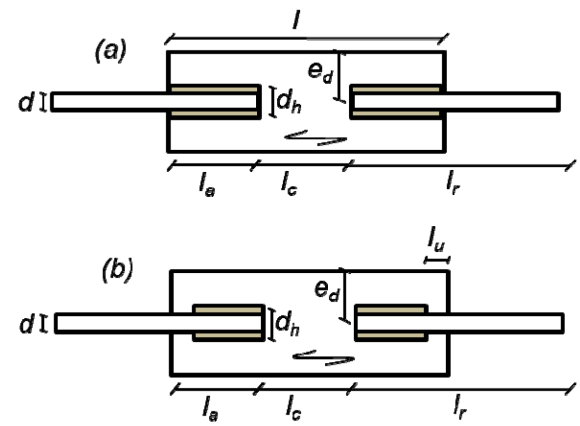


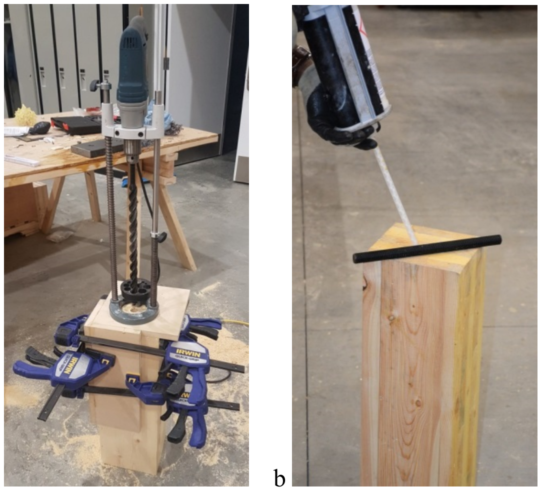
Figure 1: *Specimen schematic and photo for single rod (a) completely bonded in timber (b) partially bonded in timber*

Table 1: *Test series overview*

Label	d (mm)	d_h (mm)	l_u (mm)	l_a (mm)	e_d (mm)	l_c (mm)	l_r (mm)
1/2-6L-175	12.7	15.9	-	76	100	448	376
1/2-10L-175	12.7	15.9	-	127	100	346	427
1/2-14L-175	12.7	15.9	-	178	100	244	478
3/4-6L-175	19.1	22.2	-	114	100	371	264
3/4-10L-175	19.1	22.2	-	191	100	219	491
3/4-14L-175	19.1	22.2	-	267	100	67	567
1/2-6L-139	12.7	15.9	-	76	100	448	376
1/2-10L-139	12.7	15.9	-	127	100	346	427
1/2-14L-139	12.7	15.9	-	178	100	244	478
1/2-18L-139	12.7	15.9	-	229	75	143	404
3/4-6L-139	19.1	22.2	-	114	100	371	414
3/4-10L-139	19.1	22.2	-	191	100	219	491
3/4-14L-139	19.1	22.2	-	267	100	67	567
3/4-18L-139	19.1	22.2	-	343	75	114	518
1/2-6L#-139	12.7	15.9	51	76	75	224	353
1/2-10L#-139	12.7	15.9	51	127	75	143	404
3/4-6L#-139	19.1	22.2	76	191	75	67	442
3/4-10L#-139	19.1	22.2	76	267	75	114	518

2.4 SPECIMEN FABRICATION

Before gluing the rods, holes were drilled into each CLT panel using a hand drill with custom-made jigs as a guard for the drilling process (Figure 2a). The drilled holes were cleaned with compressed air to remove the residual sawdust and wood shavings. Calculated quantities of adhesives were carefully injected in each hole with the glue gun (Figure 2b) and the rods comprising of the two-rod diameters were inserted in the holes by twisting them along the way to remove the trapped air. These rods were positioned straight and held in place with the use of toothpicks distributed around the circumference of the holes. The glued joints were left to cure and placed in the climate room for at least 21 days before testing.



a b

Figure 2: *Test specimen manufacturing process (a) hole drilling (b) applying adhesive in the drilled hole*

2.5 TEST METHODS

The tests were performed in a pull-pull configuration using a 500 kN Hydraulic Universal Test Machine in the Wood Innovation and Research Lab at the University of Northern British Columbia in Prince George, Canada. Threaded cylindrical steel sleeves were attached to the rods at both ends and inserted into hydraulic collet grips attached to the testing machine. The collet grips held the rods firmly in position and also ensured the precise alignment during testing, see Figure 3.

Two steel plates (90 x 0.5 x 160 mm), one on each end, were attached to the rods. Two Linear Variable Differential Transformers (LVDTs) were installed on both ends of the test specimens touching these steel plates to measure the relative displacements between the rods and CLT panel. A displacement-controlled rate of 1 mm/min was used so that each test was typically completed in approximately 5 minutes. The applied load was recorded by the test machine's calibrated load cell and subsequently plotted against the LVDT relative displacement measurement.

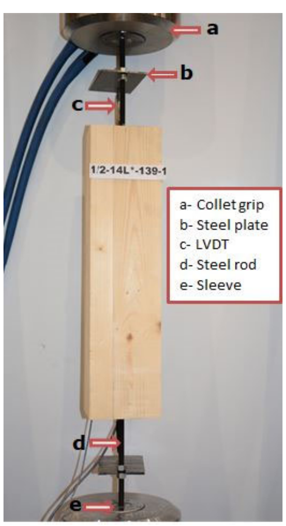


Figure 3: *Experimental test set-up*

In accordance to previous work [14] which showed that the first tests on two ended GiR test specimens did not significantly damage the surviving connection end, the results from two ended GiR test specimens can be used to provide additional data point when determining the strength of GiR connection. Therefore, upon failure of the connection in the first test, the broken (failed) rod was cut off and the unbroken second GiR was re-tested to provide more data for every specimen.

The results were assessed in terms of the load-carrying capacity (F_{max}), the displacement at capacity ($\delta_{F,max}$), and the initial stiffness (k). The latter was evaluated for the loading range between 10% and 40% of capacity.

3 RESULTS

3.1 OVERVIEW

Table 2 provides a summary of the 18 test series with the average values and their respective Coefficients of Variations (CoV) are reported. For $\delta_{F,max}$ and k, the reported averaged values are for the failed side.

Table 2: *Summary of test results*

Series	F_{max} [kN]		$\delta_{F,max}$		k [kN/mm]	
	Test	Retest	Test	Retest	Test	Retest
1/2-6L-139	25.5 (4)	35.3 (14)	0.4	2.9	93.6 (>50)	13.8 (>50)
1/2-6L-175	26.0 (8)	33.0 (11)	1.4	2	29.1 (>50)	13.5 (50)
1/2-10L-139	49.9 (12)	51.4 (18)	1.1	2.9	154.2 (>50)	23.1 (>50)
3/4-6L-175	51.3 (17)	52.0 (13)	0.6	1.4	511.4 (>50)	79.6 (>50)
1/2-10L-175	55.2 (17)	62.6 (17)	1.1	1.9	54 (47.5)	61.8 (>50)
3/4-6L-139	60.4 (13)	61.3 (10)	1.2	1.6	66.6 (>50)	65.8 (>50)
1/2-14L-139	60.6 (8)	65.2 (12)	2.0	2.6	246.1 (>50)	29.5 (>50)
1/2-14L-175	67.8 (10)	76.2 (10)	2.0	2.7	136.8 (>50)	45 (42)
1/2-18L-139	69.3 (9)	75.2 (13)	1.4	4.4	65.7 (37)	445.4 (>50)
3/4-10L-139	86.3 (13)	99.3 (19)	1.1	1.8	351.2 (>50)	67.6 (>50)
3/4-10L-175	95.9 (14)	99.0 (11)	1.1	1.6	141.2 (>50)	160.8 (>50)
3/4-18L-139	103.4 (25)	146.8 (21)	0.9	2.3	162.7 (45)	62.4 (>50)
3/4-14L-139	111.9 (19)	111.5 (21)	1.0	1.4	168.9 (>50)	176.6 (>50)
3/4-14L-175	115.0 (18)	130.0 (18)	1.2	1.7	340.3 (>50)	511.1 (>50)
1/2-6L#-139	38.6 (20)	38.8 (19)	1.0	1.7	39.7 (37)	100.1 (>50)
3/4-6L#-139	51.7 (23)	71.5 (27)	0.8	1.5	209.2 (>50)	54.5 (>50)
1/2-10L#-139	58.1 (13)	66.0 (6)	1.5	1.9	47.5 (50)	72.7 (>50)
3/4-10L#-139	64.7 (10)	88.5 (11)	0.3	1.8	333.5 (>50)	72.9 (>50)

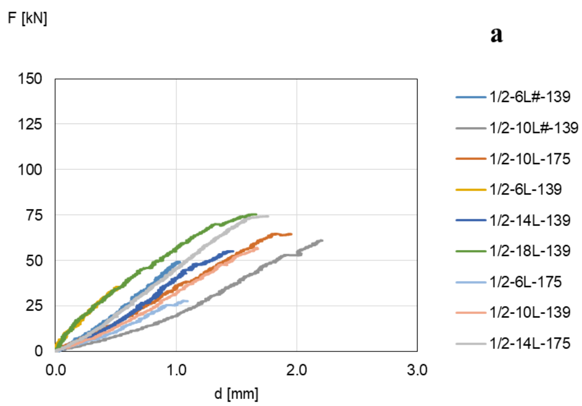
The test series average load-carrying capacity as a function of the investigated geometric parameters ranged from 25 to 147 kN. Within the range of the parameters investigated, there was an increase in load-carrying capacity with increasing anchorage length up to the length of 14d beyond which no further increase was observed. The load-carrying capacity increased with the rod diameter between 39% and 81% for the same embedment length. The panel thickness did not have any impact on the load-carrying capacity.

The displacements at maximum load ranged from 0.3 to 4.4 mm. The displacements at failure of the retested specimens were higher than those from the first tests.

The test series average joint stiffness ranged from 40 to 511 kN/mm. These values, however, were characterised by high variability (CoV > 50%) for most series.

No consistent increase in load carrying capacity was observed for the partially glued test series. The CoVs for those series were between 6 and 27% higher than that of the completely glued test series.

Figure 4 shows the load-displacement curves of a typical specimen from each test series. The responses were linear up to failure in most cases except for a few where small decreases in stiffness were observed just before reaching the capacity. All test specimens exhibited very small displacements at failure (between 0.5 and 3 mm) with no ductility.



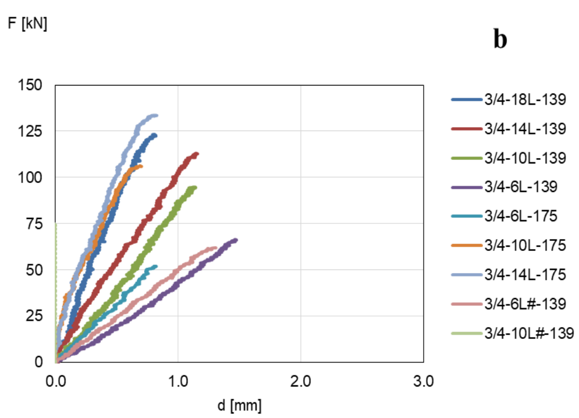


Figure 4: *Load-displacement of selected specimens for each series: a) 12.7mm rods and b) 19.1mm rods*

3.2 FAILURE MODES

The typical failure modes observed during testing are illustrated in Figure 5. Generally, the joints showed brittle failure accompanied by consistent cracking noises and then a sudden failure accompanied by a loud crack upon reaching the load-carrying capacity. These failure modes can be described as: 1) rod pull-out at the interface between timber and the adhesive as a result of the loss of adhesion between the timber and adhesive (c.f. Figure 5a,c); and 2) wood plug pull out failure which is the shear failure in timber (c.f. Figure 5d-f).

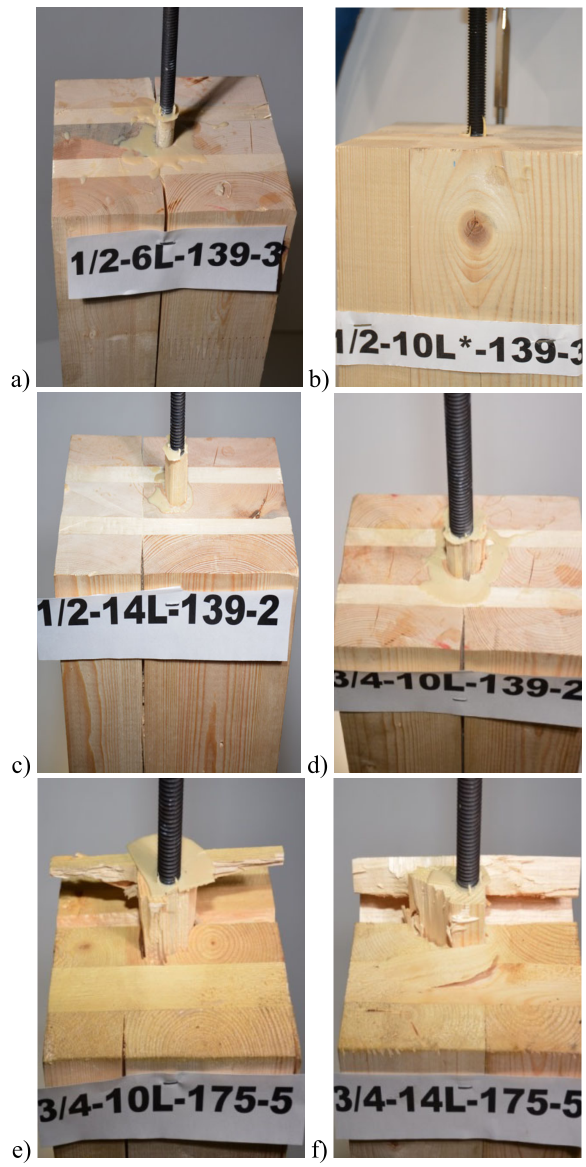


Figure 5: *Typical failure modes of GiR in CLT*

The failure mode depended on the rod diameter and the anchorage length. For the specimens with 1/2" rods, independent of anchorage length and regardless of the panel thickness, the typical failure mode was the pull-out of the rod characterised by the failure at the interface between adhesive and wood, c.f. Figure 5a,c.

However, for the specimens with 3/4" (19.1 mm) rods, the failure mode observed for both panel thicknesses was wood plug failure in which a large volume of the wood surrounding the rod away from the adhesive failed. In most instances, it was observed that the wood plug was larger for the longer anchorage length 10L, 14L and 18L (Figure 5e, f) and smaller for the shorter lengths 6L and 10L (Figure 5d). It should be noted that some of the rods were glued in-between two non-glued edges of timber in the same CLT layer and also near the non-edge glued timber in other next layers. This could have contributed to the type of failure modes obtained.

In all of the test series, just as no adhesive failure was recorded, none of the specimen split. Independent of the CLT layup, the holes into which the rods were glued on were drilled parallel to the grain into the CLT core layer. Hence, there was no interference of the rod between two-panel laminations.

For the partially glued specimens where the anchoring zone was shifted to the inner part of the timber, the failures of the specimens were internal, c.f. Figure 5c. This confirmed that moving this anchoring zone into the panel worked as desired by moving the shear away from the surface.

3.3 DISCUSSION

From the results summarized in Table 2, it can be observed that the load-carrying capacities increased with increase in anchorage length. This increase is attributable to the increased surface area for bonding at the rod/adhesive and timber/adhesive interface. Exemplarily, for the 12.7 mm diameter rods, the relation between load-carrying capacity and embedment length across the two-panel thicknesses is illustrated in Figure 6.

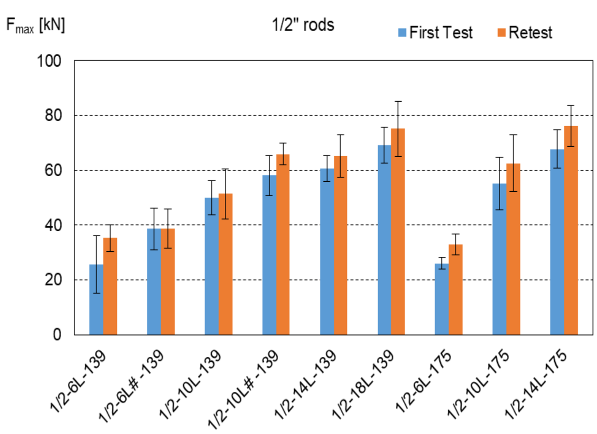


Figure 6: *Effects of anchorage length and panel thickness on the capacity of GiR with 1/2" rods*

Considering the specimen sides that failed first, for the 139 mm panel and the four anchorage lengths under consideration (6d, 10d, 14d and 18d), the greatest increase in the average capacity was seen from 6d to 10d while smaller increases were observed between 10d and 18d. A similar increase trend was observed for the 175 mm panel. The average capacity more than doubled from 6d to 10d and only increased by another 20% to 14d.

For the partially glued specimens, the capacity also increased by 51% from 6d to 10d with higher anchorage length. Interestingly, for the 19mm rod in the 139 mm panels, the load-carrying capacity in the partially glued specimens was higher than in the completely glued ones, 51% and 16% for 6d and 10d, respectively.

Comparing the retest results with the first test result, the load-carrying capacities of the retested specimen irrespective of the panel thickness were consistently higher than the first test specimens except for the 3/4-14L-139 test series which were equal (112 kN). Increases of up to 35% (3/4-18L-139) were obtained in comparison to the first test. Furthermore, the shorter embedment length specimens (specifically 6d) tend to have very similar capacities between first test and retest.

For the 3/4" diameter rods, for both partially and completely embedded rods, the results obtained were similar to those reported for the 1/2" rods, c.f. Table 2.

The impact of the rod diameter is illustrated in Figure 7. The larger (19.1 mm) rods resulted in a higher capacity than the 12.7 mm rods. Unlike the 12.7 mm rods which increased for all embedment lengths considered, the increase in the 19.1 mm rods was observed until the embedment length reached 14d (267 mm). From the length 14d mm to 18d (343 mm), the load-carrying capacity of the 19.1 mm steel rod decreased by 10%. Although as stated earlier, no significant difference exists between the two-panel sizes, it was observed that the 19.1 mm steel rod had a more visible shear failure evident by the removal of a large block of timber surrounding the rod in the 175 mm panels.

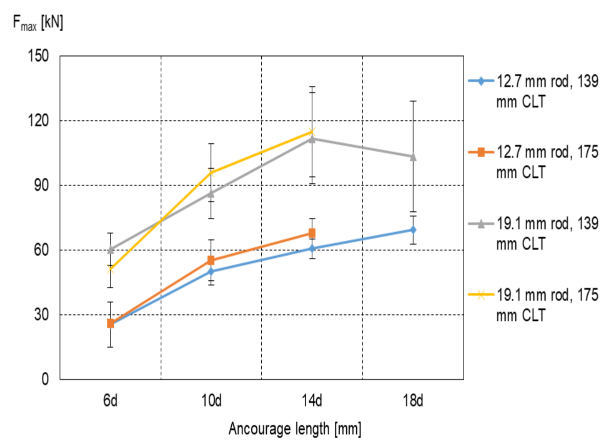


Figure 7: *Load-carrying capacity of joints*

4 CONCLUSIONS

In the research presented herein, the performance of single GiR in CLT inserted parallel to the major strength direction with the rod partially and completely glued-in was investigated under quasi-static monotonic tension loading. Based on the 180 tests, the following conclusions can be drawn:

1) Within the range of the parameters investigated, there was an increase in load-carrying capacity with increasing anchorage length up to the length of 14d beyond which no further increase was observed.

2) The load-carrying capacity increased with the rod diameter. The higher diameter rods (19.1 mm) attained higher load-carrying capacity than the lower diameter (12.7 mm) rods (between 39% and 81%).

3) The panel thickness (herein 139 and 175 mm) did not impact the load-carrying capacity of the connections.

4) The GiR connections were very stiff but there was very large variability between and within tests series

5) The displacements at failure for all test series were very small ranging from 1.4 to 4.4 mm for the retested specimen and from 0.3 and 2.0 for the first tests.

6) The predominant failure modes were rod pull-out at the interface between timber and the adhesive and wood plug pull out failure which is the shear failure in timber. These failure modes depended on the rod diameter and the anchorage length.

7) The impact of partially moving the anchoring zone towards the centre of the CLT panels on the load-carrying capacity was not consistent across test series.

8) For all test series (except one), the retested specimens achieved a higher load-carrying capacity than the first test (up to 35%). The second test showed that the connection was not damaged by the first test performed.

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REFERENCES

[1] Brandner R., Flatscher G., Ringhofer A., Schickhofer G., Thiel A.: Cross laminated timber: overview and development. European Journal of Wood and Wood Products, 74:331-351, 2016

[2] Tlustochowicz G., Serrano E., Steiger R.: State-of-the art review on timber connections with glued-in steel rods. Materials and Structures, 44:997-1020, 2011.

[3] Gagnon S., Bilek E.M. (ed), Podesto L., Crespell, P.: CLT Handbook- Introduction to cross-laminated timber. FPInnovation. 2013

[4] Steiger R., Serrano E., Stepinac M., Rajcic V., O'Neill C., McPolin D., Widmann R.: Strengthening of timber structures with glued-in rods. Construction and Building Materials, 97:90-105, 2015.

[5] Steiger R., Gehri E., Widmann R.: Pull-out strength of axially loaded steel rods bonded in glulam parallel to the grain. Materials and Structures, 40:69–78, 2006.

[6] Otero D., Estévez J., & Martín E.: Strength of Joints with Epoxy-Glued Steel Rods in Tali Timber. Journal of Materials in Civil Engineering, 23:453-458, 2011

[7] Gehri E.: Ductile behaviour and group effect of glued-in steel rods," In Proceedings of International RILEM Symposium on Joints in Timber Structures, 2001.

[8] Azinovic B., Serrano E., Kramar M., Pazlar T.: Experimental investigation of the axial strength of glued-in rods in cross laminated timber. Materials and Structures, 51:143, 2018.

[9] Azinovic B., Danielsson H., Serrano E., Kramar M.: Glued-in rods in cross laminated timber-numerical simulations and parametric studies. Construction & Building Materials, 212:431-441, 2019.

[10] Structurlam Mass Timber Corporation: Crosslam CLT Technical Design Guide v4.0. Structurlam, Canada, 2018.

[11] ANSI/APA PRG 320-2019: Standard for performance-rated Cross-Laminated Timber. The Engineered wood Association, American National Standards Institute (ANSI) and Engineered Wood Association (APA), New York, 2019.

[12] ASTM A193/A193M-20: Standard specification for alloy-steel and stainless steel bolting for high temperature or high pressure service and other special purpose applications. ASTM International, West Conshohocken, PA, 2020.

[13] ASTM D1002 - 10.: Standard Test Method for Apparaent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal). ASTM International West Conshohocken, PA, 2019.

[14] Zhu H., Faghani P., Tannert T.: Experimental investigations on timber joints with single glued-in FRP. Construction and Building Materials, 140:167-172, 2017.