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SEISMIC AND PROGRESSIVE COLLAPSE STRAIN RATE EFFECTS ON THE WITHDRAWAL STRENGTH OF SCREWS IN GLUED LAMINATED TIMBER

Nasim Ghasemi[1], Benoit P. Gilbert[2], Hong Guan[3], Chuen Yiu Lo[4], Minghao Li[5], Frank Lam[6]

ABSTRACT: Timber-to-timber connections play an important role in the robustness of timber structures. Their performance and structural integrity primarily depend on the effective transfer of loads between elements, typically achieved through metal fasteners, such as nails, screws, bolts or dowels. During their design life, these connections may be subjected to dynamic loads, such as during earthquake and progressive collapse events, and the response of the fasteners under such loads is under researched. In this study, the pull-out and pull-through withdrawal resistance of 7 mm in diameter self-tapping timber screws, driven into Glue Laminated Timber (Glulam) samples, was experimentally evaluated under four strain rates, with failure occurring between 200 s (quasi-static) and 0.2 s (corresponding to seismic and progressive collapse events). The withdrawal pull-out strength increased by 23.0% when the screws were inserted along the parallel-to-grain direction and 18.9% when inserted perpendicular-to-grain. The pull-through resistance showed a lower strain rate sensitivity with an increase of 17.2%.

KEYWORDS: Strain rate effect; Screwed connections; Dynamic rates; Glue Laminated Timber; Withdrawal resistance

1 – INTRODUCTION

Timber is gaining popularity as a sustainable alternative construction material, as traditional materials like concrete and steel contribute significantly to global CO_2 emissions [1]. Engineered Wood Products (EWP), such as Laminated Veneer Lumber (LVL), Glued Laminated Timber (Glulam) and Cross-Laminated Timber (CLT) allow Mass Timber Construction (MTC) to be erected. MTC offers the following advantages: high strength-to-weight ratio, fast erection time, prefabricated elements and reduced on-site labour costs. These make MTC a viable option for mid-rise and tall buildings [2]. As an emerging structural system, research is still needed to ensure safe design of MTC, notably under dynamic loading conditions.

Connections are key in ensuring robustness of MTC [3, 4] with the connection ductility allowing energy absorption and load redistribution. However, a recent study [5] has shown that timber connections may experience less ductility when loaded dynamically than statically. This would therefore limit energy absorption during earthquake events and the development of alternative load paths during a progressive collapse scenario. It is therefore important to understand the strain rate effect on the connection types used in MTC to ensure safe designs.

Current timber standards address the dynamic effects for the design of connections through load duration factors which adjust the connection strength relative to the time of loading. This adjustment does not apply to the connection ductility and the adjustment for stiffness (deflection) is typically only considered for long-term deformations. The

[1] Nasim Ghasemi, School of Engineering and Built Environment, Griffith University, Gold Coast, Australia, nasim.ghasemi@griffithuni.edu.au

[2] Benoit P. Gilbert, School of Engineering and Built Environment, Griffith University, Gold Coast, Australia, b.gilbert@griffith.edu.au

[3] Hong Guan, School of Engineering and Built Environment, Griffith University, Gold Coast, Australia, h.guan@griffith.edu.au

[4] Chuen Yiu Lo, School of Engineering and Built Environment, Griffith University, Gold Coast, Australia, c.lo@griffith.edu.au

[5] Minghao Li, Department of Wood Science, The University of British Columbia, Vancouver, Canada, minghao.li@ubc.ca

[6] Frank Lam, Department of Wood Science, The University of British Columbia, Vancouver, Canada, frank.lam@ubc.ca

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Eurocode 5 [6] accounts for instantaneous loading conditions, such as wind or impact, by increasing the quasi-static (failure in about 5 mins) design capacity of Glulam connections by 10% for Service Classes 1 and 2. The Australian standard AS 1720.1 [7] provides a 14% strength increase for laterally loaded fasteners between quasi-static and short-term loadings (failure in 5 seconds). The North American standard NDS [8] specifies a higher strength increase of 25% between quasi-static and impact loadings. The above highlights some discrepancies between standardised design approaches for the design of connections under short-term loading (failure in the order of seconds or less).

This study investigates the influence of the strain rate effect on one of the mechanical properties affecting the structural response of screwed timber connections, namely the withdrawal strength of screws driven in Glulam products. Both pull-out and pull-through withdrawal strengths were investigated. The withdrawal strength depends on factors such as wood density, moisture content, type and diameter of the fastener, penetration depth, load-to-grain angle, and if the holes are pre-drilled or not [9]. While studies have been performed on the previously mentioned parameters, the effect of the strain rate on the withdrawal strength has not been investigated to the best authors' knowledge. In this paper, withdrawal pull-out (both parallel- and perpendicular-to-grain) and pull-through experimental tests were conducted with 7 mm in diameter self-tapping screws driven in Glulam samples under four different strain rates inducing failure from 200 sec (quasi-static) to 0.2 sec (earthquake and progressive collapse events). The experimental setup is presented and the influence of the strain rate on the withdrawal strength is discussed.

2 – BACKGROUND

Since, to the best authors' knowledge, no studies can be found in the literature on the effect of the loading speed on the withdrawal strength of fasteners driven into timber products, the present background section focuses on summarising existing research on the parameters influencing the quasi-static withdrawal strength.

Changing the fastener type from nails to screws led to a significant increase in withdrawal strength, with the improvement ranging from approximately 5 to 11 times [10]. Threaded design of screws allows them to create a stronger bond with the wood, making them more suitable for applications where withdrawal strength is crucial [11].

The withdrawal capacity of screws also typically increases with the wood density, but this effect becomes less pronounced with increasing penetration depth and screw diameter [11-13]. For example, a 14% increase in density resulted in nearly a 35% increase in withdrawal strength, but this increase dropped to 10% when the penetration depth increased by 60%. [13]. On the other hand, an experimental campaign aimed at assessing the impact of the moisture content on the withdrawal behaviour of axially loaded self-tapping screws inserted in the side face of CLT panels revealed that increased moisture content led to reduced withdrawal resistance [14]. The withdrawal strength also exhibited a positive but non-proportional relationship with both penetration depth and screw diameter. Specifically, doubling the screw diameter from 6 mm to 12 mm led to a 73% increase in withdrawal capacity in Abukari et al. study [10]. When examining the effect of the load-to-grain angle on the withdrawal strength [15], it was observed that the strength increased as the load-to-grain angle rose from 0° (parallel-to-grain) to 30°. However, from 30° to 90° (perpendicular-to-grain), there were no significant changes in the withdrawal strength. Finally, using appropriately sized pilot holes reduces resistance during screw insertion, minimises wood splitting, and optimises withdrawal strength [16]. Test results showed a 10% difference in withdrawal strength between pre-drilled and non-pre-drilled specimens [15].

3 – MATERIALS AND METHODS

3.1 MATERIALS

All samples were made from Glulam specially manufactured by 'NeXTimber(r) by Timberlink' for this study out of radiata Pine (*pinus radiata*) MGP10, a softwood structural grade for sawn timber used in structural applications [7]. The Glulam products were delivered as 8,000 mm beams with a cross-section of 65 mm in width and 168 mm in depth.

44 lengths of 800 mm were cut from four 8,000 beams. To ensure consistency between samples tested under different strain rates, from each of the first 22 lengths, four withdrawal pull-out samples were cut next to each other. Each sample was tested under a different loading rate, therefore constituting four sets of 22 nominally identical samples. The same procedure was applied to the second 22 lengths, resulting in four sets of 22 nominally identical pull-through samples. Additionally, one moisture content sample was cut from each 800 mm length to determine the moisture content of the Glulam samples at the time of testing.

All samples were stored in an air-conditioned room set at 20^{o}C before testing. The moisture content was measured immediately after testing from the moisture content

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samples following the oven-dry method specified in the Australian and New-Zealand standard AS/NZS 1080.1 [17], resulting in an average moisture content of 10.1% and 10.8%, with Coefficients Of Variation (COV) of 5.3% and 2.3%, for the withdrawal pull-through and pull-out samples, respectively.

The density of the 800 mm Glulam lengths were also measured before cutting the samples. The density ranged from 490 kg/m³ to 560 kg/m³, with an average density of 520 kg/m³ and a COV of 2.6%.

The fasteners were LBS-type fully threaded, round head with cylindrical underhead, screws manufactured by Rothoblaas [18]. The diameter was 7 mm and the length 100 mm.

3.2 WITHDRAWAL STRENGTH PULL-OUT TEST SET UP

The withdrawal strength pull-out tests were assessed under four strain rates, with targeted failure times of 0.2 s, 2 s, 20 s, and 200 s, in accordance with the procedure outlined in the Australian standard AS1649 [19]. The dimensions of the samples were 168 mm (long) × 168 mm (wide) × 65 mm (thick), as shown in Figure 1.

Two screws were driven per sample to assess both the withdrawal pull-out capacity parallel- and perpendicular-to-grain. The screws were inserted to the middle of two perpendicular 168 mm × 65 mm sides of the samples to a penetration depth equal to 75% of the screw length (i.e., 75 mm in depth) [19]. A 4 mm pilot hole were drilled to a depth of 75 mm before inserting the screws, minimising potential splitting of the timber.

A custom-made test rig was used to pull-out the screws, as shown in Figure 2. The rig consisted of two L-shaped sections positioned 70 mm apart and fixed to the bed of the testing machine. Stopper plates were welded to the top flange of each L-shape providing support to the specimens during testing. The distance between the stopper plates was 130 mm. A tensile force was applied to the screw heads by a 100 kN Instron universal testing machine, pulling the screws out of the Glulam samples. To ensure consistent initial conditions between strain rates, each sample was quasi-statically preloaded to 2 kN and then unloaded to 0.5 kN prior to applying the final loading.

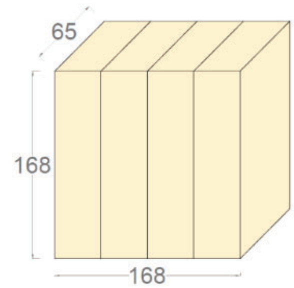

Figure 1. Withdrawal pull-out specimens

The testing machine was driven in displacement control to meet the targeted failure times. The screws were pulled out either to the complete extraction of the screws for the high loading speeds (failure in 0.2 s and 2 s) or up to a load drop of 40% from the maximum load for the low loading speeds (failure in 20 s and 200 s).

Figure 2. Withdrawal pull-out test set up

The following metrics were calculated:

- Maximum load, F_{max}, for each sample.
- Time to failure, t_f, for each sample, defined as the time from the beginning of the test to reaching the maximum load.
- Characteristic strength, f_{ch}, for each strain rate, determined following the methodology outlined in Clause 3.2 of the European standard EN 14358 [20], with the assumption of lognormal distributions.

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3.3 WITHDRAWAL STRENGTH PULL-THROUGH TEST SET UP

The withdrawal pull-through strength was also assessed under four strain rates, with the same targeted failure times as the pull-out tests. The test set up followed the guidance outlined in the European standard EN1383 [21]. The dimensions of the samples were 168 mm (long) × 168 mm (wide) × 45 mm (thick), as shown in Figure 3. Note the thickness of the samples were reduced to 45 mm from the original 65 mm of the delivered Glulam to match the requirements in EN1383 [21].

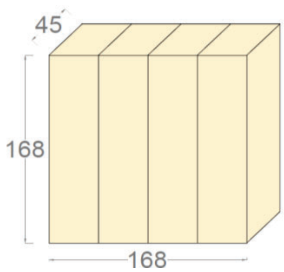

Figure 3. Withdrawal pull-through specimens

In each sample, one screw was driven in the middle of the wide face with a 4 mm pilot hole. Each screw was driven until the screw head contacted the surface of the specimen.

The samples were then tested in a 100 kN Instron universal testing machine. A custom-made test rig was used to hold the samples in place, as shown in Figure 4. The test rig consisted of a 12 mm thick steel plate with a 120 mm diameter hole to satisfy the condition $D > 2t + d_h$ in the EN 1383 [21], where D is the hole diameter, t = 45 mm is the thickness of the sample and d_h = 7 mm is the diameter of the screw. The steel plate was fixed to the bed of the testing machine using six bolts and the specimens were positioned beneath the steel plate, with the screws passing through the hole. The tip of each screw was clamped to the jaw of the testing machine which applied a tension force to pull the screws through the samples. Similar to the withdrawal pull-out tests, each sample was quasi-statically preloaded to 2 kN, then unloaded to 0.5 kN before applying the final load. The final loading was applied until the screws fully pulled through the samples for the high loading speeds (failure in 0.2 s and 2 s). For the low loading speeds (failure in 20 s and 200 s), the tests were stopped when the load dropped by 40% from the maximum load.

Same metrics as the pull-out tests were calculated for the pull-through tests.

Figure 4. Withdrawal pull-through test set up

4 – RESULTS

4.1 WITHDRAWAL PULL-OUT PARALLEL-TO-GRAIN

The measured failure times and withdrawal strengths (including average, COV and relevant characteristic values) for the withdrawal pull-out tests parallel-to-grain are summarised in Table 1. The ratio of the average withdrawal capacity to the quasi-static results (failure in 200 s) are also plotted in Figure 5 to further visualise the effect of the strain rate on the withdrawal strength.

Table 1. Withdrawal pull-out test parallel-to-grain results

Number of tests	t_f		F_{max}		
	Average (s)	*COV (%)*	*Average (kN)*	*COV (%)*	*Characteristic (kN)*
22	193.7	5.9	13.1	14.4	9.7
22	19.9	15.3	14.4	14.2	10.7
22	2.1	5.8	15.7	13.1	12.0
22	0.32	8.1	16.1	13.9	12.2

The results showed a strain rate sensitivity and a direct relationship between the withdrawal resistance and the loading rate. The withdrawal strength increased by 23.0% between failure occurring in 200 s (quasi-static) and 0.2 s. The characteristic strength values followed a similar pattern and increased by 25.4%. Such values would impact the design of screwed connections under dynamic loads, potentially leading to higher capacities or the development of a different failure mode than the quasi-static one.

4.2 WITHDRAWAL PULL-OUT PERPENDICULAR-TO-GRAIN

Similarly to Table 1, Table 2 summarises the failure times and withdrawal strengths for the withdrawal pull-out tests conducted perpendicular-to-grain. The data are also plotted in Figure 5.

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Table 2. Withdrawal pull-out test perpendicular to grain results

Number of tests	t_f		F_{max}		
	Average (s)	*COV (%)*	*Average (kN)*	*COV (%)*	*Characteristic (kN)*
22	194.5	8.2	13.5	10.9	10.9
22	19.2	9.5	14.6	11.8	11.5
22	1.82	7.9	15.4	13.7	11.7
22	0.43	13.7	16.0	14.6	11.7

The perpendicular-to-grain average and characteristic withdrawal strength values increased by 18.9% and 7.7% between the quasi-static and failure occurring in 0.2 s, respectively. These increases were lower than those observed for the parallel-to-grain direction, indicating a lower sensitivity to the loading rate. The lower increase of the characteristic value compared to the average value reflects the COV increasing with the strain rate.

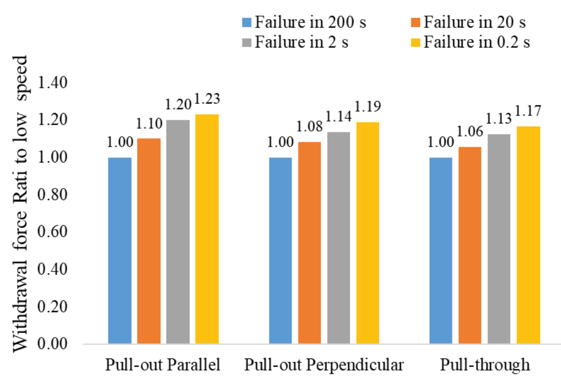

Figure 5. Ratio of the average withdrawal capacity to the quasi-static results

4.3 WITHDRAWAL PULL-THROUGH

Table 3 presents a summary of the withdrawal pull-through tests, providing the failure times and withdrawal strength values. The data are also plotted in Figure 5.

Table 3. Withdrawal pull-through test results

Number of tests	t_f		F_{max}		
	Average (s)	*COV (%)*	*Average (KN)*	*COV (%)*	*Characteristic (KN)*
22	187.5	10.9	10.4	6.0	9.3
22	18.2	13.6	11.1	8.1	9.4
22	1.88	13.6	11.8	8.0	10.1
22	0.38	10.2	12.2	8.1	10.4

The pull-through tests showed a similar level of sensitivity to the strain rate as the pull-out tests perpendicular-to-grain. The average withdrawal pull-through strength increased by 17.2% from the lowest loading speed to the highest. The characteristic strength values showed a increase of 12.7%. The COV values for the pull-through tests were lower than for the pull-out tests.

5 – CONCLUSION

This study showed that the loading rate influences the withdrawal strength of screw-type fasteners inserted into Glulam products. This sensitivity to the loading rate may have consequences in the design of connections subjected to dynamic loads. For the strain rates examined, ranging from quasi-static conditions (failure in 200 s) to earthquake and progressive collapse dynamic loading scenarios (failure in 0.2 s), the following trends were observed:

- The average withdrawal pull-out parallel-to-grain and perpendicular-to-grain strengths increased by 23.0% and 18.9%, respectively. The respective characteristic strength values showed 25.4% and 7.7% increases.
- The average and characteristic withdrawal pull-through resistances increased by 17.2% and 12.7%, respectively.
- The pull-through tests showed a lower COV than the pull-out tests.

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