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PROGRESSIVE COLLAPSE AND EARTHQUAKE STRAIN RATE EFFECT ON THE EMBEDMENT PROPERTIES OF DOWEL TYPE FASTENERS IN LAMINATED VENEER LUMBER (LVL)

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ABSTRACT: In timber engineering, embedment strength refers to the capacity of the timber material to withstand deformation under the pressure exerted by a fastener. It represents one of the key parameters in determining the design capacity of timber connections in the Eurocode 5. As this property has been shown to be sensitive to the loading rate, this study experimentally investigates the influence of the strain rate typically exhibited during earthquake and progressive collapse events on the embedment mechanical properties of dowel type fasteners inserted into softwood Laminated Veneer Lumber (LVL) structural products. Full-hole embedment tests were conducted both parallel and perpendicular-to-grain using 12 mm dowels following the method outlined in the European standard EN 383. Four different loading rates were applied, corresponding to nominal failure times of 0.2 s, 2 s, 20 s, and 200 s (quasi-static). A total of 160 embedment tests were performed. For each test, the elastic stiffness, yield stress, embedment strength and ductility were calculated. For the parallel-to-grain tests, results showed that the average elastic stiffness, yield stress and embedment strength increased by 39%, 19% and 21%, respectively, between the quasi-static and fastest loading rate. For the perpendicular-to-grain tests, these values increased by 18%, 20% and 18%, respectively.

KEYWORDS: Softwood LVL, Embedment strength, Elastic stiffness, Yield stress, Strain rate effect, Dowel type fastener

1 – INTRODUCTION

Timber structures are gaining worldwide popularity due to their numerous benefits, including low carbon footprint, natural aesthetics, superior thermal insulation, fast erection and high strength-to-weight ratio. These advantages make timber an attractive alternative to traditional construction materials like concrete and steel, which are associated with significant environmental impacts [1]. Timber structures generally fall into two categories: light-frame and mass timber buildings. Light-frame timber buildings typically use closely spaced sawn timber studs. In contrast, mass timber buildings are constructed from larger Engineered Wood Products (EWPs) such as Cross-Laminated Timber (CLT), Glued Laminated Timber (Glulam), and Laminated Veneer Lumber (LVL). Numerous examples of mid-rise to high-rise mass timber buildings, both completed and under construction, demonstrate the growing adoption of timber in the built environment. Notable examples include Ascent (2022) in the USA, a 25-story timber–concrete hybrid structure and currently the world's tallest timber building, reaching 86.6 meters [2]. Another prominent example is Mjøstårnet (2019) in Norway, a timber-only structure standing at 85.4 meters [3]. Other remarkable timber structures include the HoHo Tower

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(2020) in Austria, the Sara Kulturhus Centre (2021) in Norway, and the BskyB Building (2016) in the UK. Similarly, 25 King St (2018) and 55 Southbank Bld (2020) in Australia demonstrate the potential of timber construction for residential, commercial and mixed-use developments. The previously mentioned buildings are constructed using a combination of EWPs, assembled with mechanical fasteners typically consisting of bolts, dowels and screws [4].

For dowel type connections, either used in a steel-to-timber or timber-to-timber configuration, the embedment strength of the fastener into the timber is a critical design parameter. It is influenced by factors such as wood species, wood density, fastener diameter and load-to-grain angle [5]. Additionally, Cheng et al. [6] demonstrated that the loading rate affected the embedment strength, stiffness and ductility. This may have significant implications in the design of timber connections subjected to dynamic loads, such as those encountered during progressive collapse and earthquake events. The design rules for connections in international standards are primarily based on static testing and do not fully consider such effects. The loading rate is commonly considered by multiplying the connection static strength by a load duration factor but its influence on stiffness and ductility for dynamic loading is often ignored. The Australian Standard AS 1720.1 [7] and New Zealand Standard NZS AS 1720.1 [8] consider a load duration factor of 1.14 for laterally loaded connections and a load duration of 5 s. In contrast, the Eurocode 5 [5] uses a load factor of 1.10 for instantaneous actions for Service Classes 1 and 2 in solid timber, glulam and LVL. The North American standard NDS [9] specifies a higher strength increase of 25% between quasi-static and impact loadings.

Failure to account the full influence of the strain rate effect in the design of connections may result in unproperly designed connections, either leading to incorrect ductility factor in earthquake design or connections not able to redistribute the loads in a progressive collapse event. Table 1 presents the range of strain rates associated with different loading events affecting structural systems.

This study aims to enhance the understanding of dowel type fasteners embedded in softwood LVL by conducting embedment tests both parallel and perpendicular-to-grain. Experimental tests were performed on samples under varying strain rates, with failure times ranging from 0.2 s (earthquake and progressive collapse) to 200 s (quasi-static). The full-hole test method in the European Standard EN 383 [10] was followed with 12 mm dowels. The elastic stiffness, yield stress, embedment strength and ductility were analysed for both loading directions and discussed in the paper.

Table 1: Strain rates under different loading types [11, 12]

Loading type			**Strain rate type**	**Strain rate (s^{-1})**
Creep			Long term loading	10^{-8}
				10^{-7}
				10^{-6}
Quasi-static			Low strain rate	10^{-5}
				10^{-4}
				10^{-3}
	Earthquake			10^{-2}
			Intermediate strain rate	10^{-1}
	Vehicle crash	Blast / Impact / Explosion		10^{0}
				10^{+1}
				10^{+2}
			High strain rate	10^{+3}
				10^{+4}
			Ultra-high strain rate	10^{+5}
				10^{+6}

2 – BACKGROUND

Several studies have investigated the mechanical behaviour of timber materials under dynamic loading, with most focusing on compression and sawn timber [11, 13-17]. To the best authors' knowledge, no study has examined the dynamic compressive behaviour of EWPs, and only one study has addressed tension loading perpendicular-to-grain [6]. Regarding the embedment behaviour, studies have principally examined the quasi-static properties. For instance, a study on CLT and glulam [18] used a single quasi-static loading rate, concentrating on strength and failure mode variations. Another CLT study [19] has focused on the effect of the dowel diameter on the embedment strength, rather than varying the loading rate. Similarly, research on LVL [20] has examined embedment strength in mixed-species LVL products, but again only under a quasi-static loading rate. Only Cheng et al. [6] has explored the embedment behaviour of timber connections under dynamic loading. The study investigated 16 mm dowel type fasteners in LVL made from radiata pine *(Pinus radiata)* and Douglas fir *(Pseudotsuga menziesii)*. The samples were loaded both parallel and perpendicular-to-grain using the half-

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hole method in the ASTM D5764-97a [21]. The results showed increases in the average embedment strength of 25.2% (parallel) and 30.1% (perpendicular) as failure time decreased from 300 seconds to 0.3 seconds. However, the half-hole test setup used in the study may not accurately represent the stress conditions and embedment behaviour seen in real timber connections. Literature has shown that the embedment strength between the half-hole and full-hole test setups are providing different results [22, 23].

3 – MATERIALS AND METHODS

3.1 MATERIALS AND LOADING RATES

All specimens were produced from softwood LVL which were commercially supplied by Meyer Timber as LVL13 and manufactured from undisclosed species [24]. The LVL were delivered in boards of 4,000 mm in length, 45 mm in thickness and 90 mm in width. The samples were cut from 20 different boards to the dimensions specified in the European Standard EN 383 [10] for full-hole. Out of each board and for each loading direction, four samples were cut next to each other, constituting four sets of 20 nominally identical samples. For the parallel-to-grain tests, the specimen dimensions were 45 mm thick × 170 mm wide × 170 mm long, while for perpendicular-to-grain tests, the length was increased to 240 mm. These dimensions are illustrated in Figures 1 and 2.

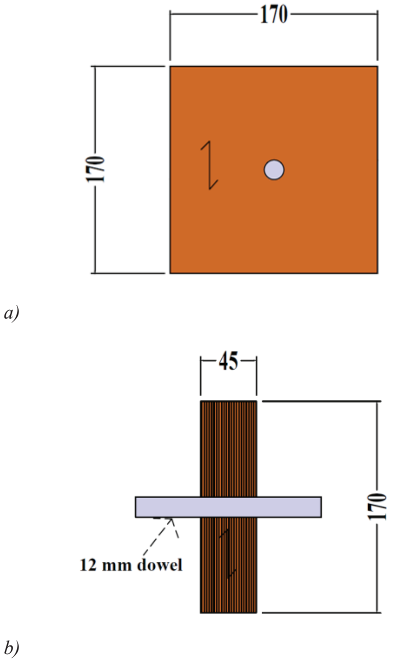

Figure 1. Embedment test samples for parallel-to-grain (a) front and (b) side views (units: mm)

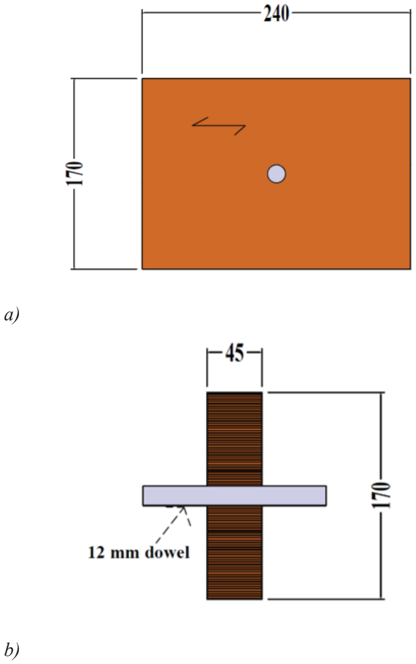

Figure 2. Embedment test samples for perpendicular-to-grain (a) front and (b) side views (units: mm)

For each loading direction, the four nominally identical sets were each tested under four loading speeds to target failure in 200 s (quasi-static), 20 s, 2 s and 0.2 s (earthquake and progressive collapse event). The number of samples of 20 per strain rate were chosen to provide statically significant results.

A ø12 mm hole was drilled in the centre of the wide face of each sample to insert a 140 mm long and ø12 dowel, made from S355 steel grade, and commercialised by Rothoblaas [25].

Prior to testing, all specimens were conditioned in an air-conditioned room set at 20°C. One moisture content sample was cut from each LVL board and used to determine the moisture content using the oven-dry method in accordance with the Australian and New-Zealand Standard AS/NZS 1080.1 [26]. The average moisture content was 9%, with a Coefficient of Variation (COV) of 8%. The density of each sample was also determined by measuring its weight and dimensions before drilling and testing.

3.2 EMBEDMENT TEST METHODS

The embedment behaviour was assessed using the full-hole embedment test as outlined in EN 383 [10]. Prior to testing, each sample was centred between two L-shaped steel plates bolted to the bed of a 100 kN Instron Universal testing machine, as illustrated in Figures 3.

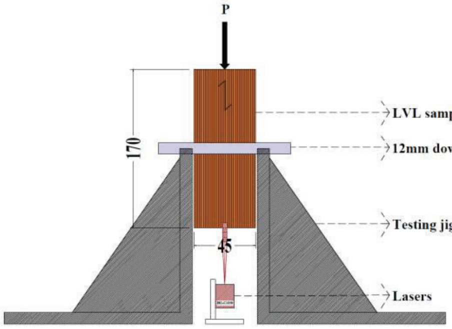

Figure 3. Schematic view of the full-hole embedment test setup

A loading block, made from a steel square hollow section, was used to apply the load evenly across the top surface of the sample. All tests were conducted in displacement control with the stroke rate set to achieve the targeted failure times. The displacement δ of the samples was recorded as the average reading from two laser displacement transducers symmetrically placed beneath the samples and aimed at their bottom surface. The actual test setup is shown in Figure 4.

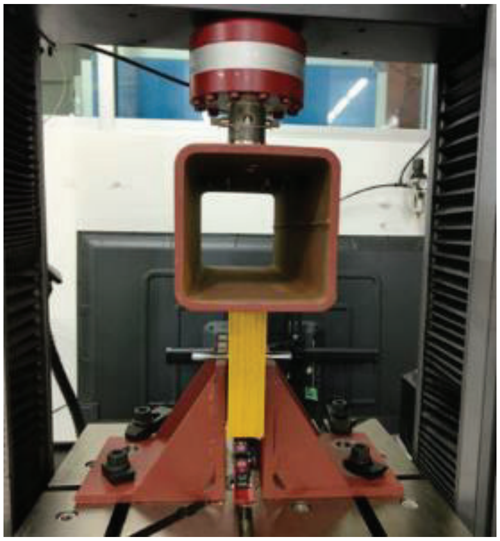

Figure 4. Actual test setup for full-hole embedment tests

To standardise the initial loading condition across all samples, each specimen was quasi-statically preloaded to 2 kN and then unloaded to 0.5 kN prior to testing, ensuring full contact between the specimens and the loading block. The tests were stopped when either the dowel displacement reached 8 mm or a significant load drop (exceeding 40% of the maximum load) was observed.

The embedment stress σ applied to each sample was determined as:

$$\sigma = \frac{P}{td} \qquad (1)$$

where P is the applied load, t is the measured thickness of the sample and d is the measured diameter of the dowel. The embedment stress σ - displacement δ curve was derived for each test to evaluate the following criteria illustrated in Figure 5:

- Time of failure, T_f: defined as the time at which the dowel displacement reached 5 mm, in accordance with EN 383 [10], or when the load decreased by 10% from the maximum load, whichever occurred first.
- Elastic stiffness, K_{el}: calculated as the slope of the linear section of the stress-displacement curve, determined by performing a linear regression between 10% and 40% of the embedment strength.
- Yield stress, $f_{y,5\%}$: defined as the stress at which the line corresponding to the offset by $0.05d$ of the linear K_{el} line intersects the stress-displacement curve as defined in the ASTM D5764-97a [21]. If the maximum load was reached before the intersecting stress, then $f_{y,5\%}$ was taken as the maximum stress.
- Embedment strength, σ_{emb}: taken as the stress measured either at a 5 mm displacement or at the maximum stress if it occurred before reaching the 5 mm displacement [10].
- Ductility, Δ: computed as the displacement at which the load dropped by 10% of the maximum load. Note, that if no load drop was encountered before the tests were stopped, ductility was not calculated.

The embedment strength characteristic values were determined for each strain rate based on the number of tests conducted using the methodology outlined in Clause 3.2 of the European Standard EN 14358 (2016) [27] assuming lognormal distributions.

4 – RESULTS

4.1 EMBEDMENT PARALLEL-TO-GRAIN

The embedment stress–displacement curves for the samples tested parallel-to-grain under the four different strain rates are presented in Figure 6. The corresponding measured and calculated values, along with their COV, are summarised in Table 2. Note that while in Cheng et al. [6] a load drop was observed before the tests were stopped, in this study a load drop was only observed for less than 25% of the samples. Consequently, the ductility was not calculated herein. This outlines one of the

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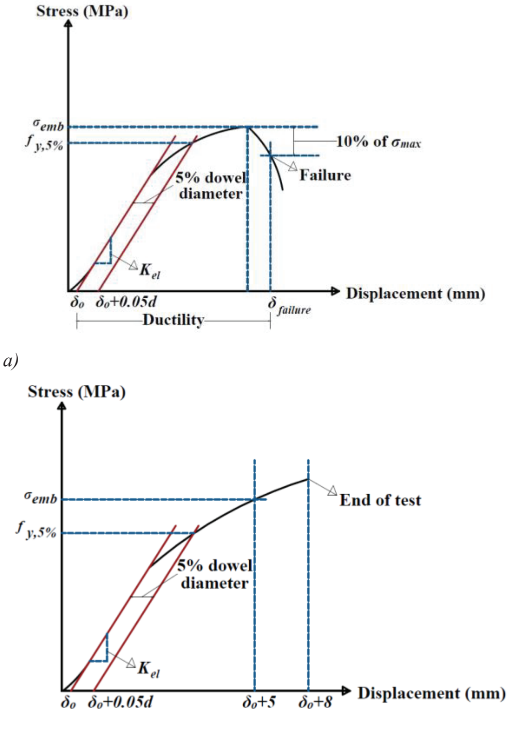
differences between the half and full-hole test setups followed in Cheng et al. [6] and this study, respectively. Additional work would be needed outside the scope of this paper to further understand the influence of the strain rate on the ductility in a full-hole test setup. This also suggests that the connections may still retain substantial deformation capacity under dynamic loading. Figure 7 shows the failure modes of one representative sample which did not experience a load drop (76.3% of samples) and one representative sample which experienced a load drop (23.7% of samples).

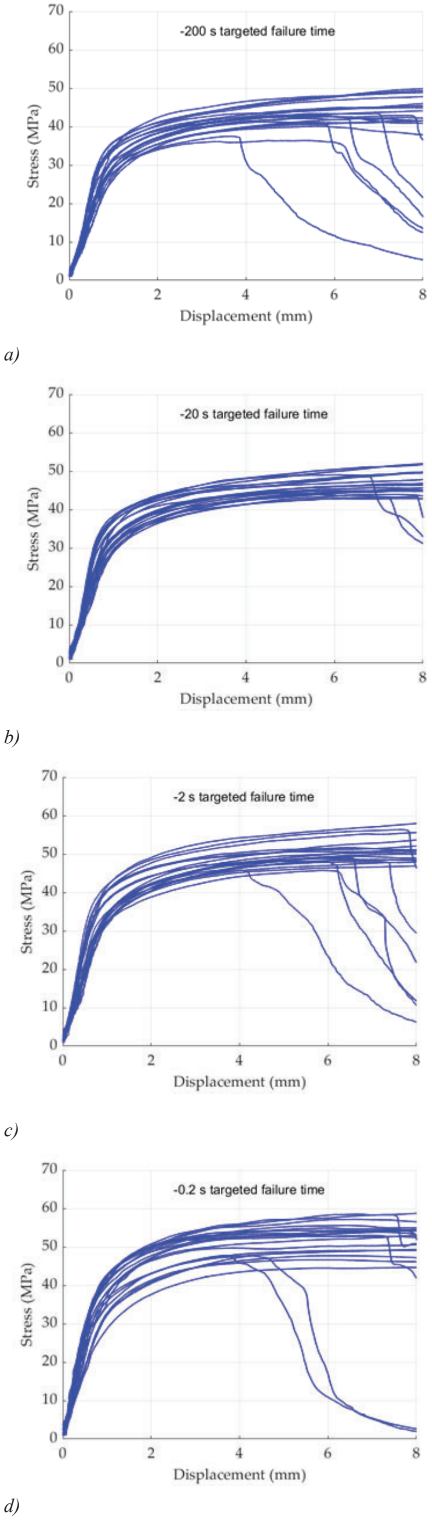


a)

b)

Figure 5. Evaluation criteria for embedment strength, (a) in the case of load drop, and (b) in the case of no load drop[6]

The results in Table 2 show that the elastic stiffness, yield stress and embedment strength are influenced by the strain rate. When comparing the results for failure occurring in 200 s and 0.2 s, the average value of the elastic stiffness, yield stress and embedment strength increased by 38.5%, 18.5% and 20.9%, respectively. The characteristic embedment strength also increased by 19.9% between the quasi-static and highest strain rate. A similar influence of the strain rate was also observed in the work of Cheng et al. [6], which found that the elastic stiffness and embedment strength increased by 11.9% and 25.1%, respectively, between failure occurring in 300 s and 0.3 s.



a)

b)

c)

d)

Figure 6. Parallel-to-grain embedment test stress-displacement curves for targeted failure in (a) 200 s, (b) 20 s, (c) 2 s, and (d) 0.2 s.

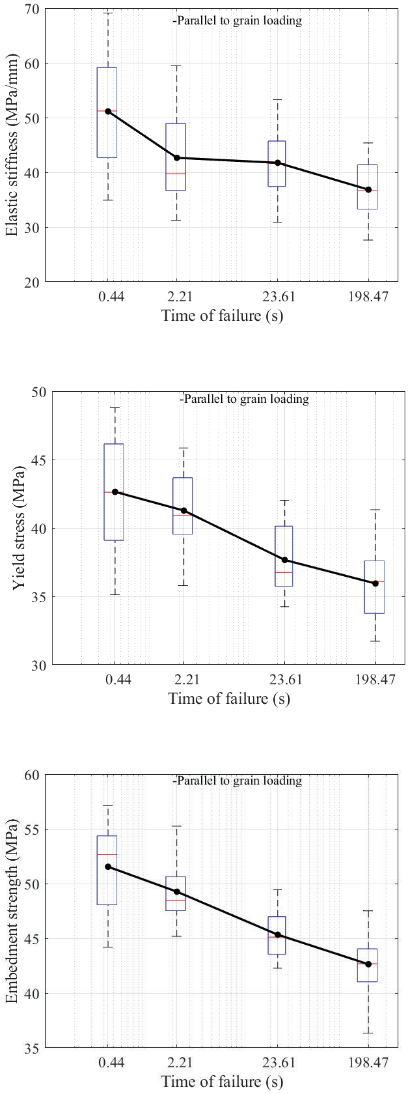
The influence of the strain rate found in the present work on the embedment properties are further illustrated in the box-and-whisker plots in Figure 8. The figure shows a nearly linear relationship between the average elastic stiffness, yield stress and embedment strength, and the logarithm value of the failure time.

Despite the test results showing high levels of ductility, the increase in stiffness and strength with increasing strain rate may imply different quasi-static and dynamic load distributions in the connections, potentially leading to higher stress concentrations and premature dynamic failure modes as observed in Cheng et al. [4].

a)

b)

Figure 7. Front view of representative samples tested parallel-to-grain experiencing (a) no load drop, and (b) a load drop



a)

b)

c)

Figure 8. Parallel-to-grain test results versus time of failure, (a) elastic stiffness, (b) yield stress and (c) embedment strength

Table 2. Embedment parallel-to-grain test results

Number of tests	***Density***		T_f		K_{el}		$f_{y,5\%}$		σ_{emb}		
	Average (kg/m^3)	***COV (%)***	***Average (s)***	***COV (%)***	***Average (MPa/mm)***	***COV (%)***	***Average (MPa)***	***COV (%)***	***Average (MPa)***	***COV (%)***	***Characte-ristic (MPa)***
20	620	4.6	198	5.4	36.8	13.9	35.9	6.8	42.6	6.9	37.2
20	624	5.6	23.6	1.6	41.7	14.8	37.7	6.5	45.3	4.8	41.2
20	619	5.3	2.2	2.8	42.7	19.8	41.3	6.4	49.3	5.7	44.2
20	618	5.6	0.44	8.2	51.1	20.5	42.7	8.9	51.5	7.3	44.6

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4.2 EMBEDMENT PERPENDICULAR-TO-GRAIN

The embedment stress-displacement curves for the perpendicular-to-grain embedment tests are presented in Figure 9 for the four different strain rates. The measured and calculated values are detailed in Table 3.

The strain rate was also found to influence the perpendicular-to-grain embedment properties with the elastic stiffness, yield stress and embedment strength all increasing with the strain rate. When comparing the results for failure occurring from 200 s to 0.2 s, the elastic stiffness, yield stress and embedment strength increased by 17.9%, 20.6% and 18.0%, respectively. A 21.4% increase in characteristic embedment strength was observed from the quasi-static to the highest strain rate conditions. These increases are less than the increases found by Cheng et al. [6] of 35.4% and 30.1% for the elastic stiffness and embedment strength, respectively, between failure in 300 s and 0.3 s.

The results are further illustrated in the box-and-whisker plots in Figure 10. Similarly to the parallel-to-grain, the figure shows a nearly linear relationship between the average elastic stiffness, yield stress and embedment strength, and the logarithm value of the failure time. Similar to Cheng et al. [6], no load drop was observed before the tests were stopped and the ductility was not calculated for these tests. The failure mode of a representative sample is shown in Figure 11.

5 – CONCLUSION

This study analysed the influence of the strain rate on the embedment behaviour of dowel-type connections in softwood LVL, with failure occurring between 200 s (quasi-static) to 0.2 s (earthquake and progressive collapse events). Results showed that the strain rate influences the embedment properties. For the range of strain rates investigated, the following findings were observed:

- The elastic stiffness increased by 38.5% and 17.9% for the parallel and perpendicular-to-grain tests, respectively, for failure time between 200 s and 0.2 s.
- Yield stress increased by 18.5% (parallel) and 26.0% (perpendicular) over the same failure time range, while the embedment strength rose by 20.9% (parallel) and 18.0% (perpendicular).

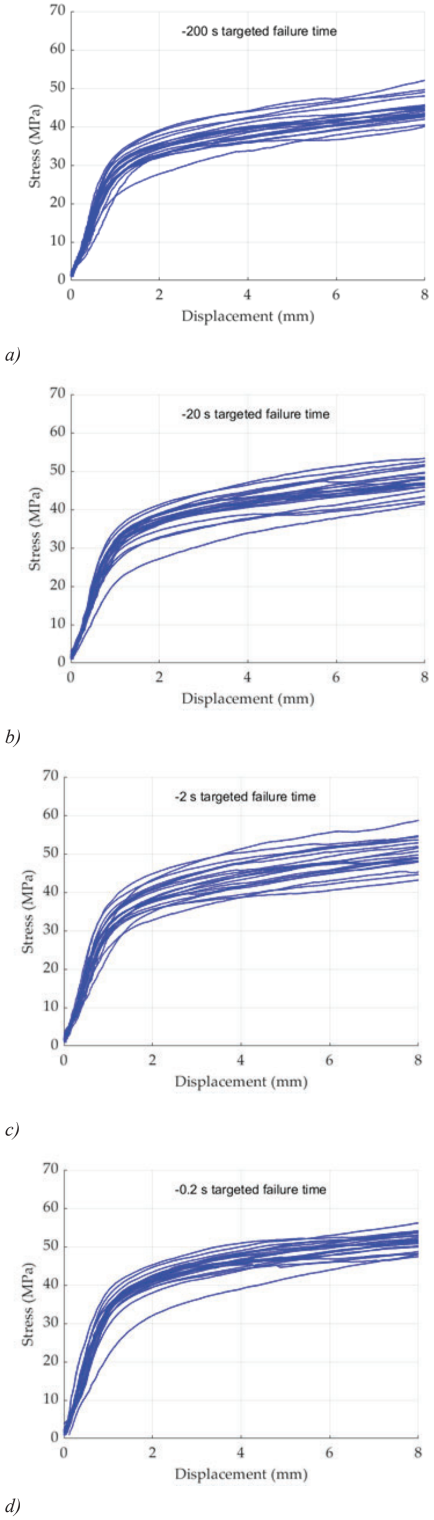

Figure 9. Perpendicular-to-grain embedment test stress-displacement curves for targeted failure in (a) 200 s, (b) 20 s, (c) 2 s, and (d) 0.2 s.

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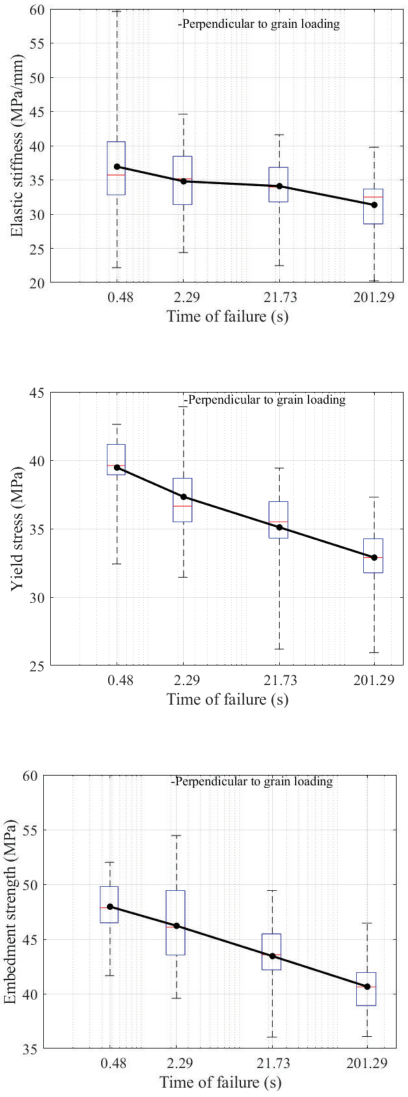
Table 3. Embedment perpendicular-to-grain test results

Number of tests	***Density***		T_f		K_{el}		$f_{y,5\%}$		σ_{emb}		
	Average (kg/m3)	***COV (%)***	***Average (s)***	***COV (%)***	***Average (MPa/mm)***	***COV (%)***	***Average (MPa)***	***COV (%)***	***Average (MPa)***	***COV (%)***	***Characte-ristic (MPa)***
20	656	4.5	201.3	1.7	31.3	15.2	32.9	7.5	40.7	6.9	35.6
20	658	3.7	21.7	1.9	34.1	12.3	35.1	8.6	43.4	7.6	37.3
20	655	3.8	2.3	4.2	34.8	14.5	37.3	8.0	46.2	8.3	39.3
20	651	3.8	0.5	12.0	36.9	20.6	39.5	5.5	48.0	5.2	43.2



a)

b)

c)

Figure 10. Perpendicular-to-grain test results versus time of failure, (a) elastic stiffness, (b) yield stress and (c) embedment strength

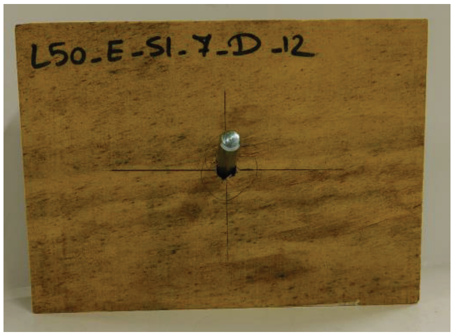


Figure 11. Front view of a representative sample tested perpendicular-to-grain.

- Characteristic embedment strength increased by 19.9% (parallel) and 21.35% (perpendicular) between the slowest and fastest loading rates.
- The failure mode remained ductile across all tests, suggesting that LVL connections retain substantial deformation capacity under rapid loading.

Despite the observed high level of ductility, the increase in embedment stiffness and strength also suggest that different quasi-static and dynamic load distributions may develop in the connections, potentially leading to higher stress concentrations and premature dynamic failure modes. Considering the embedment rate sensitivity would be critical to design resilient timber connections.

6 - ACKNOWLEDGEMENTS

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