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SEISMIC AND PROGRESSIVE COLLAPSE STRAIN RATE EFFECTS ON THE COMPRESSIVE AND TENSILE MECHANICAL PROPERTIES OF SOFTWOOD LAMINATED VENEER LUMBERS (LVL)

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ABSTRACT: This study experimentally investigates the strain rate effects encountered during seismic and progressive collapse events on the parallel-to-grain compressive and tensile mechanical properties of softwood Laminated Veneer Lumber (LVL). Specifically, it examines the compression modulus of elasticity, strength and ductility of the material under four distinct strain rates, corresponding to nominal failure times of 0.2 s, 2 s, 20 s, and 200 s, and the tension strength under two strain rates, with failure occurring in 0.2 s and 200 s. Results showed that the LVL material exhibits some level of strain rate sensitivity, with the compression strength increasing by 14.6% between the two extreme strain rates. The modulus of elasticity and ductility in compression, as well as the tensile strength, remained stable, showing no significant differences across strain rates.

KEYWORDS: Strain rate effect; Laminated Veneer Lumber; Compression parallel-to-grain; Tension parallel-to-grain

1 – INTRODUCTION

Mass timber buildings are gaining worldwide popularity for mid- to high-rise structures due to their lower carbon emissions, faster construction time, and aesthetic appeal when compared to concrete and steel buildings [1]. The emergence of Engineered Wood Products (EWPs), such as Glued Laminated Timber (Glulam), Laminated Veneer Lumber (LVL) and Cross Laminated Timber (CLT), enables to set new records in building height while allowing for prefabrication. Renowned mass timber structures, such as Ascent (USA, 2022, 86 m), Mjøstårnet (Norway, 2019, 85.4 m), and HoHo Wien (Austria, 2020, 84 m) showcase the capabilities of timber as a sustainable building material to be used in the mid- to high-rise sector.

Such buildings must be designed to withstand the dynamic events they may experience during their service life, such as earthquakes or progressive collapse, the latter resulting from a local damage spreading through the building due to an accidental load. However, while the strain rate typically influences the mechanical properties of materials [2], research on understanding this influence on EWPs is very limited. Published studies principally focused on the behaviour of sawn timber in compression and under "high" strain rates, i.e., with failure developing in less than 0.01 seconds [3-6]. This

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leaves gaps in understanding the mechanical properties of EWPs under the "intermediate" strain rates encountered during seismic and progressive collapse events (i.e., relevant to this study). For such events, the strain rates range between 10^{-3} s^{-1} and 10^{-1} s^{-1}, corresponding to failure in about 0.1 s and 10 s for timber. On the other hand, quasi-static strain rates for timber are typically inducing failure between 120 s to 300 s [7]. The ranges of strain rates for different types of events are provided in Table 1.

In international timber design standards, the strain rate effect is typically considered through the load duration factor. For instance, under instantaneous loading (wind or accidental), the quasi-static design capacity of structural members is increased by a factor of 1.10 in the Eurocode 5 [8] for Service Classes 1 and 2 buildings. While, the Australian standard AS 1720.1 [9] does not consider a strength increase for structural member and load durations of up to 5 s, Wood's [10] hyperbolic strength-load duration curve suggests a 20% strength increase between a quasi-static loading and failure occurring in 5 s. Additionally, strain rate effects were also shown to not only influence the capacity but also the stiffness and ductility [11, 12]. Therefore, to ensure the safe design of mass timber buildings under dynamic loading, a thorough understanding of the effect of the strain rate on the mechanical properties of EWPs, as the primary construction material for mass timber buildings, is essential.

This study presents compression and tension parallel-to-grain experimental tests conducted on softwood LVL samples under different strain rates, inducing failure between 0.2 s (intermediate) and 200 s (quasi-static). For the compression tests, the influence of the strain rate on the strength, Modulus of Elasticity (MOE) and ductility were investigated and reported. For the tension tests, only this influence on the strength was measured.

2 – BACKGROUND

As mentioned in the introduction, limited research has been conducted on timber samples at intermediate strain rates, with most studies performed in compression and at the high strain rates associated with explosions (Table 1). These studies [3-6, 11, 13-17] consistently found that the compression strength increased with the strain rate, although the reported ranges for this increase vary, likely depending on different factors such as wood species and loading direction (parallel or perpendicular-to-grain). Between 10^{-3} s^{-1} and 10^{3} s^{-1}, the increase in the parallel-to-grain strength were found to range between 34% and 41% while the increase ranged between 29% and 47% when loaded perpendicular-to-grain [16]. From 10^{-4} s^{-1} to 10^{-1} s^{-1}, the parallel-to-grain increase varied between 14% and 24% [5]. The strain rate effect was typically more pronounced in the perpendicular-to-grain direction rather than parallel-to-grain according to [13].

Regarding tension, to the best authors' knowledge only two investigations, focussing on hardwood [11] and softwood LVL[12], looked at the strain rate effect on the tensile strength. The samples were tested perpendicular-to-grain under quasi-static and seismic strain rates. These studies showed that the tension strength was not affected by the strain rate. No studies were found on shear.

3 – MATERIALS AND METHODS

3.1 MATERIALS

The tested samples were cut from softwood LVL commercialised by Meyer Timber and assembled from various undisclosed veneer species [18]. LVL boards, measuring 45 mm in thickness, 90 mm in width and 4,000 mm in length, were delivered. To ensure consistency between samples tested under different strain rates, 20 different LVL boards were selected. From each board, one set of four compression samples and one set of either two (first 10 boards) or four (last 10 boards) tension samples were cut. The samples for each loading type were cut next to each other. For the compression tests, the four samples in one set were tested under four different strain rates (see Section 3.2.1), totalling 20 samples per strain rates with a nominally identical population of samples per strain rate. For the tension tests, only two strain rates were investigated (Section 3.2.2) but with a higher number of samples per strain rate than for the compression tests due to the larger variability in mechanical properties of the timber material in tension compared to compression [19]. For each strain rate, one tension sample was selected from the first 10 LVL boards and two samples from the last 10 boards, totalling 30 samples per strain rate.

Table 1. common strain rates observed in solid materials under different loading conditions [2]

Load Type	Creep loads		Static loads			Earthquake			Vehicle crash		Explosion				
Strain rate(s^{-1})	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	10^{0}	10^{+1}	10^{+2}	10^{+3}	10^{+4}	10^{+5}	10^{+6}

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All specimens were stored in an air-conditioned room set at 20ºC before testing. Additionally, two moisture content samples (one for each tested loading condition) were cut from each board to determine the moisture content of the LVL samples at the time of testing. For each loading condition, the moisture content was measured immediately after testing, using the 20 samples, following the oven-dry method specified in the Australian and New-Zealand standard AS/NZS 1080.1 [20], resulting in an average moisture content of 7.2% and 9.7%, with Coefficients Of Variation (COV) of 2.1% and 6.1%, for the compression and tension samples, respectively.

3.2 MECHANICAL PROPERTIES

3.2.1 COMPRESSION

The mechanical properties in compression were assessed under four strain rates, with targeted failure times of 0.2 s, 2 s, 20 s, and 200 s, following the test setup outlined in the Australian and New-Zealand standard AS/NZS 4357.2 [21]. The dimensions of the samples were 45 mm (thick) × 90 mm (wide) × 270 mm (long), as shown in Figure 1. The samples were tested in compression in a 500 kN MTS universal testing machine run in displacement control, with the stroke rate set to best reach the maximum load at the targeted failure times. The bottom platen of the testing machine was fixed while the top platen was mounted on a spherical seat so that to adjust and provide uniform pressure to the samples. A preload of 0.5 kN was applied to all samples, for the platens to be in full contact with the samples at the beginning of the tests. The compression test setup is shown in Figure 2.

A 50 mm range extensometer was attached to all samples, measuring the strain ε used in the calculation of the MOE. Additionally, the stroke δ of the testing machine was recorded to evaluate the overall deformation behaviour, providing insights into the material's ductility across different strain rates.

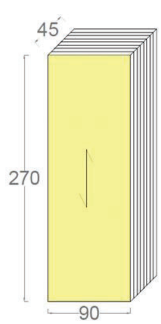

Figure 1. Compression test specimen sketch (dimensions in mm)

The following metrics were calculated for each sample:

- Time to failure T_f, defined as the time from the beginning of the test until reaching the maximum load.
- Compression strength f_c, obtained as the maximum applied stress defined as,

$$f_c = \frac{F_{max}}{A} \qquad (1)$$

where F_{max} is the maximum applied load and A is the measured cross-sectional area.
- Characteristic compression strength $f_{ch,c}$, determined based on the number of tests performed following the methodology outlined in Clause 3.2 of the European standard EN 14358 [22], with the assumption of logarithmically normally distributions.
- Ductility, calculated as the ratio of the ultimate stroke displacement δ_u (i.e., at maximum load) to the yield stroke displacement δ_y. δ_y was calculated from the load-displacement curve as the displacement at the intersection of the linear regression line fitted between 10% to 40% of the maximum force and the horizontal line corresponding to the maximum force.
- MOE E, determined as the slope of the stress-strain curve, determined by performing a linear regression between 10% and 40% of f_c.


Figure 2. Compression test setup

3.2.2 TENSION

The tensile tests were conducted following a modified version of the dog bone sample presented in the ASTM D143-14 standard [23]. The gauge dimensions of the specimens were increased to more than twice the ASTM recommendations to increase the volume of material subjected to a uniform tensile stress. The overall length

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of the samples was 1,000 mm, with the gauge being 200 mm long, 20 mm thick and 40 mm wide, as shown in Figure 3. A special jig, with serrated plates and screws, clamped the ends of the samples. The jig was attached to the jaws of a 500 kN capacity MTS universal testing machine, run in displacement control, with the samples tested in tension at a stroke rate set to reach a targeted failure time of either 0.2 s or 200 s. The test setup is shown in Figure 4. A preload of 0.5 kN was applied to all samples.

The following metrics were calculated for each sample:

- Time to failure T_f, defined as the time to reach the maximum load.
- Tension strength f_t, obtained as the ratio of the maximum applied load F_{max} to the measured gauge cross-sectional area A as,

$$f_t = \frac{F_{max}}{A} \qquad (2)$$

- Characteristic tension strength $f_{ch,t}$, calculated as for the compression samples in Section 3.2.1.

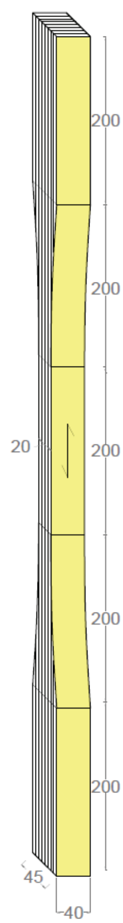

Figure 3. Tension test specimen sketch (dimensions in mm)

Figure 4.Tension test setup

4 – RESULTS

4.1 COMPRESSION

The applied stress-stroke displacement curves resulting from the compression parallel-to-grain tests are shown in Figure 5 for all strain rates. Average failure times, and measured mechanical properties, with associated COV, are summarised into Table 2.

The average compression strength f_c increased as the strain rate increased, with an increase of 14.6% between the slowest and fastest strain rates. Similarly, the characteristic compression strength $f_{ch,c}$ exhibited a comparable trend with an increase of 10.5%. The variation of the average compression strength f_c is plotted versus the failure time in Figure 6 to further illustrate the relationship between the two values.

The above findings suggest that the Eurocode 5 [8] offers a more accurate estimation of the characteristic compression strength increase for LVL under intermediate rate loading, whereas the AS 1720.1 [9] and Wood's model, may underestimate and overestimate the capacity under intermediate rate loading, respectively.

The MOE remained constant, with no clear increasing or decreasing observed trend. Additionally, while the calculated ductility factor also remained constant in Table 2, Figure 5 shows that in the post failure stage, the load tended to drop at a faster rate when the strain rate increases and would need further investigation.

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4.2 TENSION

The average failure times and tension strengths for the tension parallel-to-grain tests are summarised in Table 3.

The average tension strength remained constant with no significant difference (only showing a 2.7% decrease) between the quasi-static strain rate and failure occurring in 0.2 s. The minor variation in the characteristic values of 2.6% also suggests that in the investigated range, the strain rate would not affect the design value for LVL. The average tensile strength versus the failure time is plotted in Figure 7.

As international standards do not differentiate between loading types for the load duration factors, opposite findings than for compression can be drawn. By proposing short term load-duration factor of 1.10, the Eurocode 5 [8] overestimates the tension capacity under intermediate rate loading whereas the AS 1720.1 [9] provides a satisfactory load duration factor of 1.0. Wood's model, also overestimates the short-term tension capacity.

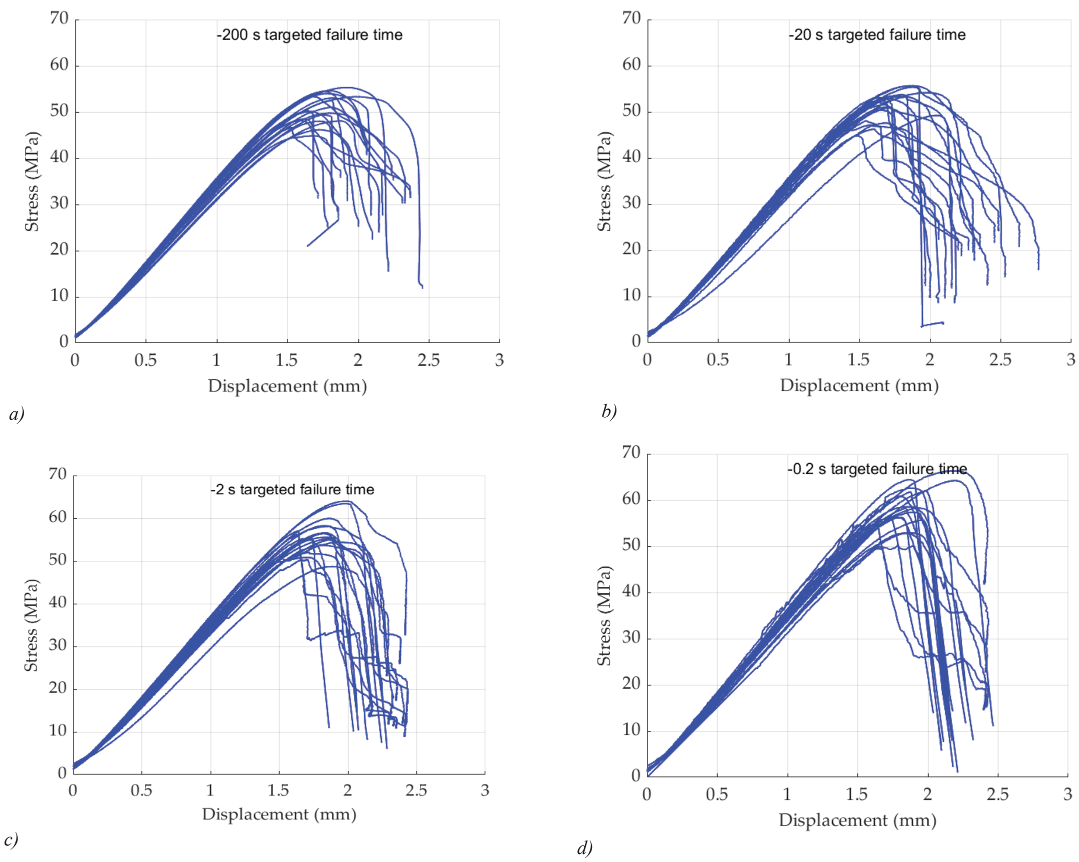

Figure 5. Compression tests stress-stroke displacement curves for targeted failure time of (a) 200 s, (b) 20 s, (c) 2 s, and (d) 0.2 s.

Table 2. Compression parallel-to-grain test results

Number of tests	T_f		f_c			E		Ductility	
	Average (s)	*COV (%)*	*Average (MPa)*	*COV (%)*	*Characteristic (MPa)*	*Average (MPa)*	*COV (%)*	*Average*	*COV (%)*
20	184.9	7.1	50.6	6.2	44.8	13,787	15.7	1.15	2.8
20	18.6	8.5	51.3	6.3	45.3	14,122	14.5	1.13	3.3
20	1.95	6.7	55.6	7.2	48.4	14,370	12.4	1.12	5.4
20	0.21	10.4	58.0	8.1	49.5	13,852	21.1	1.12	3.6

Table 3. Tension parallel-to-grain test results

Number of tests	T_f		f_t		
	Average (s)	*COV (%)*	*Average (MPa)*	*COV (%)*	*Characteristic (MPa)*
30	195.6	24.4	56.6	16.0	50.8
30	0.18	20.2	55.0	14.3	49.5

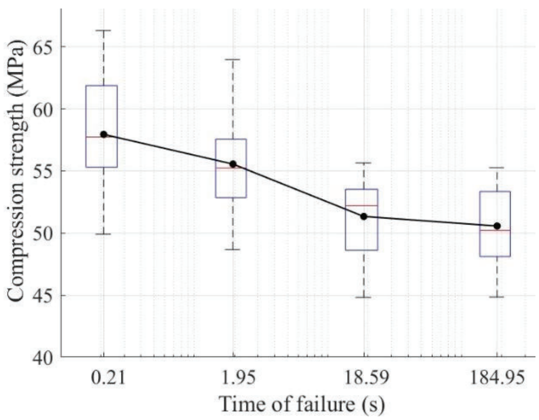

Figure 6. Average compression strengths versus time to failure

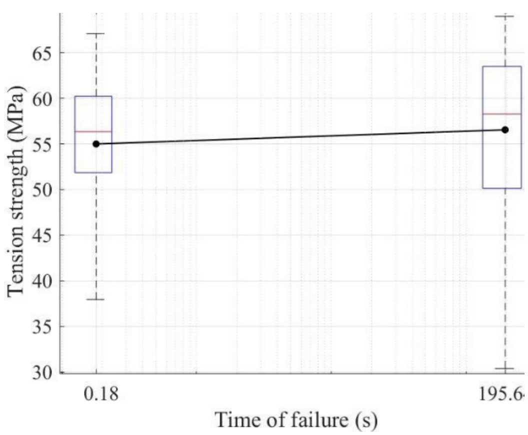

Figure 7. Average tension strengths versus time to failure

5 – CONCLUSION

This study experimentally examined the influence of the strain rate on the compression and tension mechanical properties of softwood LVL. The strain rates considered induced failure between 200 s (quasi-static) and 0.2 s, with the faster rate corresponding to the strain rate encountered during seismic and progressive collapse events. Different behaviours were observed in compression and tension:

- The compression strength increased by 14.6% between failure occurring in 200 s and 0.2 s, demonstrating strain rate sensitivity and increased load-bearing capacity.
- The MOE and compression ductility were found to be insensitive to the strain rate in the investigated range. However, the post-failure ductility seemed to be impacted by the strain rate.
- The tension strength was also found to be insensitive to the strain rate.
- The load duration factor of 1.10 proposed in the Eurocode 5 for short-term duration would be appropriate for compression but not tension, whereas the load duration factor of 1.0 proposed in the AS 1720.1 would be appropriate for tension but not compression.

6 - ACKNOWLEDGEMENTS

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