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STRAIN RATE EFFECTS ON FRACTURE ENERGY AND STRENGTH PROPERTIES OF RADIATA PINE AND SPOTTED GUM

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ABSTRACT: Timber structures are increasingly used in construction due to their high strength-to-weight ratio and sustainability benefits. However, the dynamic behaviour of timber connections under seismic and accidental impact loading remains insufficiently understood. This study investigates the strain rate effects on key mechanical properties of Radiata Pine and Spotted Gum sawn timber, including Mode I and II fracture energies, tensile strength perpendicular to the grain, and embedment strength parallel to the grain. Laboratory experiments were conducted across a range of strain rates, and the results were critically compared with previous findings on engineered wood products. The study revealed that, Mode I fracture energy decreased with increasing strain rate by approximately 15–20% per 10 times strain rate increase, while Mode II fracture energy exhibited a slight increase or remained stable. Tension strength perpendicular to the grain showed minimal sensitivity to loading rate, consistent with the brittle nature of timber failure dominated by natural defects. Embedment strength and stiffness also exhibited slight decreases with strain rate, while ductility significantly reduced by approximately 26% per decade. These observations diverge from previous studies on laminated veneer lumbers, where increases in dynamic embedment strength were reported. The findings suggest that the dynamic response of sawn timber species may differ significantly from engineered products, emphasizing the need for further experimental investigation. Incorporating realistic dynamic properties into design models is essential for improving the safety and reliability of timber structures under seismic and impact conditions.

KEYWORDS: Strain rate effect; Fracture energy; Embedment strength; Tension perpendicular to grain; Radiata Pine; Spotted Gum

1 – INTRODUCTION

Timber has gained increasing attention as a sustainable and versatile construction material, offering significant advantages over traditional materials such as steel and concrete in terms of strength-to-weight ratio, environmental impact [1] and aesthetic appeal. Recent developments in engineered wood products, such as laminated veneer lumber (LVL) and cross-laminated timber (CLT), have allowed timber to be used in mid- and high-rise structures traditionally reserved for heavier materials in lieu of durability [2] and dimensional stability [3]. However, despite these advancements, the behaviour of timber structures and connections under dynamic and cyclic loading conditions remains an active area of research, particularly given timber's natural variability and susceptibility to brittle failure. Based on authors earlier research, the mechanical properties of timber, including fracture energy, tensile strength, and embedment strength, are sensitive to the rate of loading. Prior research by Ardalany et al. [4,5] and Vasić et al. [6] indicated that timber often exhibits strain rate dependency, with mechanical strength and energy absorption capacity typically increasing under rapid loading. Similar trends have been reported by Cheng et al. [7], who studied the strain rate effects on the embedment strength and fracture behaviour of softwood LVLs. Their results showed that dynamic loading could enhance embedment strength by up to 30%, although

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ductility was reduced under fast loading, an observation critical to the seismic design of timber connections.

In addition to monotonic loading, the cyclic behaviour of timber connections has been the subject of extensive research. Ataei et al. [8] investigated the cyclic behaviour of embedded bolted shear connectors in steel-timber composite beams and found that cyclic degradation of strength and stiffness could be substantial, depending on the connector type and load history. Further work by Ataei et al. [9] on the cyclic behaviour of shear connectors demonstrated that both stiffness and energy dissipation capacity decrease with repeated quasi-static loading, emphasizing the importance of connection detailing for maintaining performance under seismic conditions. Although significant progress has been made for engineered wood products and hybrid timber-steel systems, there is still a lack of comprehensive studies focusing on the dynamic performance of natural sawn timber species, such as Radiata Pine (*Pinus radiata*) and Spotted Gum (*Corymbia maculata*). Furthermore, there is almost no data on the effects of strain rate on different failure modes—such as Mode I and Mode II fracture energies, tensile strength perpendicular to grain, and embedment strength—highlight the need for further investigation in the literature regarding. While Cheng et al. [7] observed increased dynamic strength, other studies have reported more complex behaviours, including rate-dependent stiffness changes under compression and variable fracture patterns, depending on species and test configurations.

To address these gaps, the present study investigates the strain rate effects on the mechanical properties of Radiata Pine and Spotted Gum. Using controlled laboratory experiments at different strain rates, this study measures Mode I and II fracture energies, tensile strength perpendicular to grain, and embedment strength parallel to grain. The results are critically compared with the findings of Cheng et al. [7], Ataei et al. [9,10], and other relevant literature, aiming to clarify the dynamic performance of sawn timber under different loading conditions similar to those encountered during seismic or progressive collapse events. Improved understanding of these behaviours will contribute to the development of more accurate and safer design models for timber structures exposed to dynamic loads.

2 – METHODOLOGY

2.1 Materials

In this study, two timber species commonly used in Australia were selected to represent hardwood and softwood categories: Spotted Gum (*Corymbia citriodora*) with F14 grading, and Radiata Pine (*Pinus radiata*) with F7 grading. The average densities were measured to be approximately 1025 kg/m³ for Spotted Gum and 495 kg/m³ for Radiata Pine. Specimens were cut following a detailed cutting plan to avoid timber defects such as knots and resin pockets. Before testing, they were conditioned at a temperature of 20 ± 2°C and 65 ± 5% relative humidity (RH), as recommended by AS/NZS 1080.1:2012, to reach equilibrium moisture content. Moisture contents were determined by the oven-dry method according to the same standard (Figure 1). The average equilibrium moisture content was recorded as 13.3% for hardwood and 14.9% for softwood.

Figure 1. Conditioning specimens in a humidity chamber

2.2 Experimental Program

The experimental program consisted of four main test stages, each targeting a specific mechanical property essential for timber connection design: Mode I fracture energy, Mode II fracture energy, tension perpendicular to grain, and embedment strength parallel to grain. Tests were performed under four different loading rates corresponding to different target failure durations to simulate quasi-static to dynamic loading conditions. For fracture energy Mode I, loading speeds of 0.1 mm/s, 1 mm/s, 10 mm/s, and 80 mm/s were applied. For Mode II fracture energy tests, the loading speeds were 0.8 mm/min, 8 mm/min, 80 mm/min, and 800 mm/min. Tension perpendicular tests were conducted at 0.21

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mm/min, 2.1 mm/min, 21 mm/min, and 210 mm/min, while embedment tests were performed at 0.6 mm/min, 6 mm/min, 60 mm/min, and 600 mm/min. Accordingly, the targeted time to failure was measured for corresponding loading rates. Specimens were tested using MTS and Instron universal testing machines with capacities ranging from 30 kN to 500 kN depending on the test setup. All load and displacement data were recorded using LabView software, with calibration checks carried out before testing.

2.3 Test Procedures

Mode I fracture energy was measured using a three-point bending setup where the specimen rested on two rollers 600 mm apart, with load applied at the mid-span [4] . The experimental setup, sample dimensions and loading procedure for Mode I are depicted in Figure 2 and Figure 3. Preloading to 10 N followed by unloading to 1 N was applied before the actual test to ensure proper specimen seating.

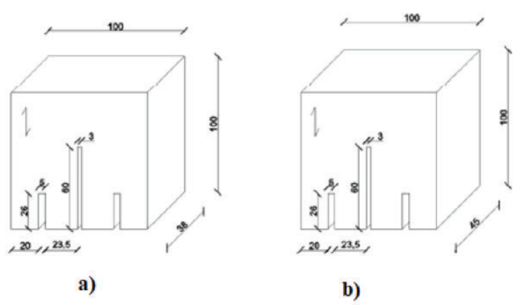

Figure 2. Specimen dimensions for mode I tests a) hardwood and b) softwood sawn timber

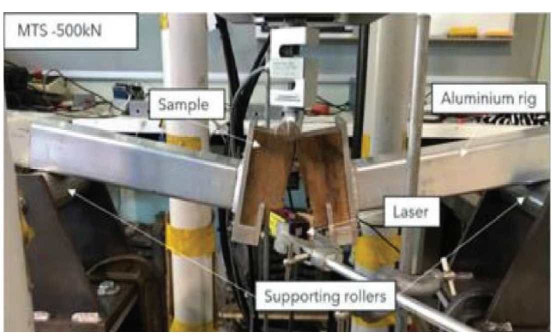

Figure 3. Loading process of the specimen tested in mode I

Mode II fracture energy was evaluated through a shearing configuration using specimens notched symmetrically along the centreline [11,12]. The loading setup involved applying force parallel to the grain, inducing shear failure at the notch plane, as shown in Figure 4. The specimens' dimension was same as shown in Figure 2. Preloading of 2 kN and unloading to 0.2 kN were carried out before loading. Care was taken to monitor lateral shifts that could affect results, and specimens touching the support sides were noted and excluded if necessary.

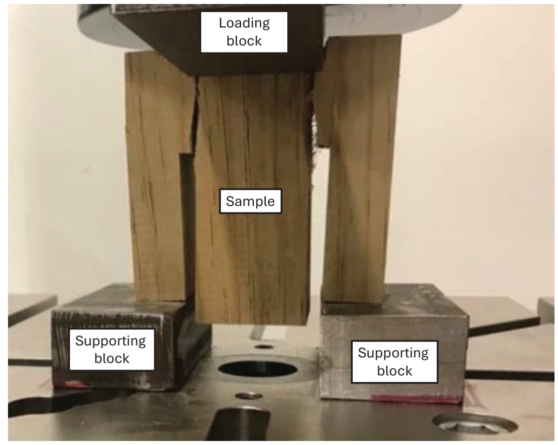

Figure 4. Loading process of the specimen tested in mode II

Tension perpendicular to the grain was tested by placing specimens between C-shaped grips in an Instron machine, following ASTM D143-94 standards. Specimen dimensions and the loading setup are illustrated in Figure 5 and Figure 6. Preloading of 300 N and unloading to 30 N were applied to ensure firm grip. The maximum tensile stress was calculated by dividing the peak load by the cross-sectional area at the failure plane.

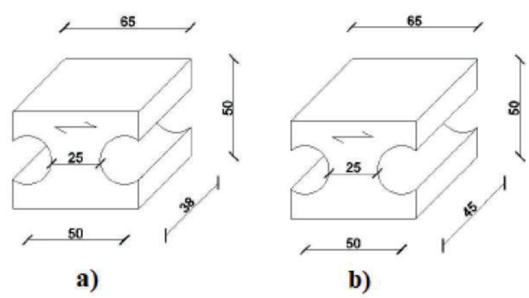

Figure 5. Specimen dimensions for tension perpendicular to the grain tests a) hardwood and b) softwood sawn timber

Embedment strength was measured by the half-hole embedment test method in accordance with ASTM D5764-97a. Specimens were prepared with a 16 mm drilled hole and loaded through a steel dowel attached to two aluminium plates for alignment, as shown in Figures 20 to 22. Preloading of 3 kN and unloading to 0.3 kN were performed before the final loading. Tests were terminated upon reaching either 6 mm dowel displacement or a significant drop in load.

Figure 6. Test setup for measuring tension perpendicular to the grain

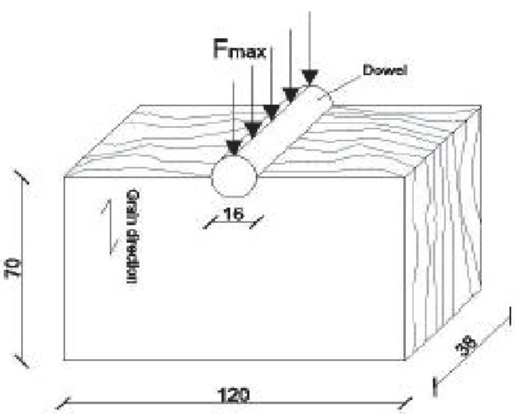

Figure 7. A schematic view of the embedment test sample

2.4 Data Processing and Analysis

Load and displacement data were processed using standard calculation methods. Fracture energy for both Mode I and Mode II was determined as the area under the load–displacement curve normalized by the fracture area. Tensile strength perpendicular to grain was computed by dividing the maximum load by the specimen's minimum cross-sectional area. Embedment strength was calculated following ASTM methods, including the determination of proportional limit force, yield strength, and ultimate force. For each test type and timber species, mean values, standard deviations, and coefficients of variation were computed. Characteristic values were determined assuming lognormal distributions according to EN 14358. Stress-displacement curves were analysed for initial stiffness, peak load, and failure modes.

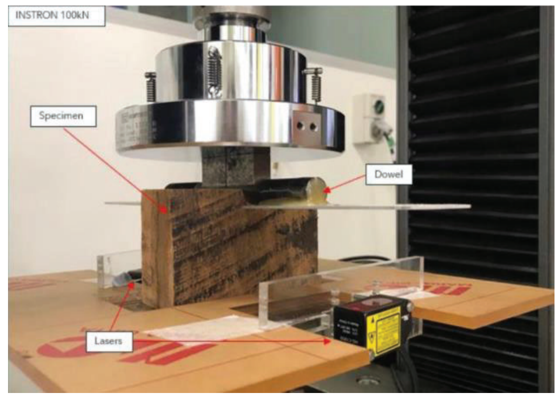

Figure 8. Test setup for measuring embedment strength parallel to the grain using the half-hole test method given by the ASTM D5764-97a

3 – RESULTS

3.1 Mode I Fracture Energy

The Mode I fracture energy results are presented in Figure 9. Interestingly, for both timber species, an increase in fracture energy was observed with decreasing strain rate. For Radiata Pine, the mean Mode I fracture energy decreased by approximately 17% each time the strain rate increased by a factor of 10. Spotted Gum exhibited a similar trend, with about a 15% reduction in fracture energy for every tenfold increase in strain rate. This trend is not consistent with the general findings in the literature [4,6], where an increase in strain rate typically leads to an increase in fracture energy. While the test setup used to measure fracture energy is well-recognised—particularly for Mode I—the results suggest potential limitations in capturing certain aspects of the response, especially under other test conditions. It is important to note that numerous repeat tests were conducted, and a consistent trend was observed across all experiments.

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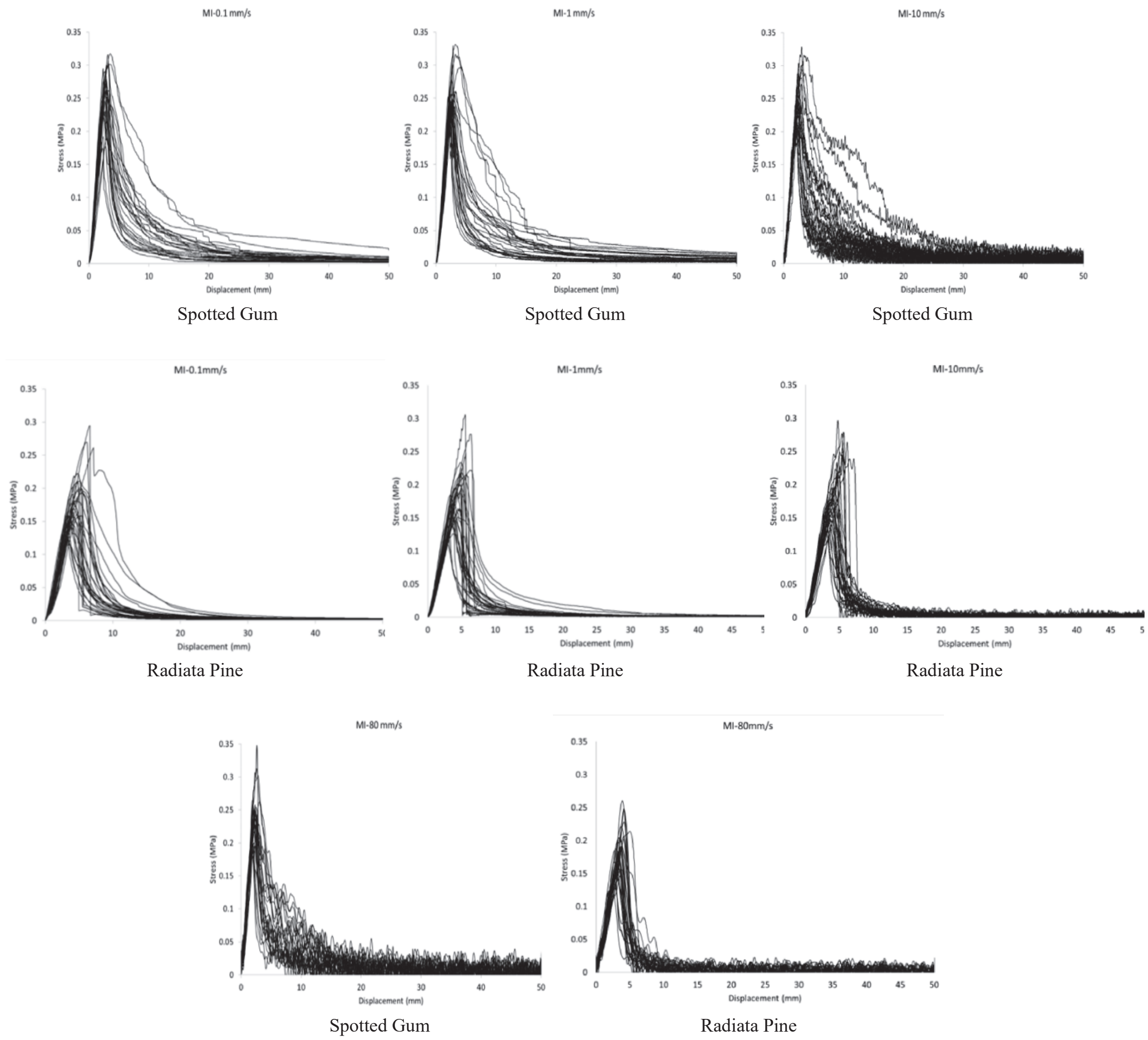

Figure 9. Stress-displacement graphs of fracture energy mode I at different strain rates.

3.2 Mode II Fracture Energy

The Mode II fracture energy results are shown in **Error! Reference source not found.**. The Mode II tests exhibited a higher coefficient of variation compared to the Mode I results. Although a clear and consistent trend was not observed in Mode II tests, on average with removing in consistent results, the fracture energy decreased by approximately 20% for Radiata Pine and 12% for Spotted Gum with every tenfold increase in strain rate. These observations are consistent with the findings of Franke and Quenneville [12], who reported that dynamic loading improves the shear fracture resistance of timber connections. Shear failure predominantly occurred along the notched plane without major deviation, and the fracture surfaces exhibited limited fibre pull-out. This indicates a brittle shear failure mode, especially at higher strain rates.

3.3 Tension Perpendicular to Grain

The tensile strength perpendicular to the grain results are presented in Figure 11. Similar to the Mode II fracture energy results, the tensile strength results did not show a consistent trend across different strain rates; however, the coefficient of variation (CoV) was considerably lower for the maximum stress measurements. On average, the results showed a 1.3% reduction in tensile strength for Radiata Pine and a 2.3% reduction for Spotted Gum with every tenfold increase in strain rate. Therefore, the impact of strain rate on the variation of maximum tensile strength perpendicular to the grain appears to be less pronounced. This limited strain rate sensitivity is consistent with previous findings, which suggest that tensile failures perpendicular to the grain are largely controlled by the presence of natural defects and are relatively insensitive to dynamic effects [13,14]. All specimens failed in a brittle manner, characterised by sudden splitting perpendicular to the grain.

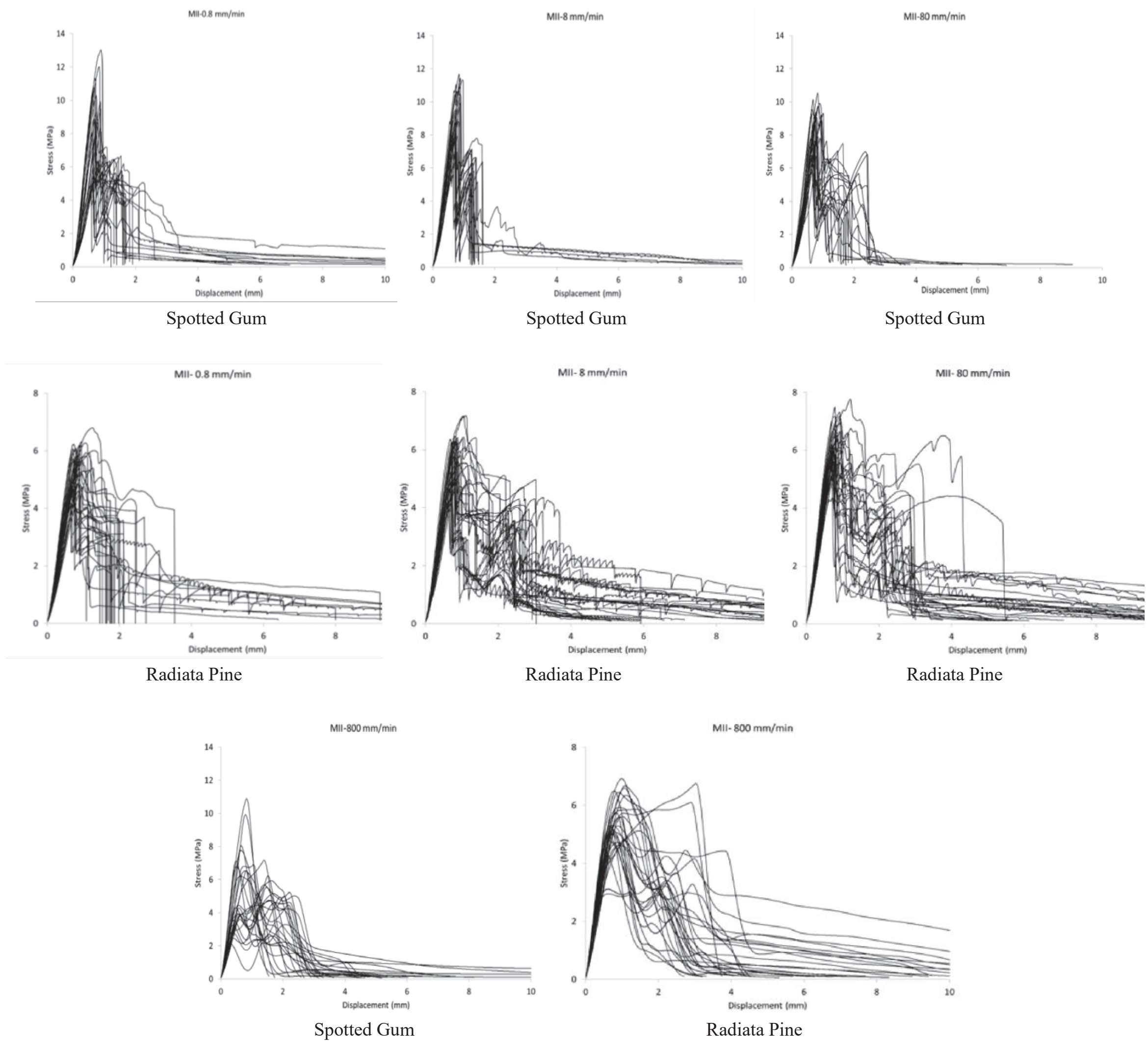

Figure 10. Stress-displacement graphs of fracture energy mode II of softwood (Radiata Pine) at different strain rates.

3.4 Embedment Strength

The embedment strength parallel to the grain results are presented in Figure 12. Except for the highest strain rate of 10 mm/s, a clear decrease in strength with increasing loading rate was observed, with an average 6.3% reduction in strength for every tenfold increase in strain rate. Stiffness also exhibited a similar trend, with an average reduction of 4.3% per tenfold increase in strain rate. Ductility, however, remained more consistent across all considered strain rates, showing an average 26% decrease for every tenfold increase in strain rate. The enhancement in embedment strength under dynamic loading conditions can be attributed to localized stiffening and delayed fibre crushing, as observed in previous studies [7,15,16]. The load–displacement curves typically exhibited a linear elastic region followed by yielding, with higher peak loads achieved at faster loading rates.

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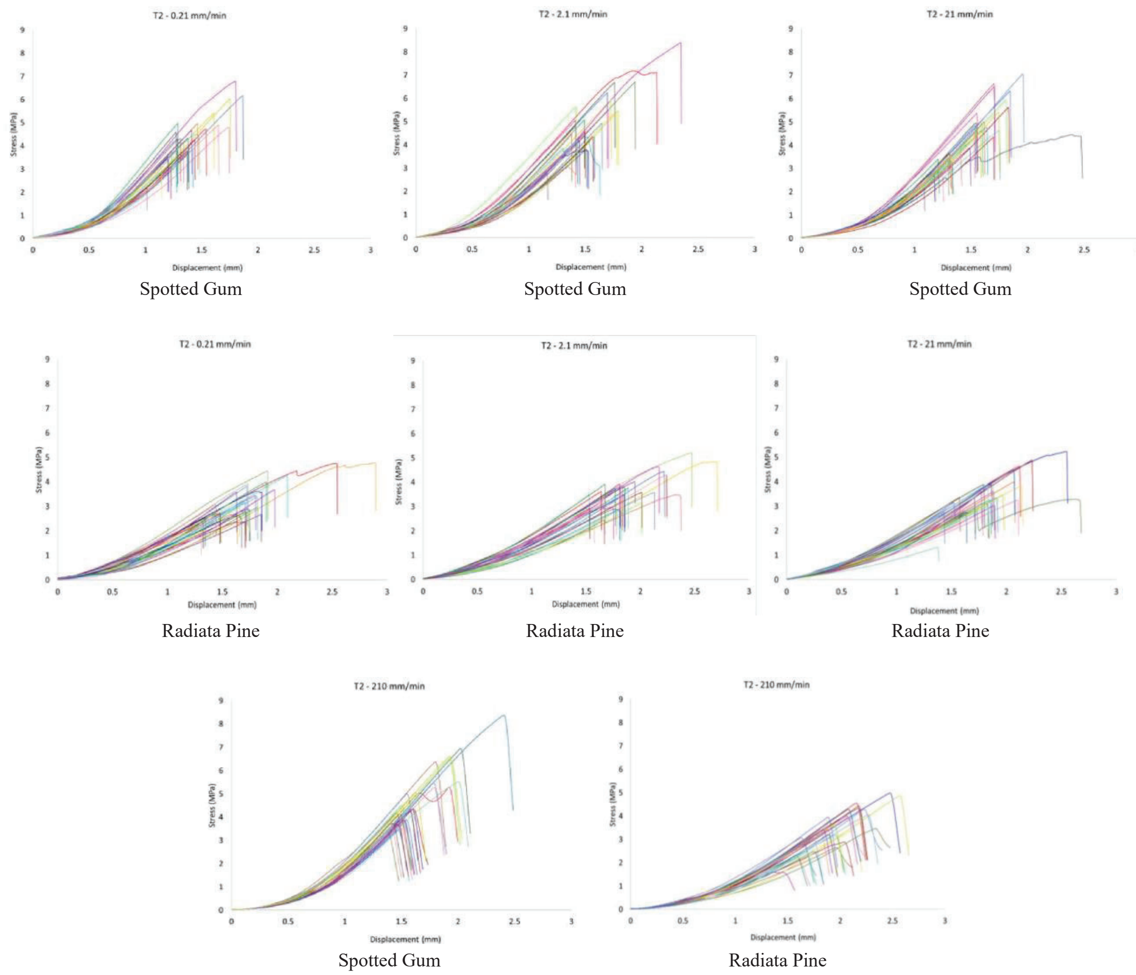

Figure 11. Stress-displacement graphs of tension perpendicular to the grain of softwood (Radiata Pine) at different strain rates.

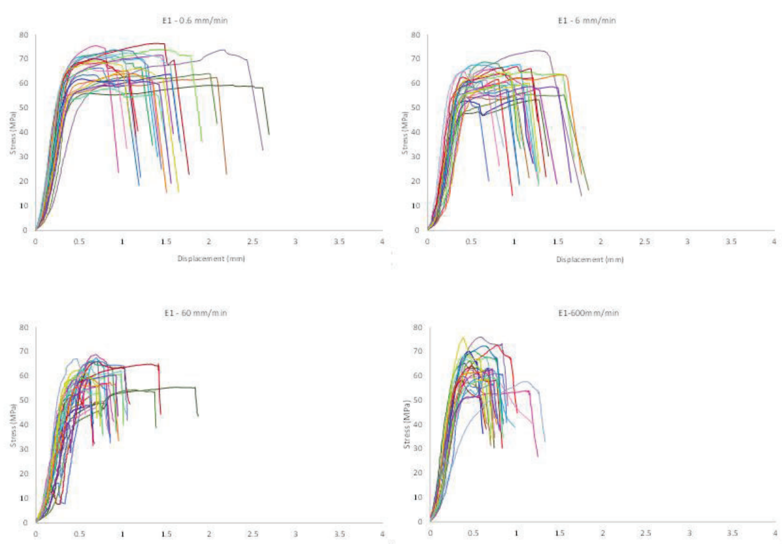

Figure 12. Stress-displacement graphs of embedment test parallel to the grain of hardwood (Spotted Gum) at different strain rates.

4 – CONCLUSION

This study investigated the strain rate dependency of key mechanical properties of Radiata Pine and Spotted Gum, including Mode I and II fracture energies, tension strength perpendicular to grain, and embedment strength parallel to grain. The results showed that fracture energy in both Mode I and Mode II decreased with increasing strain rate, by approximately 17%–20% per decade increase in strain rate, contrary to trends reported in previous studies such as Cheng et al. (2023). Tension strength perpendicular to grain exhibited minimal strain rate sensitivity, consistent with prior findings. Embedment strength and stiffness also decreased slightly with increasing strain rate, while ductility experienced a notable reduction of approximately 26% per decade increase. These observations suggest that timber elements subjected to dynamic loading may experience reduced fracture energy absorption and lower embedment strength than previously expected, potentially increasing their susceptibility to brittle failures. When compared to findings by Cheng et al. (2023), where increases in dynamic embedment strength and stable fracture energies were reported, the discrepancies highlight the need for further experimental investigations under controlled conditions to ensure reproducibility and accurate dynamic property characterization. Understanding and incorporating the real dynamic behaviour of timber materials into design models is crucial for ensuring the safety and reliability of timber structures, especially under seismic or accidental impact events.

5 – ACKNOWLEDGEMENT

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