Journal of
Composites Science

Article

Effect of Primer and Fibre Orientation on Softwood–Hardwood Bonding

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Abstract: Softwood is widely employed in construction and faces high demand. Australia is grappling with substantial timber scarcity, specifically related to radiata pine, which is the dominant structural timber in the construction sector. However, Australia has a significant hardwood population, which can be utilized to reduce the high demand for radiata pine. This paper aims to investigate the bond properties of both Australian softwood (radiata pine) and hardwood (shining gum). It also discusses the potential to combine softwood and hardwood in glue or cross-laminated timber by evaluating the bond properties of the radiata pine–shining gum interface. For hardwood, the effect of primer is also investigated to determine its efficacy in improving failure mode, bond strength, and stiffness. Lastly, both glulam and cross-laminated timber bonding scenarios are simulated for bond testing by examining the effect of relative fibre orientation on the bond properties of the aforementioned species individually and in combination. Instead of conventional block shear testing, which is predominantly used for same-species bond testing, push-out testing is adopted in this study. However, a comparison with block shear testing is also made in this article. The results indicated that the use of primer on hardwood reduced the inconsistencies in the bond properties and improved wood-side failure rates. It was also concluded that the effect of fibre orientation in a CLT scenario with combined hardwood and softwood failure modes can vary significantly, which leads to a higher standard deviation in the results. Nevertheless, this study outlines the challenges and opportunities for producing hardwood–softwood hybrid glue or cross-laminated timber.

Keywords: hardwood; softwood–hardwood; primer; bond properties

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Citation: Subhani, M.; Lui, H.Y. Effect of Primer and Fibre Orientation on Softwood–Hardwood Bonding. *J. Compos. Sci.* **2024**, *8*, 192. https://doi.org/10.3390/jcs8060192

Academic Editor: Francesco Tornabene

Received: 18 April 2024
Revised: 6 May 2024
Accepted: 16 May 2024
Published: 21 May 2024

1. Introduction

Engineered timber products are commonly crafted from sawn boards, veneers, and/or lamellae and bonded using structural-grade adhesives. A diverse range of species, with a particular emphasis on softwoods, are commonly utilised for the production of laminated products. Examples include European species like Norway Spruce [1,2] and Irish Sitka Spruce [3]. Additionally, North American softwoods [4], Canadian Black Spruce species [5,6], Hemlock [7], Japanese Cedar [8], and New Zealand and Australian Radiata Pine [9–11] have been utilised.

Softwood timber has been the dominant resource used within construction when compared to hardwood due to its low density and versatility. In Australia, a significant portion of commercial softwood plantations, approximately 97.5%, are dedicated to producing sawlogs. In contrast, around 86% of commercial hardwood plantations are managed for pulp log production [12]. This difference in utilisation has raised concerns about the potential shortage of softwood. According to a report by the Australia Bureau of Agricultural and Resources Economics and Science (ABARES), there is a looming shortage of softwood [13]. Hardwood is a great alternative to softwood, as its high density leads to its having greater strength properties [14].

Australia's forests cover a vast expanse of 134 million hectares and are classified into three main categories: The main type consists of native forests, which encompass the majority at 132 million hectares, with hardwood constituting 77% of this native forest area. The remaining categories include commercial plantations, covering 1.95 million hectares, and other forest types, spanning around 0.47 million hectares [15]. Specifically, within the 1.95 million hectares of commercial plantations, 48% are dedicated to various hardwood species, while the remaining 52% are planted with softwood species [15]. Softwood species, like radiata pine (Pinus radiata D. Don), serve as a prevalent choice for general-purpose timber due to their extensive cultivation in regions such as South Australia, Victoria, and New South Wales. However, there has been a notable rise in environmentally managed plantations featuring hardwood species in recent years, driven by the advantageous mechanical properties they offer. One example of such hardwood species is shining gum (Eucalyptus nitens), which has shown great potential for use in engineered timber products [16].

Bonding is reported to be a challenge for laminated hardwood products. The bond performance at the wood interface is subjected to several influencing factors. These factors encompass, but are not confined to, wood species, treatment applied to the wood (whether chemical or thermal), the type of adhesive used, the bond line thickness achieved, the duration of curing, environmental conditions during bonding and curing processes, the surface characteristics of the timber substrate, the details of the manufacturing process (including the quantity of adhesive, applied pressure, duration of pressure, etc.), and the moisture content [17].

Hardwood typically demonstrates a more intricate anatomical structure when compared to softwood [18]. Hardwoods exhibit pores, known as vessels or lumens, which vary in diameter and size along the length of a specimen. Achieving optimal bond performance at a wood interface generally entails the applied adhesives effectively "wetting" the wood surface, allowing key components to penetrate within the wood structures adequately [18]. There are a number of reasons for poor bonding. For high-density timber, such as Australian hardwoods, these reasons are summarised in [19]. These include a high content of extractives that interfere with the glueing process and lower porosity and permeability, leading to reduced adhesive penetration, among others [19]. Additionally, the presence of pores and vessels in hardwoods can hinder the effectiveness of certain adhesives. Consequently, the process of adhering hardwood can be inherently challenging [20,21].

Structural adhesives applied for timber bonding need to meet various specified standards [22,23] and industrial handbooks [24]. Some of these structural adhesives include melamine–urea–formaldehyde (MUF), phenol–resorcinol–formaldehyde (PRF), one-component polyurethane (PUR), and emulsion–polymer–isocyanate (EPI) adhesives. These adhesives are specifically designed for timber laminating and are used in various timber construction applications, including cross-laminated timber (CLT) and glue-laminated timber (GLT). Among these structural adhesives, PRF and PUR adhesives are extensively employed due to their accessibility and cost-effectiveness. Furthermore, they demonstrate high strength in both dry and wet conditions and exhibit notable resistance to water and damp atmospheres [16]. PRF adhesives, in particular, excel in terms of resistance to wood at elevated temperatures and during chemical ageing. However, it is essential to note that PRF adhesives are currently raising concerns related to their formaldehyde content, which is now classified as a carcinogen [25]. In contrast, PUR adhesives' gap-filling properties enhance adhesive penetration into wood, efficiently addressing gaps and irregularities on the wood surface, which is especially beneficial for bonding hardwoods. Importantly, PUR formulations do not contain formaldehyde [26].

When utilising structural adhesives for bonding softwood species on hardwood species, adjustments to the glueing process may be necessary to achieve the prescribed standards of bonding quality. Lopez and Richter [27] applied two distinct HMR (hydroxymethylated resorcinol)-based primers and a PUR adhesive for Eucalyptus globulus GLT, all of which exceeded the delamination (EN 391) and shear strength (EN 392) requirements. Furthermore, they showcased a reduction in delamination. Nevertheless, HMR-based primer systems face limitations in industrial applications due to their extensive activation times [28]. A recently developed primer system, PURBOND PR 3105 by Henkel, stands out in contrast to HMR-based primers. This system boasts a remarkably short activation time, enabling its seamless integration into existing production processes. The PURBOND PR 3105 primer, identified as a hydrophilic emulsifier [29], employs a hydrophilic emulsifier solution to modify the affinity between wood and PUR. This modification leads to a decrease in delamination and an elevated wood fracture percentage [30].

Glue-laminated timber (GLT) is manufactured from bonded lamellae parallel to the fibre's orientation [31], while cross-laminated timber (CLT) involves the arrangement of timber layers in orthogonal directions, and therefore the layers are bonded perpendicular to each other [32]. Previous research by the author exhibited that variations in the fibre orientation of anisotropic materials can significantly impact their bonding properties [33]. The effect of the difference in fibre orientation between two consecutive layers can be amplified when multiple species, such as different species of softwood/hardwood or combinations of hardwood and softwood, are used to make cross-laminated timber.

In evaluating the bond strength of timber, two commonly used standards are the block shear test and the lap shear test. However, each method presents its own set of challenges when dealing with a combination of multiple species. The block shear test necessitates the assembly of two blocks side by side. However, if multiple species (e.g., hardwood–softwood) are used to make a block shear specimen, the bond line may not be subjected to pure shearing if the hardwood is stronger/stiffer. The lap shear test, another method with established standards for bond strength, involves tensile shear force. Tensile force can be subject to slipping or local crushing in the gripping region [34], thereby influencing the test results, even in cases where complete failure does not occur.

In response to the aforementioned issues associated with block shear tests and lap shear tests, the push-out test was selected for this study. The push-out test is primarily implemented for steel–concrete composites, with only a few instances involving timber components but none exclusively focusing on timber. Notably, the push-out test addresses concerns about the block shear test by employing a symmetrical design [35]. The configuration of the push-out test guarantees the unhindered movement of the timber under the applied force, as the block experiencing the force is elevated above the level line with the other two blocks (see Figure 1). The other two blocks simply require a flat surface for support.

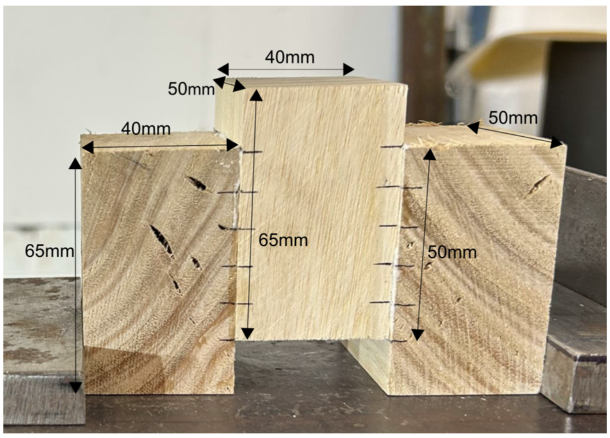


Figure 1. Specimen's dimensions.

Therefore, the objectives of this study are to examine the effect of using primer while bonding hardwood with hardwood or softwood, to evaluate suitable testing methods for determining bond properties between multiple species, and to investigate the effect of fibre orientation on hardwood–softwood interface properties. To achieve these objectives, the push-out test methodology is employed to examine the bond behaviour at the interface of softwoods (radiata pine) or hardwoods (shining gum), as well as their combination (radiata pine and shining gum). In addition, various fibre orientations, including parallel and perpendicular directions, are investigated. Moreover, the effect of the primer on the hardwood was also examined. The bond performance was evaluated in terms of the failure mode, bond stress vs. slip curve, bond strength, and bond stiffness. The study aims to understand how these parameters are influenced by changes in bond directions, wood species (lamellae combinations), the use of primers, and the occurrence of different failure modes.

2. Experimental Program

2.1. Material and Sample Preparation

The present study sourced commercial timber materials, specifically radiata pine (softwood) and shining gum (hardwood), for this study. These timbers were precision-cut to conform to dimensions of 40 mm × 50 mm × 65 mm (width w × depth d × height h) in both the parallel-to-grain (PAL) and perpendicular-to-grain (PER) orientations. The bond area was kept at 50 × 50 mm. Figure 1 illustrates the dimensions of the samples.

A primer is a chemical used to prepare a surface for adhesive bonding in hardwood. The LOCTITE® PURBOND PR 3105 primer from Henkel Australia was employed to prepare the hardwood surface before bonding it to the softwood. According to the manufacturer's datasheet, the recommended airing time was 10 min. The PR 3105 primer had a concentration of 20%, a viscosity of 500 mPa·s, and a density of 1100 kg/m^3.

The adhesive used was the recommended companion to the PURBOND PR 3105 primer, LOCTITE® HB S109 PURBOND, a high-performance, single-component polyurethane adhesive from Henkel Australia. This adhesive is formaldehyde-free and meets the requirements of adhesive type I as per the AS/NZS 4364 [36] standard. According to the manufacturer's datasheet, the assembly and press times were 10 and 75 min, respectively. The HB S109 primer has a viscosity of approximately 24,000 mPa·s and a density of 1160 kg/m^3.

All specimens were produced within the structural laboratory at Deakin University, including the cutting processes and subsequent sample preparations. At first, the timber boards were placed in a conditioning chamber (23 °C with 65% RH) to ensure 12% moisture content was achieved. Once the targeted moisture content was achieved, the wood blocks were cut to the specified dimensions in both the parallel-to-grain (PAL) and perpendicular-to-grain (PER) directions. The weight of individual wood pieces was measured to calculate the wood density. If primer was required in the specimens, a mixture of 1 part PURBOND PR 3105 and 4 parts water was used to dilute the primer. This diluted solution was then applied to the target areas (50 mm × 50 mm) of the hardwood surface at an application rate of 20 g/m^2, following the recommendations outlined in the handbook (Primer PURBOND PR 3105). Subsequently, the hardwood was left exposed to ambient air for a 10 min curing time. The adhesive was then applied to the same target areas (50 mm × 50 mm) at a rate of 160 g/m^2, in accordance with the guidelines provided in the handbook (LOCTITE HB S309 PURBOND).

The central wood block was oriented in the parallel-to-grain (PAL) direction, while the blocks on both sides were also aligned in the parallel-to-grain (PAL) direction, as depicted in Figure 2, denoted as 'PAL-PAL' in the sample designation. In another configuration, the middle wood block remained in the parallel-to-grain (PAL) direction, but the flanking blocks were arranged in the perpendicular-to-grain (PER) direction, as shown in Figure 3, and referred to as 'PAL-PER' in the sample designation. When preparing specimens with perpendicular-to-grain (PER) blocks, efforts were made to keep the annual ring orientation symmetrical to the middle block, as illustrated in Figure 3. Further details regarding the specimen categories are summarised in Table 1. Subsequently, the specimens were subjected to a press machine with a distributed load of 1.0 N/mm^2 for 1.5 h. Following this process, the samples were stored in a conditioning chamber (23 °C with 65% RH) to ensure 12% moisture content was achieved.

Table 1. Details of specimen categories for testing.

Sample Designation	Combination/Variable		No. of Sample
	Middle Block	Side Blocks	
SW-HW_PAL-PAL (No Primer)	Radiata pine, parallel grain, no primer	Shining gum, parallel grain, no primer	10
SW-HW_PAL-PAL (Primer)	Radiata pine, parallel grain, no primer	Shining gum, parallel grain, with primer	10
SW-HW_PAL-PER (No Primer)	Radiata pine, parallel grain, no primer	Shining gum, perpendicular grain, no primer	10
SW-HW_PAL-PER (Primer)	Radiata pine, parallel grain, no primer	Shining gum, perpendicular grain, with primer	10
HW-HW_PAL-PAL (No Primer)	Shining gum, parallel grain, no primer	Shining gum, parallel grain, no primer	10
HW-HW_PAL-PAL (Primer)	Shining gum, parallel grain, with primer	Shining gum, parallel grain, with primer	10
HW-HW_PAL-PER (No Primer)	Shining gum, parallel grain, no primer	Shining gum, perpendicular grain, no primer	10
HW-HW_PAL-PER (Primer)	Shining gum, parallel grain, with primer	Shining gum, perpendicular grain, with primer	10
SW-SW_PAL-PAL	Radiata pine, parallel grain, no primer	Radiata pine, parallel grain, no primer	10
SW-SW_PAL-PER	Radiata pine, parallel grain, no primer	Radiata pine, perpendicular grain, no primer	10

2.2. Test Setup and Evaluation

At the end of the conditioning period, an adjustment was made by grinding the top and bottom surfaces of the specimen to ensure they were flat. Additionally, the moisture content and density of each individual wood piece were measured immediately before conducting the push-out tests.

In the push-out tests, a compressive load was applied to the middle wood block, which was always kept parallel to the grain direction, using a 300 kN INSTRON universal testing machine. The wood blocks on both sides were supported on the lower platform, as illustrated in Figure 4. PAL-PAL represents the grain direction of both side blocks parallel to the loading direction (Figure 2), while PAL-PER represents the grain direction of both side blocks perpendicular to the loading direction (Figure 3). The load was applied at a displacement control rate of 0.5 mm/min until failure. The middle block was assembled above the level line of the wood blocks on both sides, allowing the middle block to undergo downward displacement under the compressive load.

The bond strength, τ_{bond}, and bond stiffness, k_s, are two important parameters that were obtained from the tests using Equations (1) and (2).

$$\tau_{bond} = \frac{V_u}{A_{bond}} \tag{1}$$

$$k_s = \frac{\tau_{bond,2} - \tau_{bond,1}}{\delta_2 - \delta_1} \tag{2}$$

where V_u is the maximum shear load of the test sample; A_{bond} is the bonding area; $\tau_{bond,1}$ and $\tau_{bond,2}$ represent the bond stresses recorded from the tests related to 0.2 τ_{bond} and 0.6 τ_{bond}; and δ_1 and δ_2 are relevant displacements corresponding to aforementioned $\tau_{bond,1}$ and $\tau_{bond,2}$, respectively.

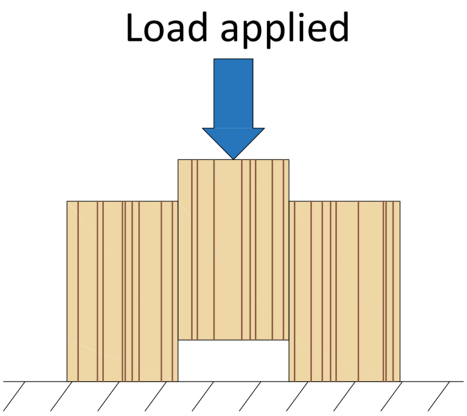


Figure 2. PAL-PAL.

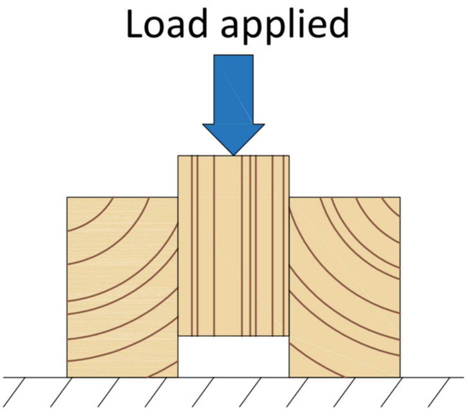


Figure 3. PAL-PER.

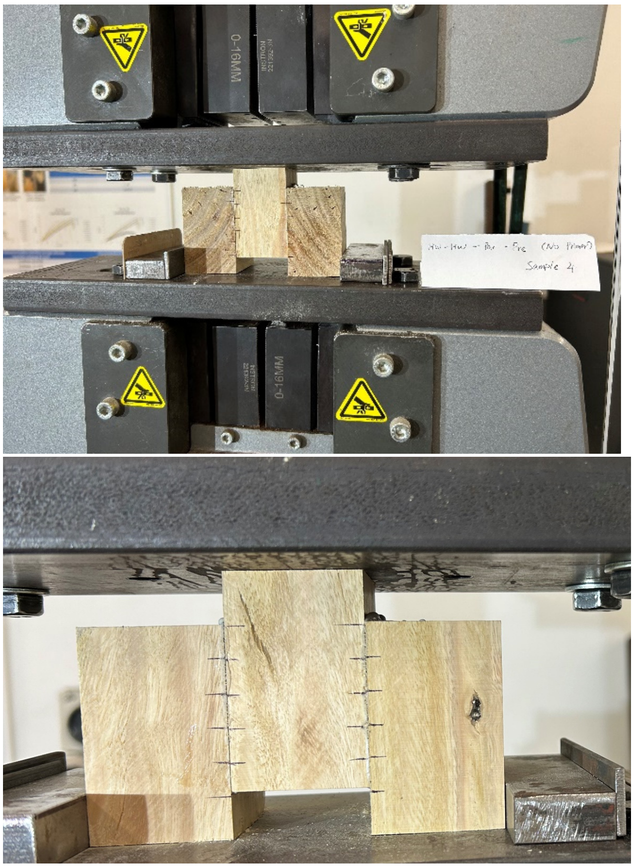


Figure 4. Specimen in INSTRON testing machine.

2.3. Density and Moisture Content of the Specimen

As mentioned earlier, the density of each block and their corresponding moisture content were measured just before testing and are listed in Table 2. Efforts were made to keep the densities of the left and right wood blocks the same. However, this was not always possible, as evident in Table 2. The moisture content varied by ±1% between groups; however, the MC was similar within the same group, with slight differences. It can also be noted that the hardwood samples (shining gum) in the HW-HW_PAL-PAL (no primer) group were denser than those of any other hardwood group, while the HW-HW_PAL-PAL (primer) group exhibited a higher standard deviation.

Table 2. Mean density and moisture content of the tested specimens just before testing.

Sample Designation	Left Woodblock		Middle Woodblock		Right Woodblock	
	Density (kg/m^3)	MC (%)	Density (kg/m^3)	MC (%)	Density (kg/m^3)	MC (%)
SW-HW_PAL-PAL (No Primer)	674.8 ± 18.6	12.5 ± 0.1	476.4 ± 16.3	12.2 ± 0.3	674.9 ± 23.5	12.6 ± 0.3
SW-HW_PAL-PAL (Primer)	676.7 ± 13.7	12.2 ± 0.3	493.4 ± 15.3	12.4 ± 0.3	687.5 ± 14.4	12.5 ± 0.4
SW-HW_PAL-PER (No Primer)	685.7 ± 17.9	12.4 ± 0.3	487.3 ± 20.9	12.5 ± 0.3	675.4 ± 21.1	12.4 ± 0.4
SW-HW_PAL-PER (Primer)	683.4 ± 20.2	12.4 ± 0.3	491.4 ± 22.8	12.5 ± 0.4	684.0 ± 17.6	12.6 ± 0.4
HW-HW_PAL-PAL (No Primer)	780.4 ± 20.2	13.1 ± 0.4	773.3 ± 22.6	12.8 ± 0.7	789.3 ± 18.4	12.8 ± 0.5
HW-HW_PAL-PAL (Primer)	693.0 ± 140.3	12.4 ± 1.0	698.4 ± 112.3	12.1 ± 1.2	606.8 ± 106.4	12.3 ± 1.4
HW-HW_PAL-PER (No Primer)	693.9 ± 132.7	12.7 ± 0.9	720.3 ± 60.3	12.7 ± 0.7	716.8 ± 80.2	12.7 ± 0.6
HW-HW_PAL-PER (Primer)	679.9 ± 58.7	13.2 ± 0.6	685.3 ± 79.4	13.1 ± 0.4	655.2 ± 89.0	13.4 ± 0.5
SW-SW_PAL-PAL	447.6 ± 35.3	11.8 ± 0.5	436.5 ± 33.1	12.4 ± 0.7	429.6 ± 25.8	11.9 ± 1.0
SW-SW_PAL-PER	471.7 ± 45.1	12.5 ± 0.8	506.4 ± 29.1	13.2 ± 0.9	473.6 ± 56.5	12.5 ± 1.2

2.4. Statistical Analysis

The statistical analysis consisted of an analysis of variance (ANOVA) and pairwise comparisons using Fisher's least significant difference (LSD) tests, which were performed to evaluate various effects. The effects of the primer on hardwood, the difference in relative fibre orientation, and the effect of combining species were studied in terms of bond strength. The interaction effects of multiple parameters (species difference, primer, and relative fibre orientation) were also considered. This analysis was performed using the commercial software Minitab 21.4.2.

3. Results and Discussions

3.1. Failure Modes

The failure modes of the tested samples are of great interest to note the various types of failure that can occur in laminated timber products. The typical failure modes observed in the bond tests are depicted in Table 3. Failure mode F2, or wood side failure, is the most desired failure mode for laminated timber since it requires certain properties for the timber only, with no concern for the glue line integrity [37]. However, various failure modes can be observed during testing, especially when multiple species are bonded.

Table 3. Various failure modes observed in the study.

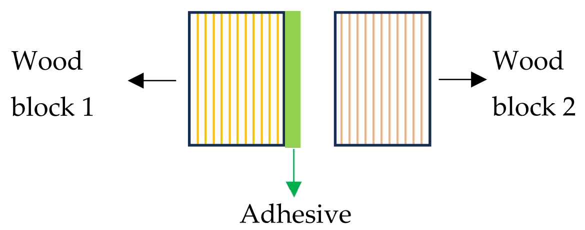
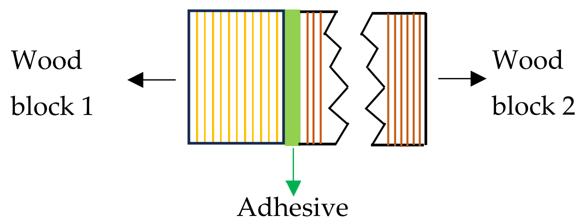
Failure Mode	Schematic/Photo
Failure mode F1: Adhesive (delamination) failure	
Failure mode F2: Substrate (wood failure)	

Table 3. *Cont.*

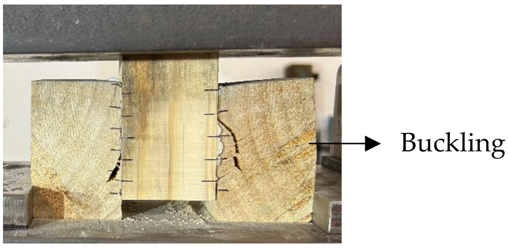
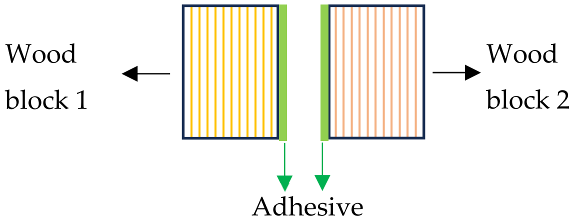
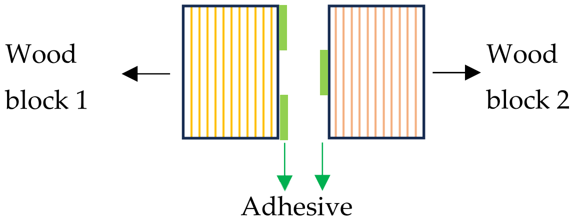
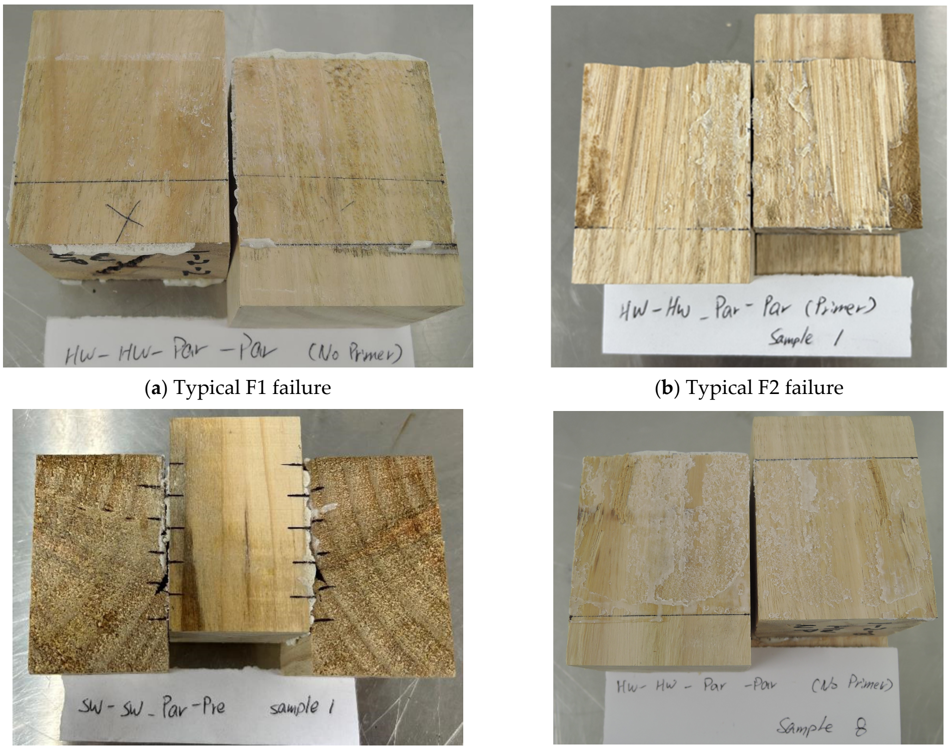
Failure Mode	Schematic/Photo
Failure mode F3: Buckling of the perpendicular block	
Failure mode F4: Cohesive failure	
Failure mode M: Mixed mode (combination of two)	

Table 4 lists the common failure modes observed in each group, while Figure 5 illustrates photos of the failure interface while subjected to the failure modes outlined in Table 3. Failure mode F4 was not observed in any specimen. While most of the samples (62/100) failed on the wood side, 38% of the samples exhibited other types of failure. An unusual one is failure mode 3 (F3), which was only observed for the testing of softwood in the PAL-PER direction. The PER-oriented woodblock underwent slight buckling, which initiated failure in 4/10 samples. Since softwood has a lower compressive strength and modulus perpendicular to the grain than hardwood, it was only observed for the SW-SW_PAL-PER group. However, the buckling amount was not significant.

Table 4. Various failure modes for each group.

Combination	F1	F2	F3	F4	M
HW-HW_PAL-PAL (NP) #10	-	4	-	-	6
HW-HW_PAL-PAL (P) #10	-	9	-	-	1
HW-HW_PAL-PER (NP) #10	-	5	-	-	5
HW-HW_PAL-PER (P) #10	-	9	-	-	1
SW-HW_PAL-PAL (NP) #10	4	6	-	-	-
SW-HW_PAL-PAL (P) #10	-	9	-	-	1
SW-HW_PAL-PER (NP) #10	8	2	-	-	-
SW-HW_PAL-PER (P) #10	3	7	-	-	-
SW-SW_PAL-PAL #10	-	8	-	-	2
SW-SW_PAL-PER #10	-	3	4	-	3

NP = no primer.



(**a**) Typical F1 failure (**b**) Typical F2 failure

(**c**) Typical F3 failure (**d**) Typical M failure

Figure 5. Typical failure modes observed during testing.

The benefit of using primer is apparent from the failure mode. For the PAL-PAL direction, 9/10 samples were subjected to wood-side failure. This is true for both the HW-HW and HW-SW groups. However, some delamination (3/10 samples) was still observed for the SW-HW_PAL-PER (P) group. It can also be seen that without primer, delamination is indeed the governing failure mode for the SW-HW_PAL-PER (NP) group. This reflects the fact that bonding between hardwood and softwood as different layers in CLT may pose some challenges since delamination can be a potential failure mode for hardwood–softwood CLT.

3.2. Load vs. Slip Plot

Figure 6 depicts the load vs. slip plots of all 10 groups and 100 specimens. The colours indicate various failure modes, as outlined in the plot. The columns of the plot (Columns 1–3) can be compared to see the effect of species on the load-slip behaviour. Row 1 vs. 2 and Row 4 vs. 3 signify the effect of primer, whereas Row 2 vs. 3 (and Row 1 vs. 4) displays the effect of the relative fibre orientation.

It can be noticed that the load vs. slip behaviour is relatively consistent when the same species are used (Columns 1 and 3). However, with the combination of species (Column 2), both the slope (bond stiffness) and ultimate bond strength vary significantly. While combining multiple species, there are higher possibilities of having natural variations in densities, anatomical structures, moisture contents, and natural defects. Thus, there could be more weak links in the specimen that can lead to different failure mechanisms. As a result, higher inconsistencies were observed for the SW-HW combinations. However, the use of primer on HW was found to be effective in reducing this inconsistency in the SW-HW samples, as the failure modes became slightly more consistent (mostly F2 instead of F1).

Reduction in load-carrying capacity by more than half in the PAL-PER combinations compared to their PAL-PAL counterparts (Row 2 vs. Row 3). The failure is also more gradual for the PAL-PER groups. This behaviour aligns with the conclusions reported by the authors in their previous studies as well [16,33].

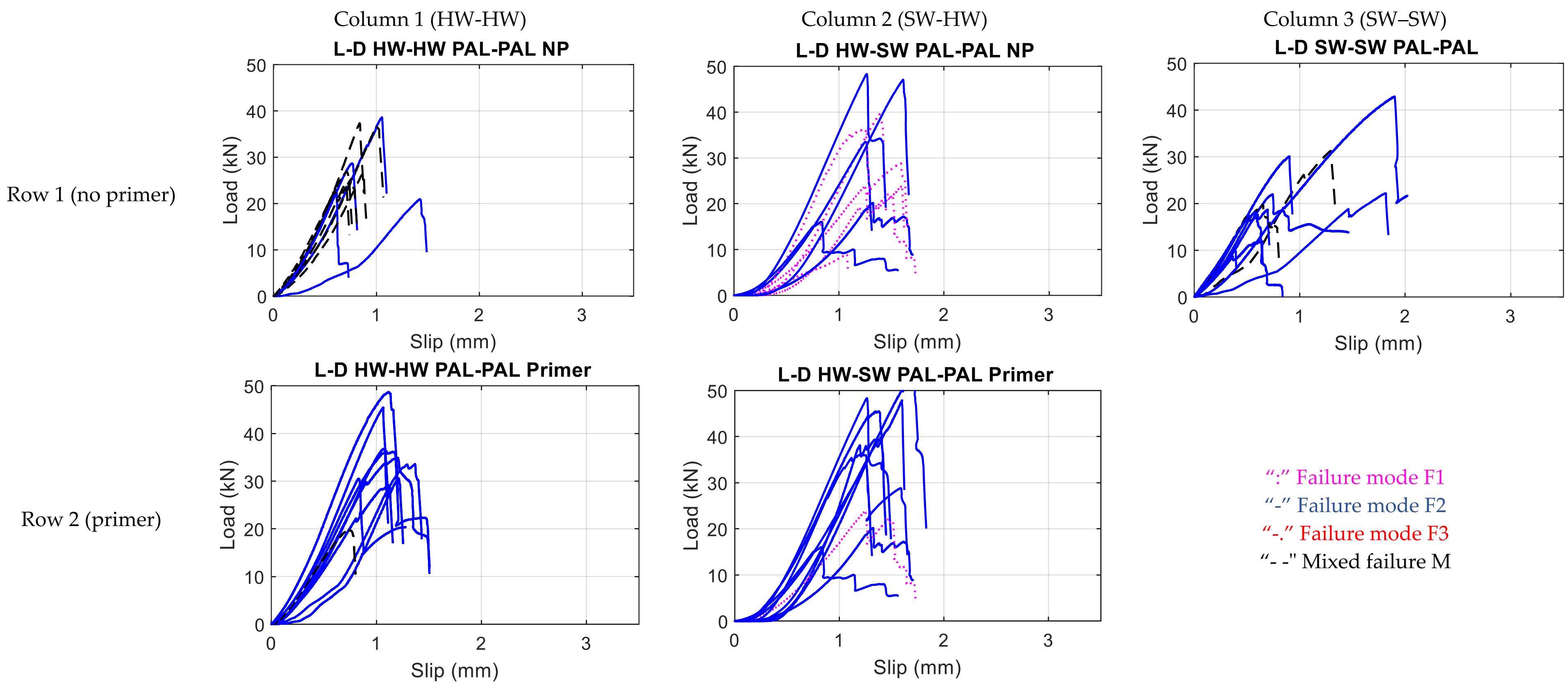


Figure 6. *Cont.*

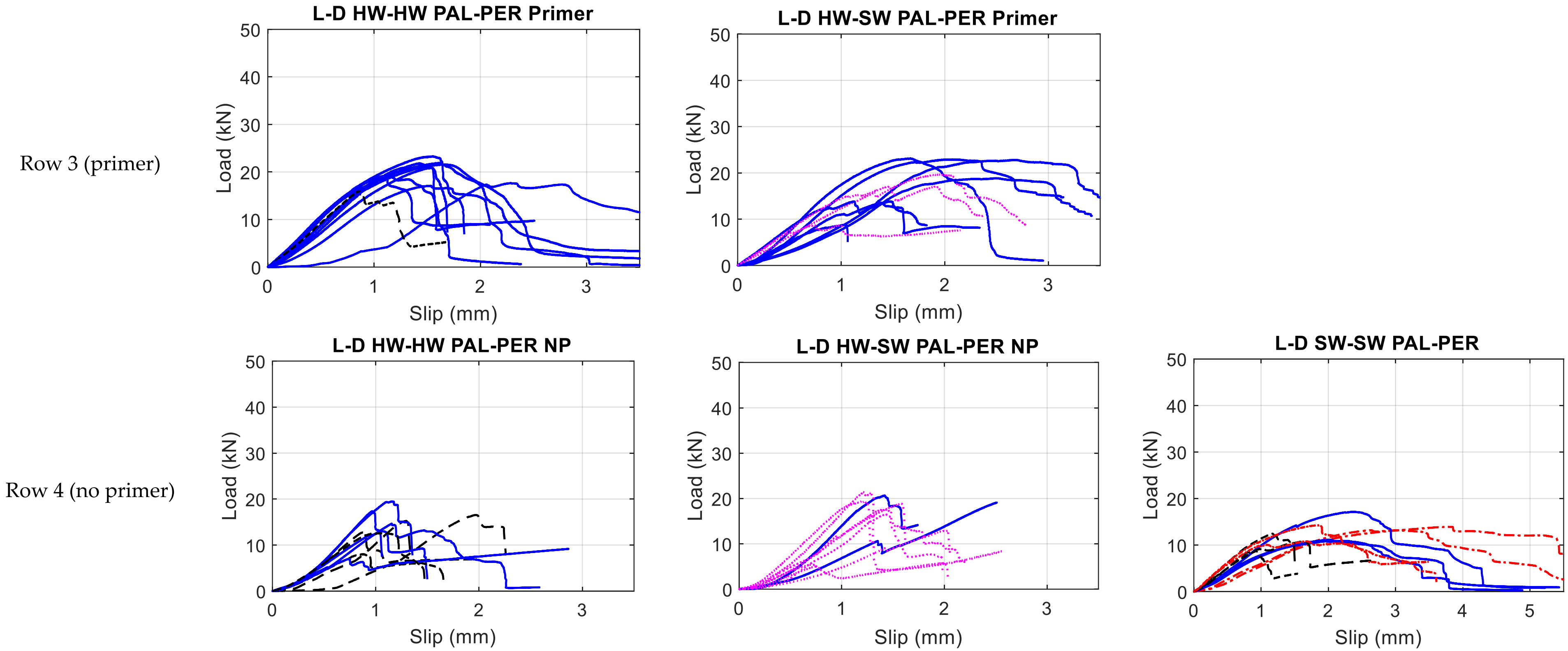


Figure 6. Effect of species, fibre orientation, and primer on the load vs. slip curve.

While comparing Row 3 vs. 4 in Figure 6, it can be seen that the use of primer enhanced both the ductility and stiffness in the PAL–PER scenario. This could be due to the improvement in load transfer at the interface, which may also behave more nonlinearly when primer is used. In softwood (SW–SW), the PAL–PER sample is even more ductile. The red lines indicate failure mode F3. A reduction in bond stiffness can be observed in F3, which was induced by the buckling of the side block, as discussed in Section 3.1.

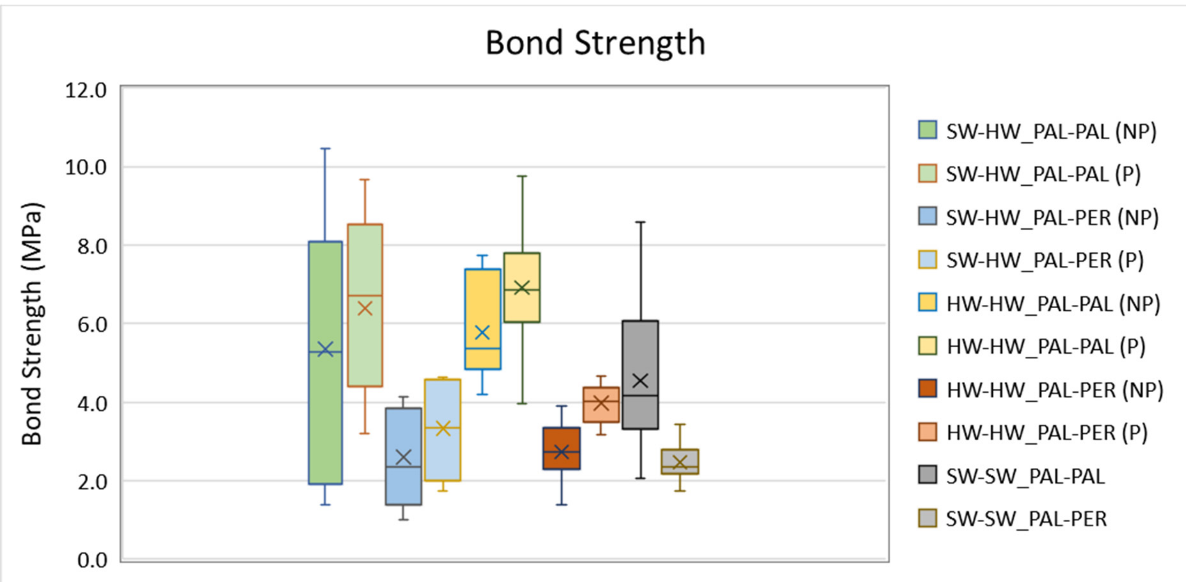
3.3. Bond Properties

The bond characteristics of the various groups are evaluated in terms of bond strength and stiffness, which are determined as per Equations (1) and (2). Figure 7 compares the box and whisker plots of the bond strength (7a) and stiffness (7b) of various groups. It can be seen there that the mean value contains the average of all the samples within the group, i.e., variations due to the failure modes are not taken into account. This is due to the fact that no specific trends in the load vs. slip curves (Figure 6) were observed when the failure modes were different.

The most obvious characteristic is the large standard deviation (first and third quartiles) of the SW-HW_PAL-PAL (NP) group, which was significantly reduced with the use of primer (for both strength and stiffness). The reason for this is discussed in Section 3.2. Figure 7a,b clearly display that the mean bond strength and stiffness increased and their standard deviations decreased (with the exception of the HW-HW_PAL-PAL (P) group) with the use of primer.

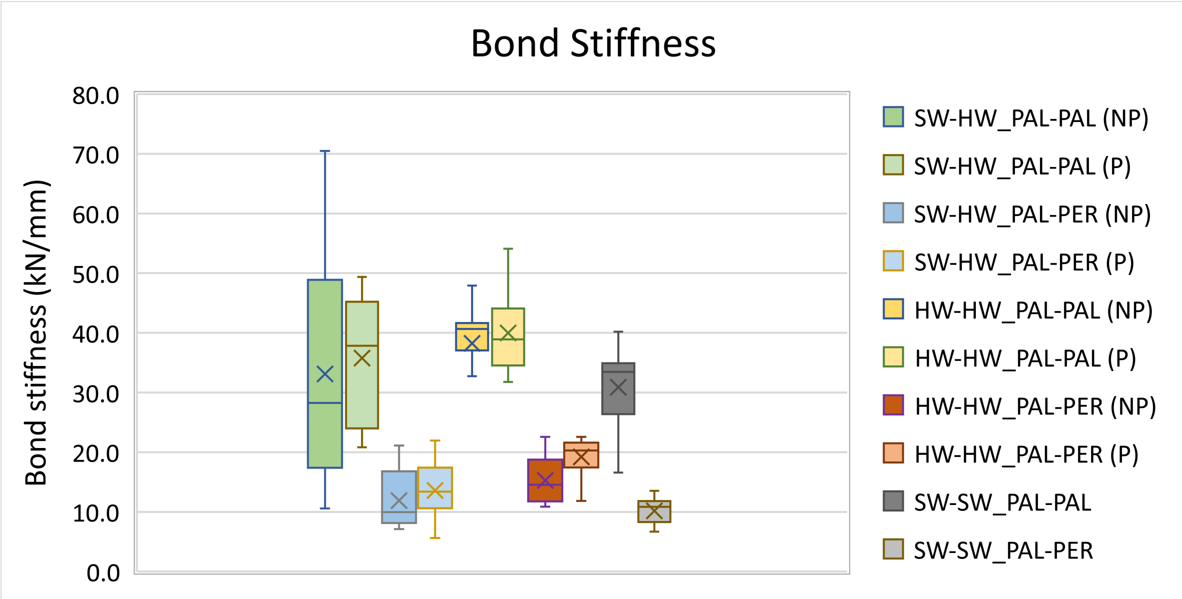
In addition, the HW-HW bonding yielded a higher mean bond strength and stiffness compared to those in the SW-SW scenario. This is expected since failure in softwood is governed by wood-side failure, and softwood has lower mechanical properties than hardwood. Since hardwood is stronger than softwood, it maximises the shear strength of the adhesive at higher load values, resulting in superior bond strength. This behaviour is applicable for both the PAL-PAL and PAL-PER directions when comparing HW-HW against SW-SW bonding.

The potential reasons behind the higher standard deviation in the HW-HW_PAL-PAL (P) group compared to the HW-HW_PAL-PAL (NP) group may be attributed to the higher standard deviation in the densities and the lower densities of the boards used for the HW-HW_PAL-PAL (P) group, as listed in Table 2. However, this effect of density is found to affect bond stiffness more than bond strength.



(**a**) Bond strength

Figure 7. *Cont.*



(**b**) Bond stiffness

Figure 7. Box and whisker plot of bond strength and stiffness of various groups.

3.4. Effect of Various Factors

The effects of three factors—species combination, relative fibre orientations, and use of primers—were considered in the present study. To analyse the interactions between these factors, an interaction plot for bond strength is presented in Figure 8. The interaction between the primer and the interface indicates that the primer indeed improved the SW-HW and HW-HW bonding, and this improvement shows a similar slope, indicating there was no interaction between the primer and the interface. Hence, only one parameter was responsible for this improvement. Fisher's individual test (Table 5, last row) indicates that it was the primer that significantly affected the bond strength, since it has a *p*-value of 0.004, which is less than 5% level of significance.

For the interface–relative fibre orientation interaction, there could be potential interactions between these two factors since the slopes between the PAL-PAL and PAL-PER directions are not parallel to each other. A difference in slope for the primer–fibre orientation interaction is also apparent, as the slope for P (primer) is steeper compared to the NP (no primer) situation, suggesting that bond strength will be reduced more for the PAL-PER scenario (in CLT, for instance) when primer is applied to the hardwood.

Table 5 discusses the *p*-values related to bond strength and stiffness considering, the effects of species combination, relative fibre orientations, and the use of primer. *p*-value in bold indicates the factors that have significant effect on the bond properties. As per Fisher's pairwise comparison (at a 5% level of significance), relative fibre orientations and primers have a significant impact on the bond strength, while the effect of the species combination was found to be less significant. For bond stiffness, however, the effect of primer was found to be less significant, but the species combination is more important to consider. It was found that the SG-SG bond stiffness is notably different from the RP-RP and RP-SG combinations. This implies that the higher modulus of elasticity of hardwood (shining gum) governs the bond stiffness instead of the interface, and therefore, the use of primer does not play an important role in stiffness. The relative fibre orientation is significant for bond stiffness as well.

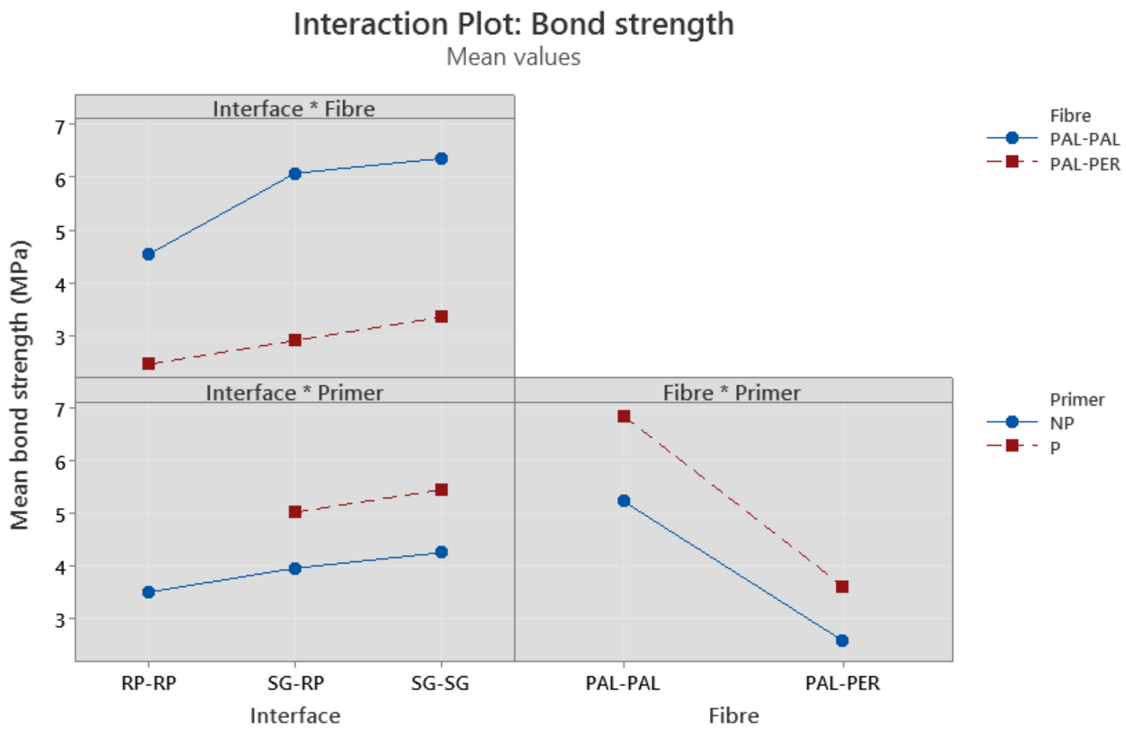


Figure 8. Interaction plots with respect to primer, fibre orientation, and species.

Table 5. Fisher individual tests for difference in means (SE = standard error).

Parameters	Difference in Means	SE of Difference	T-Value	*p*-Value	Difference in Means	SE of Difference	T-Value	*p*-Value
	Bond Strength				**Bond Stiffness**			
Effect of various interfaces								
SG-RP–RP-RP	0.421	0.504	0.84	0.406	1.81	2.46	0.73	0.464
SG-SG–RP-RP	0.781	0.504	1.55	0.124	6.4	2.46	2.6	**0.011**
SG-SG–SG-RP	0.360	0.381	0.95	0.346	4.59	1.86	2.46	**0.016**
Effect of relative fibre orientation								
PAL-PER vs. PAL-PAL	−2.873	0.340	−8.44	**0.000**	−21.46	1.67	12.94	**0.000**
Effect of primer								
P–NP	1.127	0.381	2.96	**0.004**	2.51	1.86	1.35	0.181

4. Comparison

4.1. Comparison with Block Shear Test

In this study, push-out (PO) testing was implemented to evaluate the bond strength of laminated timber. However, block shear (BS) testing is a common practice for determining bond strength. The reason behind selecting PO testing is explained in Section 1. In a previous study [16], the authors conducted BS testing to evaluate the bond strength of hardwood, softwood, and the hardwood–softwood interface of the same species. In this section, the bond strengths obtained from the BS and PO tests are compared.

It can be noted that for BS testing, the authors did not investigate the effect of the primer. This results in six groups for comparison, as depicted in Figure 9. The first notable difference is the higher standard deviations in push-out testing. Since PO testing involves two side blocks, there are more failure paths available in the specimen. The variations include differences in densities, moisture contents, annual ring orientations, and natural defects. As a result, larger variations in the bond strength values in PO testing are noticeable.

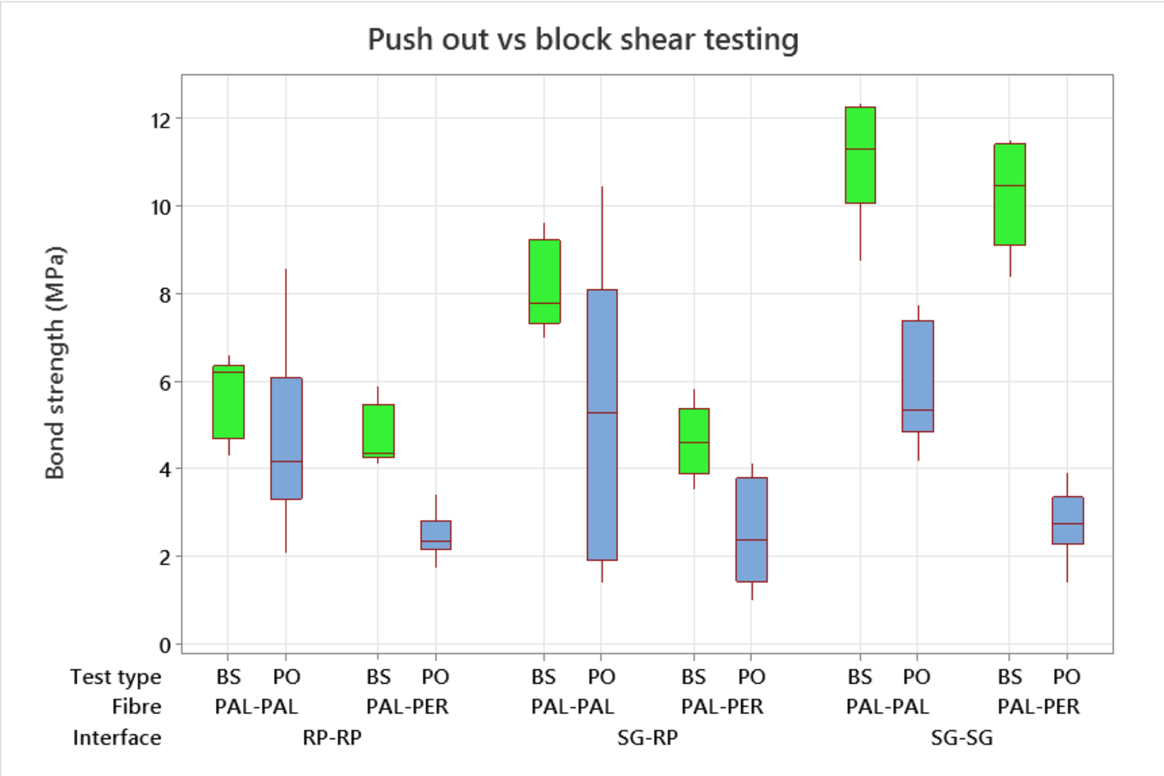


Figure 9. Difference in bond strength: push-out test (this study) vs. block shear test [16].

Based on Fisher's individual tests on the mean bond strength, the *p*-value was found to be 0.000, indicating that PO and BS testing attained significantly different results. Nevertheless, from Figure 9, it can be noticed that this difference is more prominent when hardwood (shining gum) is involved. This higher difference for hardwood is most probably related to the densities of shining gum used during BS and PO testing. As shown in Table 6, the mean density of the shining gum used in BS testing was 900 ± 28 kg/m^3, while the same used in PO testing was only 675 ± 66 kg/m^3.

Another major difference found between PO and BS testing is the effect of the relative fibre orientation. When the same species were used (RP-RP or SG-SG), the ratios between PAL-PER and PAL-PAL for RP-RP and SG-SG were 0.84 and 0.92, respectively, in BS testing. However, these ratios were reduced to 0.54 and 0.47 in PO testing. Most probably, the difference in the annual ring orientation (for the PAL-PER setting) between the two side blocks in PO testing is responsible for these reductions. This implies that for five- or more-layered CLT, where multiple cross-layers are present (simulating PO tests more realistically), the PAL-PER interface can be the weakest link.

For the mixed-species PAL-PER interface, both PO and BS testing exhibited a reduction in bond strength. In the mixed-species situation (RP-SG), the ratios between PAL-PER and PAL-PAL for BS and PO testing were 0.55 and 0.47, respectively, resulting in a similar reduction. This implies that for hybrid SW-HW CLT, the PAL-PER interface can lead to debonding.

4.2. Comparison with Other Species

In this section, the bond strengths of the selected species (shining gum and radiata pine) are compared against some other softwood and hardwood species. This comparison is only associated with the PAL-PAL direction of bonding. Also, testing methods for other species, obtained from the literature, are indicated in Table 6, which exclusively involves block shear testing. The table shows that the mean bond strength obtained from the push-out tests indeed align well with that of other species of similar densities.

Table 6. Comparison of bond strength of various species (all parallel to the grain).

Species	Mean Density (kg/m^3)	Mean Bond Strength (MPa)	Testing Method	Reference
Shining gum (HW)	675 ± 66	6.91 (P) 5.78 (NP)	Push-out	This study
	900 ± 28	11.14	Block shear	[16]
Eucalyptus urophylla × *E. grandis* (HW)	580	4.00	Block shear	[38]
Acacia mangium (HW)	673	5.00	Block shear	[37]
Fagus sylvatica L. (HW)	710	6.10	Block shear	[39]
Radiata pine (SW)	461 ± 39	4.54	Push-out	This study
	481 ± 10	5.69	Block shear	[16]
Pinus pinaster Ait. (SW)	500	7.05	Block shear	[40]
Hem-fir (SW)	633	3.89	Block shear	[41]
Larix kaempferi (SW)	680	2.21	Block shear	[42]

5. Conclusions

Timber is considered one of the most sustainable materials. The current study aimed at revealing one of the crucial concerns in producing hybrid CLT, which is the bond properties of the softwood-to-hardwood interface. This study focused on Australian softwood (radiata pine) and hardwood (shining gum). The effect of primer on the hardwood and the relative fibre orientations between layers to simulate CLT were considered in this article as well.

The results indicated that the predominant failure mode for hardwood bonding is delamination. However, this can be improved using primer. Primer not only improves the bond strength but also reduces standard deviations. In addition, primer can successfully shift the failure to wood-side failure, which is more desirable. The hardwood-to-hardwood interface yielded a higher bond strength than that observed for the softwood-to-hardwood interface. The mean bond strength of the hardwood–softwood interface was also found to be higher, however, with a higher standard deviation.

It is concluded that softwood–hardwood bonding will remain a challenging issue since an extremely high standard deviation was observed at the radiata pine–shining gum interface. This challenge becomes even more pronounced when the relative fibre orientation between layers changes (e.g., the CLT situation). Bonding between multiple species with one species as a cross-layer (fibres perpendicular to the loading) and another longitudinal (fibres parallel to the loading) exhibited a reduction in bond strength of up to 50%.

The current study considered push-out tests to evaluate the bond strength in order to simulate more realistic bonding scenarios for CLT. However, comparisons were made with the block shear testing of the same species conducted by the authors of a previous study. It was found that block shear testing is not affected significantly by differences in the relative fibre orientation between layers when the same species are bonded. However, a higher standard deviation is obtained in push-out testing, even for same-species bonding. This implies that for five or higher-layered CLT, where multiple cross-layers are present (simulated by push-out tests more realistically), the parallel–perpendicular interface can be prone to failure.

Based on the present study, it is advisable to use primer on the hardwood side for hardwood–softwood bonding in order to reduce potential large variations in bond strength. It was also concluded that the hardwood–softwood alternate layer in CLT is the weakest component of hybrid CLT. Therefore, if, say, softwood as longitudinal layers and hardwood as cross-layers are used to produce hybrid CLT, the failure of the CLT might be governed by the delamination of the longitudinal-to-cross-layer interface. It is also pointed out that block shear tests may predict higher bond strengths where bond properties between multiple species are concerned. Therefore, push-out tests can provide a realistic variation that may exist when bonding different species.

Author Contributions: Conceptualisation, M.S.; Methodology, M.S.; Software, M.S.; Validation, M.S. and H.Y.L. Formal analysis, M.S. and H.Y.L.; Investigation, M.S.; Resources, M.S.; Data Curation, M.S. and H.Y.L.; Writing—original draft, M.S. and H.Y.L.; Writing—Review & Editing, M.S.; Supervision, M.S.; Visualisation, M.S.; Project administration, M.S. and H.Y.L.; Funding Acquisition, M.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by internal grant provided by the Faculty of Science, Engineering and Built Environment at Deakin University.

Data Availability Statement: Data can be provided on request.

Acknowledgments: The authors would like to thank Henkel Australia for their in-kind support to provide primer and adhesive for the project. We are also grateful to Michael Shanahan and Ned Parsons for their technical supports in conducting some of the experiments.

Conflicts of Interest: The autrhos declare no conflict of interest.

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