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Maximizing the Use of Out-of-Grade Hybrid Pine in Engineered Wood Products: Bond Performance, the Effect of Resin Streaking, Knots, and Pith

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Abstract: The evolution toward small-diameter and fast-growing plantation timbers such as the *Pinus elliotti* var. *elliottii* (Engelm) × *Pinus caribaea* var. *hondurensis* (Sénéclauze) (PEE×PCH) hybrids around the world is producing large volumes of core wood that are falling short of structural sawn timber grading requirements. Engineered timber products such as cross-laminated timber (CLT) and glue-laminated (glulam) offer potential solutions to value-adding this resource, but the bond performance of this feedstock and the extent to which current standards and guides address its common characteristics for bond performance need to be understood. This study investigated the bond quality and performance of clear defect-free, low stiffness out-of-grade PEE×PCH and evaluated this performance using the pass/fail criteria of the CLT bond performance requirements of three national CLT standards. 5-layer CLT delamination samples and shear block test samples were glued using one-component polyurethane (PUR). This process was repeated for common occurring characteristics in this resource of resin, knots, and pith to understand their impact and inform an evaluation on the need to restrict their inclusion. Clear samples had an average glue line delamination of 2.9% and an average glue line wood failure of 96.7%. Resin achieved 9.3% and 92.6%, respectively. While knots had the lowest performance at 24.4% and 77.4%, respectively. When pith was at or adjacent to the glue line, wood failure occurred through the pith and its immediate surrounding fiber. Shear strength and wood failure tests were carried out on glulam and CLT-oriented samples. CLT knot samples were tested in two load orientations. Glulam-oriented samples in clear, resin, pith, and knots achieved an average shear strength of 8.5 MPa, 8.2 MPa, 7.9 MPa, and 8.2 MPa, respectively, and wood failure of 86%, 85%, 90%, and 69%, respectively. CLT-oriented samples in clear and resin both achieved average shear strengths of 4.0 MPa; 0°-loaded and 90°-loaded pith samples achieved 3.6 MPa and 2.4 MPa, while 0°-loaded and 90°-loaded knot samples achieved 4.2 MPa and 4.7 MPa respectively. Average wood failures were 90%, 89%, 96%, 96%, 83%, and 51%, respectively. PRG320 was found to be the most restrictive standard. Resin, knots, and pith were not addressed in the evaluation of delamination or shear strength in any standard, and PRG320 was the only standard to restrict these characteristics over and above structural grading rules. The amount and type of characteristics present vary considerably in structurally graded wood, and even more so for this out-of-grade resource. It was determined that the negative impact that resin, knots, and pith have on bond quality and bond performance calls for some restriction of their inclusion in order to achieve the author's interpretation of the intended bond performance requirements of the CLT standards, which currently do not address these characteristics well or at all. A proposed modification to the PRG320 effective bond area was presented as a proactive solution.

Keywords: delamination; resin; knots; pith; CLT; glulam; PUR; engineered wood products; low grade; out-of-grade

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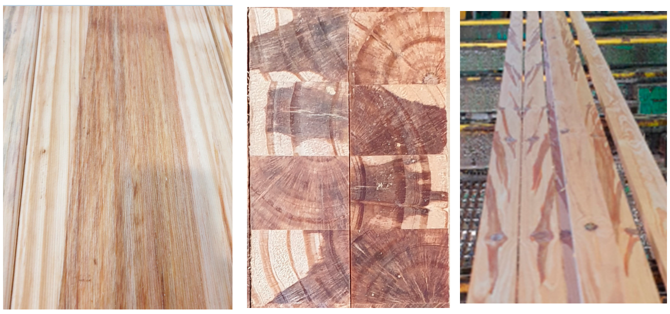
1. Introduction

The adoption of fast-growing tree species by plantation tree growers is leading to an abundance of low-stiffness wood that, when processed into timber, does not meet the requirements of structural grading standards. The *Pinus elliotti* var. *elliottii* (Engelm) × *Pinus* caribaea var. *hondurensis* (Sénéclauze) (PEE×PCH) hybrid is one such fast-growing plantation pine increasingly being grown around the world [1–7]. In a recent study by Cherry et al. [8], it was confirmed that a majority of the sawn PEE×PCH that fell short of Australian Machine Graded Pine (MGP) standards was low-stiffness timber from the core wood zone of the tree. The industry is looking to value-add this abundant out-of-grade resource, and engineered timber products such as glulam and cross-lamination timber (CLT) offer solutions [9]. With increasing demand for structural timber and engineered timber products, it makes sense to substitute out-of-grade timber in place of structural-grade timber wherever possible. But to perform its role as a structural composite material, the timber and adhesive in engineered wood products must interact and perform predictably and reliably as a system under service conditions over the life of the structure.

As a relatively new taxa, very few studies have looked at PEE×PCH as a material resource for engineered timber products [10,11]. Cherry et al. [8], investigated the mechanical properties of low-stiffness out-of-grade PEE×PCH and found that some portion would be suitable as a substitute for high-grade in low-stress applications such as the inner layers of CLT. They found that the majority of out-of-grade PEE×PCH was from the low-quality inner core of the tree, in which resin streaking and high-angled clustered conical-shaped knots connected to or located near the pith were frequent. As seen in Figure 1, resin streaking can be described as strips of resin-filled lumen. Resin streaks can be associated with knots, shaking, and other defects. Other researchers have also found resin streaking to be common in this PEE×PCH hybrid [1,12,13].



(**a**) (**b**) (**c**)

Figure 1. Resin streaking in PEE×PCH pine (**a**) along the board, (**b**) throughout the cross section, and (**c**) associated with knots.

No research was found specific to the bond performance of PEE×PCH; however, research is available on other species [14–18]. None of these studies looked specifically at out-of-grade core wood, juvenile wood, resin streaking, pith, or knots, which present challenges for gluing [19]. In fact, the majority of publications focus on the bonding of mature rather than juvenile wood [20]. Moreover, researchers intentionally excluded large knots from their studies [18,20] even though knots have shown good shear performance [21–24], which is desirable for inner layers in glue-laminated timber (Glulam) and CLT.

From a feedstock perspective, the most obvious foreseeable challenges are the lack of any reference or guidance on delamination and shear due to the effect of wood variation due to the presence of resin, pith, or knots at the glueline interface. Moreover, openings found along knots or resin pockets are disregarded or not addressed in the assessment of delamination in a number of current CLT and glulam standards [25–27] and therefore do not deal with the challenges they present. Out-of-grade PEE×PCH timber has a higher quantity of these characteristics, and to ensure an engineered product manufactured from this feedstock performs safely and reliably in service, the bond quality and performance of its characteristics need to be analyzed using suitable test methods and criteria that reliably measure and evaluate them rather than disregarding their impact.

Delamination and shear tests are commonly used to assess the bonding strength and quality of glue lines. Methods and assessment criteria for these tests are provided in numerous engineered timber product standards [25–29]. The delamination test looks at bond lines and wood failure percentages and is used to assess the ability of engineered wood products to resist wood shrinkage and swelling stresses under climatic conditions and, to some extent, the ability of the adhesive to withstand moisture degradation. While the shear test assesses the ability of the adhesive to transfer stress between the two adhered pieces of wood under shear loading. These tests also provide information on which is the weakest link between wood, the wood-adhesive interface, or the adhesive itself. Given that these tests provide different information, it is often recommended that both tests be used for a better understanding [16,19,30,31].

Three standards are being considered in this study, including the International Standard ISO16696-1 Timber Structures—Cross-Laminated Timber [27], the European Standard EN16351 Timber Structures—Cross-Laminated Timber versions 2015 and 2021 [26,28], and the American National Standard ANSI/APA PRG320 Standards for Performance-Rated Cross-Laminated Timber [25]. ISO16696-1 is based heavily on the draft European standard EN16351 and North American Standard PRG320 versions of that time. The current versions of all three standards have differences in test methods and/or assessment criteria for the bond quality of face bonds between layers. EN16351:2015 has been replaced with EN16351:2021, and there have been changes between the two editions on the assessment of bond quality between layers.

ISO16696-1 specifies delamination testing for bond quality, and where delamination exceeds limits, it gives the option to retest those same samples for wood failure as a secondary check and confirmation of bond quality. Test methods are to be as per an appropriate national standard. There is no requirement or option for shear testing of the bond line of face joints. This most recent version introduced a note that allows the exclusion of delamination associated with knots and other defects permitted by national standards.

The American standard, PRG320-2019, specifies the use of both delamination and wood failure for bond quality. Delamination is assessed on samples that have undergone a wet/dry cycle, while the wood failure percentage is assessed on smaller samples that have been loaded under shear until failure. There is no shear strength requirement for the sheared sample like there is in EN16351:2015. There is no wood failure assessment option on the delamination samples like there is in ISO16696-1 and EN16351:2015 and 2021, and $Delam_{max}$ is not considered. $Delam_{tot}$ is often found to be the limiting test [14,32], which may explain why the focus is only on $Delam_{tot}$ in this standard. PR320 is conservative, allowing only half the $Delam_{tot}$ limit of EN16351:2015 and 2021 and ISO16696-1. However, there are some slight differences to EN16351, which may help alleviate these tighter criteria, including the smaller sample size, allowing lower pressure in the wet cycle, as low as 483 kPa, and a higher percentage of original weight, up to 115%, and therefore higher moisture content and likely less moisture variation at the time of assessment. PRG320 does not specify how to interpret the delamination associated with knots, pith, resin, or other grade characteristics in the assessment. ANSI A190.1:2022 Product Standard for Structural Glued Laminated Timber [33] calls for AITC Test T110 Cyclic Delamination [34]. It is reasonable to use the AITC Test 110 approach to knots or other grade characteristics for the interpretation of results of delamination for CLT tested under PRG320 [35]. AITC Test 110 excludes delamination associated with knots or other grade characteristics. By using wood failure percentage assessment on shear tests rather than shear strength, PRG320 assesses if the bond line or the wood shear strength is higher without regard to the magnitude of the shear strength performance.

EN16351:2021 gives two options for bond quality. After samples have undergone a wet/dry cycle, Option 1 requires samples to be assessed for delamination, and where samples fail the criteria, they are subsequently assessed for wood failure. The second option is to go directly to the wood failure assessment only. The pass/fail criteria for these assessments is the same as ISO16696-1. Openings in the glue line found along knots or resin pockets are not regarded as delamination, and there is no reference to the assessment of resinous timber or pith. EN16351:2015 gives two options for bond quality, including option 1 of EN16351:2021, with option 2 being a test for shear strength. EN16351:2015 edition states that no correlation exists between the shear and delamination tests and specifies the shear testing as the "reference test method", so it is interesting that it is no longer an option for face bonding in EN16351:2021. Aicher et al. [36] state that delamination testing is of higher importance than shear block tests, and many researchers found the two options given in the 2015 edition to give very different results [16,30] with delamination being the more conservative. This may help explain the move away from shear strength in EN16351:2021.

With limited national standards for CLT available around the world, standards such as these three provide options for test methods and evaluations of the suitability of feedstock and processes for the production of CLT. While EN16351 and ISO16696-1 may restrict knots and pith from a structural performance perspective through the structural grading requirements of feedstock, PRG320 is the only standard that restricts their inclusion from a bond performance perspective, and it does so equally based on the area of the characteristic at the bond line without consideration to their individual impact on bonding. Furthermore, all three CLT standards considered in this study do not address resin, knots, and pith in the evaluation of delamination or bond line shear strength. While this may be acceptable for feedstock with a limited occurrence of these characteristics, due to their frequency and magnitude in some timber resources, such as low-stiffness out-of-grade PEE×PCH, they may need to be assessed and restricted. It is unlikely that the unrestricted inclusion of all the characteristics of low-stiffness out-of-grade PEE×PCH would be acceptable for use in CLT because of their impacts on structural and bond performance, so a targeted evaluation of each of these characteristics separately is required.

The weakest link theory has been used to explain and predict the failure location in solid wood [37]. Marra [38] applies the weakest link theory to bond lines in laminated timber, separating the bond line into nine zones. Each zone is described as a link in a system. Many variables impact the strength of these zones or links, including the wood itself [39]. The use of wood containing resin, knots, and pith at the bond line adds additional complexity for bonding and is expected to cause weakened links within the bond line by inhibiting structural bonding and/or introducing additional stress and stress concentrations. This then leads to weakening and stress concentrations in regions of the larger bonded area between layers of CLT, leading to the failure of the glue line. It is important that these weakened links are limited sufficiently so that they do not, individually or in combination, reduce the bond performance below the requirements of the CLT panel in service. An understanding of the contribution of each of these characteristics toward causing weakening of the bond line could be used to inform grading rules for the restriction of the same into CLT.

This study will focus on the bond quality and bond performance of out-of-grade PEE×PCH to produce CLT. First, it will determine the bond quality and performance of low-stiffness out-of-grade clear defect-free wood and then evaluate this performance against the pass/fail criteria of the CLT bond performance requirements of three national CLT standards. This process will be repeated for resin, knots, and pith samples and compared to the clear defect-free wood to determine the extent to which bond performance is impacted by the presence of these characteristics and to determine if any restriction on these characteristics would be required to achieve the passing requirements for bonding in these CLT standards. It will discuss the findings and unique challenges that characteristics of this out-of-grade feedstock present for delamination, shear testing, and standards, and compare the pass/fail results of test methods. It will use the information gained through the testing and assessment processes to inform and present an avenue to maximize the inclusion of out-of-grade timber characteristics of resin, knots, and pith in CLT while also restricting the same so as to not compromise the intended bond performance requirements of the standards that currently do not address these characteristics.

2. Materials and Methods

Shear and delamination tests will be carried out on four different sample types of out-of-grade timber in accordance with the test methods set out in the current CLT standards: PRG320 [25], ISO16696-1 [27], EN16351:2021 [26], and EN16351:2015 [28]. The delamination test will be in CLT configuration, while the shear test will be in both CLT and glulam configuration. Student T-tests with a significance level of 0.05 will be used to analyze the difference between sample-type results.

2.1. Sample Manufacture and Preparation

The timber used for this study is a 31-year-old plantation-grown PEE×PCH hybrid grown in Cowra, Queensland, Australia. This timber is the common structural framing size of 90 × 35 mm^2, but it failed to meet the requirements of AS1748 [40] and AS1720.1 [41] for MGP grades, and the industry is looking for value-add opportunities. This out-of-grade resource was found to be from the core wood zone of the tree, to contain frequent resin streaking, high-angled conical-shaped and clustered knots often connecting to the pith, to have high density relative to structural performance and have low structural properties compared to in-grade timber, but still sufficient for low-stress regions in engineered wood products [8]. The approach taken for determining the sample types was to use clear wood as the benchmark and to determine the ability of the clear wood to meet the bond performance requirements of the CLT standards. Clear wood can be graded and docked out of a longer piece and then finger-jointed back together to avoid the inclusion of any unwanted characteristics. But to capture more volume of the out-of-grade resource to use in CLT, commonly occurring characteristics such as resin, knots, and pith would need to be included, which makes it important to also understand their impact on bond performance and quality. Therefore, these characteristics were targeted, evaluated individually, and compared to the results of the clear sample benchmark. This information was then used to inform an assessment of any requirement to limit their inclusion in CLT from a bond perspective. These characteristics, as shown in Figure 2, form the variables of this study and are described as:

1. Clear—containing no obvious defects in addition to the occasional presence of pith (Figure 2a);
2. Resin—resinous timber, covering at least 30% of each glued face. No obvious defects are present in addition to the occasional presence of pith (Figure 2b);
3. Knots—containing knots with knot area ratios (KAR) of at least 50% (Figure 2c) measured in accordance with AS2858 [42];
4. Pith—is a weak, non-structural cork-like material from the very center of the tree. Pith occurs at least 95% of the length at the bond line.

The adhesive used for this study is a type 1 one-component polyurethane, LOCTITE HB S309, which is compliant with European EN14080 [43] and Australian standard AS/NZS 4364 [44] for the manufacture of glue laminated timber products. The glue was applied within the specifications given by the manufacturer at a spread rate of 180 g/m^2. All boards were planed on their wide faces to a finished cross section of 33 × 90 mm^2 (thickness × width). A Delmhorst-RDM-2 moisture meter (Delmhorst Instrument Co, Towaco, NJ, USA) was used to measure the moisture content of all pieces before bonding, and all were within the glue manufacturers' specified range of 8% to 18%, with an average of 11.9% and a standard deviation of 2.3%. An industrial press (Hyne, Maryborough, Australia) was used at a pressure of 0.72 MPa, and the assembly and pressing times were in accordance with the adhesive manufacturer's specifications of 30 min and 75 min, respectively. All gluing and pressing occurred within 6 h of planning the boards as recommended for resinous timber [28].

(**a**) (**b**) (**c**) (**d**)

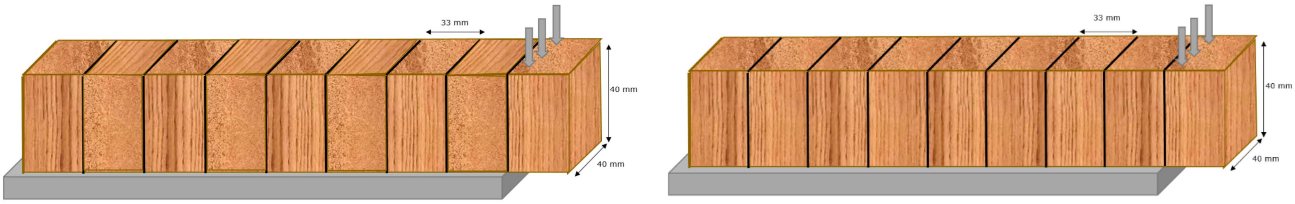
Figure 2. Examples of (**a**) clear, (**b**) resin, (**c**) pith, and (**d**) knot types.

For the delamination testing, one 5-layer CLT panel was manufactured for each of clear, resin, and knots. From these panels, 10 samples of dimensions 100 × 100 × 165 mm^3 (width × length × thickness), as shown in Figure 3c, were cut. To ensure there were knots present in every delamination sample, short lengths containing large knots (Figure 3b) were cut and formed layers 2 and 4, while knotty timber was used for layers 1, 3, and 5.

(**a**) (**b**) (**c**)

Figure 3. CLT delamination samples (**a**) are 5 layers deep, (**b**) knot samples are made from small lengths containing knots, and (**c**) 100 × 100 mm^2 samples are cut from these.

The shear samples were made as a matching set in two orientations in clear, resin, pith, and knots. A glulam orientation has the grain of all layers running parallel, while the CLT orientation has the grain of each adjacent layer at 90 degrees. Both the glulam and the CLT-oriented samples were made from timber with each of the four characteristics mentioned above. Bars of 40 × 40 mm^2 shear samples, as shown in Figure 4, were cut from these sections. The large size of the knots and knot clusters made it difficult to capture the impact of the knot and associated characteristics, including the branch wood, deviated grain, resin streaking, and compression wood within the 40 × 40 mm^2 samples. Therefore, knot samples were taken over the knot area, including the surrounding fiber. The quantities and combinations of test samples for delamination and shear testing are presented in Table 1.



(a) (b)

Figure 4. (**a**) Shear CLT and (**b**) shear glulam test sample dimensions and grain orientation.

Table 1. Number of test samples.

Test	**Delamination**	**Shear Glulam**	**Shear CLT**
Sample size	100 × 100 mm^2 × 5 layer	40 × 40 mm^2	40 × 40 mm^2
	Number of samples	Number of gluelines	Number of gluelines
Clear	10	32	32
Resin	10	32	32
Knots	10	64	32 (loaded 90° to grain) 32 (loaded 0° to grain)
Pith	Observed from clear and resin samples	32	32 (loaded 90° to grain) 32 (loaded 0° to grain)
Total	**30**	**160**	**192**

2.2. Test Procedure

2.2.1. Delamination Test of the Glue Line

A delamination test was carried out to evaluate the glue line integrity between layers in accordance with EN16351:2021. Samples were submerged in a pressure vessel, and a vacuum of 85 kPa was applied for 30 min, then released, followed by 600 kPa of pressure for 2 h. Finally, samples were dried in a Thermoline scientific dehydration oven (Thermoline Scientific, Wetherill Park, Australia) at a temperature of 70 °C ± 5 °C until samples reached within the range of 100% to 110% of their pre-test weight. Within 1 h of completing this process, the length of each delamination section on each glue line was measured and recorded. Contrary to EN16351:2021, Section C4.2, all delamination occurring in the vicinity of knots was included in these measurements for the knot samples. This was conducted to understand the impact of knots on bondline performance. Three values for delamination were determined using Equations (1)–(3). $Delam_{max}$ is the percentage of the longest delamination within a single glue line. $Delam_{tot}$ is the percentage of the sum of all delamination within a single sample. $Delam_{GL}$ is the percentage of the sum of all delamination within a single glue line. $Delam_{max}$ and $Delam_{tot}$ were assessed against pass/fail criteria as set out in Section 5.2.5.4.2 of EN16351:2021. $Delam_{GL}$ was used to provide further information on the bond performance.

$$Delam_{max} = 100\frac{l_{max,delam}}{l_{glueline}} \tag{1}$$

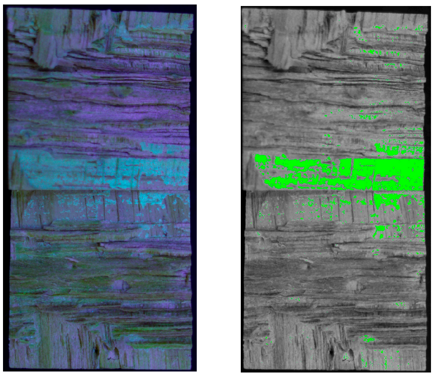
$$Delam_{tot} = 100\frac{l_{tot,delam}}{l_{tot,glueline}} \tag{2}$$

$$Delam_{GL} = 100\frac{l_{tot,delamGL}}{l_{glueline}} \tag{3}$$

where $l_{max,delam}$ is the maximum delamination length; $l_{glue\ line}$ is the perimeter of one glue line in a specimen; $l_{tot,delam}$ is the total delamination length; $l_{tot,\ glue\ line}$ is the sum of the perimeters of all glue lines in the specimen; and $l_{tot,delam\ GL}$ is the total delamination in a single glue line.

2.2.2. Wood Failure Post-Delamination

After evaluation for delamination, every glue line on every sample was split using a metal wedge and hammer and photographed under ultraviolet light. These images were analyzed, and the wood failure percentage was measured using ImageJ2 software version 1.54d [45]. The threshold was adjusted so the green area matched the glue failures that could be seen under the UV light, as can be seen in Figure 5. The ImageJ2 measure tool was then used to measure the area of wood failure.



(**a**) (**b**)

Figure 5. (**a**) Example showing matched glue failure under UV light to (**b**) ImageJ Threshold adjustment.

Again, contradictory to EN16351:2021 Section C4.2, all glue line failures occurring in the vicinity of knots were included in these measurements for the knot samples. The wood failure percentage for each glue line (WF_{GL}) was calculated using Equation (4), and the wood failure percentage of the total sample (WF_{tot}) was calculated using Equation (5).

$$WF_{GL} = 100\frac{Area_{WF-GL}}{Area_{GL}} \quad (4)$$

$$WF_{tot} = 100\frac{Area_{WF}}{Area_{totalglue}} \quad (5)$$

where $Area_{WF\text{-}GL}$ is the area of wood failure within a single glue line, $Area_{GL}$ is the total area of a glue line, $Area_{WF}$ is the sum of all wood failure areas, and $Area_{total}$ glue is the sum of all glued areas in a sample.

2.2.3. Shear Test of Glue Line

Shear strength testing is a common test used to assess the ability of the adhesive to transfer stress between the two adhered pieces of wood under shear loading. Shear block tests are intended for the same oriented timber layers in glulam. When used on transverse adjoining layers in CLT, the results can be difficult to interpret due to the different behaviors of timber under longitudinal and perpendicular grain loading, with large deformation and likely rolling shear failures on the perpendicular-oriented side of the sample [25]. Shear tests were carried out as shown in Figure 6 and in accordance with EN16351:2015 to determine the bonding strength of glue lines. Both parallel (glulam) and perpendicular (CLT) orientations were tested in this study. The pith and knot CLT samples were tested in two orientations. 32 were tested with the load applied longitudinally to the grain of the pith or knot piece (0°-loaded), and 32 were tested with the load applied perpendicularly to the grain of the pith or knot piece (90°-loaded). In Figure 4a, for CLT orientation, glue line A is considered 0°-loaded, while glue line B is considered 90°-loaded. Each glue line was loaded until failure, and the maximum load was used to calculate the shear strength (f_v) using Equations (6) and (7) from EN16351-2015.

$$f_v = k\frac{F_u}{A} \quad (6)$$

$$k = 0.78 + 0.00044t \quad (7)$$

where F_u is the ultimate load (in N), A is the sheared area (in mm^2), k is the adjustment factor for sample size, and t is the thickness (in mm).

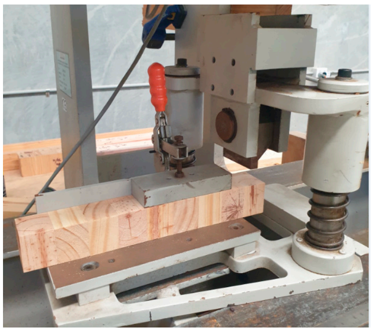
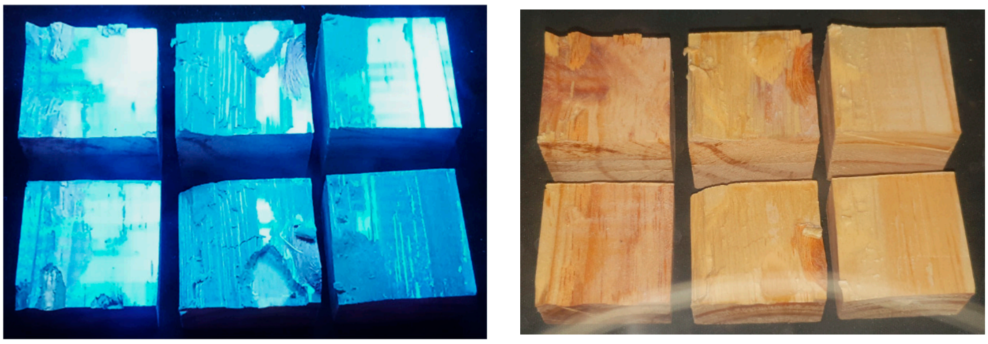


Figure 6. Shear test setup.

Once the shear test was completed, each sample was inspected for failure type under an ultraviolet light. The fluorescein in the glue creates contrast between the wood fibers and glue under ultraviolet light, as seen in Figure 7. The process used in ImageJ to measure the wood failure on the delamination samples was also used for the wood failure in the shear samples.



(**a**) (**b**)

Figure 7. (**a**) Under ultraviolet light, the fluorescein in the glue highlights the presence of glue at the surface of the glue line failure, which is difficult to see under (**b**) standard lighting.

2.2.4. CLT Standards: Assessment of Bond Quality and Strength

Assessments and evaluations were carried out according to the processes and criteria of the International Standard ISO16696-1 Timber Structures—Cross-Laminated Timber [27], the European Standard EN16351 Timber Structures—Cross-Laminated Timber, versions 2015 and 2021 [26,28], and the American National Standard ANSI/APA PRG320 Standards for Performance-Rated Cross-Laminated Timber [25].

For ISO16696-1, $Delam_{max}$ and $Delam_{tot}$ were measured after the wet-dry cycle. If a glue line or sample exceeds the $Delam_{max}$ or $Delam_{tot}$ limits, the glue lines are then split and assessed for WF_{GL} and WF_{tot}. To achieve a passing result, $Delam_{max}$ and $Delam_{tot}$ must be $\leq$40% and $\leq$10%, respectively. While a minimum wood failure percentage of each split glue line is required to be $\geq$50%, the sum of wood failure on all split glue lines is required to be $\geq$70%.

For PRG320-2019, $Delam_{tot}$ was measured after the wet/dry cycle, and WF_{tot} was measured on the sheared samples. To achieve a passing result, $Delam_{tot} \leq 5\%$ is required. Where $Delam_{tot}$ exceeds this limit but is ≤10%, a second test specimen can be extracted and tested for a limit of ≤5% to pass. To achieve a passing result, the average WF_{tot} of all sheared specimens combined must be ≥80% and at least 95% of all specimens ≥ 60%. For sheared specimens with wood failure below 50%, a second specimen from the same glue line may be tested, and this second specimen must have $WF_{tot} \geq 80\%$.

For EN16351:2021 and EN16351:2015, $Delam_{max}$ and $Delam_{tot}$ were measured after the wet/dry cycle. To achieve a passing result, $Delam_{max}$ and $Delam_{tot}$ must be ≤40% and ≤10%, respectively. All samples were split at the glue line and assessed for WF_{GL} and WF_{tot}. The minimum wood failure percentage of each split glue line is required to be ≥50%, and the sum of wood failure on all split glue lines is required to be ≥70% for a passing result.

For EN16351:2015, to achieve a passing result, the shear samples required a population characteristic shear strength of ≥1.25 MPa and ≥1 MPa for each glue line for crosswise bonded layers, while parallel bonded layers require a characteristic shear strength of ≥3.5 MPa and ≥2 MPa with a wood failure of 100% for a single glue line.

3. Results and Discussion

3.1. Wet/Dry Cycle Samples-Delamination and Wood Failure

The delamination and wood failure test results revealed good performance in clear samples with little delamination and a high wood failure percentage, but as expected, there was increasing variability and decreasing performance for resin and knots. Examples of typical delamination samples post-drying are shown in Figure 8. Small radial cracks were common and would provide stress relief within the sample. During the wet/dry cycle, resin is exuded onto the surface of the resin and knot samples. The knot samples were highly distorted in comparison to clear and resin, showing signs of the higher stresses caused by the complex composition of knots and surrounding fiber. After the wet/dry cycle and the delamination assessment were complete, the glue lines were split.

(**a**) (**b**) (**c**)

Figure 8. Typical samples post-delamination test for (**a**) clear, (**b**) resin, and (**c**) knots.

3.1.1. Clear

The clear samples performed well with little delamination and an average of 2.9% $Delam_{GL}$ (0% median) and $Delam_{tot}$ (0.6% median) (Table 2). This is less than that seen in other studies. Sikora et al. [30], Betti et al. [16], and Knorz et al. [14] all looked at spruce and found average delamination between 9% and 20%. Hindman and Bouldin [17] investigated southern yellow pine, which had an average delamination of 17.2%. The average $Delam_{max}$ for the clear samples was 7.2% (1.9% median).

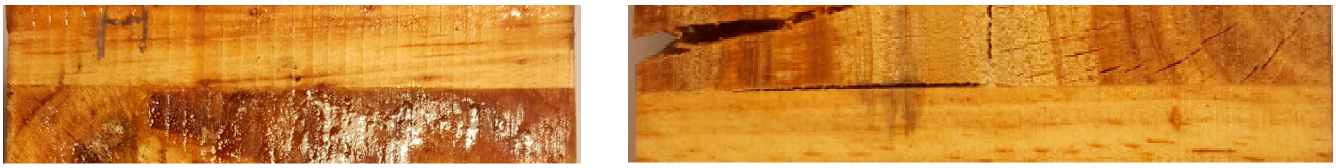
Table 2. Delamination and wood failure test results.

		Ave (%)	Std Dev	Median (%)	5th %ile (%)	Min (%)	Max (%)
$Delam_{GL}$—delamination in each glue line	clear	2.9	5.8	0.0	19.4	0.0	24.2
	resin	9.3	12.5	2.7	34.8	0.0	40.5
	knot	24.4	17.6	22.9	48.5	0.0	75.0
$Delam_{tot}$—delamination in all 4 glue lines within a sample	clear	2.9	4.1	0.6	9.0	0.0	9.3
	resin	9.3	6.5	7.6	20.9	2.1	24.0
	knot	24.4	10.7	22.5	41.7	11.2	48.2
$Delam_{max}$—the worst delamination in a glue line of each sample	clear	7.2	9.9	1.9	22.4	0.0	24.2
	resin	25.1	10.8	24.5	39.2	4.6	40.5
	knot	42.9	12.5	39.6	62.7	30.4	75.0
WF_{GL}—wood failure in each glue line	clear	96.7	5.6	100	88.0	69	100
	resin	92.6	14.4	97	61.0	35	100
	knot	77.4	21.9	85	29.8	23	100
WF_{tot}—wood failure all 4 glue lines within a sample	clear	96.7	2.2	97.5	92.9	91.3	98.8
	resin	92.6	6.3	95.5	81.3	80.5	97.5
	knot	77.4	14.1	81.3	56.6	47.0	97.5

Clear samples performed well for wood failure and had an average of 96.7% for WF_{GL} (100% median) and WF_{tot} (97.5% median). These results are higher than those of spruce studied by Sikora et al. [30], which were approximately 70% and 83%, respectively, for samples with similar clamping pressures. The good performance of clear samples can be attributed to the low density, low MOE, and reduced differential shrinkage of this core wood timber, combined with the flexibility of the 1C PUR adhesive.

3.1.2. Resin

Resin had a negative effect on delamination, with significant differences to clear samples for $Delam_{GL}$ ($p = 0.002$), $Delam_{tot}$ ($p = 0.008$), and $Delam_{max}$ ($p < 0.001$), and also had a higher standard deviation than clear samples (Table 2). On average, delamination for resin samples was 217% higher than clear. No clear relationship could be seen between the percentage of resinous timber at the glue line faces and delamination. As can be seen in Figure 9a, wood that is very heavy in resin can achieve good bonding with no delamination, while b clear wood with no obvious resin content can have bonding issues and delaminate adjacent to resinous wood that does not. This shows that the presence of resin streaking does not necessarily confirm that poor bonding will be achieved. However, it is clear that the resinous samples did not bond as well as the clear samples, indicating that background resin may be more of a contributor and is causing the bonding issues rather than resin streaking alone.



(**a**) (**b**)

Figure 9. Examples of delamination where (**a**) resinous wood is at the glueline with no delamination and (**b**) with resinous and clear wood showing delamination in some areas and not in others. Background resin may be more of a bond issue than resin streaking.

Resin had a negative effect on wood failure, with significant differences from clear samples for WF_{GL} ($p = 0.046$) and WF_{tot} ($p = 0.030$). On average, wood failure for resin samples was 4.3% less than clear. No clear relationship could be seen between the percentage of resin at the interface and wood failure.

3.1.3. Knots

Knots had a negative effect on delamination, with significant differences between clear and resin samples for $Delam_{GL}$ (clear and resin: $p < 0.001$), $Delam_{tot}$ (clear and resin: $p < 0.001$), and $Delam_{max}$ (clear and resin: $p < 0.001$). On average, delamination for knot samples was 730% higher than clear.

Knots had a negative effect on wood failure, with the lowest performance and highest standard deviation. There were significant differences between knots and clear samples for both WF_{GL} (clear and resin: $p < 0.001$) and WF_{tot} (clear: $p < 0.001$, resin: $p = 0.003$). On average, wood failure for knot samples was 20.0% less than clear.

3.1.4. Pith

There were no separate delamination samples for pith; instead, pith was observed in the other sample types. Samples with pith located at or adjacent to the bond line typically experienced wood failure through the pith or immediate surrounding fibers where a radial crack was already present. Pith is a weak, non-structural cork-like material, and the very young juvenile wood in the first 3 or so growth rings surrounding the pith has low structural properties [46] and often contains cracks radiating out from the pith. The ability of this low-strength pith and surrounding fiber to transfer stresses effectively through the bond line is minimal, resulting in premature wood failure rather than glue line failure. Arguably, this is wood failure and should be considered a structural topic rather than a bond line topic, but when in such close proximity to the bond line, it would be wise to consider its negative impact on the bond line performance.

3.2. Block Shear Strength and Wood Failure

3.2.1. Glulam–Failure Types

Figure 10 shows some typical failures for glulam-oriented samples in clear, resin, pith, and knots. Separation between earlywood and latewood boundaries was common. Where pith was located at or adjacent to the bond line, failure occurred through the pith. Knot samples experienced more glue line failures than the clear and resin sample types. These usually occur across the branch wood and immediate surrounding fiber and are likely linked to glue starvation at the bond line. Sikora et al. [47] also saw glue line failures occurring at knots. Additionally, as will be seen in this section, not all samples experiencing glue line failures are weak in shear strength.

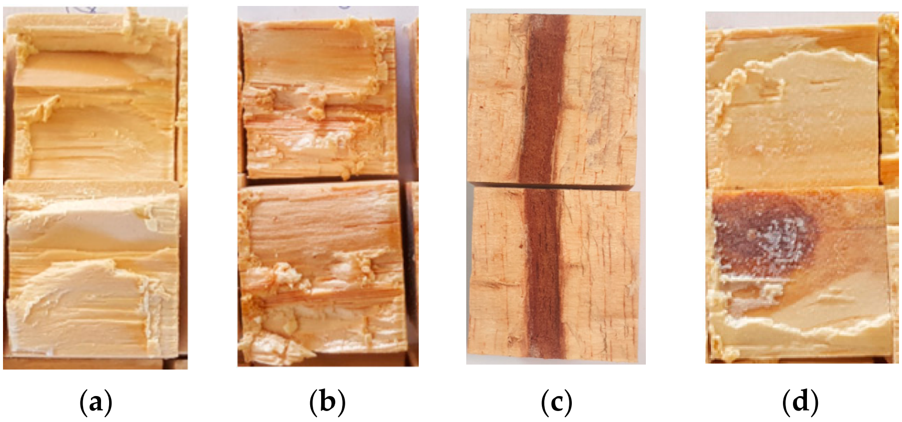


Figure 10. Examples of shear failures: (**a**) clear, (**b**) resin, (**c**) pith, and (**d**) knot samples.

Clear Glulam

The clear glulam samples performed well with an average glue line shear strength of 8.5 MPa (8.4 MPa median), a 5th percentile of 6.6 MPa, and an average wood failure of 86% (median 96%) (Table 3 and Figure 11. These results are comparable to other studies on similar pines glued with PUR in glulam orientation. Kim et al. [48] found red pine to have 10.27 MPa glue line shear strength with 92.46% wood failure. Raftery et al. [20], Steiger et al. [31], and Sikora et al. [30] all found spruce glulam had average glue line shear strengths between 8 MPa and 10.1 MPa. Wood failure was between 90% and 97% [20,31]. The bond line and glue line shear strength values are higher than the shear strength of solid wood from the same population of hybrid pine at 5.7 MPa, as found by Cherry et al. [8]. However, this difference can be explained by the impact of the size effect on the much smaller shear block samples and the different test methods used [18,49,50].

Table 3. Shear strength and wood failure results of glulam orientation.

		Average	Std Dev	Median	5th %ile	Min	Max
Glulam orientation–Shear Strength (MPa)	clear	8.5	1.0	8.4	6.6	6.2	10.2
	resin	8.2	1.0	8.4	6.8	5.7	10.0
	Pith	7.9	1.3	7.9	5.0	3.9	9.9
	knots	8.2	1.7	8.5	5.0	3.8	10.9
Glulam orientation–Wood Failure (%)	clear	86	20.4	96	40	30	100
	resin	85	21.5	96	43	31	100
	Pith	90	16.1	98	60	30	100
	knots	70	28.5	76	13.3	11	100

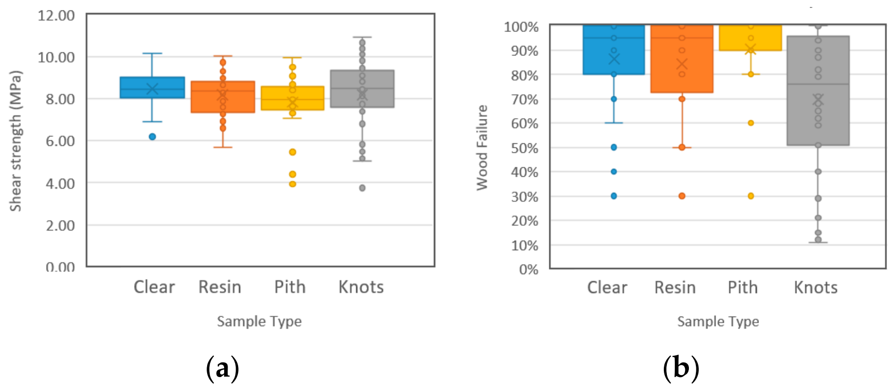


Figure 11. (**a**) Shear strength and (**b**) wood failure percentage of clear, resin, knots, and pith in glulam orientation.

Resin Glulam

There is no significant difference in glue line shear strength (p = 0.248) or wood failure percentage (p = 0.705) between resin and clear glulam samples. Resin samples are on average 3.5% lower in glue line shear strength than clear and have on average 1.5% less wood failure than clear.

Knots Glulam

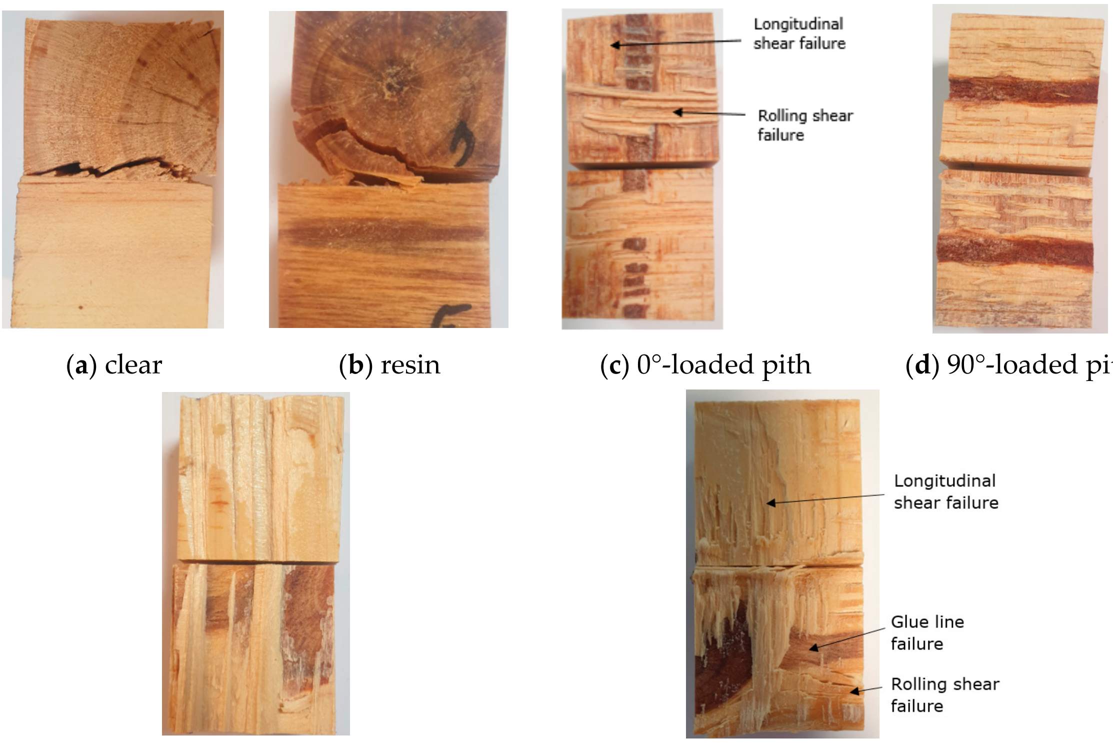
There is no significant difference in glue line shear strength (p = 1.986) between knots and clear glulam samples, but there is a significant difference in wood failure percentage ($p < 0.001$). Knots are 3.5% lower in glue line shear strength than clear, have the lowest 5th percentile at 5.0 MPa, and have on average 19.2% lower wood failure than clear. This shows that samples with low wood failure percentages can still achieve glue line shear strengths similar to samples with high wood failure percentages.

Pith Glulam

There is a significant difference in glue line shear strength (p = 0.031) between pith and clear glulam samples, but wood failure is not significantly different (p = 0.385). Pith is on average 5.8% lower than clear and has a lower 5th percentile than clear at 5.0 MPa, which aligns with that of knots. Pith achieved the highest wood failure and has on average 4.6% more wood failure than clear.

3.2.2. CLT Orientation–Failure types

Figure 12 shows some typical failures for CLT-oriented samples in clear, resin, pith, and knots. The majority of CLT-oriented samples experienced rolling shear failures in the cross layers, which is common in the literature [17,48,51]. The pith and knot samples were tested in two orientations. The first orientation loaded the pith or knot side of the sample parallel to its grain (0°-loaded). The second orientation loaded the pith or knot side of the sample perpendicular to its grain (90°-loaded). In 0°-loaded orientation, the pith samples almost always failed with a combination of rolling shear and longitudinal shear failure. The 90°-loaded pith samples typically failed to roll shear in the adjoining piece. In both orientations, the knot side of the sample experienced little wood failure, with the majority of failures occurring in the glue line or on the other side of the sample. The majority of failures in the 0°-loaded samples occurred as rolling shear failures in the adjoining clear piece; some had sections of glue line failures, and in 2 samples there were small sections of longitudinal shear failures in the deviated grain surrounding the knot, leaving a scalloped-out shape. The 90°-loaded samples experienced more variation in failure types, with combinations of one or more longitudinal shear failures in the adjoining clear piece, glue line failures, and small sections of rolling shear failures in the clear grain surrounding the knot. The glue line failures in the knot samples usually occurred across the branch wood and are likely linked to glue starvation at the bond line.



(**a**) clear (**b**) resin (**c**) 0°-loaded pith (**d**) 90°-loaded pith

(**e**) 0°-loaded knot (**f**) 90°-loaded knot

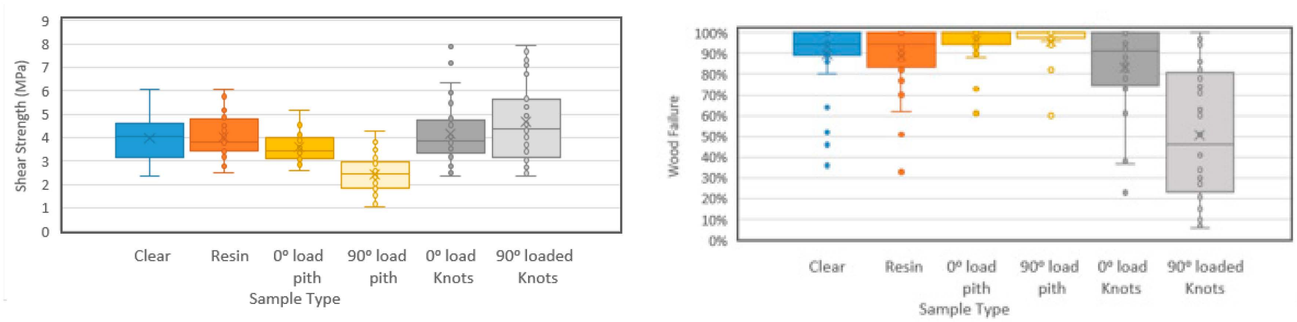
Figure 12. Examples of failures in CLT: (**a**) clear with rolling shear failure; (**b**) resin with rolling shear failure; (**c**) pith 0°-loaded with a combination of rolling shear and longitudinal shear failure through the pith; (**d**) pith 90°-loaded with rolling shear failure; (**e**) knots 0°-loaded with glue line failure over the knot and rolling shear failure in the adjoining piece; and (**f**) knots 90°-loaded with small sections of longitudinal shear failure in the adjoining piece, small sections of rolling shear failure in the clear wood surrounding the knot, and glue line failure over the knot.

Clear CLT

The clear CLT samples performed well, with an average glue line shear strength of 4.0 MPa (4.1 MPa median), a 5th percentile of 2.6 MPa, and an average wood failure percentage of 90% (94.5% median) (Table 4 and Figure 13). These results are comparable to other studies on similar pines glued with PUR in CLT orientation. Hindman and Bouldin [17] and Lim et al. [51] found Southern Pine CLT had glue line shear strengths of 4.38 MPa and 3.68 MPa and wood failure of 81.6% and 93.6%, respectively. Kim et al. [48] found red pine CLT had a glue line shear strength of 3.5 MPa and a wood failure of 90.3%. Sikora et al. [30] and Betti et al. [16] found that spruce CLT had glue line shear strengths between 2.0 MPa and 4.0 MPa. Rolling shear strength was the limiting factor for clear samples.

Table 4. Shear strength and wood failure results of CLT orientation.

		Average	Std Dev	Median	5th %ile	Min	Max
CLT orientation Shear Strength (MPa)	Clear	4.0	1.0	4.1	2.6	2.3	6.0
	Resin	4.0	0.9	3.8	2.8	2.5	6.1
	Knots (0°-loaded)	4.2	1.3	3.8	2.5	2.4	7.9
	Knots (90°-loaded)	4.7	1.7	4.4	2.4	2.4	8.0
	Pith (0°-loaded)	3.6	0.6	3.5	2.8	2.6	5.2
	Pith (90°-loaded)	2.4	0.8	2.4	1.1	1.0	4.3
CLT orientation Wood Failure (%)	Clear	90	16.6	95	49	36	100
	Resin	89	16.3	95	57	33	100
	Knots (0°)	83	21.0	91	32	23	100
	Knots (90°)	51	31.0	46	7	6	100
	Pith (0°-loaded)	96	9.0	100	69	61	100
	Pith (90°-loaded)	96	10.0	100	61	60	100



(**a**) (**b**)

Figure 13. (**a**) Shear strength and (**b**) wood failure percentage of clear, resin, 0°-loaded pith, 90°-loaded pith, 0°-loaded knots, and 90°-loaded knots in CLT orientation.

Resin CLT

There is no significant difference between resin and clear CLT samples for glue line shear strength (p = 0.814) or wood failure (p = 0.851). Resin samples have the same glue line shear strength as clear, a similar 5th percentile of 2.8 MPa, and 1% less wood failure than clear. Rolling shear strength was the limiting factor for resin samples.

Knots CLT

There is no significant difference between the average glue line shear strength of clear and 0°-loaded knot samples (p = 0.493); however, there is a significant difference between the clear and 90°-loaded knot samples (p = 0.042). The 0°-loaded knot samples and 90°-loaded knot samples were 5% and 17.5% stronger than clear, respectively. There is no significant difference in average shear strength between the 0°-loaded and 90°-loaded knot CLT samples (p = 0.165), but as can be seen in Figure 13, the 90°-loaded knot CLT had more variation in shear strengths.

There is no significant difference in average wood failure percentage between the 0°-loaded knot and clear samples (p = 0.157). However, there are significant differences between 90°-loaded and clear samples ($p < 0.001$) and between 90°-loaded and 0°-loaded knot samples ($p < 0.001$). On average, 0°-loaded knots have 7% less wood failure percentage than clear, and 90°-loaded knots have 43% less wood failure than clear. Again, the variation in the 90°-loaded samples is much higher than the other sample types. The rolling shear strength of the clear side of the sample was the limiting factor for the 0°-loaded knot samples, whereas the 90°-loaded knot samples were less limited by rolling shear but instead experienced a variety of failure types.

The occurrence of longitudinal shear failures on the clear side of the sample piece for the 90°-loaded knot samples aligns with the higher shear strength results. Timber is stronger in longitudinal shear than it is in rolling shear. The knots cause different stress distributions within the samples and have higher rolling shear strengths at the interface, exceeding those of the glue line and/or adjoining sample piece, which resulted in more variation in failure types, wood failure percentages, and shear strengths. This shows that where bonding layers of timber are perpendicular to each other, such as in CLT, knots in the transversal layers, which experience perpendicular grain stress, will provide superior glue line shear strength performance compared to knots in the longitudinal layers. This is because in the 0° samples, the adjoining clear wood will likely fail to roll shear before the glue line or knot reaches its shear capacity. Shahhosseini et al. [52] found knots significantly increased rolling shear modulus and strength with a 23.5% and 37.8% difference, respectively. They found that knots distributed the load more evenly, blocked shear cracks, and did not show the high stress concentrations seen in clear timber samples.

Pith CLT

There is a significant difference between 90°-loaded pith and clear CLT samples for glue line shear strength ($p < 0.001$). However, there are no significant differences between 0°-loaded pith and clear shear strength ($p = 0.077$). The 90°-loaded pith and 0°-loaded pith have glue line shear strengths of 39% and 9.1% less than clear, respectively.

There is no significant difference between 90°-loaded pith ($p = 0.071$) or 0°-loaded-pith ($p = 0.053$) and clear wood failure percentage. The 90°-loaded pith and 0°-loaded pith have on average 7% less wood failure than clear.

3.3. Bonding

3.3.1. Bonding Clear Wood

Knorz et al. [53] found that the more elastic 1C PUR allowed for smoother strain transitions and showed fewer shear strain peaks in the bond line than other commonly used timber adhesives. Polyurethanes generally have molecular weights too high to penetrate cell walls, so adhesion depends on penetration into the cell lumen [54], and the low-density early wood with its large cell lumens enables this. Moreover, early wood shrinks less and experiences lower moisture-induced stresses compared to late wood [14,19], and the high differential shrink-swell behavior between the connecting longitudinal and transverse layers is often blamed for the high delamination of CLT [14,16,30,32]. So where the difference between longitudinal and transverse shrinkage of adjoining transverse layers is reduced, so too is the shrinkage-induced stress in the bond line joining the two. Several studies have shown that longitudinal shrinkage increases while transverse shrinkage decreases closer to the pith in pines [55–57], which can be attributed to the high microfibril angle of juvenile wood and the high percentage of compression wood found in this core wood zone [58]. Moreover, the low MOE of this resource means the timber fibers flex and move with the shrink-swell behaviors of the timber, reducing strain concentrations at the bond line.

3.3.2. Bonding Resinous Wood

The lower performance of resin compared to clear samples can be attributed to the resin's tendency to reduce wettability [59], obstruct adhesive flow through pits and rays [58], and fill the cell lumen, which is an important cavity for adhesion by PUR [54]. Furthermore, the pH and buffering capacity of resin can interact negatively with the adhesive [60]. Bockel et al. [61] describe PUR adhesives as being robust but found they were influenced by acids in resin, which reduced the tensile shear strength. Moreover, adhesion to resin, which is a non-structural component within wood, would lead to reduced performance.

3.3.3. Bonding Knots

Knots are a complex mixture of branch wood, deviated grain, resin, and compression wood, all of which can negatively impact bond performance and contribute to these poorer results. The amount of glue available at the bond line significantly affects bond performance [62]. Hass et al. [63] found that PUR adhesive was very fast to penetrate longitudinally into the exposed cut cells of wood. Adhesive flows into the cell lumens as it follows the path of least resistance, but this can result in overpenetration and glue starvation at the joint [62,64]. The branch wood and three-dimensional deviated grain provide many exposed cut cells at the bonding surface and, therefore, opportunity for the adhesive to flow deeper into the wood along these cell lumens, starving the glue line. An example of this can be seen in Figure 14a. The bark surrounding bark-encased knots is porous and provides cavities for adhesive to flow into and away from the bonding surface. Glue starvation typically causes cohesive failure in the adhesive or adhesive interphase [59] regions, which were seen in some of the split and sheared knot samples in this study. Additionally, Cherry et al. [8] found that knots had 54% and 95% higher performance in perpendicular to grain MOE and strength, respectively, than clear timber. The knots act like pillars during pressing, creating higher pressures at the knot locations and lower pressures in the surrounding bond line, and pressure is known to impact bond performance [30]. The high pressure at the knot could lead to glue line starvation by way of glue either penetrating the cell lumen away from the bond line or escaping to the surrounding lower pressure areas, which may not receive sufficient pressure for good bonding. This would lead to a wide variation in bond performance over and around the knot area.

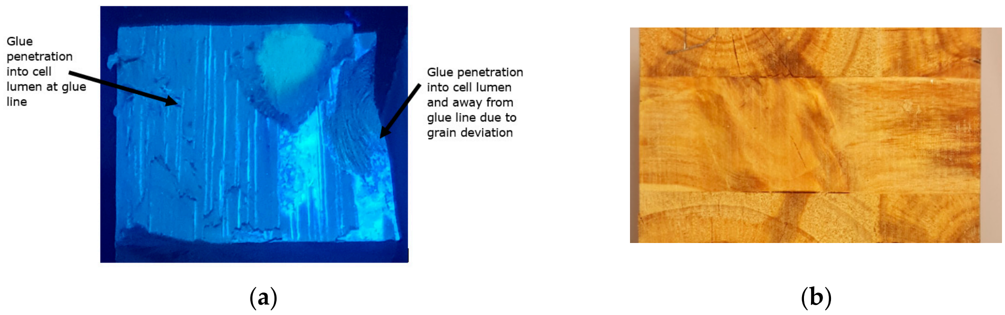


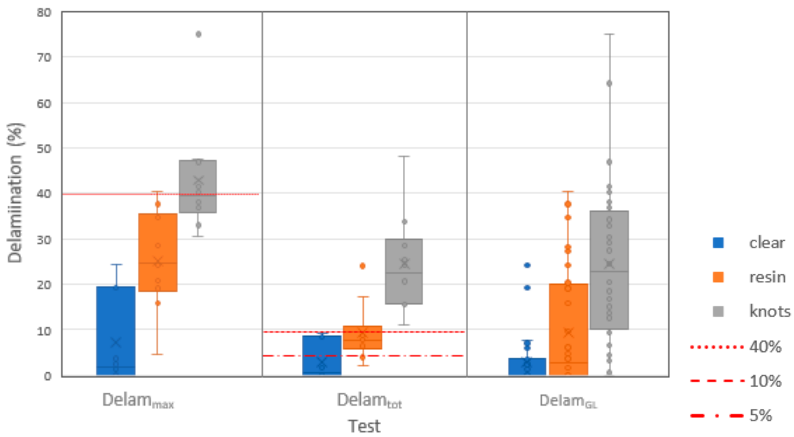
Figure 14. (**a**) A sample under UV light showing glue penetration into the cell lumen; (**b**) an example of delamination and wood failure on opposite glue lines of the same knot.

Another complexity is the differential shrinkage created by the deviated grain around knots. Moisture-induced swelling and shrinking stresses are known as the main causes of bond failure [59]. Ivkovic et al. [56] found longitudinal grain shrinkage for juvenile wood in radiata pine was 20% of that in the perpendicular grain direction. Dundar et al. [65] found the tangential and radial shrinkage at knots in scots pine was 45% and 28% less than that in clear wood. Branch wood and grain deviation cause longitudinal and perpendicular grain shrinkage within close proximity to each other. This occurs in the same plane, within a board and between adhered boards, and causes further stress concentrations as the low-shrinkage rate longitudinal fibers act as pillars against the high-shrinkage rate perpendicular fibers pulling away from the surface. Figure 14b shows an example of delamination in the knot sample types where one bond line has sufficient bond performance to cause wood failure in the adjoining lamella while the other face has delamination at the bond line.

4. CLT Standards Assessments

Delamination and wood failure pass/fail results for wet/dry cycled samples of each sample type and for each of the standards, including EN16351:2015, EN16351:2021, ISO16696-1, and PRG320, are presented in Table A1 in Appendix A. The individual test criteria for EN16351 and ISO16696-1 are the same and are given in columns 2 to 5. EN16351:2015 and ISO16696-1 assess $Delam_{GL}$ and $Delam_{tot}$ with the option to use WF_{GL} and WF_{tot} as secondary tests; the results are given in column 6. EN16351–2021 uses either $Delam_{GL}$ and $Delam_{tot}$ followed by WF_{GL} and WF_{tot} or, alternatively, just an assessment of WF_{GL} and WF_{tot}. Results are given in either column 6 or column 7, depending on which option is chosen. Finally, PRG320 only assesses $Delam_{tot}$, and results are given in column 8. Column 9 shows if the sample qualifies for a retest under PRG320.

Figures 15 and 16 illustrate the delamination and subsequent wood failure results, respectively. Also included are the percentage limits of 5%, 10%, and 40% for delamination and 50% and 70% for wood failure, which are used in PRG320, EN16351, and ISO16696-1 for comparison. It becomes clear in these graphs that $Delam_{tot}$ is far more conservative than $Delam_{max}$ or WF, and that the PRG320 5% $Delam_{tot}$ limit would be a challenge to achieve with this resource.



(**a**) (**b**) (**c**)

Figure 15. Percent of delamination in (**a**) the glue line of each sample with the maximum delamination, (**b**) each test sample, and (**c**) each of the 40 glue lines for each sample type.

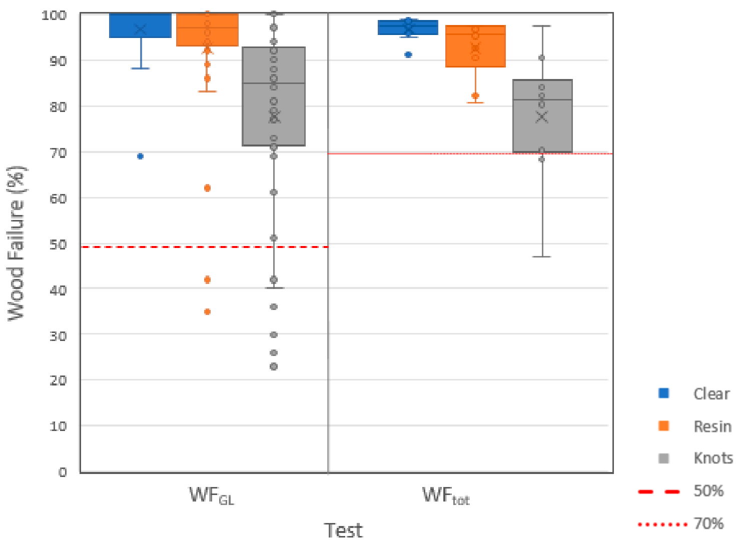


Figure 16. Wood failure of individual glue lines and total wood failure within a sample.

4.1. ISO16696-1 Timber Structures—Cross-Laminated Timber

Under the delamination and subsequent wood failure assessment of ISO16696-1, clear, resin, and knots had 100%, 90%, and 50% pass rates, respectively. All clear samples passed $Delam_{max}$ and $Delam_{tot}$ requirements with no need for a wood failure assessment. All clear samples also passed the WF_{GL} and WF_{tot}. 30% of resin samples failed one or more individual criteria of $Delam_{GL}$, $Delam_{tot}$, or WF_{GL}. 100% of knot samples failed $Delam_{tot}$, and 70% also failed for other criteria. When following the standard process of delamination followed by wood failure assessment, only 10% of samples were considered failed results, and 50% of knots passed. By using this method, one resin sample that had low WF_{GL} would not be detected as a failed sample; all other low WF samples also failed the delamination criteria. DKN02 and DKN05 showed that a sample could fail both delamination tests but pass both wood failure tests. DR06 shows that a sample could pass both delamination tests but fail the wood failure percentage. If the standard procedure of ignoring openings in the glue line along or near knots was followed, 100% of the knot samples would have passed. There is no requirement or option for shear testing of the bond line of face joints in ISO16696-1.

4.2. EN16351 Timber Structures—Cross Laminated Timber

EN16351:2021 provides two options for assessment. Option 1 assesses $Delam_{GL}$ and $Delam_{tot}$, with the option to subsequently assess WF_{GL} and WF_{tot}. Option 2 assesses only WF_{GL} and WF_{tot}. 100% of the clear samples passed options 1 and 2. A total of 90% of resin samples passed option 1, while 80% passed option 2. 50% of knot samples passed both options 1 and 2. All samples that failed option 1 also failed option 2, and the final results were very similar between these two options, with option 2 failing only 1 additional sample in the resin type. This supports the decision to save on resources in completing the delamination measurement process and only conduct option 2 for wood failure. EN16351:2015 had equivalent criteria to ISO16696-1, which has given very similar results to EN16351:2021.

There is no requirement or option for shear testing of the bond line of face joints in EN16351:2021; however, EN16351:2015 did provide criteria for shear strength. The clear, resin, 0°-loaded pith and knot samples in both the CLT and glulam orientations exceeded the population characteristics and minimum shear strength requirements of EN16351:2015 as presented in Table 5. However, the 90°-loaded pith failed the population characteristic requirement by 0.05 MPa and only just met the minimum requirement at 1 MPa. Shear strength criteria proved to be less conservative than delamination.

Table 5. Shear strength results.

	Sample Type	Minimum MPa	Population Characteristic MPa
Glulam orientation	Clear	6.2	6.7
	Resin	5.7	6.5
	Pith	3.9	5.4
	Knots	3.8	5.2
	EN16351:2015	≥2	≥3.5
CLT orientation	Clear	2.4	2.4
	Resin	2.5	2.6
	0°-loaded pith	2.6	2.6
	90°-loaded pith	1.0	1.2
	0°-loaded knot	2.4	2.4
	90°-loaded knot	2.4	2.2
	EN16351:2015	≥1	≥1.25

4.3. PRG320 Standards for Performance-Rated Cross-Laminated Timber

With the stricter limit of 5% $Delam_{tot}$ under PRG320 clear, resin and knots had a pass rate of 70%, 20%, and 0%. Three clear samples failed $Delam_{tot}$, but all three qualified for a retesting with $Delam_{tot}$ of 8.4%, 8.7%, and 9.3%. Eight resin samples failed, six of which qualified for retesting, and 10 knot samples failed, with none qualifying for a retest. There is no information specific to the assessment of delamination adjacent to or near knots. It should be noted that the more conservative sample size, wet cycle pressure, and final weight percentage of the EN16351 standard were used for this assessment, so these results could be considered slightly conservative. There is no requirement or option to assess wood failure on the delamination samples in PRG320, but it does require it on shear block samples.

PRG320 does not use shear strength for assessment but instead uses the wood failure percentage of samples that have been loaded under shear until failure. The CLT-oriented clear, resin, 0°-loaded pith, 90°-loaded pith, and 0°-loaded knot samples all exceeded the minimum requirement of PRG320 for both average failures of all specimens combined to be at least 80% and for 95% of all specimens to have a minimum of 60% wood failure, but 90°-loaded knot samples did not (Table 6). The reason for the low wood failures in these samples is the higher performance of knots in rolling shear at the interface, exceeding that of the bond line, meaning that despite higher shear strength, these samples failed this test. The 0°-loaded pith and 90°-loaded pith achieved the requirement for at least 95% of all specimens to have wood failure of at least 60%. No other sample types achieved this, but they did have some samples with <50% wood failure that qualified for a second block shear specimen.

Table 6. Shear wood failures.

Sample Type	Average WF (Shear)	Count of Samples ≥60% WF	% of Samples ≥60% WF	Count of Samples <50% WF
clear	90%	29	91%	2
resin	89%	30	94%	1
0°-loaded pith	96%	32	100%	0
90°-loaded pith	96%	32	100%	0
0°-loaded knot	83%	29	91%	3
90°-loaded knot	50%	14	44%	16
PRG320	≥80%		≥95%	

4.4. Standards and Test Comparison

PRG320 proved to be the most conservative standard. Only pith sample types pass the requirement for at least 95% of all specimens to have a wood failure of at least 60%, with resin being the next closest at 94%. EN16351:2021 option 2, which considers only WF_{tot} on the delamination samples, was the second most conservative, with all sample types combined achieving an overall pass rate of 77%. Next are ISO16696-1 and EN16351:2015, and option 1 of version 2021, which considers a combination of $Delam_{max}$ and $Delam_{tot}$ on delamination samples, with the option of following up with WF_{max} and WF_{tot} to achieve an 80% pass rate, and finally, the EN16351:2015 option of shear strength is the least conservative, achieving a 100% pass rate.

Of the individual tests and assessments, $Delam_{tot}$ under PRG320 was the most conservative, followed by $Delam_{tot}$ under EN16351 and ISO16696-1, with all sample types combined achieving 30% and 60% pass rates, respectively. Of the test methods and assessments in the current versions of the standards, WF_{tot} under EN16351 and ISO16696-1 are the least conservative, with a 90% pass rate for all sample types combined. The pass rates by individual test, assessment, and sample type are presented in Table A2 in Appendix A. The results of this study align with other research and show that the delamination and shear block tests of EN16351:2015 give different results [16,30], with delamination being the more conservative.

Shear strength of the face layer bond under EN16351:2015 is the least conservative of the tests carried out in this study, with 100% of samples passing in both CLT and

Glulam orientations. The results of this study align with other research and show that the delamination and shear block tests of EN16351:2015 give different results [16,30], with delamination being the more conservative. The shear test was considered the reference test in EN16351:2015; it is not an option in EN16351:2021. The considerable difference between delamination results and shear results may help explain the removal of the shear test as an option so as to maintain the more conservative of the two. EN16351-2015 focused on shear strength with wood failure percentage as a secondary assessment when poor shear strength results were achieved, while ISO16696-1 does not require shear tests for face bonds. PRG320 requires only a wood failure percentage on sheared samples, focusing on whether the bond line shear strength is stronger than the shear strength of the timber without consideration of actual shear strength values. This created a mismatch between EN16351: 2015 and PRG320, where samples with <50% wood failure but ≥ the required shear strength values in EN16351:2015 would pass EN16351 but fail PRG320, which equates to 11% and 13% of CLT and glulam samples, respectively. Yusoh et al. [62] state that high shear strength and a high wood failure percentage indicate good bonding. Both shear strength and wood failure are important factors in evaluating bond performance, as they give further insight that cannot be realized by looking at one alone. For example:

1. High wood failure demonstrates that the shear strength of the timber is not as high as the adhesive and bonded interface. The shear strength values reveal whether the shear strength is reasonable for that species and grade of timber. The combination of this information could be used to identify that there has been a change in the timber resource or that a processing issue has occurred, such as a weakened layer below the wood surface caused during dressing prior to gluing;
2. Low wood failure demonstrates that the shear strength of the timber is higher than the adhesive and/or the bonded interface. The shear strength values reveal if the shear strength is reasonable for that adhesive and timber combination. The combination of this information could be used to identify that there has been a change in product or a processing issue, such as a bad batch or incorrectly mixed or applied adhesive, insufficient pressures during gluing, or changes in the timber resource.

Figure 17 illustrates the cumulative distribution of shear strengths for both glulam and CLT-oriented samples and highlights samples with less than 50% wood failure, showing that low wood failure does not necessarily reflect low shear strength. In fact, pith samples that experienced the highest wood failures had the lowest average shear strengths. Without the combination of wood failure and shear strength values, some production issues with lower shear strength would go undetected, while other high shear strength timber bond lines would fail to meet the wood failure criteria in the standards. While no standards now include the shear strength option, the combination of shear strength and wood failure percentage provides considerable benefit, especially when compared to other research and in ongoing production quality assurance and troubleshooting.

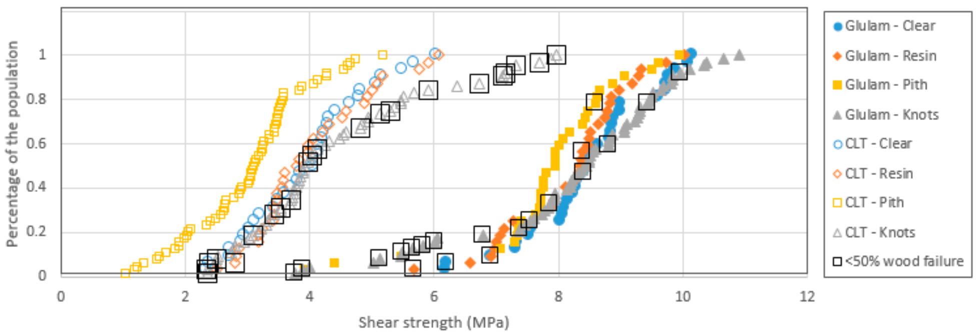


Figure 17. Glulam and CLT bond line shear strengths. Black boxes represent samples with less than 50% wood failure, the majority of which are knot sample types.

4.5. Maximizing Out-of-Grade into CLT

To maximize the use of out-of-grade hybrid pine into engineered wood products, a balance must be achieved between the inclusion of its common characteristics to capture large volumes of this resource while also limiting these same characteristics to achieve, among other things, bond performance requirements. The challenge is determining what this balance is and developing a proactive and practical solution to measuring and monitoring the bond performance of this out-of-grade resource in CLT. Looking to the test methods and criteria from the existing standards and to the results from this and other studies to provide such solutions and guidance for this out-of-grade resource has its own challenges.

Firstly, the small test samples are being relied upon to be reflective of the much larger CLT panel it was cut from, which should not be an issue with feedstock with few characteristics; however, the out-of-grade resource in this study had a high content and wide range of characteristics present [8]. Additionally, from a bond performance perspective, EN16351, ISO16696-1, and PRG320 do not address resin streaking, knots, or pith in the evaluation of delamination or bond line shear strength, and given the results seen in this study, limits should be put in place where an abundance of these characteristics are present. PRG320 is the only standard that has a limit for knots and pith from a bond perspective using an affective bond area rule, which is a proactive solution, but there is opportunity for further development.

Moreover, as is seen in this and other studies, the different test methods and assessments give different results. Delamination tests are more conservative than shear block tests under current test methods and criteria [16,30]. Before resorting to only considering delamination test results for guidance, there are many things to consider if an optimum solution is to be found. As discussed, both shear and delamination tests provide different and valuable information. There are also variations between delamination tests within the same standard and between the different standards, some of which are more conservative. Differences in the shape of the sample (round or square), sample size (small and large), age, cycling processes, drying requirements, and assessment criteria can lead to differences in results. Knorz et al. [14] investigated the difference between round and square-shaped delamination samples and found that on average, the delamination for round samples was 21.2% lower than for square samples. They attributed this to the high stresses occurring in the square sample corners as well as the different top area sizes. Aicher and Reinhardt [66] explain that the validity of the delamination test methods is based on long-term practical experience rather than a scientifically based illustration, and where delamination test results are positive, the glue line will keep its integrity. On the other hand, it is also often argued that the delamination test and pass criteria in EN16351 are too harsh for CLT given its restrictions in use [14,16,30,32]. This indicates that the least conservative delamination test may well suffice and provide an opportunity for the inclusion of more characteristics of out-of-grade timber.

In regard to resin, ISO16696-1 and PRG320 call for bond surfaces to be free of exudation that is detrimental to satisfactory bonding, but it is up to the manufacturer to determine what is detrimental. EN16351:2015 calls for planing to be carried out within 6 h before bonding for high resin content timber. EN16351:2021 does not specifically single out resin as a reason but requires all timber to be planed for 6 h before bonding, except for a few species listed. While the delamination test methods and assessment criteria serve as a reactive approach to alerting the manufacturer of poor bonding, which would include, but not be limited to, poor bonding due to resin, a proactive approach would be a better option. PRG320 specifies an effective bond area that could have been used for resin streaking; however, in this study, neither the area of resin streaking across the interface nor the length of resin streaking along the bond line (Figure 9) showed a clear relationship with delamination and wood failure results, and therefore neither of these make good indicators for predicting delamination. Furthermore, the impact of resin on the bond performance was far less than knots, meaning that the presence of resin need not be penalized at the same rate as knots. Further research is needed to understand the effect of background resin compared to resin streaking on bond performance, to identify if resin streaking indicates the presence of high background resin, and to find an easily measurable metric and set the criteria to use to limit resin to an extent that it does not detrimentally affect bond performance.

In regard to knots, when using AITC Test T110 assessment of delamination for PRG320 as suggested by Yeh [35], all three standards ignore the delamination associated with knots, and therefore the post-manufacture test method and assessment that would capture poor bonding due to resin do not capture poor bonding associated with knots. PRG320 is the only one of these three standards that restricts the inclusion of knots over and above structural grading requirements. Given that knots show good potential for central layers because of their good rolling [23] and longitudinal shear [21,22] performance, it would be beneficial to utilize them in CLT. But given their negative impact on bond performance, it would be unwise not to restrict their inclusion, as they could reach a level that is detrimental to the bond performance of the panel.

EN16351 requires the CLT feedstock to be strength graded to EN14081-1 [67], while ISO16696-1 allows solid sawn timber with a density of at least 300 kg/m^3 and graded in conformity with appropriate national standards. As an example, Machine-Graded Pine (MGP) is Australia's most common grading method for structural pine. The limits placed on knots are a structural requirement, meaning that knots must be limited as appropriate to deliver the required strength properties [68]. EN14081-1 also restricts knots from a structural performance perspective and not from a bonding perspective. Moreover, under EN14081-1, timber can be machine graded or visually graded under various national standards. These national standards are valid for certain species and provenances, and they have different grade separations, evaluation methods, and criteria for restricting knots and therefore give different grade yields for the same resource. Stapel and Kuilen [69] compared British, German, Scandinavian, French, and Swiss visual grading and found rejection rates varied from 4% up to 83%. They linked this to the different methods of measuring knots and the number of grades in a standard. Almazan et al. [70] compared the Spanish and German national standards and found that on average, 40% of pieces were rejected compared to only 5%, respectively, and attributed this to the knottiness of the timber. Brunetti et al. [71] compared machine grading to the Italian national standard UNI 11035-1,2 [72] for visual grading of larch and found rejection rates around 2% for machine grading compared to 19% for visual grading, again attributing this difference to knots. Adding even more variation is that knots are assessed independently or within lengths commonly no more than 150 mm [69] without consideration to the accumulation along the full length of a piece. Consequently, ISO16696-1 and EN16351 allow knotty timber without limit from a bond perspective, despite the negative impact of knots on bond performance. There was no evidence found to show this has caused issues for CLT manufactured under these standards; however, knots in out-of-grade timber are larger and more frequent than their in-grade counterpart, and given the results for knot samples in this study, limits need to be in place to ensure the amount of knots is not detrimental to bond performance.

Regarding pith, the low structural performance of the pith and immediate surrounding fiber resulted in premature wood failure rather than glue line failure in the delamination and shear tests. Given this behavior, it is recommended that when pith forms part of the glued surface, it be considered to have limited integrity for the purposes of transferring stresses between lamella, and the total area of pith at the bonded surface be restricted during manufacture and form part of the allowance for effective bond area.

PRG320 requires the wide glued faces of the lamella to have an effective bond area of at least 80%, which must be free of knots and other major visual characteristics such as wane, decay, torn and raised grain, resin pockets, and glue skip. The minimum of 80% effective bond area used in PRG320 provides a convenient and proactive solution to start with; however, there is opportunity to further optimize this method by creating more complex rules based on the characteristics of the out-of-grade resource and their impact on bond performance. The 80% minimum criteria was a decision based on actual production experience and took into consideration the wane allowance and distribution of the common #2 and #3 timber grades used in CLT [35]. Wane is an absence of timber fiber and, therefore, provides no bond performance, but on the other hand, while characteristics such as knots, resin, and pith do not provide the same level of bond performance as clear timber, they do provide some, and a weighted system could be used to account for that contribution. In setting these weightings, consideration should be given to bond line shear strength and delamination.

In this study, the shear strength of the bond lines was all above the minimum, so it is reasonable to not apply a penalty for shear other than for pith, which was very close to the minimum requirements in the CLT orientation. On the other hand, delamination and wood failure percentages did not meet requirements in some resin and knot samples. As a starting point, the worst of the 5th percentile values will be used as the main input for this first iteration of weightings. These weightings for each characteristic of the effective bond area rule are presented in Table 7. While it was determined earlier that resin streaking is not a good indicator of bond line performance, in the absence of another indicator at present, resin streaking has been used here as an example and for completeness. Once the indicator for delamination due to resinous wood has been identified, a similar process would be used to determine the weighting. For difficult-to-bond timber, the clear timber may also be weighted, but this is not deemed necessary in this instance with the good bond performance seen in this study. Clear with a weighting of 0 is considered to have no negative impact; knots with a weighting of 0.6 are only relied upon to have 40% bond performance; and wane with a weighting of 1 is considered to provide no bond line performance (see Table 7). For example, a bond line with 5% area of pith, 5% area of resin streaking, 10% area of knots, and 10% area of wane would equate to 19% (5% × 0.2 + 5% × 0.4 + 10% × 0.6 + 10 × 1 = 19%) and, therefore, meet the criteria of ≥80% effective bond area. Under the current non-weighted percentage of area, this scenario would fail with only 70% effective bond area.

Table 7. Examples of weightings for effective bond area for the different characteristics studied in this out-of-grade resource.

Characteristic	Initial Suggested Weightings
Clear	0
Pith	0.2
Resin streaking	0.4
Knots	0.6
Wane	1

Using this method would increase the allowable volume of out-of-grade timber in CLT from a bond performance perspective. The out-of-grade core wood, being at the center of the tree, contains minimal wane when cut from mature trees, so using this method would provide the opportunity to maximize knots, resin, pith, and other frequently occurring out-of-grade characteristics where otherwise wane would have used the majority of the 20% allowance at the bond line. There is a need for further research to investigate the suitability and optimize the values of this weighted approach. While the current effective bond area rule is simple to follow, vision-scanning technologies available today can provide automated measurement, evaluation, and alert systems to help manage the more complex rules suggested.

This research has focused on the bond performance and quality of low-stiffness out-of-grade PEE×PCH pine and its common characteristics of resin, knots, and pith using 1-component PUR glue. Further research is needed on other species to check if results are aligned and if the proposed weighted method for the area of resin, knots, and pith performs satisfactorily over time. The evaluation of bond performance and bond quality over time of engineered wood products in service is difficult, with cyclic wet/dry processes for accelerating aging and associated pass/fail criteria designed to give an indication of whether the bond line will perform in service over time. These test methods and criteria were established on and are used for clear wood that does not contain the characteristics tested in this study and therefore may not give an accurate indication of the performance of these characteristics over time. For example, saturating and heating the resin may cause water-soluble components to dissolve and leach out away from the glue line, affecting the results, or while in service, resin may deteriorate the glue over time, resulting in reduced bond performance not captured by the accelerated aging tests used in this study. Moreover, bond performance and quality are not the only considerations to determine the suitability of a timber resource to produce CLT, and other research needs to be conducted, including structural performance and durability.

5. Conclusions

This study investigated the bond quality and performance of out-of-grade PEE×PCH hybrid pine using delamination and shear tests, and the effects of resin streaking, pith, and knots were identified. It identified the negative impact resin, knots, and pith have on bond performance compared to clear timber and concluded that restrictions should be placed on the amount of these characteristics included at the bond line. A modified version of this approach was presented to allow these characteristics by area of bond line interface based on a weighting of their negative impact rather than just their presence.

The main findings are as follows:

1. Clear samples performed well with little delamination and wood failure, with an average of 2.9% and 96.7%, respectively. The good performance of clear samples can be attributed to low density, low MOE, reduced differential shrinkage, and the flexibility of the 1C PUR adhesive;
2. Resin was significantly different from clear, with delamination and wood failure averages of 9.3% and 92.6%, respectively. The lower performance of the resin compared to clear can be attributed to the resin's tendency to reduce wettability, obstruct adhesive flow, influence PUR adhesive, and provide a non-structural surface to bond to. No clear relationship was found between length of resin and delamination along the bond line, or resin area at the glue line interface and wood failure percentage;
3. Knots were significantly different from clear and resin, with delamination and wood failure averages of 24.4% and 77.4%, respectively. The low performance of the knots can be attributed to their complex characteristics, leading to a large variation in bonding environments, including glue starvation, high and low pressures, and differential shrinkage;
4. Wood failure occurred instead of delamination and glue line failure at pith. Given that wood failure is desirable under these assessments, pith could be considered to have good results; however, these high wood failures were accompanied by lower strengths compared to the other sample types. Therefore, the amount of pith occurring at the bond line should be restricted to ensure the good structural performance of the bond line;
5. All glulam-oriented sample types performed well in shear strength, with no significant differences and average shear strengths except for pith samples. Average shear strengths of 8.5 MPa, 8.2 MPa, 7.9 MPa, and 8.2 MPa for clear, resin, pith, and knots, respectively;
6. There was no significant difference between the clear and resin samples, with average wood failure percentages of 86% and 85%, respectively. There was a significant difference for pith and knot samples compared to clear, with an average wood failure percentage of 90% and 70%, respectively;
7. All CLT-oriented sample types performed well in shear strength except for 90°-loaded pith, which was significantly different and on average 39% less than clear samples. The 90°-loaded knots were also significantly different at 4.7 MPa, but they performed better than clear. There is no significant difference between the average shear strengths of clear and resin, 90°-loaded pith, or 0°-loaded knots at 4 MPa, 4 MPa, 3.6 MPa, and 4.2 MPa, respectively;

8. There was no significant difference between clear and resin, 0°-loaded pith, 90°-loaded pith, or 0°-loaded knots for wood failure at 90%, 89%, 96%, 96%, and 83%, respectively. The 90°-loaded knots were significantly different at 51%. The 90°-loaded knots were the highest on average in bond line shear strength and the lowest on average in wood failure, and in contrast, the 90°-loaded pith was the lowest on average in bond line shear strength and the highest on average in wood failure. Wood failure proved to be a poor indicator of glue line shear strength;
9. Most CLT samples experienced rolling shear failures in the cross layers. The 0°-loaded pith typically experienced combinations of rolling shear on the pith side of the sample and longitudinal shear on the clear side of the sample. The 90°-loaded knot samples experienced a variety of failure types, with combinations of one or more longitudinal shear failures in the adjoining clear piece, glue line failures, and small sections of rolling shear failure in the clear grain surrounding the knot;
10. PRG320 is the only CLT standard that limits characteristics from a bond performance perspective. EN16351 and ISO16696-1 only limit knots from a structural perspective, and this results in a wide range of knot inclusion.

The results of this study provide valuable information about the bond performance of out-of-grade hybrid pine and some of its characteristics. It shows that good bond performance can be achieved; however, some characteristics cause poorer bond performance and should be restricted. It proposes a proactive solution using the effective bond area presented in PRG320, with a weighted area for each characteristic, to maximize the use of out-of-grade hybrid pine while ensuring minimum bond performance requirements are achieved. Further research is required to investigate the suitability and optimize the values of this weighted approach.

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Conflicts of Interest: Rebecca Cherry is an employee of Hyne Timber. Warna Karunasena and Allan Manalo declare no conflict of interest.

Appendix A

Table A1. Delamination and wood failure results.

	EN16351 and ISO16696-1 Individual Test Results				EN16351 2015, EN16351 2021 and ISO16696-1 2019	EN16351:2021	PRG320	
Sample Number	**Delam$_{max}$ (≤40%)**	**Delam$_{tot}$ (≤10%)**	**WF$_{GL}$ (≥50%)**	**WF$_{tot}$ (≤70%)**	**Delam and Subsequent WF**	**WF**	**Delam$_{tot}$ (≤5%)**	**Qualify for Retest**
				Clear				
DC01	pass	pass	pass	pass	pass	pass	fail	yes
DC02	pass	pass	pass	pass	pass	pass	pass	

Table A1. *Cont.*

	EN16351 and ISO16696-1 Individual Test Results				EN16351 2015, EN16351 2021 and ISO16696-1 2019	EN16351:2021	PRG320	
Sample Number	**$Delam_{max}$ (≤40%)**	**$Delam_{tot}$ (≤10%)**	**WF_{GL} (≥50%)**	**WF_{tot} (≤70%)**	**Delam and Subsequent WF**	**WF**	**$Delam_{tot}$ (≤5%)**	**Qualify for Retest**
				Clear				
DC03	pass	pass	pass	pass	pass	pass	pass	
DC04	pass	pass	pass	pass	pass	pass	pass	
DC05	pass	pass	pass	pass	pass	pass	pass	
DC06	pass	pass	pass	pass	pass	pass	fail	yes
DC07	pass	pass	pass	pass	pass	pass	pass	
DC08	pass	pass	pass	pass	pass	pass	pass	
DC09	pass	pass	pass	pass	pass	pass	pass	
DC10	pass	pass	pass	pass	pass	pass	fail	yes
Pass Rate					100%	100%	70%	
				Resin				
DR01	pass	pass	pass	pass	pass	pass	fail	yes
DR02	Fail	fail	fail	pass	fail	fail	fail	no
DR03	pass	pass	pass	pass	pass	pass	fail	yes
DR04	pass	pass	pass	pass	pass	pass	pass	
DR05	pass	pass	pass	pass	pass	pass	pass	
DR06	pass	pass	fail	pass	pass	fail	fail	yes
DR07	pass	fail	pass	pass	pass	pass	fail	no
DR08	pass	pass	pass	pass	pass	pass	fail	yes
DR09	pass	pass	pass	pass	pass	pass	fail	yes
DR10	pass	pass	pass	pass	pass	pass	fail	yes
Pass Rate					90%	80%	20%	
				Knots				
DKN01	fail	fail	fail	fail	fail	fail	fail	no
DKN02	fail	fail	pass	pass	pass	pass	fail	no
DKN03	pass	fail	pass	pass	pass	pass	fail	no
DKN04	pass	fail	pass	pass	pass	pass	fail	no
DKN05	fail	fail	pass	pass	pass	pass	fail	no
DKN06	pass	fail	fail	pass	fail	fail	fail	no
DKN07	pass	fail	pass	pass	pass	pass	fail	no
DKN08	fail	fail	fail	pass	fail	fail	fail	no
DKN09	fail	fail	fail	fail	fail	fail	fail	no
DKN10	pass	fail	fail	fail	fail	fail	fail	no
Pass Rate					50%	50%	0%	

Table A2. Pass rate of standards tests.

Pass Rate	Test–Standard–Sample Type
100%	(1) $Delam_{max}$—EN16351 and ISO16696-1—clear (2) $Delam_{tot}$—EN16351 and ISO16696-1—clear (3) WF_{tot}—EN16351 and ISO16696-1—clear (4) WF_{tot}—EN16351 and ISO16696-1—resin (5) WF_{GL}—EN16351 and ISO16696-1—clear (6) Shear strength CLT orientation—EN16351:2015—clear (7) Shear strength CLT orientation—EN16351:2015—resin (8) Shear strength CLT orientation—EN16351:2015—pith (9) Shear strength CLT orientation—EN16351:2015—knots (10) Shear strength CLT orientation—EN16351 (2015)—all samples combined (11) Shear strength Glulam orientation—EN16351:2015—clear (12) Shear strength Glulam orientation—EN16351:2015—resin (13) Shear strength Glulam orientation—EN16351:2015—pith (14) Shear strength Glulam orientation—EN16351:2015—knots (15) Shear strength Glulam orientation—EN16351:2015—all samples combined (16) Shear WF $\geq$ 60%—PRG320—pith
94%	(17) Shear WF $\geq$ 60%—PRG320—resin (18) Shear WF $\geq$ 80%—PRG320—pith
91%	(19) Shear WF $\geq$ 60%—PRG320—clear (20) Shear WF $\geq$ 60%—PRG320—0°-loaded knots
90%	(21) $Delam_{max}$-EN16351 and ISO16696-1—resin (22) WF_{tot}-EN16351 and ISO16696-1—all samples combined
88%	(23) Shear WF $\geq$ 80%—PRG320—clear
86%	(24) Shear WF $\geq$ 60%—PRG320—all samples combined
84%	(25) Shear WF $\geq$ 80%—PRG320—resin
80%	(26) $Delam_{tot}$—EN16351 and ISO16696-1—resin (27) WF_{GL}—EN16351 and ISO16696-1—resin (28) $Delam_{max}$—EN16351 and ISO16696-1—all samples combined
77%	(29) WF_{GL}—EN16351 and ISO16696-1—all samples combined
75%	(30) Shear WF $\geq$ 80%—PRG320—0°-loaded knots (31) Shear WF $\geq$ 80%—PRG320—all samples combined
70%	(32) Delamtot—PRG320—clear (33) WFtot—EN16351 and ISO16696-1—knots
60%	(34) $Delam_{tot}$—EN16351 and ISO16696-1—all samples combined
50%	(35) $Delam_{max}$—EN16351 and ISO16696-1—knots (36) WF_{GL}—EN16351 and ISO16696-1—knots
44%	(37) Shear WF $\geq$ 60%—PRG320-90°—loaded knots
30%	(38) $Delam_{tot}$-PRG320—all samples combined
28%	(39) Shear WF $\geq$ 80%—PRG320—90°-loaded knots
20%	(40) $Delam_{tot}$—PRG32—resin
0%	(41) Delamtot—PRG320—knots (42) Delamtot—EN16351 and ISO16696-1—knots

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