DEVELOPMENT OF SUSTAINABLE BUILDING TECHNOLOGIES FROM OUT-OF-GRADE TIMBER

A Thesis submitted by

Rebecca Cherry
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ABSTRACT

The study investigated the structural and bond performance of out-of-grade *Pinus elliotti* var. *elliottii* (Engelm) x *Pinus caribaea* var. *hondurensis* (Sénéclauze) (PEExPCH) hybrid pine, to provide information necessary to make informed decisions on incorporating this abundant and underutilised building material into sustainable building solutions. An in-depth critical review of the literature was completed and provided an understanding of the challenges, strengths and opportunities of out-of-grade pine. Cross laminated timber (CLT) was identified as an opportunity for using large volumes of out-of-grade timber and therefore investigated as an example in this research of a sustainable building system solution for utilisation of out-of-grade PEExPCH. An extensive experimental study was completed to investigate the structural properties of out-of-grade PEExPCH and the impact of commonly occurring characteristics of resin, knots and pith. Clear samples contained no major defect other than occasional occurrence of pith, resin contained naturally occurring heavy resin deposits in the timber and the third sample type contained knots, these were further separated into samples with and without pith. There was equal representation of each of these three sample types in tests completed. Modulus of elasticity (MOE) and strengths were determined and compared on a total of 105 bending, 105 compression parallel to grain, 105 compression perpendicular to grain, 90 longitudinal shear and 135 rolling shear samples. 105 samples were tested for tensile strength. Engineered wood products, such as CLT, rely on their glue lines to perform reliably and consistently over time in service and therefore bond performance was also assessed. After an accelerated aging process, 30 five-layer cross laminated timber (CLT) samples glued with one-component polyurethane glue (PUR) were assessed for delamination and wood failure. Additionally, 160 bond line shear tests in glulam orientation and 192 in CLT orientation were conducted, both of which are options for bond line assessment in EN16351(2015) CLT standard. 16 large-scale specimens were tested for bending MOE and strength to evaluate the performance of CLT made from out-of-grade PEExPCH. Wood and wood-based reinforcements were used to evaluate their effect on increasing bending properties including high-grade timber and plywood. Testing was performed according to AS4063.1:2010 and modified planar shear test was used for rolling shear performance. The results showed that the bending MOE of the

out-of-grade PEExPCH is low at around 6.9 GPa and is the predominant reason for not achieving highly sought after structural grades. Resin achieved between 98% and 116% of the structural performance of clear samples while, knots achieved between 46% to 196% of clear samples. Pith achieved between 75% and 121% of non-pith, had higher density and had a mixed effect on structural properties. Growth ring pattern had a significant effect on rolling shear properties. Clear out-of-grade PEExPCH had good bond performance results with 3% delamination, 96% wood failure, 8.5 GPa bond line shear strength as Glulam, 4.0 MPa bond line shear strength as CLT and a 100% pass rate under two international CLT standards. Resin and knots had a negative impact on delamination and wood failure while pith experienced premature wood failures. The bending MOE and strength of CLT were low at 6.2 GPa and 24.9 MPa, respectively. The use of high-grade timber as reinforcement in the outer layers provided the largest improvement on both bending MOE and strength with increases of 53% and 93%, respectively. Using the mechanical properties determined in this study, the shear analogy method predicted bending MOE to within 11% of that measured in the experimental study. The results of this study can provide valuable information for the timber and building and construction industries for design, product development, optimisation and manufacture utilising out-of-grade PEExPCH. For example, the results show that for structural applications there is no need to treat resinous timber differently to clear when looking to achieve MOE and strength targets for most properties. Whereas, if minimising self-weight is a critical design factor then excluding resinous timber would be beneficial. All timber has mechanical properties and if looking to source a low cost timber population to low stress applications within building systems such as noggings, bottom plates of single story houses or partition walls in some applications, the structural properties determined through this research informs engineers of their capacity to withstand design loads to determine their suitability to perform safely in these applications. The safe use of this out-of-grade timber in place of in-grades makes better use of the entire log, reduces waste providing a more sustainable solution, in some instances may reduce lead times because out-of-grade timber is readily available and can also provide a cost saving as out-of-grade timber is less expensive. Some restriction is needed on knots for structural performance requirements and knots, resin and pith for bond performance requirements.

CERTIFICATION OF THESIS

I Rebecca Cherry declare that the PhD Thesis entitled *Development of Sustainable Building Technologies from Out-of-grade Timber* is not more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references, and footnotes.

This Thesis is the work of Rebecca Cherry except where otherwise acknowledged, with the majority of the contribution to the papers presented as a Thesis by Publication undertaken by the student. The work is original and has not previously been submitted for any other award, except where acknowledged.

Date: 23 February 2024

Endorsed by:

Professor Karu Karunasena
Principal Supervisor

Professor Allan Manalo
Associate Supervisor

Student and supervisors' signatures of endorsement are held at the University.

STATEMENT OF CONTRIBUTION

The journal papers produced for this study are a joint contribution of the authors. The contributions are presented below.

Paper 1: Published Cherry, R., Manalo, A., Karunasena, W., & Stringer, G. (2019). Out-of-grade sawn pine: A state-of-the-art review on challenges and new opportunities in Cross Laminated Timber (CLT). *Construction and Building Materials, 211*, 858-868. doi:https://doi.org/10.1016/j.conbuildmat.2019.03.293 (Top 10% journal; Impact factor: 7.4 and SNIP: 2.339)

Rebecca Cherry contributed 95% to this paper. Collectively A. Manalo, W Karunasena and G. Stringer contributed the remainder.

Paper 2: Published Cherry, R., Karunasena, W., & Manalo, A. (2022). Mechanical Properties of Low-Stiffness Out-of-Grade Hybrid Pine; Effects of Knots, Resin and Pith. *Forests, 13(6),* 927. doi:https://doi.org/10.3390/f13060927 (Top 10% journal; Impact factor: 2.9 and SNIP: 0.923)

Rebecca Cherry contributed 95% to this paper. Collectively W Karunasena and A. Manalo contributed the remainder.

Paper 3: Under Review Cherry, R., Karunasena, W., & Manalo, A. (2024). Rolling Shear Modulus and Strength of Low-stiffness Out-of-grade Hybrid Pine; Effects of Knots, Resin, Pith and Growth Ring Pattern. (Under review) (Top 10% journal; Impact factor: 2.9 and SNIP: 0.923)

Rebecca Cherry contributed 95% to this paper. Collectively W Karunasena and A. Manalo contributed the remainder.

Paper 4: Published Cherry, R., Karunasena, W., & Manalo, A. (2023). Maximizing the Use of Out-of-Grade Hybrid Pine in Engineered Wood Products: Bond Performance, the Effect of Resin Streaking, Knots, and Pith. *Forests, 14(9),* 1916. doi:https://doi.org/10.3390/f14091916. (Top 10% journal; Impact factor: 2.9 and SNIP: 0.923)

Rebecca Cherry contributed 95% to this paper. Collectively W Karunasena and A. Manalo contributed the remainder.

Paper 5: Ready for submission Cherry, R., Karunasena, W., & Manalo, A. (2024). Structural performance and Evaluation of Cross Laminated Timber Manufactured from Low-stiffness Out-of-grade Hybrid Pine, and the Effect of Wood-based Reinforcements.

Rebecca Cherry contributed 95% to this paper. Collectively W Karunasena and A. Manalo contributed the remainder.

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CHAPTER 1: INTRODUCTION

1.1. Background and motivation

Sustainable plantation softwood is the future timber material resource for building and construction industry because of its many benefits. The demand by the building and construction industry for structural timber is increasing into the future. There is finite land currently available for growing softwood plantations, and with a typical 28 to 30 year clear-fell harvest age, it takes considerable time to grow a crop for milling. This coupled with the recent fires in Australia that devastated softwood plantations reducing the amount of available trees for milling creates a challenge for the timber industry to meet growing demand for structural in-grade timber. On the other hand, out-of-grade timber is an abundant and underutilised material resource produced as a by-product from the production of in-grade structural timber may present part of the solution. There is potential to incorporate large volumes of out-of-grade PEExPCH timber in place of in-grade timber into CLT which is a renewable building material already used in the construction of residential and other buildings. This building material can be used to help address the housing crisis by providing additional structural building materials to construct more dwellings.

For the purposes of this study, out-of-grade timber refers to sawn timber that has failed to meet the machine graded pine (MGP) structural framing requirements of AS1748.1 and AS1720.1, which specify minimum characteristic values of stiffness, strength and place limits on defects including resin shake, wane, splits, pockets, manufacturing defects and distortion, some of which can be seen in Figure 1.

Figure 1 End view of a pack of out-of-grade PEExPCH sawn timber showing typical characteristics

Australia is at risk of not being able to consistently meet demand for new housing because of a growing gap between supply and demand of sawn softwood timber. The predicted annual demand will exceed the locally produced supply by 2.6 million m^3 by 2050 due to constraints on sawlog supply (Wood & Houghton, 2022). To satisfy this increased demand, and increase area of softwood plantation of 468,000 hectares is required (Wood & Houghton, 2022), which equates to a 46% increase on the existing 1.007 million hectares as at 2023 (ABARES, 2024). The existing softwood plantation area has remained relatively stable and between 990 and 1040 hectares for the last 20 years (ABARES 2024). Historically, it has taken 49 years to increase softwood plantation area by this magnitude with 565,000 hectares in 1975 reaching a peak of 1.039 million hectares achieved in 2019 (ABARES, 2024). Since then there has been a slight decline and in 2023 there was 1.007 million hectares (ABRAES, 2024). It will take time and commitment to establish additional softwood plantation area and with a harvest age of around 30 years, these plantation softwoods should have been planted 5 years ago for harvesting in 2050. Furthermore, government targets to significantly increase plantations in the past such as the 1972 aim of planting 1.25 million hectares of pines by the year 2000, or the commitment in 1996 to triple Australian plantation area by 2020 (Mercer & Underwood 2002) have not been fully achieved.

Southern pines were introduced into Australian plantations in the 1920's (Akins et al., 1990) with current species including *Pinus caribaea (PCH*), *Pinus elliottii (PEE)*, hybrids of both (PEExPCH) (Department of Agriculture Fisheries and Forestry, 2013; HQPlantations, n.d.) and to a lesser extent *Pinus taeda* (Lee, 2015). Forestry Corporation NSW have what they regards a large scale plantings of the PEExPCH but continue planting the pure species of slash and loblolly pine while further investigations are carried out (Forestry Corporation, 2016) however, a different situation exists for South East and Central Queensland. Forestry Plantations Queensland progressed through plantings of different species with majority F1 from 1993 through to 2009, until the sale of the management of state-owned plantations to HQPlantations Pty Ltd (HQP) in 2010 (Timber Queensland and Queensland Government, 2012). HQP manages approximately 136,000 ha (Lee, 2015) and made an abrupt change in planting in their planting strategy and have planted almost 100% F2 throughout their South East and Central Queensland softwood plantations since 2010 (Kain, 2017) as seen in Figure 2.

With a typical 28 to 30 year clear-fell harvest age, the PEExPCH hybrids are now the vast majority of sawlog for the structural framing market in Queensland and will remain so into the foreseeable future of at least 30 years. This has made the significant plantation softwood species for saw milling in South East and Central Queensland recently become the *Pinus elliottii var. elliottii x P. caribaea var. hondurensis* F1 and F2 Hybrids (PEExPCH) with an expected log production volume exceeding 1 million m^3/year (Leggate et. al., 2019). Given the significant volumes and the importance of the PEExPCH to Queensland Australia, it is the species of focus for this research. Further detailed information on the PEExPCH is included in the literature review of Chapter 2.

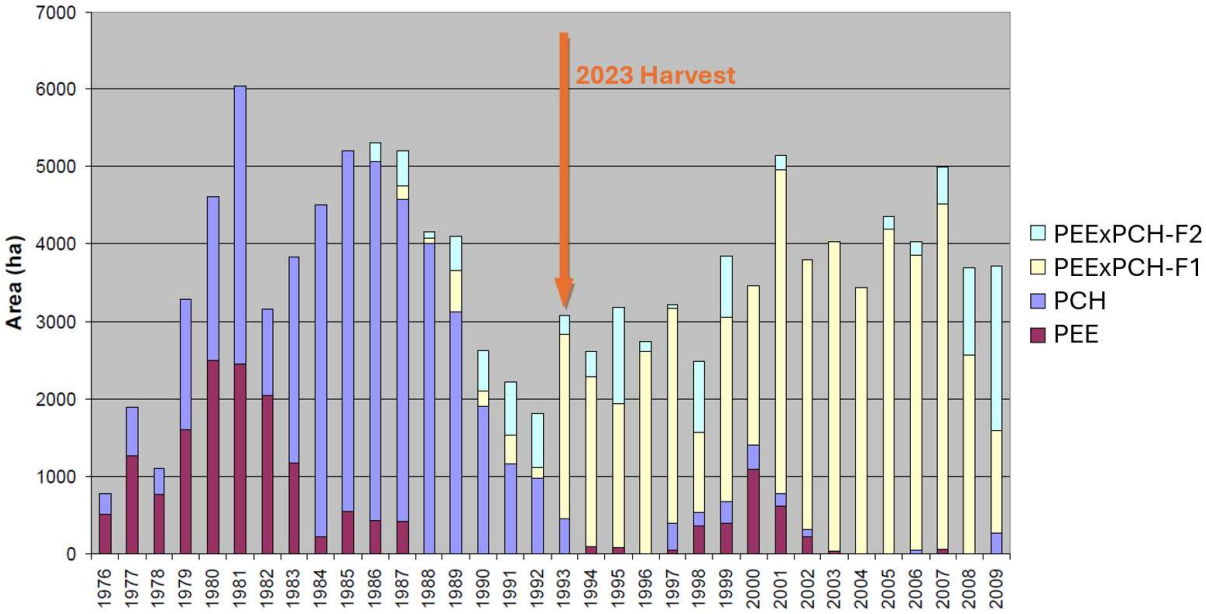

Figure 2 Area planted by planting year by taxa for south-east Queensland estate 1976 to June 2009. Adapted from Harding et al. (2010).

Fast growing pine hybrids provide a way to increase wood production from finite plantation land area (Lopez et al., 2018) within shorter rotation times, but tree breeding and hybridisation can also lead to increased diameters of low quality inner core wood (Malan, 2010). Economic pressures are leading to plantation managers seeking to reduce rotation times, but wood quality is an important consideration (Kain, 2003). Variation of wood properties within PEExPCH have been found to be large and trees grown specifically on ex-pasture land having average basic densities about 30 kg/m^3 less than those that were planted on ex native forest lands (Harding 2008). Large volumes of out-of-grade PEExPCH will be produced over the coming decades that these trees continue to be harvested. This production provides an abundant underutilised resource of out-of-grade timber that could help provide solutions to the structural timber shortage.

In Australia, 97.7% of softwood plantations are managed to supply the Australian housing market with sawlogs (ABARES, 2016) as structural framing products (Harding et al., 2010). These sawlogs are typically purchased by volume and priced accordingly to their different categories. While various additional features can be considered in purchasing logs such as defects like branch whorls, shake or large abrupt changes in diameter (James, 2001), these sawlog categories are

typically based on small end diameter, lengths and sweep with an increase in price associated with increase in small end diameter up to an optimised size of around 30 cm to 35cm (James, 2001, KPMG., 2023). Sawlogs are a very broad category of log and often contain a range of quality classes or grades (James, 2001,).

Through the process of converting a round log into rectangular cross sections, about 50% of the log volume is recovered as sawn timber with the remainder being low value by-products such as offcuts, chip and sawdust. Several sawing studies investigating PEE, PCH and PEExPCH discussed by Harding et al. (2008) show an average of 49.9%, with a range of 43.8% to 52.2% of log volume is recovered as green sawn boards with an average of 12% of that sawn board volume being rejected before structural grading due to defect such as large resin shake..

MOE and strength are some of the major factors for meeting grade for structural framing products. Bailleres et al., (2019) conducted extensive research on plantation pines grown in Queensland and Northern New South Wales using innovative resource characterisation methods. This study showed that there is large variation in MOE profiles of different plots of trees and large variation of MOE within a single log which increases from pith to bark. For example, of the 54 plots compared, 4 plots began producing wood fibre with MOE of 10 GPa between 6 to 8 years of age. 2 plots took until 35 and 40 years of age to started producing 10 GPa wood fibre while 6 plots never produced wood fibre of 10 GPa. At age of 17 years, only 12 of the 54 plots were producing 10 GPa wood fibre. While some trees produce high stiffness wood from a relatively young age, other trees never produce wood stiff enough to achieve MGP10 within their 30 year rotation period (Ballieres et al., 2019).

Moreover, other attributes of the corewood zone of the logs, such as large percentage of early wood (Mead, 2013), spiral grain (ASTM International, 2011), compression wood (Koch, 1972), high microfibril angle (Plomion et al., 2001, Malan, 2015, Forest Products Laboratory, 2010), resin shake (Harding, 2008) and pith (Koch, 1972) lead to unacceptable issues in sawn boards such as distortion or low strength properties. These corewood attributes and other defects result in some of this timber being rejected for reasons other than just low MOE.

As a result of MOE and characteristics, once the log has been put through the process of sawmilling into green timber boards, drying, finish dressing and grading, finished products with large differences in market value are produced. Recent and

current projects have been looking at methods of evaluating density and MOE profiles of standing plantation pines and logs (Ballieres et al., 2019, Downes et al., 2020). These provide opportunity to incorporate other characteristics for determining and valuing suitable sawlogs with the option to divert lower quality logs to other markets in the future. However, for now at least, the cost to the sawmiller for the fibre within a log that produces low-value out-of-grade timber is the same as the cost of the fibre within that log that produces high-value in-grade timber.

The timber boards recovered from the logs give considerable differences for in-grade volume recovery rates depending on the log quality, sawing strategy, drying processes and grading rules. Several sawing studies investigating PEExPCH, PEE and PCH discussed by Harding et al. (2008) show an average of 32% of sawn board volume fell short of structural grading requirements of F5 or MGP10. The range was between 10% to 57.7% of board volume as out-of-grade. 'F' grades were developed before MGP grades and were based on testing of small clear timber specimens and as a visually graded structural product as set out in AS2858:2004 (Standards Australia, 2004). MGP grades were later introduced to get better alignment in structural properties of structural sized Australian grown pine. The MGP grade mechanical properties were determined using full-size members of Australian grown pine from multiple locations across the country and in accordance with AS4063 series (Standard Australia, 2010). The characteristic properties of F5 and MGP10 are given in AS1720.1 (Standards Australia, 2010) with F5 having lower characteristic mechanical properties than MGP10.

The PEExPCH trials discussed by Harding (2008) achieved a range of between 10% and 22.8% of sawn volume falling short of F5 grade while the PEE and PCH had ranges of out-of-grade volumes between 12.6% to 57.7% and 28.6% to 38.% respectively. The PEExPCH specific compartments investigated in these studies (Harding et al., 2008) were older and between 30 and 32 years of age compared to the PEE and PCH at 20 to 30 and 20 to 24 years of age and tree age can have significant impact on grade recovery.

Bailleres et al., (2019) conducted extensive research on plantation pines grown in Queensland and Northern New South Wales using innovative resource characterisation methods. This research included PEExPCH and its parents species and shows that by harvesting a tree of these species at an older age, provides a higher percentage of mature wood which has higher structural properties compared

to the trees own core wood. Typical examples given in this study show an MOE of 3 to 4 GPa near the pith of the log with a 8 to 12 GPa near the bark for trees around 15 years of age with a flattening of the MOE curve with increasing age. The MOE profile from pith to bark was best represented by a sigmoidal curve. Shorter rotation times reduce the amount of this higher performing mature wood available for extraction of higher grades of timber.

Characteristics present in out-of-grade timber such as distortion, low strength, knots, splits, shakes and other defects cause issues with processing leading to increased costs of production of out-of-grade timber. These processes include log merchandising, sawmilling, sorting, drying, planning, grading, sorting and packing. Processing speeds and therefore production rates are slowed in an attempt to minimise the occurrence and impact of damage and skews caused by distorted, weak and broken boards. These boards can jam up, hit and damage machinery and grading equipment and be difficult to stack into finished packs requiring manual labour for correction or removal. Furthermore, different drying schedules can be used to reduce over drying and distortion of corewood and this requires additional sorting and processes for separation of the green timber prior to drying. Capital expense is required for the technologies and equipment required to identify the timber to be separated, as well as additional costs associated with training staff to operate and maintain that equipment. Capital expense is required for the equipment required to do the separation and storage of that timber as well as additional costs associated with maintaining this equipment. Resin is common in the low-quality corewood zone of the trees and is common in PEExPCH (Nel et al. 2017, Harding et al. 2008). Resin builds up on rollers, scanning equipment, in the kilns and along the processing line requiring regular cleaning. Not maintaining cleanliness of this equipment causes increased risks of error in measurement equipment, issues with processing, fire risk and damage to equipment and product. These all lead to increased cost for additional equipment required, additional processing, slower production rates, repairs, cleaning and downtime events as well as safety risks to team members while removing damaged and jammed boards.

While large investments can be and are made in technologies such as scanners and acoustic graders to try and identify loss making out-of-grade timber and remove it as early as possible from the process, care must be taken to not exclude too much and miss opportunity to extract as much wood from the resource

to supply the high demand of the construction industry, but also to extract as much high value in-grade timber as possible via optimisation in grading systems and with cutting strategies. This means that out-of-grade timber continues to be produced alongside in-grade timber with the cost to produce the lower value out-of-grade timber higher than the in-grade structural timber.

The Australian Pine Log Price Index reports (KPMG., 2020) provide insight into the volume and price information of Australian softwood logs from data provided by growers. For January to June 2020 period, KPMG (2020) reported average weighted prices for sawlog for intermediate, medium and large sawlogs of $55.78, $79.60 and $84.87 per cubic meter of log. In 2019, Baillieres et al., (2019) reported values for out-of-grade pine timber at $80 per cubic meter. This difference between cost of log and out-of-grade timber leaves very little to no room for the processing costs required to convert the low-grade volume of a log into the out-of-grade timber it produces. Out-of-grade timber is often sold at a loss due to limited market opportunities (Baber et al., 2020, Dewbury, 2016).. Structural grades of MGP10 and above were worth 77% more than out-of-grade timber, at $350 per cubic meter, also reported in 2019 by Baillieres et al., (2019). The sawmiller must rely on any higher value structural in-grade products they produce from these logs to supplement the value of out-of-grade timber, or find value-add options for out-of-grade timber to make it independently profitable or at least to cover its own costs.

Substituting this low value out-of-grade timber in place of high value in-grade timber wherever possible has potential to not only find purpose for and value add this resource, but also free up in-grade structural timber to fill the ever-increasing demand for applications where higher structural performance is essential. Making use of more of the tree to meet industry demand for sustainable building solutions is becoming increasingly critical and makes economic sense.

With a lack of supply of in-grade timber, customers will begin searching for alternative solutions to substitute for the in-grade timber. Imported timber may offer a solution but the fuel consumed for shipping across long distances results in increased carbon footprint and increases greenhouse gas emissions (Deng, 2012). Timber imports also present the risk of bringing in foreign pests and diseases which could pose serious threat to native species, ecosystems, agriculture and the forestry industry. While imported timber can present cheaper at face value than a locally sourced supply, using imported timber can negatively impact the local timber

industry through lower demand leading to job losses, especially in regions highly dependant on the forestry and timber industry (Wood & Houghton, 2022). The long term annual average proportion of imported timber makes up 19.7% of total timber supply, which would have to double to fulfill the entire gap, but historically it has been seen that increasing this proportion of imported timber is likely to lead to increase volatility in pricing (Wood & Houghton, 2022). Furthermore, imported timber may not meet Australian Standards requirements which can lead to durability and safety issues. Out-of-grade PEExPCH has the benefits of being locally grown and sourced from sustainably managed plantations in Queensland, will not bring pests in from overseas or interstate. Using this product supports the local timber industry, it is cheaper for the consumer compared to in-grade timber, is readily available in the Australian market and being local it does not have the negative environmental impact of shipping long distances. Once known, its properties can be matched to design requirements and used as a suitable substitute in place of in-grade timber, freeing up this in-grade timber for other applications.

Engineered timber products such as cross laminated timber (CLT) are structural composites, they possess more uniform mechanical properties than solid sawn timber while allowing the use of smaller, lower quality and underutilised timber and residues keeping forest products competitive in the market (Falk & Colling, 1995; Lam, 2001). As a mass timber and engineered wood product, CLT enables the use of smaller pieces of timber in large complex structures. Given the recent development and adoption of these hybrids, limited mature fibre has been available for exploration into engineered timber products and those found in the literature have focused their research on young trees. Almeida et al., (2012) investigated young PEExPCH at 7 years of age for plywood and found it did not produce plywood panels with sufficient strength and stiffness for structural applications. Surdi et al., (2015) investigated young PEExPCH in the production of oriented strand board panels and found a reduction in apparent density and mechanical properties compared to *pinus taeda*. PEExPCH has not yet been used to produce CLT due to its recent introduction and the lack of mature fibre as well as a focus on other more abundantly available and familiar species such as Radiata pine in Australia and New Zealand. In recent years, some of the PEExPCH plantations in South East Queensland have reached harvest age. These have been milled and graded for structural framing products alongside its parent species of PEE and PCH, and the MGP graded timber

is also now used by Hyne & Son to produce glue-laminated timber beams (D. Bennetts, personal communication, 30 June 2023).

CLT is increasingly being used to provide residential, commercial, industrial, infrastructural and agricultural solutions due to its many benefits with interest in this structural building product continuing to grow worldwide (De Araujo et al., 2023, Harte, 2017). CLT has the ability to substitute concrete and steel in many areas of construction (Brandner et al., 2016) while also providing an opportunity to value add to out-of-grade sawn timber resource. Timber based structural products such as CLT are becoming more important as the construction industry moves towards sustainable construction solutions (Harte, 2017). Opportunity exists to offer economically viable projects for residences in modular housing form through large scale projects and large scale industrialisation of processes (De Araujo et al., 2023). There are many residential type buildings already constructed from CLT (Harte, 2017). CLT is a very efficient lightweight prefabrication solution which is produced in high-technology production plants but further research is needed to provide knowledge about CLT products (De Araujo et al., 2023).

There is a large global market opportunity for this product to be expanded (De Araujo et al., 2023). Since its beginning in the 1990's, intensive research and further developments of CLT has enabled it to become considered as economic and more sustainable solutions compared to other more traditional materials (Harte, 2017). There are CLT manufacturers on five continents (De Araujo & Christoforo, 2023), mostly located in the Northern Hemisphere. These manufacturing plants are using at least eight different wood species and four types of structural resins to produce this building product with high structural integrity and strength (De Araujo et al., 2023). To produce these large volumes of CLT, manufacturers are using extensive volumes of biomaterials with high carbon fixation and from highly renewable sources (De Araujo et al., 2023).

CLT provides many benefits. Its high structural integrity, strength, flexibility, suits multiple applications and meets various rigorous standards for earthquake and fire resistance and has been used to produce robust tall buildings (De Araujo et al., 2023). The flexibility of design allows freedom of shape and placement of openings (Harte, 2017). The prefabrication of CLT building components as well as the ease of working with wood makes for a low-dust and low-noise assembly with minimal site waste with quick assembly times on site (Harte, 2017). Exposed timber has proven

to improve liveability. Psychological benefits, improved concentration, faster recovery in patients, lower heart rates and lower stress levels have all found to be benefits of exposed timber in school and health care facilities (Harte, 2017). There are also some cost savings compared to concrete alternatives which come from the low density of timber which lowers the weight of the building and provides savings on foundation works (Harte, 2017).

CLT has environmental advantages over alternatives. CLT stores considerable amounts of carbon over the lifecycle of the building, during which numerous forest rotations occur sequestering even more carbon (Harte, 2017). Many studies have compared concrete, steel and timber construction and found the timber to have better environmental performance. Duan et al., (2022a) conducted an extensive review and analysed 62 peer-reviewed articles focused on life cycle assessments of mass timber construction and found that the average embodied greenhouse gas emissions of reinforced concrete is 42% higher than mass timber alternative. Robertson et al. (2012) investigated the environmental impacts associated with two alternative designs of reinforced concrete frame and CLT and glulam combination for a typical North American five story mid-rise office building through a cradle-to-construction analysis. They found the CLT and Glulam construction had a lower environmental impact in 10 of the 11 assessment categories. Durlinger et al. (2013) investigated a 10 story CLT residential building constructed in Melbourne Australia and found that in comparison to steel reinforced concrete, using CLT had 22% lower global warming potential and even with the CLT being imported, the CLT version has a lower impact for materials and transport combined compared to the concrete version. CLT is now produced locally in Australia and therefore likely to have even lower global warming potential without the need for long distance shipping.

Hemmati et al. (2024) compared the global warming potential impact of mass timber to steel frame of a residence building using a life cycle assessment of cradle-to-construction site. They found that the mass timber building version had 19% lower carbon emissions and had about 2757 tonnes of stored carbon dioxide. Dolan and Harte (2014) found there was a 74% reduction in embodied carbon between reinforced concrete to timber structural elements. Duan et al. (2022b) found compared to reinforced concrete, CLT and hybrid CLT alternatives produce 15% and 10.8% lower life cycle greenhouse gas emissions, and 46.5% and 37.2% lower

embodied greenhouse gas emissions. The good air-tightness and low coefficient of thermal conductivity of timber used in the external building envelope makes it easier to achieve passive or net zero energy building (Harte, 2017). Liu, Y. et al. (2016) conducted a cradle-to-grave feasibility study of using CLT instead of the conventional concrete for the construction of a seven story building in two cities in cold regions of China. They looked at three stages throughout the life span of the building being materialisation, operation and end-of-life. Using CLT instead of concrete was found to reduce energy consumption by more than 30% and reduced CO_2 emissions by more than 40% in both city locations. Hawkins et al.(2020), compared the embodied carbon of a CLT, concrete and steel typical medium-rise building structure and found CLT has the smallest overall environmental impact with further benefits where timber components were prevented from releasing stored carbon such as continued re-use. Andersen et al. (2022), found CLT had a substantially lower impact for Global warming when compared to concrete and could help mitigate climate change.

The adhesives used in CLT can present a challenge for recycling and reuse. Bio-based adhesives are being investigated for adhering wood and offer an environmentally friendly solutions which include tannin, lignin, soy protein, carbohydrates and unsaturated plant oils (Wang et al., 2022, Yauk et al., 2020, Li et al., 2004, Sun et al., 2021, Messmer, 2015, Maulana et al., 2022). These adhesives could provide a solution where their structural performance is sufficient to meet the needs of CLT in structural applications. Moderate bond strength, poor water resistance and high viscosity have been barriers for commercial applications of soy-based adhesives (Sun et al., 2021, Li et al., 2004). Many methods have been used in an attempt to improve the performance of starch-based wood adhesives but their bonding capacities are insufficient to glue structural wood products (Wang et al., 2022). More research is needed on the feasibility of these renewable wood adhesives in construction (Messmer, 2015).

Messmer (2015) compared the environmental impacts of melamine-urea-formaldehyde (MUF), phenol-resorcinol formaldehyde (PRF), phenol formaldehyde (PF) and polyurethane (PUR). For the environmental impact due to production of raw materials the PRF ranked the highest impact while MUF ranked the lowest. For production of the adhesive, PRF ranked the highest impact again while PF ranked the lowest. For final disposal, PRF ranked the highest impact and MUF and PUR

were the same. The impact assessment of the production of 1kg adhesive with 100% solids content was highest for fossil depletion (40%) on all glue types followed by climate change human health (14%) and ecosystem (8%). PF and PRF had the highest g/m^2 required for gluing 3 layered CLT followed by MUF and PUR at 40% of PF and PRG. The environmental impact should be taken into consideration when selecting a CLT product and adhesives have an impact with PUR having the best environmental performance. PUR had the benefits of being able to be applied cold with no need for a hardener and used much less adhesive to bond the timber...

There has been some focus on the potential negative environmental and internal air quality impact of glues used in the manufacture of CLT. This becomes more important as the improved design and construction practises has led to buildings becoming increasingly air-tight (Yauk et al., 2020). The four commonly used adhesives in CLT are melamine-urea-formaldehyde (MUF), emulsion polymer isocyanate (EPI), phenol-resorcinol formaldehyde (PRF) and one-component polyurethane (PUR) (De Araujo et al., 2023). PUR and MUF make up 60% and 24% of the global market respectively (Yauk et al., 2020). Formaldehyde has both carcinogenic and neurotoxic effects and is emitted from some adhesives used in the manufacture of CLT, as well as from the wood itself (Yauk et al., 2020). Polyurethane-based materials can emit isocyanate compounds during production which is known as one of the main causes of occupational asthma (Baur et al., 1994). The workplace exposure standard for airborne contaminants (Safe Work Australia, 2024) limits Isocyanates to 0.02 mg/m^3 for 8 hour average and 0.07 mg/m^3 for short term exposure limit. Irritation of respiratory track and eyes can occur with direct contact with high isocyanate emissions while skin contact can cause inflammation (Messmer, 2015)

Yauk et al. (2020) investigated the volatile organic compound (VOC) emissions of CLT made using soy-based cold set adhesive, PUR and melamine-formaldehyde (MF) and compared these to CLT made using dowels without adhesives. The formaldehyde emissions for CLT glued with soy-based and PUR adhesives were low and similar to the dowel sample that had no glue at 2.5, 1.4 and 2.3 µg/m^3 respectively. The MF sample was much higher at 54.4 µg/m^3. CLT panels made from Canadian spruce and pine using PUR can easily achieve indoor air quality standards and no correlation was seen between VOC's and the thickness

or number of glue lines of the panel and results of between 10.6 and 21.5 μg/m^3 average over 24 hours (Karacebeyli & Gagnon, 2019).

Four hours of exposure to 380 μg/m^3 has been the lowest concentration reported to cause sensory irritation to the eyes, increased blinking and redness can appear at 600 μg/m^3 and at concentrations below 100 μg/m^3, it is not considered to be an adverse health effect. (World Health Organisation, 2010, Golden, 2011). The Australian Environmental Protection (Air) Policy (Queensland Government, 2019) has air quality objectives for formaldehyde to maintain health and wellbeing is 54 μg/m^3 in a 24 hour average concentration and for protecting aesthetic environment is 109 μg/m^3 in a 30 minute average concentration. The World Health Organisation provides guidelines for indoor air quality at a maximum of 100 μg/m^3 for a 30 minute average concentration (World Health Organisation, 2010). The impact on air quality should be taken into consideration when selecting a CLT product and this is highly dependant on the glue that is used in CLT with soy-based and PUR adhesives having minimal to no difference to formaldehyde levels while MF has a large impact.

There exists many opportunities for exploration of these sustainably grown PEExPCH pines in development of sustainable building technologies such as CLT. New and innovative building technologies from out-of-grade PEExPCH must be developed to value add to this timber resource. It is important to explore the opportunity to produce CLT from out-of-grade PEExPCH and capture the many benefits of this green and sustainable building material. To do this, the structural properties, bond quality and performance and the impact of the most commonly occurring characteristics, such as resin, knots and pith, need to be understood. Knowing the impact of these characteristics informs decisions about whether their inclusion needs to be limited to achieve stiffness, strength and bond performance requirements of engineered wood products and supports grading decisions for timber feedstock into such products for variation structural applications.

1.2. Aim and Objectives

The main aims of this study are to investigate out-of-grade PEExPCH hybrid pine and to provide information necessary to make informed decisions on incorporating this low-value and underutilised building material into sustainable building solutions. This includes structural and bond performance of out-of-grade PEExPCH and the impact of its common characteristics of resin, knots and pith.

Finally, to investigate and demonstrate an example of using out-of-grade PEExPCH in a sustainable building solution.

The specific objectives to achieve this project include:

1. Understand the challenges, strengths and opportunities of out-of-grade PEExPCH through exploring the various characteristics found in this resource and matching these to applications in building systems that take advantage of strengths while avoiding weaknesses. Review the latest research and practices including building design methods, practices and technologies that could be used to allow substitution of out-of-grade in place of in-grade in timber building systems and discuss CLT as a good example for further investigation.
2. Evaluate the mechanical properties of out-of-grade PEExPCH including the effect of it's common characteristics of resin, knots and pith on structural performance:
    a. bending,
    b. compression parallel to grain,
    c. compression perpendicular to grain,
    d. shear parallel to grain,
    e. tension and
3. Evaluate the rolling shear MOE and strength of out-of-grade PEExPCH including the effect of resin, knots, pith and growth ring pattern
4. Investigate the bond performance in glulam and CLT orientation, of out-of-grade PEExPCH including the effect of it's common characteristics of resin, knots and pith. Discuss the extent to which current standards and guides address out-of-grade PEExPCH and its common characteristics on bond performance.
5. Evaluate the performance of CLT manufactured from out-of-grade PEExPCH, the effect of wood-based reinforcements to increase structural performance and verify the accuracy of the shear analogy method in predicting bending MOE of CLT made from out-of-grade PEExPCH.

1.3. Study Limitations

This thesis studied the structural properties and bond performance of out-of-grade PEExPCH hybrid pine and its opportunity and performance in the sustainable building system of CLT. The approach taken was to evaluate the clear timber and then identify the effect of commonly occurring characteristics of resin, knots and pith. This provides information that is relevant to establishing grading rules for any end use application. In order to limit the scope of this study given the available resources and time, other characteristics also present in this out-of-grade resource have not been included, such as wane, resin shake and distortion, but could be considered in future studies. Knots, resin and pith were selected as they were found to be most predominant in this resource. The glue used for bond performance and durability assessments is one component polyurethane glue. The development of CLT from a new timber resource requires extensive research in a range of specialty areas that are outside the scope of this research. These include fire performance, connections, durability and acoustic performance of the completed product.

1.4. Thesis Organisation

This thesis is presented by publication with papers used as 5 of the chapters to address the objectives as illustrated in Figure 3. Chapter 1 is the introduction of the work and sets out the background and motivation behind the study and addresses objective 1. Chapter 2 further addresses objective 1 and presents an extensive review of the literature highlighting the characteristics of this out-of-grade resource, the positive and negative attributes of these characteristics, value adding opportunities including examples of potential uses and innovations that can enable the use of this resource in sustainable building systems including CLT. Chapter 3 addresses objective 2 through an extensive experimental study that evaluates the structural performance of out-of-grade PEExPCH and the effect of resin, knots and pith on these properties. Chapter 4 addresses objective 3 as it investigates the rolling shear properties of out-of-grade PEExPCH, the effect of resin, knots and pith on rolling shear and also compares the effect of growth ring pattern on rolling shear performance. Chapter 5 addresses objective 4 by evaluating the bond performance using shear tests and the bond durability using delamination testing of Glulam and CLT layups glued with one-component polyurethane glue. It also discusses the limitations of the current standards to evaluate out-of-grade resource as a feedstock

in engineered wood products. Chapter 6 addresses objective 5 through experimental tests of CLT manufactured from out-of-grade PEExPCH and investigates the effect of wood-based reinforcements. It also verifies the accuracy of the Shear Analogy method to predict bending MOE and strength of CLT.

The five journal papers written as part of this research are:

Paper 1 (published): Cherry, R., Manalo, A., Karunasena, W., & Stringer, G. (2019). Out-of-grade sawn pine: A state-of-the-art review on challenges and new opportunities in Cross Laminated Timber (CLT). *Construction and Building Materials, 211*, 858-868. doi:https://doi.org/10.1016/j.conbuildmat.2019.03.293 (Top 10% journal; Impact factor: 7.4 and SNIP: 2.339)

Paper 2 (published): Cherry, R., Karunasena, W., & Manalo, A. (2022). Mechanical Properties of Low-Stiffness Out-of-Grade Hybrid Pine; Effects of Knots, Resin and Pith. *Forests, 13(6),* 927. doi:https://doi.org/10.3390/f13060927 (Top 10% journal; Impact factor: 2.9 and SNIP: 0.923)

Paper 3 (under review): Cherry, R., Karunasena, W., & Manalo, A. (2024). Rolling Shear Modulus and Strength of Low-stiffness Out-of-grade Hybrid Pine; Effects of Knots, Resin, Pith and Growth Ring Pattern. *Forests.* (Under review) (Top 10% journal; Impact factor: 2.9 and SNIP: 0.923)

Paper 4 (published): Cherry, R., Karunasena, W., & Manalo, A. (2023). Maximizing the Use of Out-of-Grade Hybrid Pine in Engineered Wood Products: Bond Performance, the Effect of Resin Streaking, Knots, and Pith. *Forests, 14(9),* 1916. doi:https://doi.org/10.3390/f14091916. (Top 10% journal; Impact factor: 2.9 and SNIP: 0.923)

Paper 5: (Ready for submission) Cherry, R., Karunasena, W., & Manalo, A. (2024). Structural performance and Evaluation of Cross Laminated Timber Manufactured from Low-stiffness Out-of-grade Hybrid Pine, and the Effect of Wood-based Reinforcements.

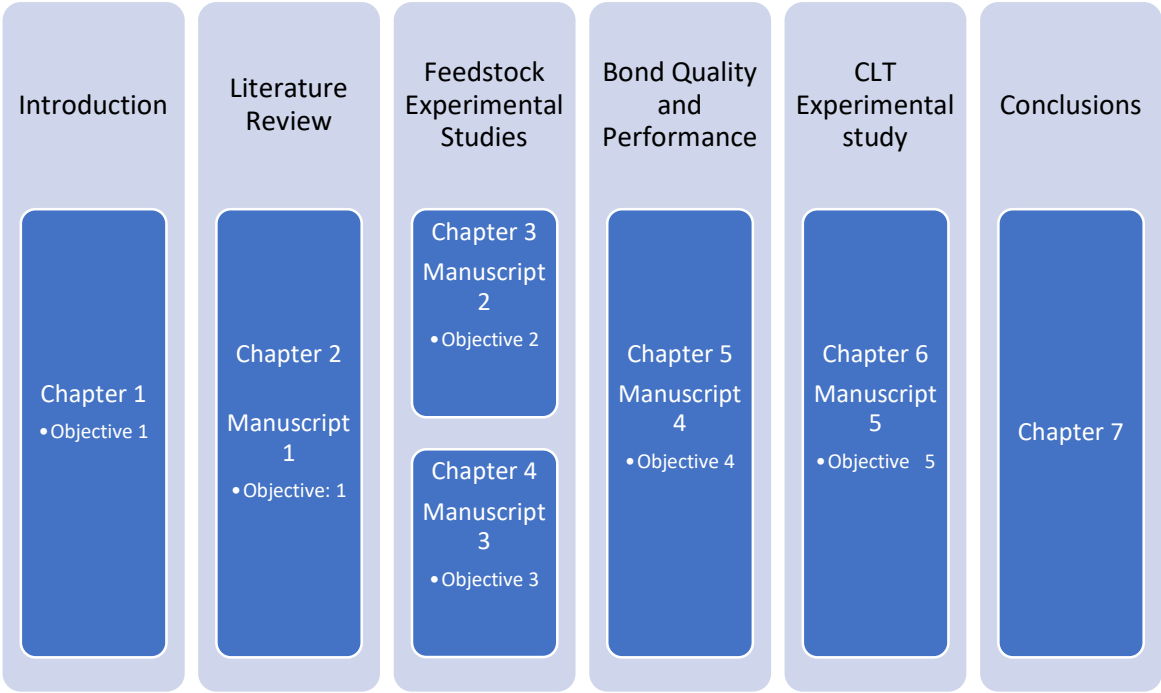

Figure 3. Thesis Flow Chart

1.5. Summary

Out-of-grade PEExPCH is an abundant resource that is underutilised while demand for structural timber is increasing. The available land for sustainable pine plantations is finite and increasing yield is difficult and typically results in compromising structural properties, so it is important to make the most of the available resource. Where suitable, substituting out-of-grade for in-grade timber in building systems offers a potential value add solution while also freeing up structural grade to fulfil future demands.

CHAPTER 2: LITERATURE REVIEW - PAPER 1 – OUT-OF-GRADE SAWN PINE: A STATE-OF-THE-ART-REVIEW ON CHALLENGES AND NEW OPPORTUNITIES IN CROSS LAMINATED TIMBER (CLT)

2.1. Introduction

Chapter 1 highlighted the importance of making the most of the available plantation pine resource to meet the increasing needs of the building and construction industry through sustainable building solutions. It identified that in Queensland Australia, PEExPCH has recently become the predominant species for structural framing and that large volumes of this timber fall short of the structural grading requirements. This by-product is considered out-of-grade, abundantly available, often sold at a loss, is in need of value-add options and could be part of the solution. The need to understand the mechanical properties, bond performance and optimisation opportunities of this resource and the effect of its commonly occurring characteristics to facilitate its use and substitution of in-grade timber in sustainable building systems was identified. Chapter 2 provides further detailed information on out-of-grade PEExPCH including key characteristics with comparisons to other species. An in-depth review of the literature focused on understanding the common characteristics of out-of-grade pine and discussing their potential applications in sustainable building systems that avoid their weaknesses and take advantage of their strengths. It summarises the latest research and practices including building design methods, practices and technologies that can be used to facilitate substitution of out-of-grade in place of in-grade in sustainable timber building systems and discusses CLT as a good example.

Southern pines were introduced into Australian plantations in the 1920's (Akins et al., 1990) with current species in Queensland including *Pinus caribaea (PCH*), *Pinus elliottii (PEE)*, hybrids of both (PEExPCH) (Department of Agriculture Fisheries and Forestry, 2013; HQPlantations, n.d.) and to a lesser extent *Pinus taeda* (Lee, 2015). The PEE population was established using seed introduced from north Florida and south Georgia in the 1920's and was found to be straighter, more wind-firm, and was more tolerant of poorly-drained sites compared to PCH. The PCH population was established in the 1940's using seed imported from Belize and was found to have faster growth, superior branch quality and less variation in wood fibre (Nikles, 2000). The PEE and PCH were crossed in 1955 with the aim to achieve superior quality of both parent species which was successful for growth and

stem straightness on very poorly-drained sites in south-east Queensland and for stem growth on majority of coastal lowlands in south-east and central Queensland compared to PEE (Nikles 2000).

There was an abrupt change in planting strategy in Queensland, which moved away from planting a combination of PEE and PCH to planting a vast majority of *Pinus elliottii var. elliottii x P. caribaea var. hondurensis* F1 and F2 Hybrids (PEExPCH). Between 1993 and 2009, PEExPCH-F1 hybrid was planted with almost 100% PEExPCH-F2 hybrid thereafter (Kain, 2017). With a typical 28 to 30 year clear-fell harvest age, the PEExPCH hybrids are now the vast majority of sawlog for the structural framing market in Queensland and will remain so into the foreseeable future of at least the next 30 years.

The PEExPCH-F1 or PEExPCH-F2 Hybrid name was derived from “F” being short for “filial” or generation, “1” or “2” being the first or second generation and “Hybrid” referring to the mix of species, in this case the PEExPCH (*Pinus elliottii* var. *elliottii* x *Pinus caribaea* var. *hondurensis*). The first generation of the PEExPCH hybrid (PEExPCH-1) was developed by Queensland Forest Research Institute in the 1950’s, followed by the second generation (PEExPCH-F2) with both demonstrating similar timber properties (Harding, 2008, Harding & Copley, 2000). The additional benefit of PEExPCH-F2 was that it provided ease of propagation (Kain, 2017). Comparisons between F1 and F2 PEExPCH hybrids show similar wood properties between these taxa (Harding 2008). The hybrid was bred with an aim to develop a species which possesses the straightness, wood density, wet site tolerance of PEE with the fast growth, fine branching and evenly textured wood of the PCH pine (HQPlantations, 2017). Typically the traits of the PEExPCH lay between those of the parent species (Dieters & Brawner, 2007).

Fast growing pine hybrids provide a way to increase wood production from finite plantation land area (Lopez et al., 2018) within shorter rotation times, but tree breeding and hybridisation can also lead to increased diameters of low quality inner core wood (Malan, 2010). Economic pressures are leading to plantation managers seeking to reduce rotation times, but wood quality is an important consideration (Kain, 2003). Highest MOE and strength is not the highest priority in deployment selection with consideration to other characteristics such as spiral grain in growth rings, sweep, density and occurrence of ramicorn branches also affecting rankings (Harding et at., 2008) which is associated with their impact on a finished product

such as recovery, distortion and strength of structural graded timber. Harding et al. (2008) investigates 32 clones at the age of 6 years and identifies the top 12 selected for deployment. Of these top 12, 33% are below average for MOE and 25% are below average for strength. The lowest rankings in the top 12 clones was 29 out of 32 for MOE at 5.65 GPa compared to a population average of 7.2 GPa and 31 and 32 out of a total 32 for strength at 34.48 MPa and 33.97 MPa respectively, with a population average of 42.4 MPa. At 28 years of age, well-managed stands of PEExPCH are expected to be predominantly mature wood whereas at 20 years of age the mature wood is likely to be less than 50% (Kain, 2003). These shorter rotation times are making it more critical that juvenile and corewood are higher quality but a multitude of factors aside from MOE and strength contribute to which ramits are deployed which eventually impact the quality of wood produced for milling and grading.

The PEExPCH was developed through a targeted research and tree improvement program with much of the work being focused on young trees (Nikles, 2000, Dieters & Brawner, 2007, Haring et al., 2007, Harding et al., 2008, Wessels, 2011). The growth patterns of the PEExPCH were a combination of the parent species which provides vigour advantage as PEE had vigorous early season growth followed by a steady decline later in the season and dormancy in winter, PEE grows most actively in summer and least active in winter but continues to grow throughout the year (Slee, 1972). The PEExPCH has more uniform wood compared to the PEE with less difference between earlywood and latewood density (Malan, 2015).

The PEExPCH has higher stem volume compared to PEE but similar to PCH (Kain, 2003, Gwaze, 1999). Stem volume was found to be less heritable than wood density and spiral grain and all three could be achieved through family selection (Kain, 2003) including wood acoustic velocity (Malan, 2015). The PEExPCH has been found to exhibit the high growth rate of PCH (Kain, 2003, Dieters & Brawner, 2007). The mean annual growth at age 15 years for the PEEXPCH in South East Queensland is 23.5 m^3/year which is similar to PCH at 23 m^3/year and 33% higher than PEE at 17.6 m^3/year with environmental conditions such as slope, position, soil type and management regimes also having an impact (Dieters & Brawner, 2007). Harding et al. (2008) found that growth rate changed in early age annual assessments between 3 and 6 years of age and this impacted ranking for deployment with examples given where high stiffness clones being excluded due to

lower volume advantage. A high volume growth rate is correlated with lower density (Kain, 2003, Harding, 2008) and lower structural properties. When grown on the same site the PEExPCH has a lower wood density compared to PEE but similar to PCH (Kain, 2003, Harding, 2008, Rockwood et al., 1991). When grown on the same site, latewood percentage and fibre length of the PEExPCH are between PEE and PCH although slightly more similar to PCH (Harding 2008). PEExPCH show similar trends to PEE and PCH with un-extracted basic density and latewood percentages increasing with a decrease in latitude along coastal lowlands, increasing with decreasing site index at the same location and elevation and decreasing with elevations with the same latitude (Harding, 2008, Rockwood, 1991).

Clones and parents in the tree improvement program were selected for growth and form but these showed large variation in wood properties which also became evident in the resulting PEExPCH (Harding, 2008, Rockwood, 1991). Trees grown on ex-pasture land grew with average basic densities about 30 kg/m^3 less than those that were planted on ex native forest lands (Harding 2008). This aligns with finding of Rockwood et al., (1991) who found that density and latewood increased on poorer sites. Malan (2015) found wood stiffness decreases at increasing elevations with higher proportions not meeting structural grading requirements at harvest and PEExPCH being more affected compared to other hybrid pines assessed. Nel et al. (2017) found PEExPCH between 15 and 19 years of age met density requirements for S5 structural grade timber at 380 kg/m^3, met the fifth percentile bending strength requirement of 15.8 MPa for S7 structural grade, but fell short of mean MOE requirement of 7.8GPa and about 17% of boards fell short due to other criteria which were mostly knot related defects. Malan (2015) found the young PEExPCH wood tended to be lower in stiffness than other species investigated including PEE, *Pinus patula* and *Pinus taeda*. Harding et al. (2008) found that only 4 of the top 12 clones produces juvenile wood with MOE above 8.5 GPa and so would not meet MGP grading requirements although other clones did have sufficient stiffness, they had other traits which excluded them from the top selections.

The PEExPCH has been found to exhibit wind-firmness, straightness, thin bark from PEE and fine branching of PCH (Kain, 2003, Dieters & Brawner, 2007, Gwaze, 1999). PEExPCH have a wide range of branch sizes but are typically smaller than what is found in PEE and tree improvement programs have been

successful in producing PEExPCH with fine branches which is beneficial for structural grading (Harding 2008).

Significant resin defect has been found in PEExPCH as well as its parent species of PEE and PCH (Harding 2008). PEExPCH grown in Zululand commonly has knot associated resin streaking which can impact the visual aspect and bond performance and resin shake which affects structural performance (Malan, 1995). PEExPCH was found to have a higher resin content than PEE but similar to PCH (Rockwood, 1991). The resin content decreases from pith to bark in PEExPCH and has a highly significant negate relationship with permeability (Leggate et al., 2019) which leads to challenges for treatment and bond performance.

The PEExPCH has been found to have structural properties between its parent species of PEE and PCH and both these species have been used throughout Australia for structural building applications over the past decades. Bailleres et al., (2019) conducted extensive research on plantation pines grown in Queensland and Northern New South Wales using innovative resource characterisation methods. The study found that PEExPCH, PEE and PCH have a large overlap of MOE indicating potential to produce similar stiffness wood (Ballieres, 2019). Harding and Coppley (2002) found the PEExPCH produces timber with sufficient density and strength for structural products. Dieters & Brawner (2007) recommended PEExPCH over PCH for plantings in Queensland for production of structural-grade timber. In recent years, the PEExPCH has begun to be harvested and milled on a commercial scale in Queensland and is now graded and used for structural building applications.

PEExPCH is being commercially grown and investigated for commercial growth, in numerous locations around the world in addition to Australia. The PEExPCH is successfully grown in tropical and subtropical regions (Nikles, 2000, Yang et al., 2013, Rockwood, 1991) but not well adapted for the Western Gulf Region of United States where it experienced low survival and growth rates (Gwaze et al., 2001). The PEExPCH showed good performance at low-elevation drier sites in Zimbabwe but also achieved three times the volume of PEE at a wetter site (Gwaze, 1999). In Queensland, at 21 years of age, the PEExPCH had up to 50% more volume that the previous taxon planted at each location which was attributed to the PEExPCH greater height, larger DBH, cylindrical form and thinner bark (Rockwood, 1991).

The South African Forestry Research Institute adopted PEExPCH in the 1960's with promising results (Akins et al., 1990; Nel et al., 2017). China also developed PEExPCH some 10 years later, went on to introduce Australian clones (Yang et al., 2013) and are investigating commercial and industrial breeding processes (Lv & Huang, 2012). Increasing quantities are being grown in South America due to their superior performance (Cappa et al., 2012; Gauchar et al., 2016). Figure 4 shows an example of PEExPCH growing in one of HQPlantations sustainably managed plantations in Queensland Australia.

Figure 4 Cherry. R., (2018) PEExPCH grown in Sustainable Plantations in Queensland Australia.

There was an abrupt change in planting strategy in Queensland, which moved away from planting a combination of PEE and PCH to planting a vast majority of PEExPCH hybrids in 1993, as illustrated in Figure 2. Between 1993 and 2009, PEExPCH-F1 hybrid was planted with almost 100% PEExPCH-F2 hybrid thereafter (Kain, 2017). With a typical 28 to 30 year clear-fell harvest age, the PEExPCH hybrids are now the vast majority of sawlog for the structural framing market in Queensland and will remain so into the foreseeable future of at least 30 years.

Given the significant volumes and the importance of the PEExPCH to Australia, as well as the limited research on this species, it is the focus for this research.

Given the recent development and adoption of these hybrids, limited mature fibre has been available for exploration into engineered timber products and those that have been researched have focused on young fibre. Almeida et al., (2012) found plywood made from PEExPCH at 7 years of age did not meet the requirements of structural building applications due to low strength and stiffness. Surdi et al., (2015) found oriented strand board and found PEExPCH produced panels that had low apparent density and mechanical properties and that oriented strandboard made from *pinus taeda* performed better. PEExPCH has not been used to produce CLT due to its relatively new introduction at a commercial level with a lack of mature fibre and commercial scale milling only starting in recent years. The PEExPCH plantations in South East Queensland are beginning to reach harvest age. These have been milled and graded for structural framing products alongside its parent species, and the MGP graded timber has been in use in structural building applications. Hyne & Son also now use the PEExPCH to produce glue-laminated timber beams (D. Bennetts, personal communication, 30 June 2023).

During a mill run at Hyne Tuan, 12 packs of out-of-grade PEExPCH were captured and set aside for visual inspection, each pack containing 112 boards. The mill grading system report revealed that low MOE was the most frequent reason for rejection from MGP grades, which is the same as the parent species of PEE and PCH run through the same grading system. The boards in the packs were visually inspected and this revealed that the majority of pieces were from the corewood zone of the tree. The corewood zone is in the area close to the pith or centre of the tree and is typically made up of the first 10 to 12 growth rings (Plomion, 2001, Mead, 2013). The characteristics of this out-of-grade PEExPCH included wandering pith, needle trace, high content of early wood, heartwood deposits, resin streaking, resin shake, sloping grain, high angled clustered conical shaped knots, distortion, tight radius but wide growth rings. These characteristics along with their strength and weaknesses and potential for building applications will be discussed in further detail later in this chapter. An example of out-of-grade PEExPCH timber can be seen in Figure 5, resin shake in Figure 6(a) and pith with surrounding wide growth rings containing high proportion of earlywood in Figure 6(b). The strengths of these various characteristics may align with the needs of specific layers or regions within

CLT, providing opportunity to substitute this low-value abundant resource in place of high-value highly sought after in-grade timber.

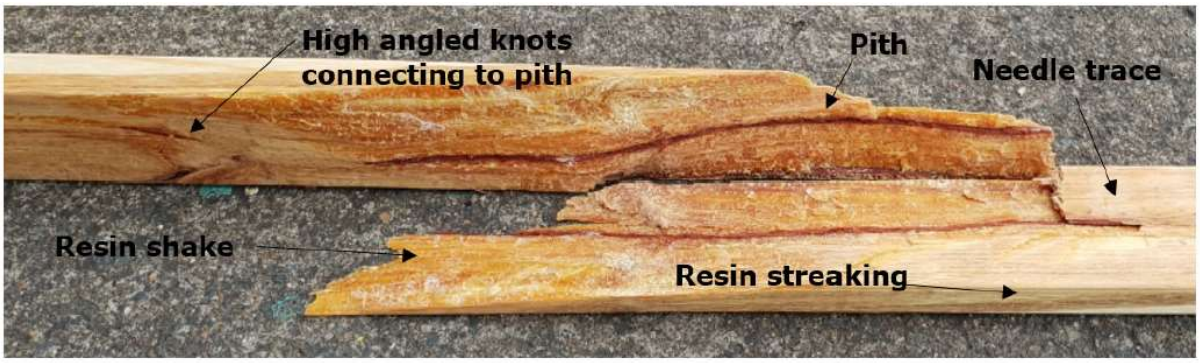

Figure 5. Some characteristics of Out-of-grade PEExPCH timber.

(a) (b)

Figure 6 (a) Resin Shake and (b) Pith surrounded by wide growth rings

2.2. Links and implications

Chapter 2 included an in depth review of the literature on the PEExPCH, looking at its key characteristics and findings from research on its structural performance, growth rates, density, branching, wind resistance and form. The differences for PEExPCH to its parents and other species were presented. The locations where the PEExPCH has been grown commercially and trailed have been included and represent tropical and subtropical climates. The growth patterns as well as environmental influences such as elevations and latitude and their impact on density, growth rate and resin have been considered. Justification of why PEExPCH is an important species for Queensland and for this research was discussed. The limited research available in the literature for this PEExPCH as engineered wood products has been included. The characteristics found in out-of-grade PEExPCH have been identified.

Chapter 2 also presented a critical review of the literature that confirmed out-of-grade pine is an undervalued and abundant resource for which new approaches and methods need to be implemented to value-add this resource and increase use of timber from existing plantations for structural applications. The commonly occurring characteristics of out-of-grade pine, their strengths and weaknesses were reviewed revealing that while not all out-of-grade pine is suitable for all applications, with a thorough understanding of these characteristics and through targeted placement in building systems and using building technologies, some is suitable for specific applications that avoid weaknesses and take advantage of strengths. Building and design methods as well as new and existing technologies that help facilitate the incorporation of out-of-grade timber were identified. CLT was recognised as providing potential to incorporate large volumes of out-of-grade timber, especially as the inner and transverse layers.

The conclusions were, that in order to evaluate the use out-of-grade pine in any structural application, the mechanical properties and effect of the commonly occurring characteristics need to be evaluated. For use in engineered wood products, the bond performance and bond quality also need to be understood along with the extent to which current standards and guides address out-of-grade timber and its common occurring characteristics. Moreover, while CLT was identified as a good opportunity to utilise large volumes of out-of-grade, the transverse layers of CLT are exposed to rolling shear stress which is a lesser utilised, researched and

known property of timber, and further understanding and optimisation opportunities need to be explored. This has provided the motivation and direction for this study as presented in chapters 3 to 6.

Chapter 3 will evaluate the mechanical properties of out-of-grade PEExPCH and the effect of resin, knots and pith. Chapter 4 will evaluate the rolling shear performance of out-of-grade PEExPCH and the effect of resin, knots, pith and growth ring pattern. Chapter 5 will investigate the bond performance and bond quality of out-of-grade PEExPCH and discuss how the CLT standards address out-of-grade timber. Finally, Chapter 6 will evaluate the bending MOE and strength properties of CLT manufactured from out-of-grade PEExPCH and the effect of wood-based reinforcements.

CHAPTER 3: PAPER 2 - MECHANICAL PROPERTIES OF LOW-STIFFNESS OUT-OF-GRADE HYBRID PINE; EFFECTS OF KNOTS, RESIN AND PITH

3.1. Introduction

Chapter 2 highlighted the requirement to understand the structural performance of out-of-grade timber and the effect of its common occurring characteristics of resin, knots and pith for evaluation and use in structural applications. Knowing the structural performance of this resource then allows for further research, product development, optimisation and to inform predictive models. Moreover, knowing the impact of characteristics in this resource on those structural properties would inform decision making for custom grade rules where the intent is to develop a customised feedstock grade that is suitable for a specific application, while also minimising waste timber.

The objectives of Chapter 3 are to evaluate the mechanical properties of out-of-grade PEExPCH hybrid pine. It provides an extensive study on the mechanical properties and characterises the MOE and strength in bending, compression parallel to grain, compression perpendicular to grain, shear and strength in tension. This is be compared to other similar softwoods in the literature. Furthermore, the effect of resin, knots, pith and density are also determined.

3.2. Published Paper

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Mechanical Properties of Low-Stiffness Out-of-Grade Hybrid Pine—Effects of Knots, Resin and Pith

Rebecca Cherry [1,2], Warna Karunasena [1,*] and Allan Manalo [1]

[1] Centre for Future Materials, University of Southern Queensland, West Street, Toowoomba, QLD 4350, Australia; rebecca.cherry@usq.edu.au (R.C.); allan.manalo@usq.edu.au (A.M.)
[2] Hyne & Son Pty Ltd., Kent Street, Maryborough, QLD 4650, Australia
* Correspondence: karu.karunasena@usq.edu.au

Abstract: Out-of-grade pine timber is an abundant material resource that is underutilised because its mechanical properties are not well understood. Increasing trends toward shorter rotation times and fast-grown plantation pines around the world such as *Pinus elliottii* x *P. caribaea* var. *hondurensis* hybrid (PEExPCH) mean low-stiffness corewood is becoming a larger portion of this out-of-grade population. This study characterised the modulus and strength properties in bending, compression parallel to grain (CParG) and compression perpendicular to grain (CPerpG), shear and tension strength of low-stiffness out-of-grade PEExPCH. The effect of resin, knots and pith on these properties were also investigated. The results show that in clear wood, the MOE in bending, CParG, CPerpG and shear modulus are 6.9 GPa, 5.78 GPa, 0.27 GPa and 0.59 GPa, respectively, while strengths are 45.8 MPa, 29.4 MPa, 6.7 MPa, 5.7 MPa, respectively. The tensile strength is 32.4 MPa. Resin significantly increased density 45% higher than clear, but performed similar with the exception of CPerpG MOE and strength which were significantly different. Resin area ratio (RAR) has a moderate correlation with density with an R^2 of 0.659 but low to no correlation for mechanical properties. Knots were significantly different to clear for all test types and within a range of 48% to 196%. Knots were high in CPerpG MOE and strength but lower for all other properties and had the largest negative impact on tensile strength. Knot area ratio (KAR) had low to moderate correlation with tension strength and CPerpG MOE with R^2 of 0.48 and 0.35, respectively. Pith was within the range of 76% to 121% of non-pith samples for structural performance, some of which were significantly different, and pith samples were higher in density than non-pith. This new information is crucial for the effective establishment of grading rules, design optimisation and utilisation of low-stiffness out-of-grade PEExPCH as a new material resource in civil engineering applications.

Keywords: PEExPCH hybrid pine; out-of-grade; low-grade; bending; compression; resin; pith; knots; corewood; juvenile wood

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1. Introduction

The *Pinus elliotti* var. *elliottii* × *P. caribaea* var. *hondurensis* (PEExPCH) hybrids are becoming an increasingly important fast-growing plantation softwood around the world. In Queensland, Australia, there are more than 90,000 ha already established [1]. As a relatively new taxa, these pines are showing promising results for growth and structural properties in Australia [2,3], Africa [2,4], China [5,6] and Central and South America [7,8]. Their high volume growth rate, good wind resistance, stem straightness and superior wood quality [3] ensure their future as a source of structural sawn timber for use in civil engineering and construction.

More than 97% of Australia's softwood plantations are managed for sawlogs [9] and structural framing products for which machine-graded pine (MGP) is the base grading method. While MGP structural sawn pine is highly sought after, its out-of-grade counterpart is in low demand and large volumes are sold at a loss [10]. Out-of-grade in this study

refers to sawn timber that has failed to meet the MGP structural framing requirements of AS1748 [11] and AS1720.1 [12] which specify minimum characteristic values of stiffness, strength and place limits on defects including resin shake, wane and distortion. There are significant volumes of out-of-grade timber produced around the world; nevertheless, perceived unfavourable characteristics can be overcome with a good understanding of their properties, and through targeted placement in manufacturing building systems and utilisation of building technologies [13]. In Australia, up to 50% of sawn production from softwood plantations is not achieving structural grade requirements [10]. A recent study from a group of 68 Australian-grown Southern Pine trees including the PEExPCH hybrids showed that 77% of boards had MOE values less than 10 GPa [14]. This is not unique to the PEExPCH with plantation growers around the world moving toward small-diameter and fast-grown plantation trees which produce high percentages of lower-performing corewood [15]. The lack of mature wood within a piece of timber can lead to reduced mechanical properties [16,17]. Nonetheless, despite the low bending MOE, some studies have found that juvenile and corewood can have some good properties and attributes including increased durability with respect to mechanical degradation, and transverse mechanical properties [18]. With the increasing supply of PEExPCH hybrids around the world [2–8], there is a need to value add the low-stiffness out-of-grade component of this new material resource and look for repurposing opportunities such as engineered timber products.

As a relatively new hybrid, very few studies have looked at PEExPCH hybrid pine as a material resource for engineered timber products. Those that have did not consider sawn timber but rather timber strands and veneers taken from young trees used in oriented strand board panels [19] and plywood [20] which gave low structural performance. Engineered timber products provide opportunity for additional utilisation of solid wood into the future, and are likely to be elements of composite systems [15]. Custom timber grades are often used for feedstock into engineered wood products such as glulam and CLT. Development of custom grades to extract suitable timber from the out of-grade population would optimise its use while providing a reliably performing product. Establishing grading rules and designing and modelling of engineered wood products requires the structural performance information of the feedstock.

This study provides an essential step toward maximising the use of out-of-grade PEExPCH hybrid pine by characterising its important physical and mechanical properties. It will compare the ratios of structural performance and bending MOE to other PEExPCH hybrid pines, young, low grade and average populations of similar pines to look for any high relative performance. It will contribute to knowledge and build on existing literature by evaluating the effects of resin, knots and pith on the bending, shear, tension and compression properties in pine. Correlations between resin, knots and density and structural performance will be evaluated. Existing models in the literature that predict structural performance based on change in density will be compared to actual change in performance. This information can be used in development and optimise custom grading rules and to inform design and modelling for various applications including development of engineered wood products, value adding to this new, emerging, and sustainable material resource.

2. Background

The grading report for the mill runs of PEExPCH show low modulus of elasticity as the most significant reason for grade rejection. As common in other pines, longitudinal MOE reduces significantly the closer to the pith in PEExPCH [14]. Visual inspections of sawn out-of-grade PEExPCH timber revealed that the majority of pieces were from the middle of the tree and showed physical signs of the corewood zone. Corewood is considered to be the first 10 to 12 growth rings from the pith [21,22]. Wandering pith, needle trace, tight-radius growth rings, high content of early wood, heartwood deposits, resin shake, resin streaking and clustered conical shape knots were all common. An example of

out-of-grade PEExPCH hybrid timber is shown in Figure 1 and illustrates the extent of wandering pith and associated grain deviation which caused multiple changes in cross-sectional growth ring orientations along a length. This study will focus on clear, resinous, and knotted timber with and without pith to capture a large majority of this out-of-grade resource, and it will not include resin shakes or distortion, the effects of which can be investigated in future studies.

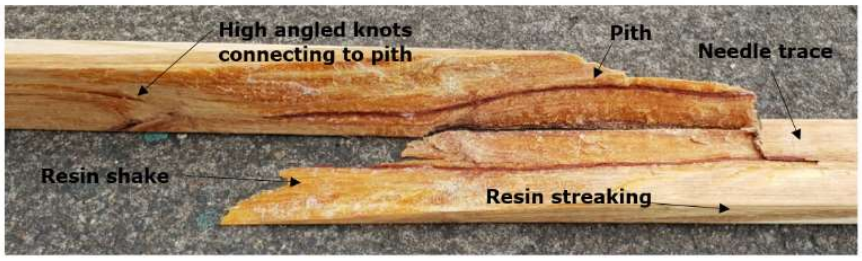


Figure 1. Example of out-of-grade PEExPCH and its features.

Knots are inherent in all timber and are more frequent and larger in out-of-grade timber compared to structural grade [23] but also have different characteristics when they occur in the core of the tree. Due to grain deviation and disruption, knots are well known to have significant impacts on some structural properties [24–26]. PEExPCH hybrids were found to have more encased knots per board than its parent species [2] but their knots are small compared to those in radiata pine [27]. Knots in timber cut close to the core have different characteristics to those in more mature wood. They are often clustered, more conical shaped, are at high angles and have connections with the pith. Knots have been known to have improved properties such as perpendicular to grain and shear [13] and to better utilise this resource; the impact of these types of knots from the core of the tree need to be better understood.

Resin increases density of a piece of timber, but limited information is available on its impact on structural performance. PEExPCH hybrids are prone to resin streaking [2,28–30] often developing from weak spots in corewood such as knots and pith [31] which are frequent in out-of-grade. The PEExPCH hybrids have been found to have high overall resin content at tree level ranging between 2% and 17%, with resin content increasing radially from bark to pith and also with the age of the tree [14]. Extractives are known to provide reinforcement from within the cell walls and lumen to resist failure which occurs as buckling of the micro fibrils in the secondary cell wall causing out-of-plane bulging deformation followed by shear or kinked bands [32]. There is very little literature available on the impact of resin on structural performance, but some research has found it can provide slight increases in strength [33–35] but the magnitude of this increase compared to the increase in density needs to be known for optimisation and design purposes.

Thus, a detailed understanding on the important mechanical properties of out-of-grade sawn PEExPCH and the effect of these commonly occurring characteristics of knots, resin and pith is essential to select, repurpose and optimise this timber resource into engineered timber products suitable for civil engineering and construction.

3. Materials and Methods

3.1. Design of Experiments

The out-of-grade timber used for this study is a common structural-grading size of 90 × 35 mm. The samples were collected over three shifts of a mill run of 31-year-old PEExPCH hybrid pine harvested from Cowra, Queensland, Australia. Ideally, sample extraction would occur over many months of production to capture the variation seen in trees. However, under normal milling processes, identification and segregation of PEExPCH from other Southern Yellow pines was not possible. This mill run was set up

for research purposes and ensured only PEExPCH was being processed and graded during the run. While the sample extraction occurred over a limited time, the mill data collected for the entire run showed it had a population average MOE and volume percentage of out-of-grade only slightly higher than that in previous mill runs of mixed Southern Yellow pines which included PEEXPCH. Therefore, it is reasonable to consider the sample representative of an average population.

Modern finger-jointing equipment enables quick and easy end joining of timber after the removal of any unwanted features and can achieve 90% of tensile strength of clear wood [36]. Thus, with a focus to provide information for development of grading rules and to understand the impact of specific features that could be removed and the piece finger jointed back together, rather than carrying out an in-grade study which would capture a population with random inclusion of a wide range of characteristics present in out-of-grade timber, small sample sizes containing specific commonly occurring characteristics previously discussed were adopted. The three sample types are presented in Table 1 and Figure 2.

- Clear containing no obvious defects with the exception of pith;
- Resin containing at least 25% of the cross-sectional area resinous timber and no obvious defects with the exception of pith;
- Knots containing at least 25% knot area ratio (KAR) and may contain pith.

Figure 2. Examples of clear and resin samples and of a typical knot sample.

Table 1. Test samples with cross section of 90 × 35 mm.

	Test Type					
	Bending	**CParG**	**CPerpG**	**Shear**	**Tension**	**Total**
Sample Length	**700 mm**	**140 mm**	**210 mm**	**200 mm**	**1800 mm**	
Clear	35 (11)	35 (10)	35 (12)	30 (14)	35 (20)	170 (67)
Resin	35 (9)	35 (18)	35 (15)	30 (14)	35 (20)	170 (76)
Knots	35 (11)	35 (14)	35 (14)	30 (16)	35 (22)	170 (77)
Total	105 (31)	105 (42)	105 (41)	90 (44)	105 (62)	510 (220)

Values in () are number of samples containing pith in the sample set.

The majority of out-of-grade was found to be from the corewood zone off the tree and as pith is an inherent characteristic of corewood of pine, no separate sample set was obtained for pith, but quantities occurring within each sample type are included in Table 1. Studies have looked at the impact of the mechanical properties of extractives using intricate and time-consuming laboratory-based extraction methods to remove resin from cell walls and lumen [34,35] which is not feasible for industrial-scale milling. Resin area ratio (RAR) gives an opportunity to quickly and easily measure the area of timber with resin-filled lumen. It needs to be determined if RAR would be a useful indicator property. RAR is the sum of the cross-sectional area of resinous timber on both ends of the sample

divided by the total cross sectional area of both ends. For the longer tension and bending samples, the RAR of the failed cross section is used. The determination of KAR is based on the method presented in AS2858 appendix C (Standards Australia, 2008a).

The results of each test will look at the failure behaviour of the samples, the structural performance and the ratio to bending MOE compared to other young, low-grade and average populations of similar pines as well as the correlation between density and MOE and strength. The analysis for the effect of resin, knots and pith are completed in the following ways:

1. The clear and resin samples are compared for MOE and strength;
2. The clear and knot samples are compared for MOE and strength;
3. Pith and no pith are compared for MOE and strength in clear, resin and knot sample types.

This is repeated for all five test types: bending, compression parallel to grain (CParG), compression perpendicular to grain (CPerpG), longitudinal shear and tension, as set out in Table 1. On-flat rather than on-edge bending was used because it is closer aligned with the orientation most often used in engineered wood products such as glulam and CLT. Additionally, the smaller sample size enabled isolation of the characteristics in the different sample types of clear, resin and knots. Tension MOE parallel to grain is a difficult parameter to test [36–38] and is not tested in this study. Doyle and Markwardt [37] found that tensile MOE is closely aligned to the true MOE with good correlation (R^2 0.898 to 0.971). Forest Products Laboratory [36] recommend an increase on bending MOE of 10% to achieve true MOE and this aligns with the findings of Baño et al. [38]. Therefore, it would be reasonable to use on-flat bending MOE as a slightly conservative estimate of tension MOE. Student *t*-tests with a significance level of 0.05 will be used to analyse the difference between sample type results.

3.2. Test Set-Up and Procedure

3.2.1. Bending

The four-point bending test configuration is shown in Figure 3. The bending MOE (E_b) and strength (f_b) are calculated using Equations (1)–(3) as per AS4063.1 [39]. Equation (2) is used where failure occurred within the zone of constant bending while Equation (3) is used where failure occurred within the outer segments of the span.

$$E_b = \frac{23}{108}\left(\frac{L}{d}\right)^3\left(\frac{\Delta F}{\Delta e}\right)\frac{1}{b} \tag{1}$$

where $\Delta F/\Delta e$ is the linear elastic slope of the load–displacement graph, b is the width in mm, L is the length in mm and d is the depth in mm of the specimen.

$$f_b = \frac{F_{\text{ult}}L}{bd^2} \tag{2}$$

where F_{ult} is the applied load initiating failure in the test piece in Newtons (N).

$$f_b = \frac{3F_{\text{ult}}(L - 2L_v)}{2bd^2} \tag{3}$$

where L_v is the distance in mm from centre of test span to bending mode point of failure.

An MTS 100 kN universal testing machine was used with a load rate of 10 mm/min. Samples were tested on flat and knots were located mid span of the knot samples.

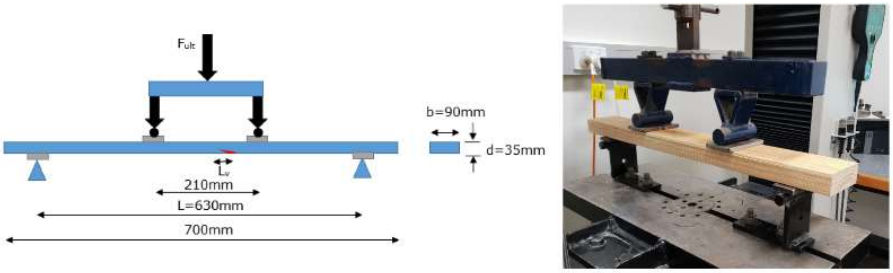


Figure 3. Four-point bending test configuration.

3.2.2. CParG

The CParG test configuration is shown in Figure 4. AS/NZS4063.1 [39] allows for a sub-set of shorter lengths. The compressive strain measurements were taken using an Imetrum DIC CAM026 and CParG MOE (E_{CParG}) was calculated using Equation (4). The CParG strength ($f_{c,0}$) was calculated according to AS/NZS4063.1 [39] using Equation (5). The samples were loaded at a rate of 3 mm/min using a SANS 2000 kN universal test machine. Glued on strain gauges were also used as a comparison to the DIC and to calculate Poisson's ratio.

CParG MOE

$$E_{CParG} = \frac{\Delta F}{\Delta e}\frac{\mathrm{L}}{(bd)} \tag{4}$$

CParG strength

$$f_{c,0} = \frac{F_{\mathrm{ult}}}{bd} \tag{5}$$

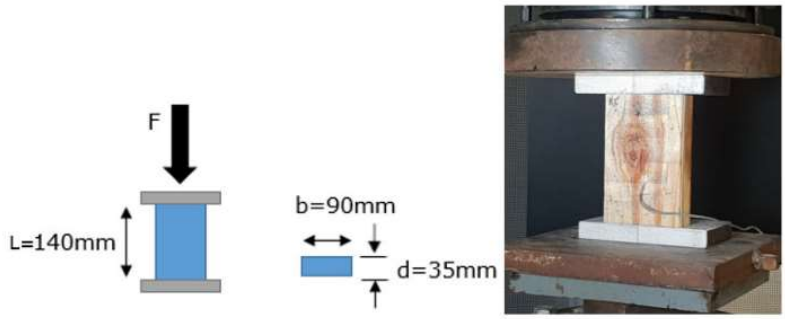


Figure 4. CParG test configuration.

3.2.3. CPerpG

The CPerpG test configuration is shown in Figure 5 and are as per AS/NZS4063.1 [39] appendix A. The CPerpG MOE ($E_{c,90}$) and strength ($f_{c,90}$) were calculated in accordance with AS/NZS4063.1 using Equation (6) and the lesser or Equation (7) or Equation (8). The equation for CPerpG MOE was multiplied by the depth of the sample to align with Hooke's law. A load rate of 3 mm/min was applied using a SANS 2000 kN universal test machine. Two steel plates measuring 90 mm-wide and 100 mm-long with a 3 mm radius along the edge of contact were used to squeeze the sample.

CPerpG MOE

$$E_{c,90} = \frac{\Delta F}{\Delta e}\frac{d}{90b} \tag{6}$$

CPerpG strength

$$f_{c,90} = \frac{F_{0.1d}}{90b} \tag{7}$$

$$f_{c,90} = \frac{F_{\text{ult}}}{90b} \tag{8}$$

where $F_{0.1d}$ is the load at deformation of $0.1d$ in N and, F_{ult} is value of applied load at failure in N.

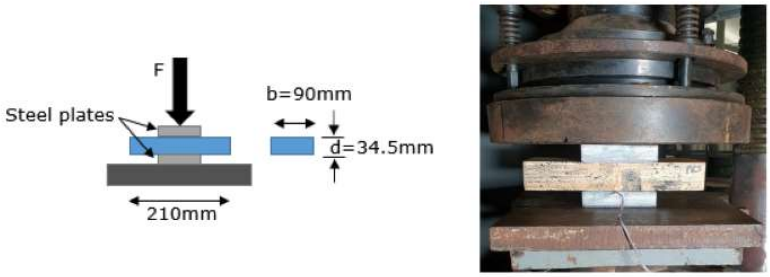


Figure 5. CPerpG test configuration.

3.2.4. Shear

The shear test configuration is shown in Figure 6 and is as per ISO 13910 [40]. The angle between shear plane and force direction was 14° and test samples were 90 mm-wide (d) and 200 mm-long (L). The wide faces of the samples were planed prior to gluing to the steel plates to achieve sufficient bond quality for the test. Samples were loaded for MOE testing using an MTS 100 kN universal testing machine at a rate of 1 mm/min and later broken on a SANS 2000 kN universal testing machine for shear strength. The shear strength ($f_{v,0}$) was calculated according to ISO 13910 [40] using Equation (9). LVDTs were used to measure displacement of steel plates and longitudinal shear modulus (G_0) was calculated using Equation (10).

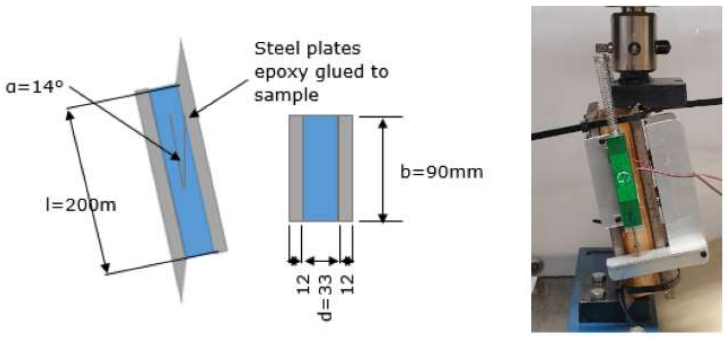


Figure 6. Shear test configuration.

$$f_{v,0} = \frac{F_{\text{ult}} cos14°}{\text{Ld}} \tag{9}$$

$$G_0 = \frac{\Delta F}{\Delta e} \frac{cos14° * d}{\text{Lb}} \tag{10}$$

where F_{ult} is failure load in N.

3.2.5. Tension

The tension test configuration is shown in Figure 7. The length between the grips of the tension tester is 700 mm so that clear knot-free wood could be tested. Tension strength ($f_{t,0}$) was calculated using Equation (11) from AS4063.1 [39].

$$f_{t,0} = \frac{F_{\text{ult}}}{\text{bd}} \tag{11}$$

where F_{ult} is the maximum load in N.

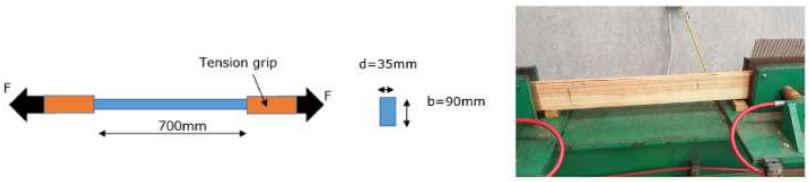


Figure 7. Tension test configuration.

3.2.6. Density

The density at the time of test (p_{test}) for each sample was calculated using Equation (12) in accordance with AS4063.1 [39]. A&D-HV-60KGL scales were used to measure the mass of the samples. A Delmhorst-RDM-2 moisture metre was used to measure the moisture content.

$$p_{test} = \frac{m * 10^9}{Lbd} \tag{12}$$

where m is the mass of the sample in kg.

4. Results

The average and 5th percentile (5th %ile) MOE and strength in bending, CParG, CPerpG, longitudinal shear and strength in tension are listed in Table 2 along with average density and moisture content. The average Poisson's ratio for the pooled clear and resin samples was calculated as 0.437 and is similar to the value published for one of its parent species slash pine of 0.418 [36]. Tension strength test for all clear and resin samples are based on samples that failed within the test span. Any tests that failed within the clamped region were excluded.

Table 2. Summary of test results.

Type	Average MOE (GPa)	MOE (5th %ile)	Average Strength (Mpa)	Strength (5th %ile)	Average Density (kg/m³)	Average Moisture Content (%)
Bending						
Clear	**6.90 (1.53)**	**4.16**	**45.8 (9.1)**	**35.2**	**510 (50)**	**13.1 (1.8)**
Pith	6.01 (1.27)	4.24	40.8 (3.9)	36.3	509 (60)	12.6 (1.9)
No Pith	7.31 (1.49)	4.30	48.2 (9.8)	34.0	510 (46)	13.4 (1.8)
Resin	**6.94 (1.08)**	**5.16**	**45.7 (8.4)**	**32.4**	**701 (83)**	**13.3 (1.8)**
Pith	6.14 (0.90)	4.73	40.8 (8.1)	31.6	711 (83)	13.9 (2.0)
No Pith	7.22 (1.01)	5.43	47.3 (8.0)	34.5	697 (84)	13.1 (1.7)
Knots	**5.37 (1.03)**	**3.90**	**26.7 (8.4)**	**12.6**	**661 (113)**	**12.8 (2.1)**
Pith	5.51 (1.12)	4.04	27.1 (7.6)	13.5	728 (114)	11.4 (2.1)
No Pith	5.29 (1.00)	4.01	26.6 (8.8)	11.8	630 (100)	13.5 (1.8)
CParG						
Clear	**5.78 (1.67)**	**3.56**	**29.4 (5.7)**	**21.1**	**490 (42)**	**12.4 (1.7)**

Pith	5.33 (1.64)	3.56	29.63 (5.96)	22.93	503 (48)	11.2 (1.1)
No Pith	5.97 (1.67)	3.71	29.32 (5.66)	20.49	485 (39)	12.8 (1.6)
Resin	**6.37 (1.58)**	**4.30**	**30.5 (5.1)**	**25.1**	**753 (94)**	**12.1 (1.4)**
Pith	6.24 (0.88)	4.71	30.4 (4.2)	25.3	768 (94)	11.8 (1.4)
No Pith	6.66 (2.07)	4.30	30.5 (6.2)	24.6	730 (91)	12.3 (1.5)
Knots	**5.04 (1.04)**	**3.38**	**26.0 (4.6)**	**19.4**	**746 (117)**	**11.6 (1.7)**
Pith	4.89 (0.73)	3.79	25.7 (2.7)	21.9	771 (115)	10.7 (1.7)
No Pith	5.07 (1.21)	3.50	26.3 (5.4)	15.4	734 (118)	12.3 (1.4)
CPerpG						
Clear	**0.27 (0.06)**	**0.18**	**6.7 (1.7)**	**4.5**	**494 (30)**	**11.9 (1.6)**
Pith	0.29 (0.06)	0.21	7.61 (1.6)	5.3	498 (32)	10.7 (1.3)
No Pith	0.26 (0.06)	0.17	6.28 (1.6)	4.6	491 (29)	12.6 (1.3)
Resin	**0.31 (0.07)**	**0.19**	**7.8 (1.6)**	**5.5**	**710 (89)**	**11.3 (1.5)**
Pith	0.29 (0.09)	0.16	8.1 (2.1)	5.1	764 (96)	11.2 (1.6)
No Pith	0.32 (0.06)	0.24	7.6 (1.0)	6.4	668 (57)	11.3 (1.5)
Knots	**0.42 (0.11)**	**0.27**	**13.1 (3.4)**	**9.5**	**718 (116)**	**11.7 (1.8)**
Pith	0.35 (0.07)	0.26	12.3 (2.5)	9.5	758 (104)	11.7 (2.1)
No Pith	0.46 (0.11)	0.29	13.7 (3.9)	10.0	690 (117)	11.7 (1.6)
Shear						
Clear	**0.59 (0.06)**	**0.51**	**5.7 (0.5)**	**5.1**	**499 (23)**	**12.9 (1.3)**
Pith	0.58 (0.05)	0.51	5.6 (0.4)	5.1	499 (25)	12.7 (1.4)
No Pith	0.60 (0.06)	0.52	5.9 (0.5)	5.1	499 (22)	13.0 (1.3)
Resin	**0.58 (0.06)**	**0.49**	**5.6 (0.8)**	**4.3**	**750 (86)**	**13.0 (1.0)**
Pith	0.58 (0.06)	0.50	5.6 (1.0)	4.2	758 (92)	13.0 (1.0)
No Pith	0.57 (0.06)	0.50	5.6 (0.8)	4.3	742 (83)	13.0 (1.0)
Knots	**0.54 (0.09)**	**0.41**	**5.2 (0.8)**	**3.7**	**720 (78)**	**12.6 (1.3)**
Pith	0.53 (0.09)	0.43	5.1 (0.9)	3.7	741 (61)	12.7 (1.3)
No Pith	0.55 (0.09)	0.40	5.3 (0.8)	4.1	696 (89)	12.6 (1.5)
Tension						
Clear			**32.4 (2.7)**	**28.1**	**528 (54)**	**11.9 (1.6)**
Pith			32.1 (2.6)	28.5	549 (39)	11.4 (1.8)
No Pith			32.7 (3.0)	29.3	511 (62)	12.4 (1.4)
Resin			**32.6 (3.8)**	**28.6**	**720 (66)**	**11.9 (1.2)**
Pith			33.1 (4.7)	28.7	724 (50)	11.8 (1.4)
No Pith			31.9 (2.4)	29.4	715 (93)	12.1 (1.1)
Knots			**15.7 (4.1)**	**10.1**	**635 (95)**	**12.1 (1.6)**
Pith			15.4 (4.3)	9.5	636 (95)	12.1 (1.6)
No Pith			16.4 (3.7)	11.6	634 (98)	12.1 (1.6)

Note: Values in () are standard deviation.

5. Discussions

This section discusses the mechanical properties and ratio to bending MOE as an indicator property and compares these to other PEExPCH hybrid pines, other young, low-grade and population averages of similar pines. It also analyses the failure behaviour and difference between structural performance of clear, resin, knots and pith samples of out-of-grade PEExPCH hybrid pine for each of the tests performed. Finally, it will establish the density relationship and the MOE and strength relationship for each test type.

A direct comparison between the relative performance of the out-of-grade PEExPCH and other studies and similar species is presented in Table 3. Such comparisons can be misleading because of the variation between and within trees, so the portion of the population studied needs to be taken into consideration. This study looks at the out-of-grade

portion of 31-year-old plantation-grown PEExPCH trees which contains a high content of juvenile and corewood. Table 3 also contains data from studies on PEExPCH hybrids, data from studies of comparable populations of juvenile or low-grade timber of similar pines and data from population averages of other similar pines not focused on juvenile wood or young trees.

Table 3. Average properties for similar species of pines and their ratios to bending MOE.

	Bending MOE E_b (Gpa)	CParG MOE $E_{c,0}$ (Gpa)	CPerpG MOE $E_{c,90}$ (Gpa)	Shear Modulus G_0 (Gpa)	Bending Strength f_b (Mpa)	CParG Strength $f_{c,0}$ (Mpa)	CPerpG Strength $f_{c,90}$ (Mpa)	Shear Strength $f_{v,0}$ (Mpa)	Tensile Strength $f_{t,0}$ (Mpa)	Density (kg/m³)	Comment
1. This Study—PEExPCH											
Clear	6.90	5.78 (0.8377)	0.274 (0.0397)	0.590 (0.0855)	45.8 (0.0066)	29.4 (0.0043)	6.7 (0.0010)	5.7 (0.0008)	32.4 (0.0047)	498 (0.0722)	
Resin	6.94	6.37 (0.9232)	0.307 (0.0445)	0.580 (0.0841)	45.7 (0.0066)	30.5 (0.0044)	7.8 (0.0011)	5.6 (0.0008)	32.6 (0.0047)	721 (0.1045)	
Knots	5.37	5.04 (0.9385)	0.422 (0.0786)	0.535 (0.0996)	26.7 (0.0050)	26.0 (0.0048)	13.1 (0.0024)	5.2 (0.0010)	15.7 (0.0029)	708 (0.1320)	
2. Other studies—PEExPCH Hybrid											
Bragg, 1990 [41]	8.17				33.10 (0.0041)					497.00 (0.0609)	19 years—70 × 35 mm
Harding et al., 2008 [41]	7.26				42.36 (0.0058)						6.8 years—70 × 35 mm
Nel et al., 2017 [2]	5.65				30.00 (0.0053)					479.00 (0.0847)	15 to 19 years—38 × 152 mm
Wessels, Dowse, and Smit, 2011 [27]	4.04				13.4 5th %ile					386.50 (0.0958)	10 years 35 × 110 mm
3. Other similar pines—similar timber characteristics											
Slash and Loblolly Moya et al., 2013 [42]	7.20				62.40 (0.0087)	33.70 (0.0047)	9.70 (0.0013)	9.00 (0.0013)		477.00 (0.0663)	25 years old
Slash and Loblolly Moya et al., 2013 [42]	4.95				44.50 (0.0090)	24.60 (0.0050)	7.10 (0.0014)	7.60 (0.0015)		393.00 (0.0793)	15 years old
Loblolly Kretschmann and Bendtsen, 1992 [43]	6.15								18.90 (0.0031)		Juvenile wood
Southern Yellow Pines Doyle and Markwardt, 1967 [37]	9.83	10.18 (1.0356)		0.920 (0.0939)	39.00 (0.0040)	28.68 (0.0029)	11.90 (0.0012)		9.17 (0.0009)	520.00 (0.0529)	50 × 100 mm Grade 3
Radiata Franke and Quenneville, 2013 [44]	8.00		0.52 (0.0644)				9.90 (0.0012)			496.00 (0.0620)	MSG8 Grade
4. Other similar pines—average values for species population											
Caribbea Forest Products Laboratory, 2010 [36]	15.40				115.10 (0.0075)	58.90 (0.0038)		14.40 (0.0009)		680.00 (0.0442)	average population

Slash Bolza and Kloot, 1963 [45]	9.45	11.79 (1.2481)			75.15 (0.0080)	41.58 (0.0044)	10.10 (0.0011)	9.79 (0.0010)		506.00 (0.0536)	average population
Slash Forest Products Laboratory, 2010 [36]	13.70		0.82 (0.0595)	(1.19)	112.00 (0.0082)	56.00 (0.0041)	7.00 (0.0005)	11.60 (0.0008)		590.00 (0.0431)	average population
Loblolly Forest Products Laboratory, 2010 [36]	12.30		1.17 (0.0955)	(0.81)	88.00 (0.0072)	49.20 (0.0040)	5.40 (0.0004)		80.00 (0.0065)	510.00 (0.0415)	average population
Loblolly Bolza and Kloot, 1963 [45]	7.24	8.48 (1.1716)			64.60 (0.0089)	35.70 (0.0049)	8.68 (0.0012)	9.48 (0.0013)		482.00 (0.0666)	average population
Radiata Bolza and Kloot, 1963 [45]	10.20	11.38 (1.1149)			80.70 (0.0079)	41.92 (0.0041)	9.93 (0.0010)	11.03 (0.0011)		525.00 (0.0515)	average population

Note: Values in () are ratio of average of property to average bending MOE.

A reduction in mechanical properties is generally accompanied by a reduction in bending MOE [36]. Bending MOE is often used as an indicator property to predict other properties of timber; so, a ratio between average properties and bending MOE can be used to give insight into relative performance between these different populations of timber. These ratios have been included in brackets in Table 3.

5.1. Bending

5.1.1. Failure Behaviour

All bending samples showed linear-elastic behaviour up to brittle failure and all but two specimens failed between the loading points. Figure 8 shows some typical failures whereby the majority of the cross section failed under tension after initial compression failures in the top of the sample. The majority of knot samples failed in deviated grain around the knot.

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

Figure 8. Some typical bending failure examples in (**a**) clear, (**b**) resin and (**c**) knots.

5.1.2. Structural Performance

The bending MOE of the clear samples is mid-range and within 10% of the average of other PEExPCH hybrids and young or low-grade similar pines. At 39% lower than population averages of similar pine (Table 3), the bending MOE is within the expected ratio range of 0.45 to 0.75 of juvenile to mature wood [36]. The bending strength of clear samples is high and similar to many of the average populations of similar species but besides pith, these are defect-free and the knot samples performed poorly in comparison. Nel, et al. [2] found that boards cut from the core of the PEExPCH hybrid had lower bending MOE and strength than their parent species and attributed this to both fast diameter growth and less density variation across the core. However, Moya, et al. [42] found the young wood

in slash can have lower bending MOE performance. The grading process would have removed any higher-performing pieces from the population in this study keeping the structural properties low, but the results of Wessels, et al. [27] and Nel, et al. [2] demonstrate that these hybrids can have even lower performance in bending MOE and strength. This must be taken into consideration when looking to use this out-of-grade PEExPCH hybrid in building systems. The results of the bending MOE and strength tests are reported in Table 2 and illustrated in Figure 9.

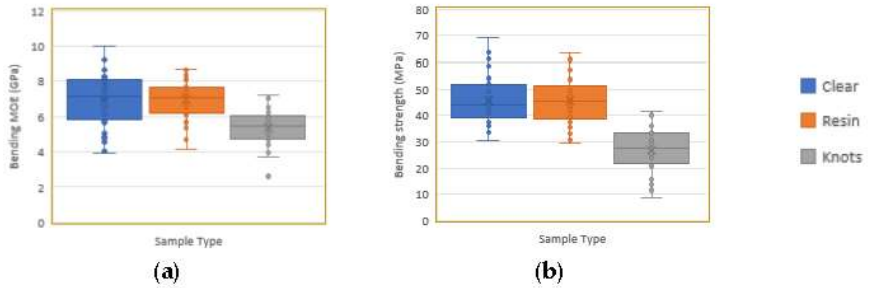


Figure 9. Box plots of (**a**) Bending MOE and (**b**) bending strength.

The MOR/bending MOE ratio for clear samples are high compared to other studies of young PEExPCH hybrid at 31% more on average, but this can be explained by the lack of knots and other defects in the clear sample set. The knot samples still performed well and are within 2% of the average. On the other hand, the MOR/bending MOE ratio is low compared to young or low-grade and population averages and of other similar pines at 8% and 17% less, respectively. As PEExPCH is limited by bending stiffness rather than strength in achieving grade [2,27,29], this low ratio for the PEExPCH studies could be seen as a positive result because this indicates that the strength and stiffness are closer aligned with grading cut-offs. Conversely, it shows that that the young and out-of-grade population of these hybrids do not offer the advantage of high MOR compared to MOE performance compared to other pines.

5.1.3. Effect of Resin

Compared to clear samples, resin had little effect for bending performance with no significant differences for MOE (p = 0.89) or strength (p = 0.92). With an average RAR of 0.46 (0.45 median), the resins are on average 0.6% higher (−1.2% median) and 0.4% lower (+3.4% median) than clear bending MOE and strength, respectively. Studies on other species also found little to no difference between the bending performance of wood with and without extractives [35,46–48] with the exception of Garcia-Iruela, et al. [35], who reported a 14% higher bending strength for resinous wood. The bending failure behaviour of timber which is initiated by its low-relative-compression properties [49] indicates that an increase in compression properties would increase bending performance. While it is later shown that resinous timber did perform better slightly in CParG MOE than clear, its impact would depend on the location of the resin within the wood structure [35] and of the resinous wood in the cross section of the bending sample. All resin-bending samples had resinous wood extending across both the tensile and compressive sides of the sample cross section. Even the samples with very high resin content showed no superior bending performance and Figure 10 shows there is no clear trend or relationship between increasing RAR and bending MOE or strength.

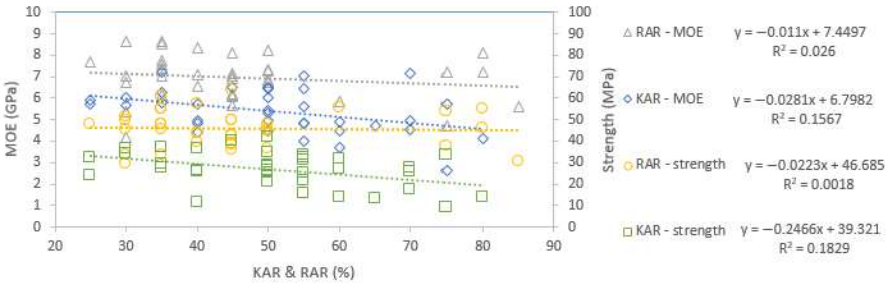


Figure 10. KAR and RAR vs. bending MOE and strength.

5.1.4. Effect of Knots

Knots had an average KAR of 0.51 (0.5 median) and were significantly different to the clear samples for bending MOE ($p < 0.001$) and strength ($p < 0.001$) with averages of 22.5% (23.1% median) and 41.6% (39.4% median) less, respectively (Figure 9 and Table 2). This is similar to reductions for KAR of 0.5 on-flat bending seen in Samson and Blanchet [50] but less than that seen for on-edge bending [51,52] which is reasonable given others have found knots to have less impact in on-flat bending [50,53]. Figure 10 shows that there is a decreasing trend for MOE and strength with increasing KAR but KAR alone was not a strong indicator with low R^2 values. The rate of change in MOE and strength with increasing KAR is low at around 45% and 20% less, respectively, than others in the literature [50–52]. This can be expected given these other studies looked at higher-longitudinal-stiffness timber which has a greater difference between longitudinal and transverse properties. Moreover, the knot type and shape near the pith are different to knots occurring in outer wood. They are more likely to be in combination with the grain deviating throughout multiple smaller conical-shaped and high-angled knots connecting with or near the pith rather than large grain deviations around large cylindrical-shaped single knots found in outer wood. Additional research is needed to obtain a more in-depth understanding of these unique characteristics and geometry of corewood knots, and to understand their impact on bending in more detail.

5.1.5. Effect of Pith

Separating the pith from the no-pith showed a significant difference for clear and resin samples in both MOE and strength but no significant difference for knot samples. Clear with pith is on average 17.7% (−18.5% median) lower in MOE ($p = 0.018$) and 12.4% (−15.4% median) lower in strength ($p = 0.031$). Resin with pith is on average 14.8% (−14.5% median) lower in MOE ($p = 0.008$) and 13.8% (−20.0% median) lower in strength ($p = 0.043$). Knots with pith are on average 4.0% (+5.8% median) higher in MOE ($p = 0.575$) and 1.8% (+4.3% median) in strength ($p = 0.875$) (Figure 11 and Table 2). This reduction in clear and resin samples can be expected given the change in cell structure the further from the pith, but it is interesting to see the sensitivity given all these samples were near the pith. The knots on the other hand had almost no difference, showing that knots are the governing factor for reduced structural performance in bending and have more negative impact on strength than MOE.

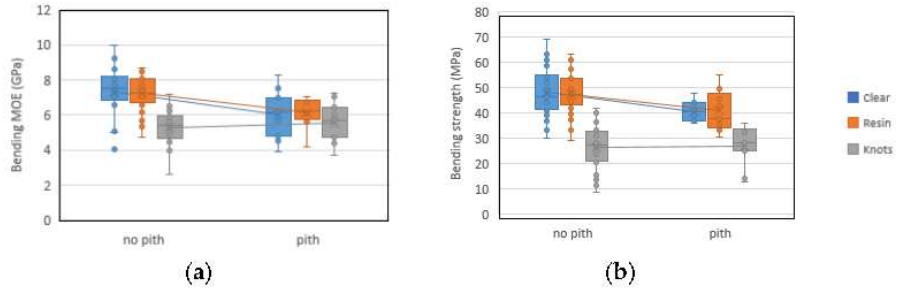


Figure 11. Box plots of bending properties with and without pith—(**a**) MOE and (**b**) strength.

5.1.6. Relationship of Density and Bending Properties

There is no clear relationship between density and bending MOE or strength with all sample types having low R^2 values (<0.1). At the average population level, the relationships presented by Doyle and Markwardt [54] were similar for clear samples but overpredicted the bending properties of resin and knots. Relationships given by Forest Products Laboratory [36] for bending MOE and MORE overestimated all sample types, showing that out-of-grade PEExPCH has high density relative to bending performance. Moreover, the density to bending relationships for juvenile wood have proven to be different and more variable than mature wood in other studies [55]. The low stiffness and variability in juvenile wood, high density of compression wood and presence of resin would not have been accounted for in these models and would contribute to some of the difference.

5.1.7. Relationship of Bending MOE and Strength

Bending MOE is a good indicator for bending strength describing 63% of strength for all sample types combined. However, as can be seen in Figure 12, this relationship improved R^2 to 71% when pith samples were removed. The results also show that this relationship is as good an indicator for knots as it is for clear timber but knots had strengths on average 24% lower for equivalent MOE. Comparing this to other research shows the R^2 values are similar [17]. As expected, the clear and resin out-of-grade PEExPCH being defect-free are strong in bending, achieving up to 40% higher strengths for the equivalent bending MOE values than southern yellow pine lumber in a study by Doyle and Markwardt [54], whereas the knots had a similar relationship.

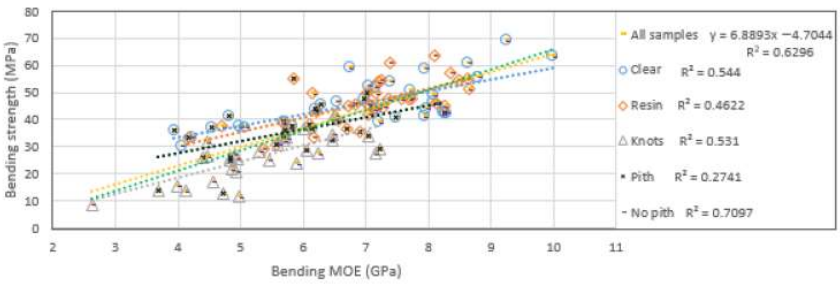


Figure 12. Relationship of bending MOE and strength.

5.2. Compression Parallel to Grain

5.2.1. Failure Behaviour

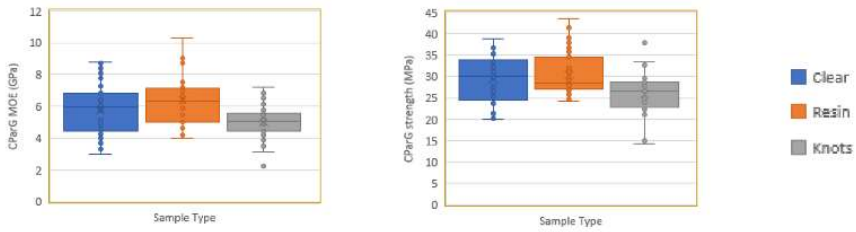
CParG failures were ductile and showed a region of linear elastic behaviour followed by slowing and then reduction in load resistance. This aligns with the typical stages of failure described in the literature [56]. Shear failure was the most common failure type and knots typically failed in the deviated grain surrounding the knot (Figure 13).

(a) (b) (c)

Figure 13. Some typical CParG failure examples in (**a**) clear, (**b**) resin and (**c**) knots.

5.2.2. Structural Performance

The CParG MOE is low compared to both low-grade and average populations of similar pines. The clear samples are 43% lower than Grade 3 southern yellow pines [54] and 45% lower than population averages of slash, loblolly and radiata [45]. CParG strength fell midrange with clear sample results within 3% of Grade 3 southern yellow pines [54] and 19% higher than 15-year-old slash and loblolly [42]; however, it was low compared to the population averages which were 37% higher on average (Table 3). The results of CParG MOE and strength test are reported in Table 2 and illustrated in Figure 14.



(a) (b)

Figure 14. Box plots of CParG properties (**a**) MOE and (**b**) strength.

The CParG MOE/bending MOE ratios of clear are low compared to other young or low-grade and average populations of similar pines at 19% and 29% less, respectively, meaning they do not have high CParG MOE for their bending MOE. Knot samples are also low at 9% and 20% less, respectively. Being under parity shows that this resource does not comply with the common assumption that CParG MOE is equivalent to bending MOE [57] and confirms using bending MOE as tensile MOE is a conservative option. Investigation into other research revealed that CParG MOE for pines can be less than bending MOE [25,44,58] but not always [45,54,59]. The CParG strength/MOE ratios of clear are mid-range and within 1% of other young or low-grade and average populations of similar pines; however, knots sample are on average 15% higher. These results show that knots have more negative impact on bending MOE than they do on CParG strength and MOE which may be explained by the high compression wood content of juvenile wood and wood surrounding knots which is known to have higher CParG strengths than normal wood [60].

5.2.3. Effect of Resin

Compared to clear, resin samples showed an increase for MOE but minimal difference for strength and neither of these increases were significant (MOE $p = 0.13$, strength $p = 0.41$). With an average RAR of 0.65 (0.65 median), resin had the highest average performance achieving on average 10% (+6.4% median) and 3.6% (−5.2% median) higher CParG average MOE and strength than clear (Figure 14 and Table 2). Extractives provide reinforcement from within the cell walls and lumen and resist buckling failure which occurs

in the secondary walls of the microfibrils causing out-of-plane bulging deformation followed by shear or kinked bands [32]; so, an increase in performance due to resin could reasonably be expected. Grabner, et al. [34] also found little difference for MOE or strength in larch and found no correlation between increasing CParG properties and extractive content, while others did find strength increased by 16% [35,47]. Ajuong and Breese [61] and Hernandez [62] found extractives within the cell wall rather than within the lumen provided the benefit. Contradicting this, Garcia-Iruela, et al. [35] proposed resin-filled cell lumen had the higher impact over cell wall and stated that the different resin location in the wood structure was the reason for discrepancies between studies. Despite the higher MOE values for resin samples, this higher performance due to resin-filled cell lumen is not evident in Figure 15, which shows no clear trend or correlation between increasing RAR and MOR or strength.

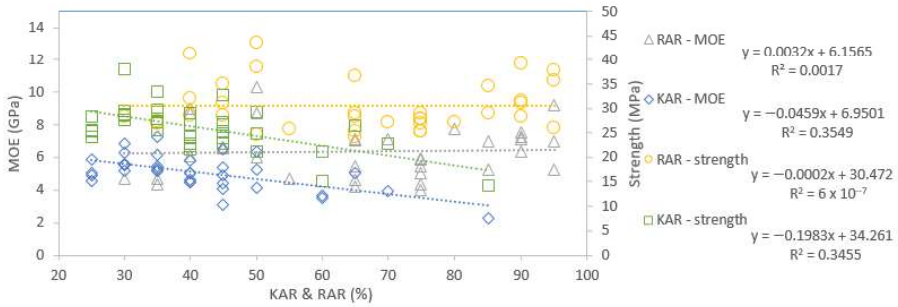


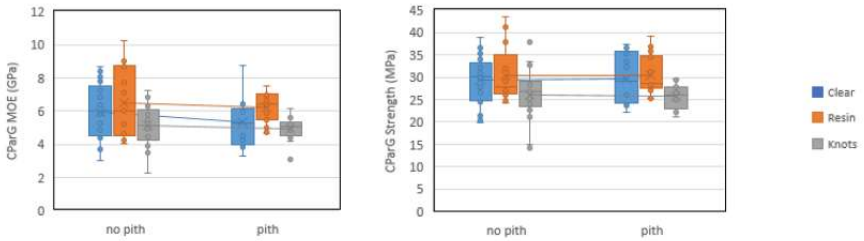
Figure 15. KAR and RAR vs. CParG MOE and strength.

5.2.4. Effect of Knots

Knots had an average KAR of 0.42 (0.40 median) and were significantly different to the clear samples for CPar MOE ($p < 0.027$) and strength ($p < 0.007$) with on average 13.0% (−15.2% median) and 11.6% (−11.4% median) less, respectively (Figure 14 and Table 2). This difference is less than that found by As, et al. [51] for Scots pine at 24%. The grain deviation and disruption associated with knots causes a transition into perpendicular to grain and shear stresses for which timber has much lower performance. Benabou [56] found that shear yield strength and local fibre misalignment were the main influences on CParG strengths. The smaller impact of knots found in this study can be explained by the knot characteristics near the pith being in combination with grain deviating throughout the knot cluster offering more parallel to grain support, the smaller difference between longitudinal and transverse properties and the presence of resin streaking, which is later seen to improve perpendicular to grain performance. Figure 15 shows that KAR is a moderate indicator of the decreasing trend for MOE and strength with increasing KAR.

5.2.5. Effect of Pith

Separating the pith from no-pith samples showed no significant difference for MOE or strength for clear, resin or knots. As seen in Figure 16 and Table 2, clear with pith is 10.7% (−12.2% median) lower in MOE ($p = 0.313$) and 1.1% (−2.8% median) higher in strength ($p = 0.885$) than no pith. Resin with pith is on average 6.3% (−1.5%) lower in MOE ($p = 2.079$) and 0.1% (+3.3% median) lower in strength ($p = 0.976$) than no pith. Knots with pith are on average 3.5% (−1.1% median) lower in MOE ($p = 0.534$) and 2.1% (−3.1% median) than strength ($p = 0.797$) than no pith.



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

Figure 16. Box plots of CParG properties with and without pith—(**a**) MOE and (**b**) strength.

5.2.6. Relationship of Density and CParG

Density is a poor indicator of CParG properties with R^2 values less than 0.23 and lowest for resin at less than 0.03. While clear showed an increasing trend, knots decreased and resin showed minimal change. Relationships between density and CParG properties published in the literature for softwoods [36,54] overpredicted the CParG MOE and strength for all sample types, showing this resource has high density relative to CParG properties which, as with bending properties, is likely linked to the presence of juvenile wood, compression wood and resin.

5.2.7. Relationship of CParG MOE and Strength

CParG MOE is a good indicator for CParG strength describing 70% of strength for all sample types combined, as can be seen in Figure 17. While this relationship is similar to Doyle and Markwardt [54] for small clears, it shows higher strengths for equivalent MOE compared to southern pine lumber. All sample types have similar trends in strength for equivalent MOE values.

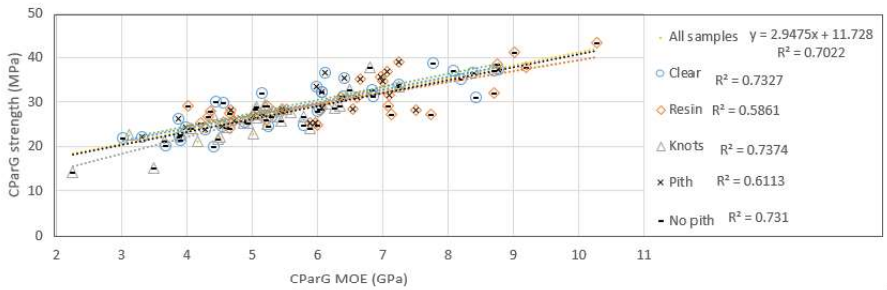
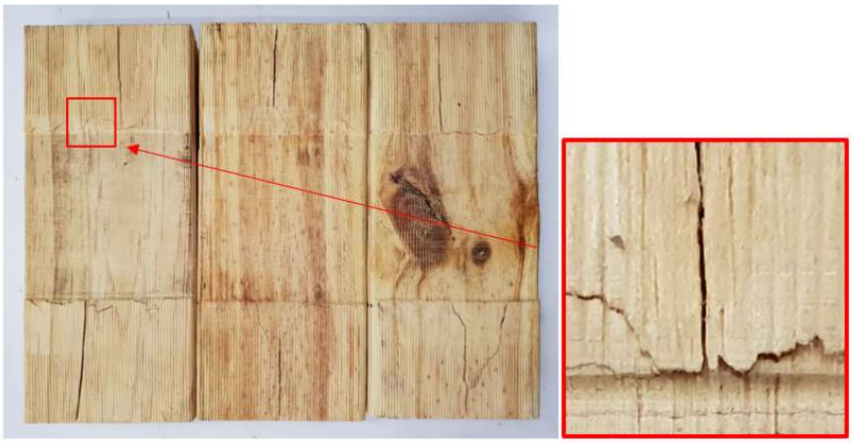


Figure 17. Relationship of CParG MOE and strength.

5.3. Compression Perpendicular to Grain

5.3.1. Failure Behaviour

CPerpG failures were typically ductile and showed a region of linear elastic behaviour followed by a slow but still increasing load resistance. Failure examples can be seen in Figure 18. Densification occurred under the load plates and shearing occurred in the cells along their edges. Longitudinal radial cracking was common and resin squeezed out of some knot and resin samples. All test samples failed for strength at 10% deformation before reaching ultimate failure load.

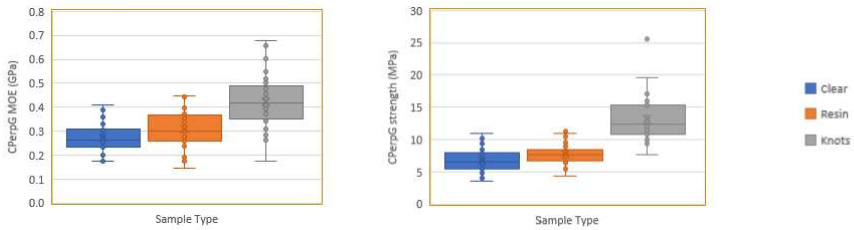


(**a**) (**b**) (**c**) (**d**)

Figure 18. Some typical CPerpG failures in (**a**) clear, (**b**) resin and (**c**) knots (**d**) shows shearing failure at edge of plates.

5.3.2. Structural Performance

The CPerpG MOE is low compared to other similar pines. Clear samples are on average 47% less in CPerpG MOE than low-grade radiata [44] and 67% lower than slash pine [45]. CPerpG strength of clear samples is low compared to other young and lo- grade and mid-range compared to average populations of similar pines (Table 3). Knot samples achieved the highest performance. Interestingly, the examples in Table 3 of young and low-grade in Section 3 performed as well as and better than the average populations of similar pines in Section 4 for CPerpG strength. The MOE and strength in CPerpG are reported in Table 2 and illustrated in Figure 19.



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

Figure 19. Box Plots of (**a**) CPerpG MOE and (**b**) CPerpG strength.

The CPerpG MOE/bending MOE ratios of clear samples are low compared to other young or low-grade and average populations of similar pines at 38% and 49% less, respectively, meaning this resource does not have good CPerpG MOE relative to its bending MOE. Knot samples on the other hand do have good performance with 22% and 1% higher, respectively. This higher knot performance can be explained by the deviated grain around knots and the branch wood providing some resistance in the direction of the load. There are limited data available in the literature for CPerpG MOE and an alternative is to use the relationship of CPerpG MOE/longitudinal MOE = 1/30 [63,64]. Longitudinal MOE is approximately 10% higher than bending MOE [36] and using this model, the clear samples in this study performed 8% higher in CPerpG MOE than the model predicted; however, comparing results of other studies, this model is consistently conservative.

The CPerpG strength/bending MOE ratio for clear samples is low compared to young or low-grade similar pines at 24% lower, but is mid-range and 16% higher than population averages of similar species. Knots with their deviated grain and branch wood offering

support in the load direction were 91% and 190% higher, respectively. CPerpG strength ratio seen in this and other studies support the theory that the high microfibril angle of juvenile wood is important for transverse direction mechanical properties [18] with young and low-grade fibre showing better performance relative to bending MOE. It must be taken into consideration that some of these studies use different test methods for CPerpG property measurement and that these variations are known to give different results [44,65,66].

5.3.3. Effect of Resin

Comparing clear and resin samples shows a significant difference for both MOE (p = 0.04) and strength (p = 0.009). With an average RAR of 0.6 (0.6 median), resin achieved on average 12.2% (13.2% median) and 15.8% (17.4% median) higher CPerpG average MOE and strength than clear (Figure 19 and Table 2). This is less than that seen by Grabner, et al. [34] where performance reached as high as double that of extracted larch but their sample size was very small. Despite these higher MOE and strength values, Figure 20 shows no clear trend or correlation between increasing RAR and increasing MOE or strength. Extractives provide reinforcement from within the cell walls and lumen [35] to resist failure which initiates as cell wall buckling at the weakest cells with the thinnest walls and largest lumen [67]. Not all lumen are inundated with resin and Grabner, et al. [34] found that it was the empty tracheids that limited CPerpG strength implying the resin filled lumen provide more support, so without continuity of the resin-filled lumen, their benefit is diminished. Nonetheless, Hernandez [62] found that extractives within the cell lumen do not contribute to variation seen in CPerpG properties. The theory of empty tracheids limiting CPerpG strength would help explain the lack of relationship between RAR and CPerpG performance while cell wall resin providing resistance to crushing would explain the higher results in the resin samples; however, further studies are required.

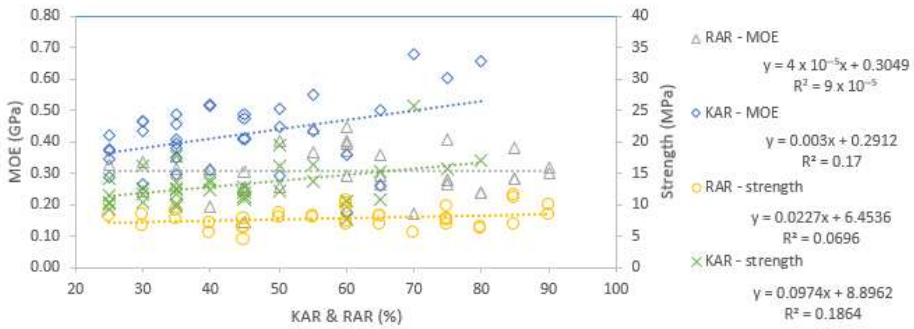


Figure 20. KAR and RAR vs. CPerpG MOE and strength.

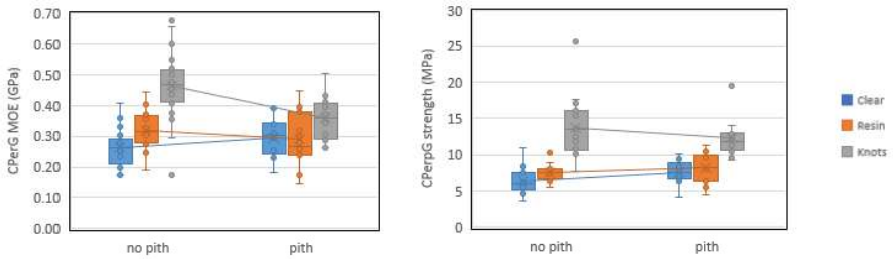
5.3.4. Effect of Knots

Knots had an average KAR of 44% (40% median) and were significantly different to clear samples for MOE (p < 0.001) and strength (p < 0.001). Knots achieved high performance with 54.1% (58.0% median) and 94.9% (88.5% median) higher average MOE and strengths compared to clear (Figure 19 and Table 2). Figure 20 shows there is an increasing trend for MOE and strength with increasing KAR but the R^2 values are low at less than 0.2. The variations in knot shapes and geometry would help explain this low correlation.

5.3.5. Effect of Pith

Separating the pith from no-pith samples in Figure 21 and Table 2 showed a mix of higher and lower performance. Clear samples with pith are on average 12.6% (+15.5% median) higher in MOE but not significantly different (p = 0.141.) and on average 21.2%

(+24.2% median) higher in strength which is significantly different (p = 0.027). Resin samples with pith are on average 9.4% (−14.9% median) lower in MOE and 7.8% (+8.1% median) higher in strength, neither of which are significantly different (p = 0.231 MOE and p = 0.291 strength). There is much less latewood than earlywood in corewood, but with its smaller cell lumen and thicker cell walls, latewood resists buckling and crushing failure more than early wood [67]. The tighter radius growth rings in the pith samples contribute to the higher strength in clear and resin samples because the latewood acts as a pillar and protects the weaker earlywood from crushing [68] and from dependence on rolling shear properties which are weaker than CPerpG properties [36]. Kijidani, et al. [69] also found higher CPerpG strength values for pith samples in Sugi wood and although they could not conclude the reason, they did find correlations with high microfibril angle, increased density in the pith samples as well as cellular structure. The density for pith samples in this study is also consistently higher than non-pith samples (Table 2). Knots with pith are on average 23.1% (−22.7% median) less in MOE than without pith and significantly different (p = 0.003) and 10.8% (−12.6% median) less in strength and not significantly different (p = 0.217). This decrease in performance in knot samples with pith is potentially associated with the connection of the conical-shaped knot wood spearing into the weak pith.



(a) **(b)**

Figure 21. Box plots of CPerpG properties with and without pith—(**a**) MOE and (**b**) strength.

5.3.6. Relationship of Density and CPerpG

Density was a better indicator of increasing CPerpG strength than CPerpG MOE. When all sample types are combined, the R^2 is 0.31 for strength while for clear, resin and knots individually, R^2 values range between 0.17 and 0.22. The R^2 for MOE are low and range between 0.002 and 0.19. The relationship between density and CPerpG strength for softwoods by Forest Products Laboratory [36] overpredicted the CPerpG strength for all sample types showing this resource has high density relative to CPerpG strength. There is an increasing trend in MOE with increased density for clear but no obvious trend can be seen in resin and knot samples, whereas all samples types show an increase in strength. At their average densities, clear and knot samples were 20% and 30% higher, respectively, in strength than the density/CPerpG strength relationships given by Forest Products Laboratory [36]. Resin was 20% lower.

5.3.7. Relationship of CPerpG MOE and Strength

CPerpG MOE is a good indicator and describes 70% of CPerpG strength when all sample types are combined as can be seen in Figure 22. The no-pith samples have the strongest correlation between MOE and strength with R^2 of 0.80. All sample types increase in CPerpG strength with increasing MOE.

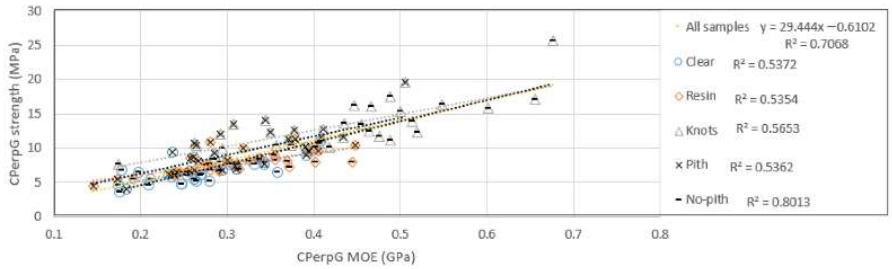


Figure 22. Relationship of CPerpG MOE and strength.

5.4. Shear

5.4.1. Failure Behaviour

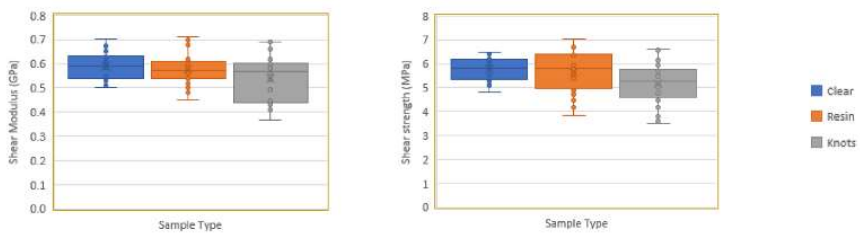
The shear samples showed linear elastic behaviour up to brittle failure. Typical shear failures are shown in Figure 23. Separation at the transition between early and latewood was frequently observed. Li, et al. [70] also described this as one of the major failures for shear in Larix kaemferi. Pith was exposed in the shear failure plane of all samples that contained pith showing its poor strength in longitudinal shear. This may also be associated with the wood rays that radiate out from the pith and are known to be structural weak points [71].

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

Figure 23. Some typical shear failures in (**a**) clear, (**b**) resin and (**c**) knots.

5.4.2. Structural Performance

The shear modulus and shear strength are both low compared to young, low-grade and average populations of similar pines. Clear samples are on average 36% less than grade 3 Southern Yellow Pines [54] in shear modulus. Clear samples are 31% less on average than the young slash and loblolly [42] and 49% less on average that average populations of similar pines in shear strength (Table 3). The results of the shear modulus and shear strength tests are reported in Table 2 and illustrated in Figure 24.



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

Figure 24. Box plots of (**a**) Shear modulus and (**b**) shear strength.

The shear modulus/bending MOE ratio for clear samples is within the lower range compared to other similar pines at 9% lower than Grade 3 southern yellow pine found by Doyle and Markwardt [37], 27% less than the average population of slash but similar to the average loblolly population at 4.9% higher [36]. There are few data available for shear modulus of similar pines and an alternative option is to use the relationship of shear modulus/bending MOE = 1/15 [12]. Compared to this model, this resource is 26% higher in shear modulus relative to bending MOE and knots are 49% higher showing knots have a higher impact on bending MOE than shear modulus. The shear strength/bending MOE ratio of clear samples is low at 40% and 18% less than young and low-grade and population averages of similar species, respectively, but still within the range seen in these populations. Knots performed slightly better at 31% and 5% less, respectively. These results do not confirm those of Xavier, et al. [72] who found good shear modulus performance in the corewood zone and Muller, et al. [73] who found high MFA and compression wood in corewood increased shear modulus and shear strength.

5.4.3. Effect of Resin

Comparing clear and resin samples shows there were no significant differences for shear modulus ($p = 0.467$) or shear strength ($p = 0.402$). With an average RAR of 0.59 (0.58 median), resin is on average 1.8% (−2.6% median) less in shear modulus and 2.6% (+0.3% median) less in shear strength than clear. Figure 25 shows no clear trend or correlation between increasing RAR and increasing shear modulus or shear strength. Li, et al. [70] found shear strain occurred in the earlywood which led to a majority of shear failures within the earlywood zone. They found density, MFA and cell wall thickness were highly influential and that earlywood failed by the tearing of the cell walls in the direction of the microfibril angle, whereas latewood shear failure was between the cells. Keunecke, et al. [74] predicted that extractives would improve shear properties; however, the results of this study do not show this. Nevertheless, the lower 5th percentile and higher standard deviation (Table 2) of shear strength in resin samples compared to clear may indicate the presence of undetected damaged fibre in the form of shake within the samples. Shake is often associated with resin streaking and is well known to reduce shear performance [75].

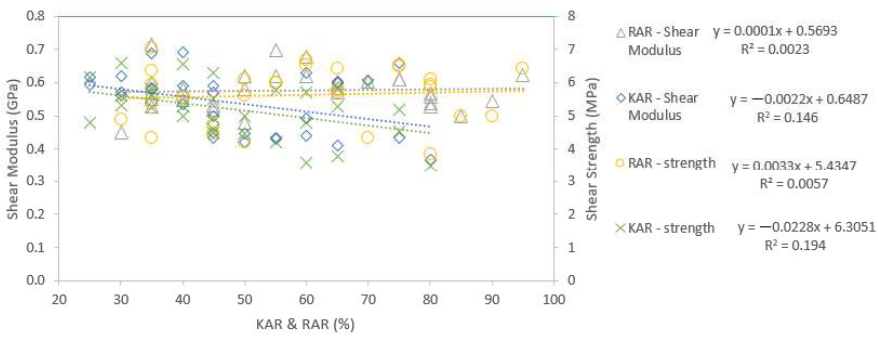


Figure 25. KAR and RAR vs. Shear Modulus and shear strength.

5.4.4. Effect of Knots

Comparing clear and knot samples shows a significant difference for both shear modulus ($p = 0.012$) and shear strength ($p = 0.001$). Knots had an average KAR of 0.49 (0.45 median) and are on average 8.5% (−3.4% median) less and 10.3% (−9.3% median) less than clear shear moduli and shear strength, respectively. Figure 25 shows there is a decreasing trend between KAR and shear modulus and shear strength but the R^2 values are low at less than 0.2. This low correlation may be attributed to the variation in knot characteristics. Doyle and Markwardt [37] found little difference in shear modulus between different grades containing various defects including knots. Chui [76], Gupta, et al. [77], Rajput, et

al. [78] and Cao, et al. [79] all found knots could have a negative or positive impact on structural performance depending on the characteristics of the knot. Gupta, et al. [77] concluded that the difference in shear strength due to a knot is not significant. In these studies, sound knots tended to be higher and unsound knots lower in shear modulus and shear strength when compared to clear defect-free timber. These studies focused on through knots that had face-to-face branch wood which is a hard and brittle material which provides shear resistance through the sample [76]. The corewood researched in this study has conical-shaped knots often occurring as knot clusters and connecting to the pith within the samples at high angles (Figure 23). These characteristics would mean knots in corewood would not necessarily provide the benefit of this face-to-face continuity and shear support. Cao, et al. [79] found that branch wood pith was weak in shear and was often where cracks occurred. The high angle of the knots in this resource place the weak pith of branch wood as well as the branch to trunk transition zone closer aligned to that of the log pith and to the alignment with the shear plane. This resulted in frequent shear failure planes through the pith of the log, pith of the branch wood and at the connection of branch to pith as seen in Figure 23. This helps explain the lower performance of knots compared to clear samples seen in this study.

5.4.5. Effect of Pith

Separating the pith from the no-pith samples in Figure 26 showed no significant differences for clear (p = 0.870 shear modulus and p = 0.051 shear strength), resin (p = 0.727 shear modulus and p = 0.905 shear strength) or knots (p = 0.456 shear modulus and p = 0.405 shear strength). Clear with pith is on average 2.5% (−0.4% median) less and 3.8% (−8.6% median) less than clear without pith in shear modulus and shear strength, respectively. Resin with pith is on average 1.4% (+6.4% median) higher and 0.7% (+4.9% median) less in shear modulus and shear strength and knots with pith are on average 4.6% (−7.4% median) less and 4.8% (−8.0% median) less in shear modulus and shear strength, respectively, than without pith.

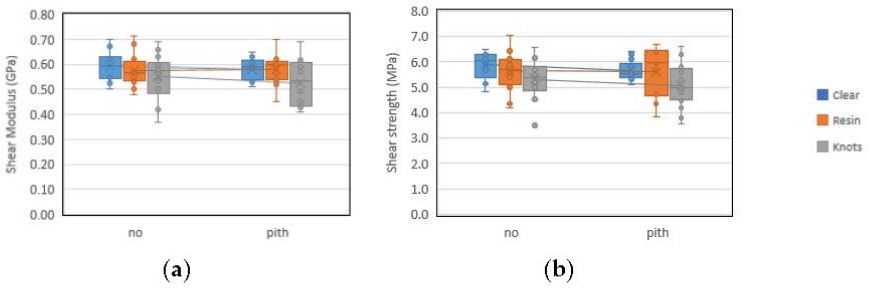


Figure 26. Box plots of shear properties with and without pith—(**a**) shear modulus and (**b**) shear strength.

5.4.6. Relationship of Density and Shear

Density is a poor indicator of shear modulus and shear strength for all sample types separately and in combination with an R^2 of less than 0.04. Muller, et al. [73] found adding density to regression equations increased the explained variability in shear modulus and shear strength in Larch but only by 10%. In this study, only the clear samples show any trend of increase in shear modulus and shear strength with increase in density, but this was small and the correlation is poor. The relationship of density to shear strength published in Forest Products Laboratory [36] over predict shear strength showing this resource has high density relative to its shear strength.

5.4.7. Relationship of Shear Modulus and Shear Strength

Shear modulus is a moderate indicator for shear strength describing 45.6% of shear strength for all samples types combined as can be seen in Figure 27. Muller, et al. [73] found a stronger relationship between shear modulus and shear strength for Larch with R^2 of 0.73. The no-pith samples have a higher correlation than the pith sample type.

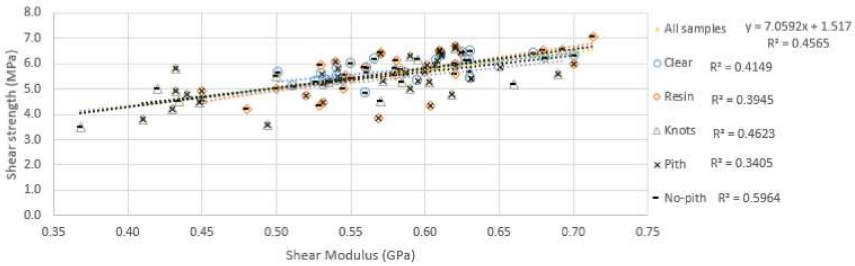


Figure 27. Relationship of shear modulus and shear strength.

5.5. Tension

5.5.1. Failure Behaviour

All tension samples had brittle failure with clear and resin samples showing failure both transverse and along the grain directions with separation between early and latewood boundaries. Typical failures can be seen in Figure 28. Bodner, et al. [71] and Galicki and Czech [80] experienced the same types of failure in their testing including separation at the earlywood–latewood boundaries. Bodner, et al. [71] found that wood rays were structurally weak and were frequently the location of either initiation or discontinuity of fractures under tensile load. The knot samples failed in the deviated grain around the knots and frequently through the pith of the branch wood. The majority of clear and resin samples failed at defects within the clamped area rather than within the test span. This left only 11 clear and 10 resin samples that could be considered representative of the clear wood fibre.

(a) (b) (c)

Figure 28. Some typical tension failures in (**a**) clear, (**b**) resin and (**c**) knots.

5.5.2. Structural Performance

The tension strength of clear samples are on average 253% and 71% higher than slash and loblolly at 15 years and 19 years, respectively [42]. However, compared to the average population of loblolly [45] clear samples are 60% less in tension strength which is slightly lower than the ratio range of 0.5 to 0.95 of juvenile to mature wood for tension strength [36]. This higher performance compared to other young pines can be explained by the clear samples having no defects other than pith however the knot samples still performed on average 71% better than 15-year-old and only 17% less than 19-year-old loblolly (Table

3). The results of the 11 clear, 10 resin and 35 knot tension strength tests are reported in Table 2 and illustrated in Figure 29.

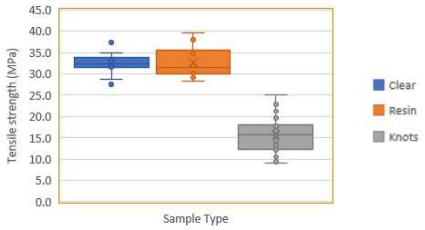


Figure 29. Tension strength.

The tension strength/bending MOE ratio is high compared to young and low-grade similar species at 4 times that of grade 3 Southern Yellow Pine researched by Doyle and Markwardt [37] and 51% higher than juvenile wood in loblolly [43] showing it has good tension strength for equivalent bending MOE. Nonetheless, these studies were on timber containing defects such as knots but looking at the knot samples, they are still on average 225% higher than grade 3 southern pine but more aligned with the juvenile loblolly at 6% less. A comparison with clear wood from the average population of loblolly [36] shows the clear sample ratio is low at 28% less. Of all the ratios given, the knot samples ratio has the largest reduction at 37% lower than clear samples reiterating that knots have a larger negative impact on axial tension than on compression, bending [36,37] and shear.

5.5.3. Effect of Resin

Comparing the clear and resin samples shows that there is no significant difference ($p = 0.893$). With an RAR of 0.58 (0.57 median), resins are on average 0.6% (−2.9% median) higher than the clear samples (Table 2 and Figure 29). Zhao, et al. [48] found pine containing extractives was 23% stronger in tension than unextracted pine and they attribute this reduced performance to the reduction in density resulting from the extraction processes. Nevertheless, in their study the extraction processes removed not only extractives but also other components of the cell structure that would affect structural performance. Figure 30 shows a decreasing trend in tensile strength with increasing RAR but the correlation is low, and the sample number is small as only the 10 samples that failed within the test span were used for analysis.

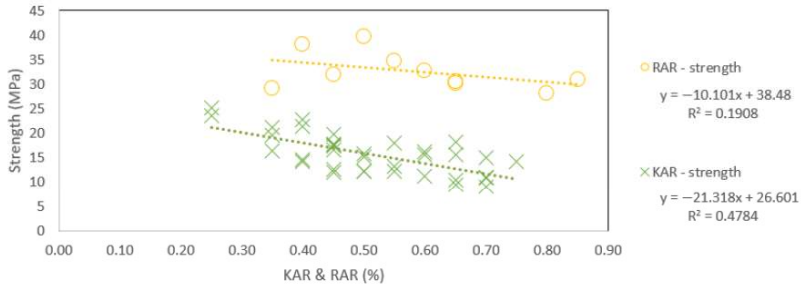


Figure 30. KAR and RAR vs. tensile strength.

5.5.4. Effect of Knots

Knots had an average KAR of 0.51 (0.50 median) and were significantly different to the clear samples ($p \leq 0.001$) with average tension strength 51.6% less (−51.8% median). Mitsuhashi, et al. [81] and Nagai, et al. [82] had similar results with a reduction in tension strength on average for knots compared to clear wood of 56% and 53%, respectively. In this study, knots had a larger impact on axial tension strength than on CParG and bending

which aligns with the literature [36,37]. Figure 30 shows that there is a decreasing trend in tensile strength with increasing KAR and that KAR is a moderate indicator of tensile strength.

5.5.5. Effect of Pith

Comparing pith and no-pith samples showed little effect for tension strength with no significant difference for clear ($p = 0.769$), resin ($p = 0.649$) or knots ($p = 0.496$). As seen in Table 2 and Figure 31, pith samples are on average 1.7% (+3.7% median) less, 3.8% (−2.0% median) more and 6.2% (−8.1% median) less for clear, resin and knots, respectively. Moody [83] found timber with pith to be 34% lower in tensile strength than timber without pith, although the non-pith samples also included mature wood which is known to be stronger than juvenile wood. Furthermore, Kretschmann and Bendtsen [43] found that the presence of juvenile wood rather than pith was an indicator of low-tensile-strength performance which aligns with the findings of this study in that samples with pith performed similar to those without and all samples would have contained juvenile wood given their close proximity to the pith.

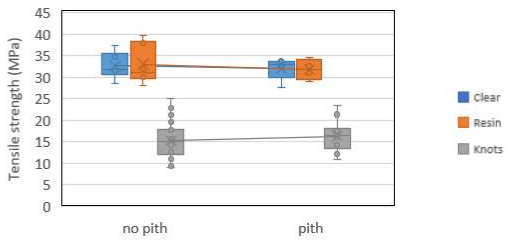


Figure 31. Box plot of tension strength—with and without pith.

5.5.6. Relationship of Density and Tension

Density is a poor indicator of tensile strength for all sample types separately and in combination with R^2 of less than 0.06. There is a slight decreasing trend for increasing density for clear and resin samples which can be explained by the slightly lower tensile strength but increased density of pith samples. Doyle and Markwardt [54] also found low or no correlations. Nonetheless, Galicki and Czech [80] found tensile strength to be strongly dependent on density when loaded along the grain, however not at an angle to the grain. Krauss, et al. [84] found latewood increased in tensile properties the further from the pith and was correlated to wood density whereas earlywood tensile properties had little change and were not correlated with density. This out-of-grade PEExPCH hybrid contains high content of earlywood as well as wandering pith and associated deviated grain, all of which help explain the lack of correlation between density and tensile strength seen in this study.

6. Overview

6.1. Structural Performance

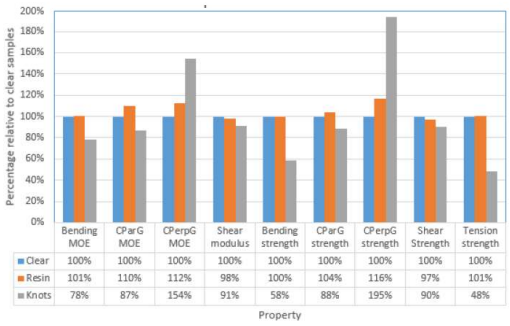
Clear samples performed well in bending strength and tension strength, mid-range in bending MOE and CParG strength and low in all other properties when compared to other PEExPCH hybrids and young and low-grade similar pines. In comparison to average populations of similar pines, bending strength and CPerpG were mid-range while all other properties were low. This is expected given the many characteristics of juvenile and corewood associated with low longitudinal properties [33] and that this resource was rejected during grading.

The ratios of structural properties to bending MOE are high for tensile strength, mid-range for bending and CParG strength and density but low for all other properties compared to other PEExPCH and young and low-grade similar pines (Table 3). Compared to

average populations of similar pines, the density to bending MOE ratio is high, shear modulus, CParG and CperpG are mid-range and all other properties are low. Knowing these structural properties and their relationships with an indicator property such as bending MOE allows for ease of grading in preparation for their design into building applications. This out-of-grade resource contains timber that would be a suitable substitute for the more expensive in-grade timber that exceeds the needs of low-stress structural applications such as internal layers in CLT. For example, inner layers in a five-layer CLT panel that experience low bending stresses.

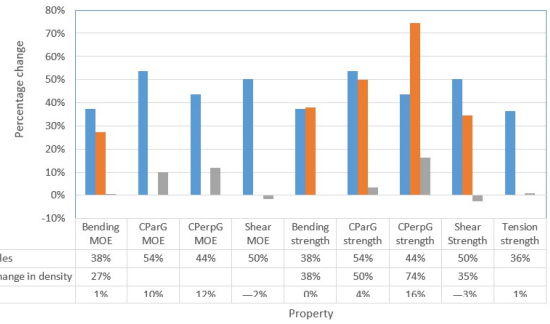
6.2. Resin

With an overall average RAR of 0.58, resin was similar to clear for all test types and within a range of 98% to 116% of clear samples (Figure 32). The average density for resin samples is 727 kg/m³ which is 45% higher and is significantly different ($p < 0.001$) to the clear samples but only CPerpG MOE and strength performed significantly different in this study. Figure 33 illustrates the percentage differences in average density between clear and resin samples for each test type, the predicted percentage change in structural performance based on the relationships given by Forest Products Laboratory [36] where available and the actual percentage change in structural performance achieved. It is clear that density due to resin causes a large overestimation of structural performance in these predictive models, especially for CPerpG and CParG strength. There is moderate correlation between RAR and density with an R^2 of 0.659 for all samples. It is important to consider this impact and remove density due to resin from these calculations or grade out resin where self-weight is critical. There are few data available in the literature on the impact of resin on structural properties of pine and how it affects predictive models.



	Bending MOE	CParG MOE	CPerpG MOE	Shear modulus	Bending strength	CParG strength	CPerpG strength	Shear Strength	Tension strength
Clear	100%	100%	100%	100%	100%	100%	100%	100%	100%
Resin	101%	110%	112%	98%	100%	104%	116%	97%	101%
Knots	78%	87%	154%	91%	58%	88%	195%	90%	48%

Figure 32. Summary of structural performance of resin and knot samples relative to clear.



	Bending MOE	CParG MOE	CPerpG MOE	Shear MOE	Bending strength	CParG strength	CPerpG strength	Shear Strength	Tension strength
Change in density from clear to resin samples	38%	54%	44%	50%	38%	54%	44%	50%	36%
Predicted change in performance due to change in density	27%				38%	50%	74%	35%	
Actual change in performance	1%	10%	12%	−7%	0%	4%	16%	−3%	1%

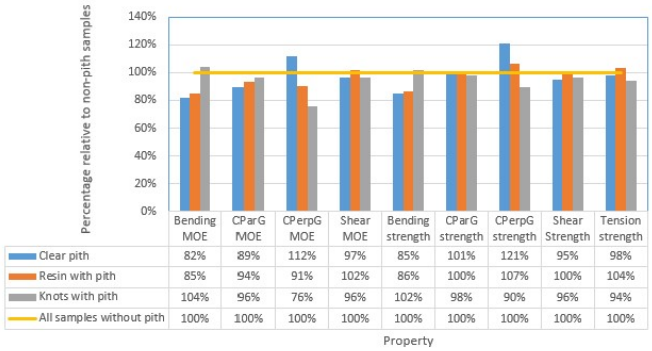
Figure 33. Change in density for resin samples, predicted and actual change in structural performance.

6.3. Knots

All knot samples performed significantly different to clear samples for all test types and within a range of 48% to 196%. Knots performed higher in CPerpG MOE and strength and lower for all other test types (Figure 32). The increase in density of knot samples was nearly as high as the resin samples with an average of 703 kg/m^3. Knot-associated resin streaking was common as seen by Nel, et al. [2] and this resin would have added to the density. Knots had the largest negative impact on tensile strength and largest positive impact on CPerpG strength.

6.4. Pith

Pith samples ranged between 76% and 121% of their non-pith counterparts (Figure 34) and not all were significantly different. CPerpG MOE was the only significantly different test type for pith versus non-pith knot samples, whereas bending MOE and bending strength were both significantly different for clear and resin. Additionally, CPerpG strength was significantly different for clear samples but not for resin or knots. Pith samples were consistently higher in density than non-pith samples.



	Bending MOE	CParG MOE	CPerpG MOE	Shear MOE	Bending strength	CParG strength	CPerpG strength	Shear Strength	Tension strength
Clear pith	82%	89%	112%	97%	85%	101%	121%	95%	98%
Resin with pith	85%	94%	91%	102%	86%	100%	107%	100%	104%
Knots with pith	104%	96%	76%	96%	102%	98%	90%	96%	94%
All samples without pith	100%	100%	100%	100%	100%	100%	100%	100%	100%

Figure 34. Summary of pith sample structural performance relative to non-pith samples.

6.5. Density

The average density for all clear samples in this study is 500 kg/m^3 which is high compared to other research on PEExPCH hybrids, young and low-grade and mid-range compared to average populations of similar pines (Table 3). Density is used as an indicator property to determine some strength values [36,64] and higher density is often associated with increased performance [55]. With the exception of CPerpG, change in density did not prove to be a good indicator for change in structural performance in this study for any sample type with all R^2 values below 0.23. Moya, et al. [42], Mackes and Shepperd [85] and Missanjo and Matsumura [55] also found poor correlation between density and structural properties for juvenile wood.

The density/bending MOE ratio for clear samples is similar to other young PEExPCH hybrid pines, on average 11% higher than other young and low-grade similar pines and 44% on average higher than other similar pines (Table 3) showing that this resource has high density for its bending MOE performance. High density relative to structural performance is not generally considered a positive outcome; however, it could provide benefit for applications where self-weight is not critical but acoustic performance is important.

7. Conclusions

This study evaluated the MOE and strength properties of out-of-grade PEExPCH hybrid pine in bending, compression parallel to grain (CParG), compression perpendicular to grain (CPerG), shear and strength in tension. The structural performance and their ratio with bending MOE as an indicator property were compared to other PEExPCH hybrids

and young, out-of-grade and average populations of similar pines. The effect of resin, knots and pith on these mechanical properties and density were evaluated. Correlations between RAR, KAR, density and structural properties were established. Changes in density were used in published models to predict changes in structural properties and compared to actual results. From the extensive experimental tests and data analyses, the following conclusions can be drawn:

- The out-of-grade PEExPCH hybrids from the low-quality inner core of the tree are typically characterised with pith, high-angled clustered knots, resin streaking, resin shake, needle trace and tight-radius growth rings with high percentage of earlywood.
- The clear timber in this resource performed well in bending strength (45.8 MPa) and tension strength (32.4 MPa), mid-range in bending MOE (6.9 GPa) and CParG strength (29.4 MPa) but poorly in CParG MOE (5.78 GPa), CPerpG MOE (0.27 GPa), CPerpG strength (6.7 MPa), shear modulus (0.59 GPa) and shear strength (5.7 MPa) compared to other PEExPCH hybrids and young and low-grade similar pines. Bending strength and CPerpG strength were mid-range compared to average populations of similar pines, but all other structural properties were low which can be expected given the timber was out-of-grade and contains juvenile wood and pith.
- The ratios of structural performance for clear samples to bending MOE revealed high tensile strength, mid-range bending and CParG strength, but all other structural properties were low relative to their bending MOE performance when compared to other PEExPCH hybrids and young and low-grade similar pines. Shear modulus, CParG and CPerpG strengths were mid-range, and all other properties were low relative to their bending MOE performance when compared to average populations of similar pines.
- The Poisson's ratio of the pooled clear and resin samples was found to be 0.4365 which is similar to slash pines as one of its parent species.
- Resin samples performed similar to and within a range of 98% to 116% of the clear samples. Resin significantly increased the density at 45% higher than clear but only CPerpG MOE performed significantly different; however, no clear relationship was found between RAR and CPerpG MOE. The resin in cell walls rather than in cell lumen is believed to have provided the increased performance. The increase in density due to resin caused large errors in predictive models that were based on density and should be subtracted from these equations. RAR showed low correlation with all structural properties with R^2 values all below 0.2 and moderate correlation with density with R^2 of 0.659.
- Knots performed significantly different to clear samples for all test types and within a range of 48% to 196%. Knots were high in CPerpG MOE and strength and lower for all other properties with the largest negative impact being on tensile strength followed by bending strength. The increase in density was similar to that for resin and knot-associated resin streaking was common which would have added to density. KAR was moderately correlated with tension strength and CParG MOE with R^2 of 0.48 and 0.35, respectively. All other correlations were low or non-existent with R^2 below 0.2.
- Pith samples were within the range of 76% to 121% of non-pith samples. Clear pith samples were significantly different and lower in bending MOE and strength and higher in CPerpG strength. Resin pith samples were significantly different and lower in bending MOE and strength. Knot pith samples were significantly different and lower in CPerpG MOE. Pith in knots for CPerpG strength had the third largest negative impact and is believed to be due to the discontinuity and connection of the conical-shaped knot wood spearing into the weak pith. Pith samples were higher in density than non-pith samples for clear, resin and knots in bending MOE and strength; knots had the largest negative impact, followed by pith for the clear and resin sample types, while resin had minimal impact and pith in knots increased performance.

- In CparG MOE and strength, knots had the largest negative impact, followed by pith. Resin had a positive impact with increased performance.
- In CPerpG MOE and strength, knots had the largest positive impact, followed by resin. Pith in clear samples also had a positive impact. Pith in resin reduced CPerpG MOE and increased strength while pith had the largest negative impact.
- In shear modulus and strength, knots had the largest negative impact, followed by pith in knot and clear samples. Resin had a small negative impact while pith in resin increased performance slightly.
- In tension strength, knots had the largest negative impact, followed by pith in knot and clear samples. Resin had little difference and pith in resin samples increased performance slightly.
- The density of clear samples at 500 kg/m^3 was high compared to other PEExPCH hybrids and young and low-grade similar pines and mid-range compared to average populations of similar pines. The ratio of density to bending MOE was mid-range compared to other PEExPCH hybrids and young and low-grade similar pines and high compared to average populations of similar pines.

While this resource has been rejected from grade, it still possesses some good mechanical properties that can be matched to structural applications that do not need high strength or stiffness values. It has high density which can be good for acoustics. However, additional research is needed on the impact on structural performance of the conical-shaped, clustered and high-angled knots found connecting with or near the pith as seen in this out-of-grade resource. This detailed information will provide an opportunity for the optimal design and use of this material resource in various civil engineering applications.

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3.3. Design Characteristic values and comparison with MGP10 requirements

The design characteristic average MOE and 5th percentile strength values using a 75% confidence level have been calculated in accordance to AS4063.2 (Standards Australia/New Zealand Standards, 2010) and are presented in Table 1. Some pith and no-pith sample sets did not have the minimum required number of 30 samples in each example (Table 1). The high standard deviation seen in some results have caused a sizable reduction in their characteristic value in comparison to the values calculated earlier. This information would be important for evaluating the use of this resource during design processes and product development. However, it must be kept in mind that this is not an in-grade study but rather a study targeted at specific characteristics. Therefore, the assumption is that finger jointing required to achieve, for example clear defect free timber, achieves at least the MOE and strengths of the timber it is joining. Once grading rules are established, a sample set should be extracted and an in-grade study completed and characterised.

Table 1. Characteristic values

Sample Type	MGP10	Clear	Resin	Knots	Pith	No-Pith
MOE (Ave) (GPa)						
Bending	10.0	6.26	6.81	5.20	6.14	6.96
CParG	-	4.70	5.72	4.67	5.50	4.94
CPerpG	-	0.266	0.298	0.409	0.282	0.282
Shear	0.670	0.572	0.570	0.527	0.573	0.570
Strength (5th %ile) (MPa)						
Bending	17	31.6	31.6	12.5	31.4	32.5
CParG	18	20.0	22.5	18	22.1	20.5
CPerpG	-	4.1	5.2	8.2	4.7	4.5
Shear	2.6[A] (torsion or beam shear)	4.8 (shear plates)	4.2	3.7	4.3	4.6
Tension	7.7	27.3	26.3	9.4	25.9	27.4

A – Torsion or beam shear
B – Shear plates method

The MOE rather than strength was found to be the limiting factor for achieving grade for out-of-grade PEExPCH, which aligns with findings in other research (Harding et al., 2008; Nel et al., 2017; Wessels, Dowse, & Smit, 2011). Compared to the requirements of MGP10 in AS1720.1 (Standards Australia, 2010) the average bending MOE and shear MOE are low. On the other hand, all except knots in bending exceeded strength requirements. With no CParG MOE requirement specified in the standard, bending MOE has been used as a substitute as they are

often assumed to be the same (Dinwoodie, 2002). All samples types are low for CParG MOE while on the other hand all strengths meet or exceed the minimum requirements. There are no CPerpG MOE or strength values listed in AS1720.1 (Standards Australia, 2010), however there is a 10 MPa bearing perpendicular to grain (BPerpG) strength requirement which uses a slightly different test method and has been shown to give approximately 10% higher values (Franke & Quenneville, 2013). Apart from knot samples the CPerpG strengths are all below 10 MPa. Knot samples showed superior CPerpG performance and benefit could be obtained by precise placement in CPerpG applications however care must be taken given the high standard deviation seen in the results.

The design characteristic properties for clear and resinous out-of-grade PEExPCH hybrid pine meets the strength class requirements of C14 and C16 (EN 338, 2016) apart from bending MOE, which on average, clear and resin samples combined are only 7% and 13% lower than C14 and C16 respectively. C14 and C16 strength class (EN 338, 2016) timber is used in the manufacture of CLT commercially (Wieruszewski & Mazela, 2017) and therefore the clear and resinous out-of-grade PEExPCH hybrid pine would also be suitable with adjustments for the slightly lower MOE value. Restrictions on the inclusion of knots would be required.

3.4. Links and implications

The study presented in chapter 3 evaluated the mechanical properties of out-of-grade PEExPCH and found that the bending Modulus of Elasticity (MOE) was low relative to in-grade timber and was the most common reason for grade rejection.. The majority of the out-of-grade resource was found to be from the middle of the tree and showed physical signs of the corewood zone. Resin significantly increased density but had minimal effect on structural performance with the exception of compression perpendicular to grain which was significantly higher than clear timber. Knots were significantly different to clear for all test types with negative impacts except for compression perpendicular to grain which was increased. Structural performance of pith samples ranged from 75% to 121% of the non-pith timber samples. Pith samples were higher in density than non-pith samples and despite this, only compression perpendicular to grain performed significantly better, showing that strength does not always increase with increasing density. Relationships given by Forest Products Laboratory (2010) for bending MOE and MOR overestimated all sample types, showing this resource has high density relative to bending performance. The new information presented in this chapter is crucial for the effective establishment of grading rules, design optimisation and utilisation of out-of-grade PEExPCH as a new material resource in sustainable building systems. Rolling shear properties and effect of resin, knots, pith and growth ring pattern are investigated in Chapter 4.

CHAPTER 4: PAPER 3 - ROLLING SHEAR MODULUS AND STRENGTH OF LOW-STIFFNESS OUT-OF-GRADE HYBRID PINE; EFFECTS OF KNOTS, RESIN, PITH AND GROWTH RING PATTERN

4.1. Introduction

Chapter 2 identified the need to understand the mechanical properties of out-of-grade timber in order to enable its evaluation for structural applications. Chapter 3 evaluated the bending, compression, longitudinal shear and tensile structural performance of out-of-grade PEExPCH hybrid pine and the effect of resin, knots and pith. Chapter 2 also identified the transverse layers in CLT as a good solution to substitute out-of-grade in place of in-grade timber.

The transverse layers of CLT under out-of-plane loading are required to resist rolling shear stresses. Historically, rolling shear MOE and strength are two of the lesser utilised and understood properties of timber. With the increased use and demand for CLT, the timber industry, CLT manufacturers and researchers are working toward filling the knowledge gaps and determining rolling shear properties for various timber species, as well as looking for optimisation opportunities.

Rolling shear strength and MOE are important properties for CLT as low rolling shear strength presents a potential failure mechanism and large rolling shear strains contribute significantly to deflection in CLT under out of plane loading. Timber that has been cut close to the pith has shown good potential for transverse layers of CLT with higher rolling shear MOE being reported compared to mature wood due to the extra support provided by the growth ring pattern (Aicher et al., 2016, Ehrhart & Bradner, 2018). The objectives of Chapter 4 are to evaluate the rolling shear MOE and strength of out-of-grade PEExPCH hybrid pine including the effect of resin, knots, pith and growth ring pattern.

4.2. Submitted Paper under review

Rolling Shear Modulus and Strength of Low-stiffness Out-of-grade Hybrid Pine; Effects of Knots, Resin, Pith and Growth Ring Pattern.

Rebecca Cherry [1,2], Warna Karunasena [1,*], and Allan Manalo [1]

[1] Centre for Future Materials, University of Southern Queensland, West Street, Toowoomba, QLD 4300, Australia; rebecca.cherry@hyne.com.au (R.C.); allan.manalo@unisq.edu.au (A.M.)
[2] Hyne & Son Pty Ltd., Kent Street, Maryborough, QLD 4650, Australia
* Correspondence: karu.karunasena@unisq.edu.au

Abstract

The transverse layers in cross laminated timber (CLT) panels under out-of-plane loading are exposed to perpendicular to grain in-plane shear, often referred to as rolling shear (RS). RS modulus of elasticity (MOE) and strength are two of the lesser utilised and understood properties of timber. With the increased demand for CLT leading to increase demand for timber feedstock, researchers are now turning their focus to investigate the RS properties of a range of timber species proposed for transverse layers in CLT. The focus of this study is *Pinus elliotti* var. *elliottii* (Engelm) x *Pinus caribaea* var. *hondurensis* (Sénéclauze) (PEExPCH) hybrid pine which is being explored for use in the commercial manufacture of CLT. The process of milling and grading PEExPCH produces large volumes of low-stiffness out-of-grade timber that do not meet the requirements of the popular structural grading standards. This out-of-grade portion is underutilised and often sold at a loss, but may be suitable for the inner and transverse layers of CLT. This study investigated the RS properties of low stiffness out-of-grade PEExPCH in the common structural framing size of 90 mm x 35 mm using the modified 2-plate shear test. It focuses on the effects of knots, resin, pith and density. The RS MOE and RS strength were found to be 108 MPa and 2.4 MPa, respectively for clear samples. While neither resin or pith had a significant effect on RS properties, knots did have a significant effect and increased RS MOE by 17% and RS strength by 13%. Growth ring pattern also had an effect with semi quarter sawn (SQS) performing the best followed by back sawn (BS) then quarter sawn (QS) for both RS MOE and RS strength but only QS was significantly different. The RS properties of low-stiffness out-of-grade PEExPCH show good potential for applications in transverse layers, out-performing some other species already used in the production of CLT.

Key Words

Rolling shear, resin, knots, out-of-grade, low-stiffness, cross laminated timber, growth ring pattern, strain map.

1. Introduction

Cross laminated timber (CLT) is manufactured with layers glued together oriented at 90 degrees to the adjacent layers. When CLT is under out of plane loading, this exposes the transverse layers to perpendicular to grain in-plane shear, often referred to as rolling shear (RS). RS is one of the lesser utilised and understood properties of timber (Forest Products Laboratory, 2021). The increased use and demand of cross laminated timber (CLT) around the world has created a need to investigate various species of timber as potential feedstock options. One such species proposed by Cherry et al. (2019) is low-stiffness out-of-grade portion of *Pinus elliotti* var. *elliottii* (Engelm) x *Pinus caribaea* var. *hondurensis* (Sénéclauze) (PEExPCH) hybrid pine. This resource is underutilised but has structural properties that would be sufficient for some building applications (Cherry et al., 2022) and has potential to achieve bond requirements (Cherry et al., 2023). PEExPCH is a relatively new taxa which has been commercially planted in South Africa, South America, China and extensively planted in Queensland Australia, (Akins et al., 1990; Cappa et al., 2012; Gauchar et al., 2016; Nel et al., 2017; Yang et al., 2013). PEExPCH has now become the predominant plantation softwood for structural framing in Queensland and will provide an ongoing abundant supply of low-stiffness out-of-grade PEExPCH for the foreseeable future of over 30 years and likely well beyond. Opportunity exists to connect the needs of the CLT manufacturers looking for feedstock with the needs of the saw millers looking to find a market for low-stiffness out-of-grade PEExPCH.

RS strength and modulus of elasticity (MOE) are important factors for designing with CLT. Because the low RS strength presents a potential failure mechanism and large RS strains contribute significantly to deflection of the CLT panel, they must be considered in ultimate and serviceability limit state design (Ehrhart et al., 2015). RS becomes more influential on the deflection of CLT panels with the smaller span to depth ratios (Cherry et al., 2019; Sandoli & Calderoni, 2020). Where low stiffness timber is used for feedstock, the span to depth ratios will be smaller, putting more importance on RS MOE of the transverse layers.

Until recently, there has been limited research conducted and therefore limited data and understanding on RS properties of timber, with the majority of numerical and experimental studies focused on Norway spruce (Ehrhart & Brandner, 2018). RS has now become a hot topic for CLT manufacturers, timber suppliers and researchers alike as they work toward filling the knowledge

gaps and expanding the options for CLT feedstock. The results are showing considerable differences in RS properties between timber species with hardwoods typically performing better than softwoods (Aicher et al., 2016; Cao et al., 2019; Ehrhart et al., 2015; Kumar et al., 2023; Li, 2017; Ukyo et al., 2019; Wang et al., 2018; Zhou et al., 2014).

No studies were found on RS properties of out-of-grade PEExPCH, however, PEE is one of its parent species and is a southern yellow pine. Researchers have started investigating the RS properties of southern yellow pine but with varying results. Cao et al. (2019), Lim et al. (2020) and Gu and Pang (2016) all determined the RS strength of southern yellow pines to be close to 2.0 MPa. Kumar et al. (2023) investigated southern yellow pine grown in Queensland and reported higher RS strengths of between 2.7 and 3.4 MPa and RS MOE between 85.5 and 98.9 MPa.

Timber cut closer to the pith in the centre of the log is known to have lower longitudinal MOE and strength but has been found to have equivalent, or in some cases higher, RS MOE and/or RS strength than timber cut from the outerwood zone (Aicher et al., 2016; Aicher & Dill-Langer, 2000; Ehrhart & Brandner, 2018; Ukyo et al., 2019). Kumar et al. (2023) compared timber with longitudinal MOE of 6 GPa to timber with 12 GPa and found they both had similar RS properties. Grandvuinet and Muszyński (2019) determine that RS properties do not depend on the grade of timber. This indicates that an opportunity exists to substitute in-grade timber with low-stiffness out-of-grade PEExPCH because despite this resource having low longitudinal stiffness, it may have RS properties as good as or better than in-grade timber, and therefore potential as transverse layers in CLT.

Researchers have been exploring optimisation opportunities and ways to maximise RS properties of transverse layers. Some factors found to affect RS include growth ring pattern, pith and distance from pith, knots, angle of lamella, lamella and panel aspect ratio, moisture content, edge gluing and gaps between lamella (Aicher et al., 2016; Bahmanzad et al., 2020; Cao et al., 2019; Ehrhart et al., 2015; Grandvuinet & Muszyński, 2019; Kumar et al., 2023; Kumar et al., 2021; Sikora et al., 2016; Ukyo et al., 2019; Wang et al., 2018). The effect of knots, pith and growth ring pattern are of particular interest to this study.

The low-stiffness out-of-grade PEExPCH resource is unique from that studied in other research. The majority of this timber is from the corewood zone of the tree, containing specific traits to that region including juvenile wood, tight-radius growth rings, high content of earlywood and commonly occurring characteristics of resin, high angled clustered conical shape knots and pith (Cherry et al., 2022). No prior study was done evaluating the effect of resin on RS properties however, Cherry et al. (2022) found there was no significant difference between resin and clear samples for longitudinal shear. The limited research carried out on knotty timber showed the presence of knots

did not reduce the RS properties of timber (Cao et al., 2019; Grandvuinet & Muszyński, 2019; Kumar et al., 2023). These studies looked at through-knots cut from the outer wood zone of the tree which are very different to the distinct high angled clustered conical shaped knots found in this resource. There are mixed results on the effect of pith on RS properties with Aicher, Christian, and Hirsch (2016) finding no significant difference for timber with pith on RS MOE but pith negatively and significantly affected strength. Cao et al. (2019) on the other hand found no significant difference in strength with the presence of pith. More research is needed to investigate the effect of resin, knots and pith on RS properties especially on low-stiffness out-of-grade portion of PEExPCH.

Being a by-product of timber produced for structural framing, low-stiffness out-of-grade PEExPCH resource is cut at the common structural framing size of 90 mm x 35 mm and not cut specifically for CLT. This means that the aspect ratio (width/thickness) after planing in preparation for gluing (planed finish 90 mm x33 mm) is 2.7, which is less than seen in other studies. The American National Standard: ANSI/APA PRG320: 2019 Standards for Performance-Rated Cross-Laminated Timber (American National Standards Institute, 2019), International Standard: ISO16696-1 Timber Structures – Cross Laminated Timber (International Standards, 2019) and European Standard: EN16351:2021 Timber Structures – Cross Laminated Timber - Requirements (European Committee for Standardization, 2021) all recognise the effect that aspect ratio has on RS properties. Unless testing is carried out, these standards place minimum limits of 3.5, 3.5 and 4.0 on transverse layers, respectively. EN16351:2021 allows the declaration of RS strength at 1.4 MPa for timber with characteristic bending strength of >=16 MPa which is structurally edge bonded without grooves, or timber with thickness up to 47 mm and not structurally edge bonded but with aspect ratios >=4. For aspect ratios less than 4, it limits RS strength to 0.7 MPa. Therefore, despite having bending strength well above the minimum of 16 MPa (Cherry et al., 2022), without testing, the declared RS strength is limited to 0.7 MPa under EN16351:2021 which is likely to be conservative. These values have proven to be conservative in the majority of cases (Aicher et al., 2016; Cao et al., 2019; Ehrhart et al., 2015; Ehrhart & Brandner, 2018; Gong et al., 2019; Li et al., 2019; River et al., 1991). The RS properties of low-stiffness out-of-grade PEExPCH need to be determined to provide information for optimisation and to maximise the use of this resource in transverse layers.

Researchers have identified that growth ring pattern effect RS properties but these were all tested on timber with aspect ratios of =>4 (Aicher et al., 2016; Ehrhart et al., 2015; Ukyo et al., 2019; Zhou et al., 2014). Ehrhart et al. (2015) noted that aspect ratio effects growth ring pattern which makes it difficult to separate their influence on RS. They also observed that tensile stresses perpendicular to grain increased with decreasing aspect ratio. Ehrhart and Brandner (2018) linked

the increase in RS MOE to the change in growth ring pattern. Other researchers have also seen differences in performance based on growth ring pattern (Aicher et al., 2016; Zhou et al., 2012). It needs to be determined if growth ring pattern has the same effect on RS properties when the timber has an aspect ratio as low as 2.7.

Where it is a design or resource limitation, it is beneficial to know the RS properties of transverse layers of CLT rather than relying on assumed conservative values. Understanding the effect of characteristics such as resin, knots and growth ring patterns allows for optimisation and development of custom grading rules to maximise the use of out-of-grade timber into CLT while still achieving desired results. This study aims to evaluate the RS MOE and strength of 90x35 mm^2 low-stiffness out-of-grade PEExPCH, the effect of resin, knots, pith, growth ring pattern and density. The results of this study are relevant to CLT manufacturers looking for alternative feedstock for transverse layers in CLT and for saw millers looking for value add opportunities for an abundant and underutilised timber resource that is often sold at a loss. It provides valuable information for assessing the suitability of substituting in-grade timber with out-of-grade for transverse layers of CLT and freeing up the in-grade timber for use in high demand and high value applications such as framing and trusses for housing.

2. Materials and methods

2.1. Samples

Low stiffness out-of-grade PEExPCH timber was used for this study. This timber was the common timber framing size of 90 mm x 35 mm and failed to meet the requirements of the Machine Graded Pine standards (MGP) as set out in AS1748 (Standards Australia/New Zealand Standards, 2011) and AS1720.1 (Standards Australia, 2010). More detail on this timber can be found in Cherry et al. (2022). The sample types and numbers are presented in Figure 1 and Table 1 and include:

1. Clear – containing no obvious defects besides occasional presence of pith
2. Resin – resinous timber covering at least 25% of the cross-sectional area (RAR), no obvious defects besides the occasional presence of pith, and
3. Knots containing at least 25% knot area ratio (KAR) measured in accordance with AS2858: 2008 (Standards Australia, 2008).

Within each sample type, there were 15 samples of each growth ring pattern as presented in Table 1. Sawing pattern names have been adopted for simplification of growth ring pattern category, are described below and illustrated in Figure 1. Reference location is to the centre of the planed (90 mm x 33 mm) sample (x=45 mm, y=16.5 mm) as shown by the Cartesian coordinate system (Figure 1).

1. Back sawn (BS) –sawn -25=>x<=25 mm and y>=15 mm from the centre of the pith, resulting in arched growth rings.
2. Semi Quarter sawn (SQS) - sawn x>25 mm and y>=15 mm from the centre of the pith, resulting in small off centred partial arches and approximately 45° growth rings.
3. Quarter sawn (QS) - sawn x>=0 mm distance in the x direction and y<15 mm from the centre of the pith, resulting in approximately 90° growth rings. Also includes small circular growth rings where pith is present.

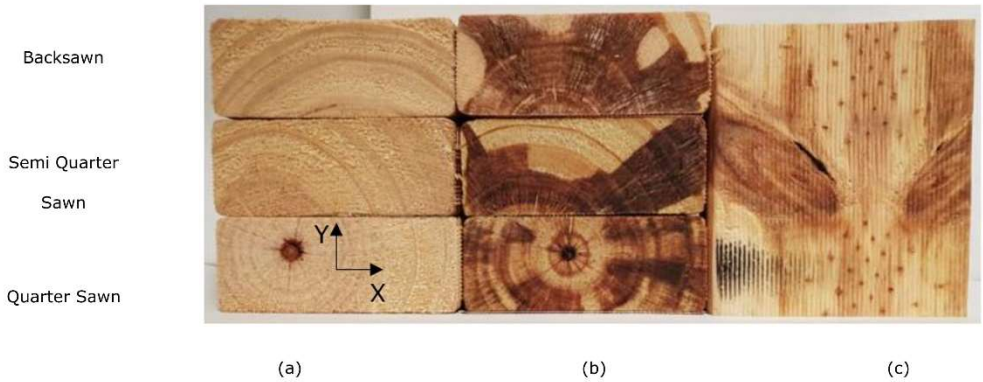


Figure 1. Examples of (a) clear and (b) resin samples and (c) of a typical knot sample.

Table 1. Test samples

	BS	QS	SQS	Total
Clear	15 (9)	15 (10)	15 (3)	45 (22)
Resin	15 (9)	15 (12)	15 (4)	45 (25)
Knots	15 (7)	15 (12)	15 (3)	45 (22)
Total	45 (25)	45 (34)	45 (10)	135 (69)

Value in () are number of samples containing pith in the sample set.

The prepared RS samples after planing were 90 mm x 33 mm x 100 mm. These were glued to the timber side plates within 6 hours of planing using 2-part epoxy resin adhesive Araldite 2011, which has a typical average lap shear strength of 27 MPa and using linear interpolation between given values, a shear modulus of 700 MPa at 25°C (Huntsman Corporation, 2015). The timber side plates were clear defect free BS southern pine with a longitudinal MOE =>15 GPa as per the data provided by the grading system.

2.2. Test Method

The modified planar shear test will be used as the test method for determining RS MOE and strength as described in Ehrhart et al. (2015). This test setup sandwiches the test specimen between two side plates and has an angle between the shear plane and the force direction of 14°.

This test setup is used and recommended by other researchers (Aicher et al., 2016; Ehrhart et al., 2015; Kumar et al., 2021; Zhou et al., 2014; Zhou et al., 2012) and is especially useful for this study as it allows for a focused investigation of factors individually. This is required to evaluate the effect of resin, knots, pith and growth ring pattern on RS properties as per the objectives of this study.

Nero, Christopher, and Ngo (2022) carried out RS tests using a modified planar shear test. They compared timber side plates using a laser sensor for deflection measurement to steel side plates using laser sensor or Digital Image Correlation (DIC) for deflection measurement. The results showed that RS strength was similar between all set ups, however, RS MOE for the timber plates and laser sensor was lower. They attributed this difference to two main factors. The low MOE properties of the timber side plates compared to the steel side plates and the uneven rotation in the samples influencing the measurement taken by the laser sensor.

Indeed, some of these observations were made in preliminary trials carried out in preparation for this study and methods were taken to minimise their impact. The timber plates used by Nero, Christopher, and Ngo (2022) were the outer layers of CLT as they were provided by CLT manufacturers, and are likely to be in the vicinity of longitudinal MOE of 6 to 12 GPa as per their feedstock testing. The timber plates used in this study were specifically selected to have high density, high percentage of latewood growth rings and high structural properties with longitudinal MOE >15 GPa. Furthermore, in the preliminary trials it was identified that orienting of the side plates was important. Bonding the face of the plates that contains the wood closest to the pith exposes the bondline to wood with lower structural properties. There is often a large centrally located section made up of earlywood because of the growth ring pattern. It was noticed in the trials that on some occasions, sections of this earlywood would break out at failure and this may impact results. By orienting the side plates so that the stiffer stronger wood closest to the bark was at the bondline, wood failures in the side plates were eliminated in the clear and resin samples. However, some knot samples still experienced small sections of timber failure in the side plates, which is believed to be associated with influence of knots redirecting the stresses and failure plane (Cao et al., 2019; Jockwer et al., 2017). The orientation of these side plates is not shown in the study by Nero, Christopher, and Ngo (2022) but this could have been impacting their results for timber side plate samples. Samples for this research were manufactured with older wood at the glue line as per Figure 2(a). Also, the LVDT brackets were screwed onto the narrow side of the plates to minimise the impact of including their longitudinal shear MOE in the measurement.

Nero, Christopher, and Ngo (2022) identified minor rotations in side plates which in their test set up resulted in substantially different measurements of shear deformation which impacted RS results. Their laser sensor was set up to measure at a distance offset to the centre of the sample

which would have exasperated the error recorded due to this uneven rotation in the side plates. In the preliminary tests for this research, the uneven rotation was most evident in the BS samples which can be attributed to the higher strain seen through the earlywood growth rings which will be discussed later. To prevent uneven rotation of the plates, to avoid erroneous LVDT measurements and to maintain shear stress rather than tensile and compressive stresses, ultra-high molecular weight polyethylene board (UHMW) was used between the top and bottom of the side plates and the LVDT and bracket were mounted and measuring centrally to the specimen (Figure 2).

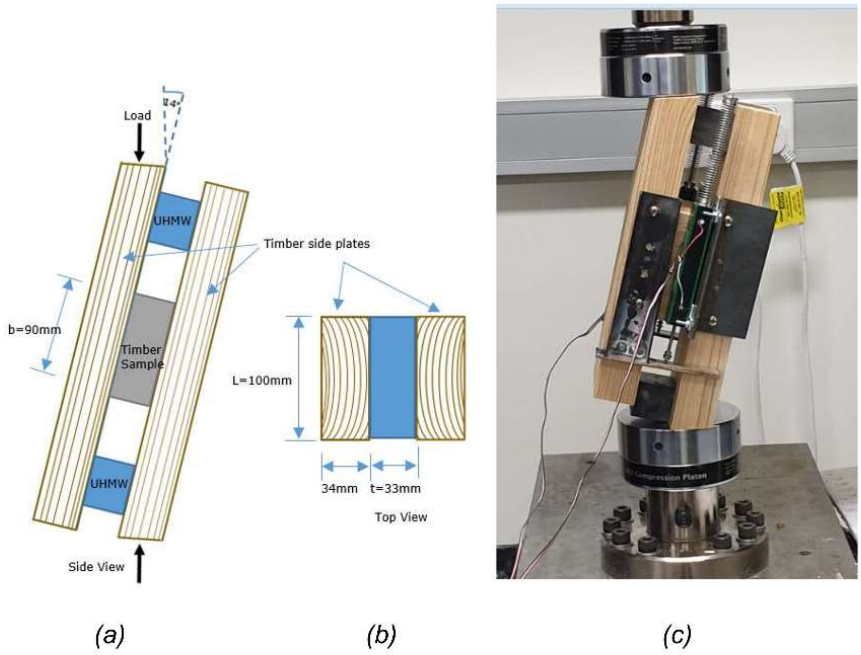


Figure 2. Test set up (a) UHMW board used to stop uneven plate rotation (b) end view showing orientation of timber side plates with strongest stiffest wood at the bond line (c) LVDT and bracket centrally mounted to avoid impact of offset on measurement

A 100kN MTS universal testing machine was used to apply the load at a rate of 0.8 mm/minute. LVDT's were used to measure the shear deflection in the sample. Approximately 60% of expected ultimate load was applied to avoid damage to the LVDTs, the LVDTs and brackets were removed and then the specimen was loaded to failure. A Delmohorst-RDM-2 moisture metre was used to take the moisture content of the test samples and the timber side plates immediately post testing. The RS MOE (G_r) and RS strength (f_r) can be calculated using equations 1 and 2 (Ehrhart et al., 2015).

$$G_r = \frac{\Delta F}{\Delta x} * \frac{\cos \alpha * t_l}{l * w_l} \qquad \text{(Eq 1.)}$$

$$f_r = \frac{F_{ult} \cos \alpha}{l * w_l} \qquad \text{(Eq 2.)}$$

where $\Delta F\ /\Delta x$ is the linear elastic slope of the load displacement curve over the load range of 10 to 40% of maximum load. α is the angle between shear plane and force direction, l is the length, t_l is the thickness and w_l is the width of the sample. F_{ult} is the maximum load at failure. T-tests were used to look for statistic significant differences between the different sample types. The significance level of 5% was used.

An Imetrum Digital Image Correlation (DIC) system with USB colour camera (ISM-Cam-026) was used to capture image recordings for RS tests of all growth patterns of BS, QS, SQS and pith. In preparation, the samples were painted white with a dark grey irregular speckle pattern applied over the top. The files produced were post processed using the 2D stain mapping tool in the Imetrum Video Gauge™ software version 5.4.4 (IMetrum, 2019) to produce 2D strain maps.

3. Results and discussions

The average and 5th percentile (5th %ile) G_r and strengths are listed in Table 2 along with average density and moisture content.

Table 2. Summary of test results

Total	G_r MOE Ave (MPa)	Std Dev	5th %ile (MPa)	f_r Strength Ave (MPa)	Std Dev	5th %ile (MPa)	MC Average (%)	Density Ave (kg/m³)
Clear	108	(21.7)	81	2.4	(0.5)	1.5	12.3	507
Pith	109	(18.7)	82	2.3	(0.5)	1.5	12.7	515
No Pith	107	(24.5)	81	2.5	(0.6)	1.7	12.0	499
Resin	111	(23.3)	84	2.3	(0.5)	1.6	12.5	723
Pith	112	(25.2)	83	2.2	(0.5)	1.6	12.3	733
No Pith	111	(21.2)	87	2.3	(0.4)	1.7	12.7	710
Knots	127	(22.5)	93	2.7	(0.6)	1.6	12.2	714
Pith	129	(22.6)	91	2.6	(0.7)	1.6	12.2	732
No Pith	124	(22.6)	94	2.8	(0.6)	2.0	12.2	697
Pith	116	(23.8)	82	2.4	(0.6)	1.5	12.4	663
No Pith	114	(23.7)	84	2.6	(0.6)	1.7	12.3	632
BS	117	(19.1)	84	2.5	(0.6)	1.6	12.1	638
Q	107	(23.9)	80	2.3	(0.6)	1.5	12.3	649
SQ	122	(25.7)	92	2.6	(0.6)	1.8	12.6	657

3.1. Failure behaviour

There was no obvious differences between the typical failure types or failure planes of clear and resin samples. However, the knot samples tended to fail adjacent to or through the glueline. The grain deviation around the knots clearly influenced the failure plane which can be seen in all three knot examples given in Table 3. The knot samples also had more glueline failure which often occurred over the branchwood of the knot and aligns with the findings of Cherry et al. (2023). Cao et al. (2019) also found knots redirected the failure plane resulting in significant wood failure adjacent to the glueline rather than through the samples. This aligns with other research that argues that knots and associated grain deviation make crack propagation under shear load more difficult (Grandvuinet & Muszyński, 2019; Jockwer et al., 2017).

The failure plane for clear and resin BS, QS and SQS samples were typically RS failure running diagonally across the sample and then adjacent to the glueline for the remaining distance. The latewood bands disrupted the crack propagation in all of the samples to varying degrees. This occurrence can also be seen in failed samples in Cao et al. (2019). In the SQS resin example, the crack travels through the earlywood band and propagated along the growth ring which is common in other research (Cao et al., 2019; Li, Ashraf, et al., 2021; Wang et al., 2018; Wu & Ren, 2021; Zhou et al., 2014). These curved cracks following the growth ring were not as common as the straight RS cracks in this study, which can be attributed to the small aspect ratio of 2.7. Wu and Ren (2021) found that the cracks in the larger aspect ratio samples were more likely to propagate along the growth ring. This trend can also be seen in the images of failed samples of Kumar et al. (2023). In alignment with other research (Aicher et al., 2016; Cao et al., 2019; Wang et al., 2018; Zhou et al., 2014), where pith is present in the sample, the failure plane almost always runs through and radially out from the pith in the direction of the wood rays.

Some BS samples experienced small tension perpendicular to grain initial cracks in a corner under high tensile stresses, but after the formation of these cracks, the sample went on to withstand higher loads. Similar small cracks can also be seen in the tensile corners of some of the failed samples by Wang et al. (2018) and Li, Ashraf, et al. (2021). Ehrhart et al. (2015) also saw this in their testing and concluded that this had no effect on MOE where cracking occurred out of the linear elastic region for the load - displacement relationship used for calculation of MOE and negligible impact on strength calculations. This is an important observation for out-of-grade timber, as it indicates there is potential to include wane in these tensile corners of the non-edge glued timber in transverse layers with minimal impact on RS performance. This needs, however, further investigation and is outside the scope of this study.

Table 3. Typical failures of clear, resin and knots in growth ring patterns of BS, QS and SQS.

	BS	QS	SQS
Clear			
Resin			
Knots			
Pith			

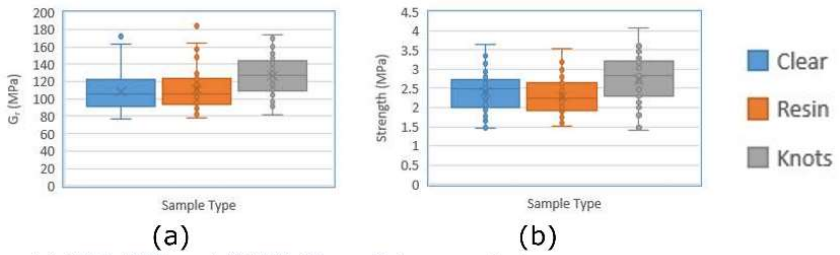
3.2. Structural performance

3.2.1. Clear

With an average RS MOE and strength of 108 MPa (106 MPa median) and 2.4 MPa (2.5 MPa median), respectively (Figure 3 and Table 2), the properties of clear out-of-grade PEExPCH are similar to that determined in other studies on southern yellow pines. Lim, Tripathi, and Tang (2020) investigated visually graded No. 2 southern yellow pine which achieved a higher RS MOE and lower strength of 132 MPa and 2.16 MPa, respectively. Cao et al. (2019) investigated visually graded No. 3 southern yellow pine (average population bending MOE of 7.54 GPa) which achieved a lower RS strength of 2.0 MPa. Gu and Pang (2016) also studied visually graded No. 3

southern yellow pine and found strengths in the range of 1.7 to 2.4 MPa. Kumar et al. (2023) investigated Queensland grown southern pine and found slightly lower MOE of between 85.5 and 98.9 MPa but higher strengths of between 2.7 and 3.36 MPa. They found the aspect ratio had a significant difference on RS strength but not on RS MOE, which could help explain the differences with higher RS MOE but lower RS strength seen in this study compared to their results. Other researchers have also found lower aspect ratio to have a negative effect on RS MOE but also on RS strength (Brandner et al., 2016; Ehrhart et al., 2015; Karacabeyli & Gagnon, 2019). Ehrhart et al. (2015) argued that the lower aspect ratio experienced higher stress peaks and therefore lower strengths achieved.

Putting aside the effect of aspect ratio, the results by Kumar et al. (2023) demonstrate that the RS of timber with low longitudinal MOE of 6 GPa achieved RS MOE and strengths as high as timber with high longitudinal MOE of 12 GPa. This good performance can be linked to the characteristics of the corewood zone of the tree. The slope of grain angle in corewood is higher than that in outerwood (Moore & Cown, 2017), and Müller et al. (2004) found a positive linear relationship between slope of grain and shear strength. The wood rays and high microfibril angle in juvenile wood provide a stiffening effect under shear loading (Keunecke et al., 2007; Reiterer et al., 2002). Moreover, Ehrhart identified that as the timber is cut closer to the pith, the growth ring pattern changes introducing patterns of latewood bans that can better resist transverse shear loading. This high RS performance is not reflected in the assumptions recommended for the shear analogy method by Gagnon and Popovski (2011) which assume RS MOE reduces linearly with reduction in longitudinal MOE.



(a) (b)

Figure 3. Box plots of (a) RS MOE and (b) RS Strength by sample type

Out-of-grade PEExPCH performs mid-range in comparison to other softwood species found in the literature and has a lower RS MOE than Japanese Larch (Gong et al., 2019), scotch pine (Ehrhart et al., 2015) and slash pine (Silva et al., 2023) which all achieved around 150 MPa. It performed similar to hoop pine (Kumar et al., 2023), spruce-pine-fir (Wu & Ren, 2021) and spruce (Ehrhart et al., 2015; Wang et al., 2018). It performed better than Norway spruce (Nero et al., 2022), radiata (Kumar et al., 2023; Li, Ashraf, et al., 2021; Nero et al., 2022) and black spruce (Zhou et al., 2014) all of which achieved between 20 and 74 MPa.

Out-of-grade PEExPCH has a lower RS strength than hoop pine (Kumar et al., 2023) and southern pine tested by Kumar et al. (2023) which achieved between 2.7 MPa and 3.68 MPa. It performed similar to loblolly (Pradhan et al., 2023), radiata (Kumar et al., 2023; Li, 2017; Li, Ashraf, et al., 2021; Nero et al., 2022), scotch pine (Ehrhart et al., 2015), slash pine (Silva et al., 2023) and Japanese larch (Gong et al., 2019). It performed better than spruce (Ehrhart et al., 2015; Wang et al., 2018), spruce-pine-fir (Wu & Ren, 2021) and Norway spruce (Nero et al., 2022) which achieved between 0.99 to 1.88 MPa.

There are relationships between longitudinal MOE and strength and RS MOE and strength presented in the literature. A relationship used for RS MOE is longitudinal MOE/160 or longitudinal shear MOE/10 (American National Standards Institute, 2019; Karacabeyli & Gagnon, 2019) which would equate to RS MOE of 43 MPa or 59 MPa, respectively, using the bending and shear MOE performance of the clear samples (Cherry et al., 2022). These relationships underestimate the RS MOE which proved to be 2.5 times higher at longitudinal MOE/64 and 1.8 times higher at longitudinal shear MOE/5.5.

Based on limited tests, Forest Products Laboratory (2021) and Karacabeyli and Gagnon (2019) place RS strength at approximately 18% to 28% and 33% of parallel to grain shear strength, respectively. In this study, the RS strength is 42% of the parallel to grain shear strength of 5.7 MPa of clear samples (Cherry et al., 2022). This is not unreasonable given the higher RS performance of wood close to the pith as seen in the literature and discussed previously in this section. EN16351:2021 has proven to be conservative, as it limits the declared value of RS strength without testing to 0.7 MPa for this particular resource which has a characteristic bending strength of >=16 MPa (Cherry et al., 2022), thickness <47 mm, is not structurally edge bonded and has a width/thickness ratio <4. At a measured RS strength of 2.4 MPa, it achieved 3.4 times that value and 1.7 times the value of 1.4 MPa allowable for width/thickness ratios >=4. The majority of research have found EN16351 to be conservative (Aicher et al., 2016; Cao et al., 2019; Ehrhart et al., 2015; Ehrhart & Brandner, 2018; Gong et al., 2019; Li et al., 2019; River et al., 1991).

3.2.2. Effect of Resin

Compared to the clear samples, resin had little effect for RS performance with no significant differences for MOE (p=0.268) and strength (p=0.143). With an average RAR of 0.57 (0.55 median), the resin samples are on average 3% higher and 5% lower than clear for RS MOE and strength, respectively (Figure 3 and Table 2). No other study was found on the effect of resin on RS properties of wood and there are mixed results in the literature on the impact of resin on the structural properties of wood (Arganbright, 1971; Luxford, 1931; Zhao et al., 2020). Garcia-Iruela et al. (2016) found extractives provided increased mechanical properties and attributed this to the contribution of resin incrustation in the cell lumen, likening its affect to reinforcement provided by

vinyl monomers in wood composite polymers. Grabner et al. (2005) found extractives increased structural performance of Larch in the transverse direction attributing the higher MOE results to a reduction of buckling of cell walls and of mechanical stresses due to resin filled tracheids. Keunecke et al. (2007) predicted extractives increased shear performance. Cherry et al. (2022) investigated this same out-of-grade PEExPCH resource and found compression perpendicular to grain was significantly improved in resin samples but the differences for other structural properties including longitudinal shear MOE and strength was not significant. Figure 4 shows a very low correlation between RAR and RS MOE or strength.

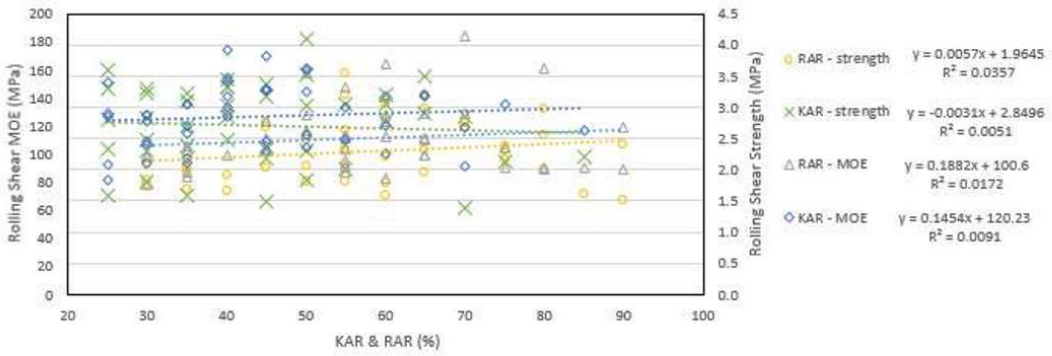


Figure 4. KAR and RAR vs. RS MOE and strength

3.2.3. Effect of Knots

Compared to clear samples, knots had a significant effect on RS performance with significant differences for MOE ($p<0.001$) and strength ($p=0.008$). With an average KAR of 0.44 (0.40 median), the knot samples are on average 17% and 13% higher than clear for RS MOE and strength, respectively (Figure 3 and Table 2). This higher performance of knots aligns with the literature. Kumar et al. (2023) investigated sound knots in BS southern pine, radiata pine and hoop pine and found knots increased average RS MOE by 36%, 17% and 55%, respectively and average strength by 26%, 21% and 23%, respectively. Grandvuinet and Muszyński (2019) found RS in CLT panels made from Douglas Fir with knotty transverse layers achieved 16.1% and 4.7% higher RS MOE and strength, respectively compared to knot free timber. They attributed this to the knots disrupting the propagation of cracks through the timber. Jockwer et al. (2017) also found that knots can disrupt and resist crack propagation in glulam beams, resulting in increased load carrying capacity. Cao et al. (2019) found that knotty timber had significantly higher RS strength compared to knot free timber with 19% to 34% increases depending on knot type. The RS strength of sound knot and decayed knots were 2.48 MPa and 2.55 MPa, respectively. They also considered the difference between knots with and without pith, but concluded that the difference in knot characteristics close to the pith meant that the comparison was not about pith alone. This observation is highly relevant to this study because the out-of-grade resource being investigated is from the centre of the tree. Therefore they contain high angled clustered conical shaped knots

which are very different to the knots found in outerwood that are considered in these other studies. This research shows that high angled clustered conical shaped knots do increase RS properties, although not as much as through-knots in outerwood seen in other studies.

Figure 5 illustrates the extent of grain deviation caused by the presence of a knot within a short distance of a 100 mm x 100 mm sample. End view 1 shows a typical BS sample in the central layer, side view demonstrates the significant change of the grain direction that can occur due to the presence of a knot. In this example the grain direction changes from parallel to up to a 60° angle to the glueline. End view 2 shows part of the branchwood and a substantial difference to the growth ring pattern in comparison to end view 1. Given the difference of strain due to growth ring patterns with high strain occurring in the earlywood bands, this example helps to provide understanding of the disruption to strain, differences in failure plane and increased RS properties in knot samples.

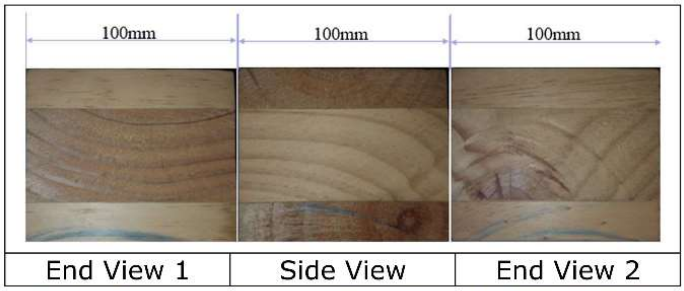


Figure 5. Substantial change to grain direction due to a knot within a 100 mm sample piece of CLT.

3.2.4. Effect of Pith

Separating the pith from the no-pith samples showed that while there is no significant difference for clear, resin or knot samples, those with pith had a slightly higher RS MOE but slightly lower RS strength. RS MOE is 2% higher and RS strength 8% lower for pith when all sample types are combined. The comparison between no pith and pith samples is included in Figure 6. Clear with pith are on average 2% higher and 8% lower than clear without pith in RS MOE (p=0.369) and RS strength (p=0.118), respectively. There is on average only 1 MPa difference for RS MOE for resin with and without pith however, RS strength is 5% lower for resin with pith (p=0.236). Knots with pith are on average 4% higher and 7% lower in average RS MOE (p=0.233) and strength, respectively (p=0.153).

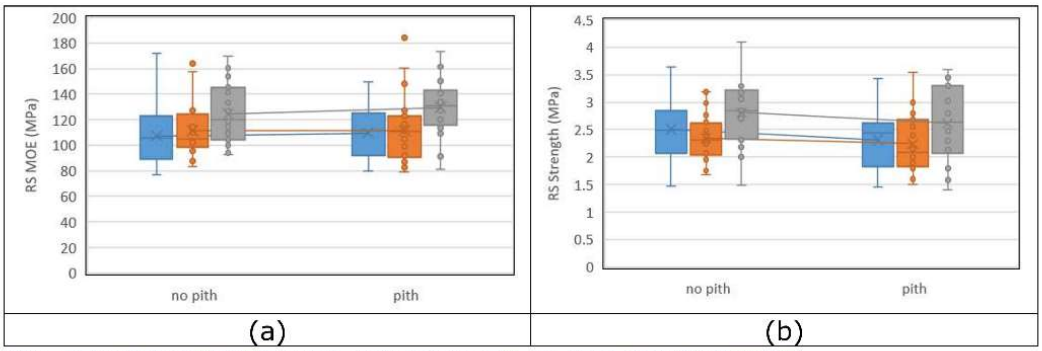


Figure 6. Box plots of RS properties with and without pith (a) MOE and (b) strength

Cao et al. (2019) also found no significant difference in the RS strength for pith samples. Aicher, Christian, and Hirsch (2016) found that the presence of pith boards had no significant effect on MOE however, they did find that strength was significantly lower for pith samples. They noted that the samples cut from the outerwood at a distance from the pith were almost defect free while almost all pith samples contained cracks which formed part of the shear failure plane, indicating that these cracks may have had little impact on RS MOE but a considerable negative impact on RS strength. While they did not mention if there were pre-existing cracks in the pith or no pith samples, there is no evidence of cracks in the images of untested samples by Cao et al. (2019) and there were minimal cracks present in the pith samples in this study. This provides further argument that the cracks rather than the pith itself could be the major contributor to the significant reduction in RS strength seen by Aicher, Christian, and Hirsch (2016).

3.2.5. Effect of Growth Ring Pattern

There are significant differences in RS MOE between growth ring pattern of QS to both BS (p=0.023) and SQS (p=0.002) for RS MOE however, the difference between BS and SQS is not significant (p=0.115). The SQS samples rank the highest for RS MOE, followed by BS at 4.1% less and QS at 12.3% less (Figure 7 and Table 2). This is also reflected in the RS strength results with QS being significantly different to BS (p=0.013) and SQS (p=0.005) while BS is not significantly different to SQS (p=0.343). As with RS MOE, SQS ranked the highest for RS strength, followed by BS at 3.8% less and QS at 11.5% less. Aicher, Christian, and Hirsch (2016) investigated beechwood and found the same ranking as this study with SQS performing best followed by BS and QS at 9% and 29% less in RS MOE, respectively, and BS and QS at 10% and 21% less in RS strength, respectively. Zhou et al. (2012) investigated black spruce and found a different rank with SQS performing the best for RS MOE, followed by QS then BS at on average 9% and 19% less, respectively. Wu and Ren (2021) investigated spruce-pine-fir combination and found on average for RS MOE, SQS performed the best followed by QS and BS at 47% and 54% less. For RS strength, however, on average SQS performed the lowest with BS and QS at 12% and 31% higher.

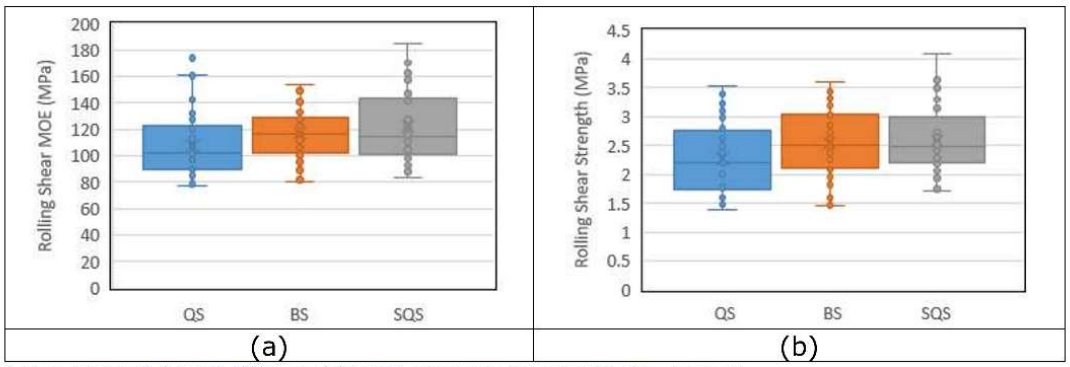


Figure 7. Box plots of (a) RS MOE and (b) RS strength by growth ring pattern

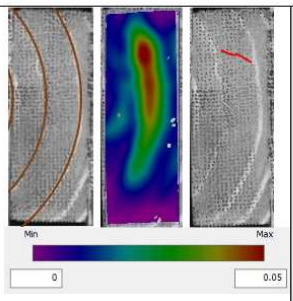
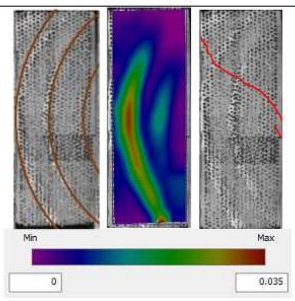
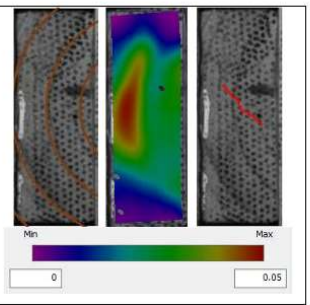
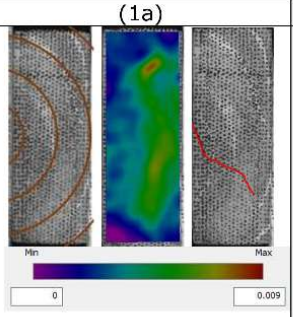
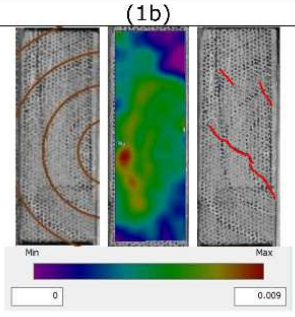
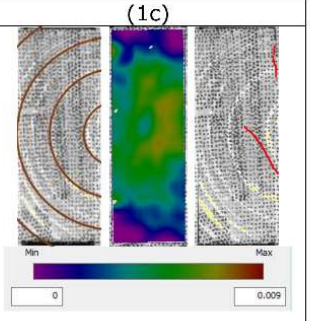
Several researchers have found larger differences between SQS and BS samples. The smaller difference seen in this study between SQS and BS is likely to be caused by the difference in growth ring formation due to their close proximity to the pith and due to the smaller aspect ratio. This aligns with the finite element model by Olsson et al. (2023) which shows an increase and then decrease in RS MOE with an increasing distance from the pith, with the region of BS close to the pith having similar predicted RS MOE to that of SQS region. Wu and Ren (2021) results show that the smaller the aspect ratio, the less difference between BS and SQS RS MOE. Ehrhart et al. (2015) noted the effect aspect ratio has on growth ring pattern and because of this, the difficulty separating their impact on RS properties. BS samples increase in RS properties as their distance from pith reduce which is linked to an increase in the presence of 45° annual growth rings (Ehrhart & Brandner, 2018; Nero et al., 2022). These growth rings transfer the shear load through their stronger stiffer latewood bands acting like a pillar and protecting the weaker and less stiff earlywood. RS properties are lowest with growth rings at 0° and 90° and highest at 45° (Aicher & Dill-Langer, 2000; Ukyo et al., 2019). The higher RS MOE performance of the BS samples compared to QS may also be explained by the presence of wood rays radiating out from the pith which provide shear reinforcement (Keunecke et al., 2007; Reiterer et al., 2002). These results confirm that the growth ring pattern does have a similar effect on the RS properties to that seen in other studies when the aspect ratio is 2.7 and cut close to the pith.

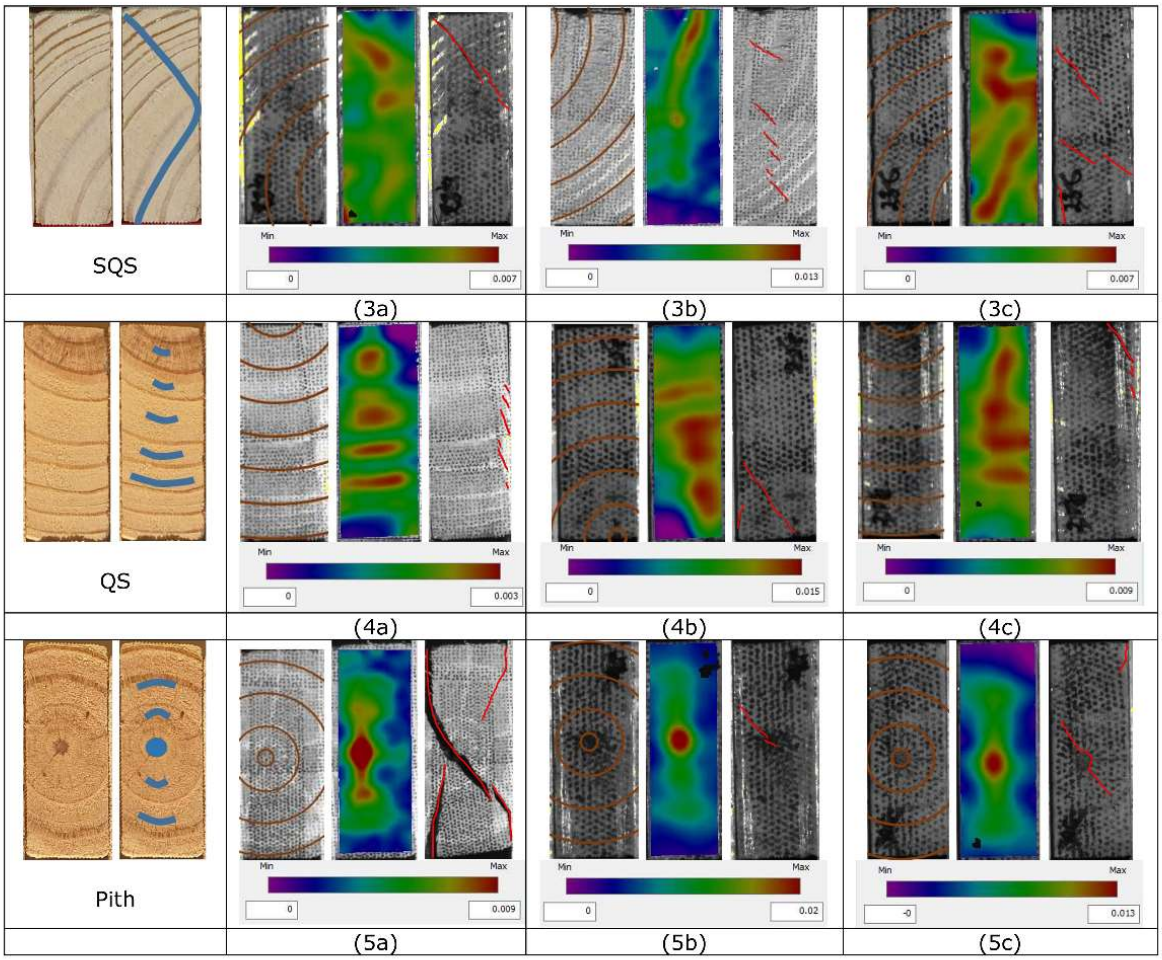
3.3. 2D strain maps under rolling shear

2D strain maps were produced from the digital image correlation (DIC) image frame immediately before initial cracking or immediately before sample failure where initial cracking did not occur or was not captured by the camera due to limitations of image frame rate at 50 frames per second. Typical examples of BS, QS, SQS and pith samples are presented in Table 4 and an indication of the typical higher strain regions have been marked in blue.

A difference can be seen between the strain distribution in the BS samples that had flatter growth rings and those with tight radius growth rings that were cut closer to the pith. The flatter growth ring samples show higher strain peaks that are concentrated in an earlywood band. While the strain can also be seen in the earlywood bands of the tight radius growth ring samples, the strain peaks are much lower and the strain is more evenly distributed across the cross section of the sample. The SQS strain maps show a tendency for the higher strain region to run diagonally across one end of the sample along an early wood band. This then change direction and ran perpendicular to the growth rings and diagonal to the sample in the opposite direction. QS strain maps show high strain in the early wood growth bands with the further from the pith, the wider the high strain band. Pith samples were reflective of the same strain patterns seen in QS samples with the addition of a high strain peak at the location of the pith. Other research shows similar strain distributions for these growth ring patterns. Ukyo, Shindo, and Miyatake (2019) conducted 2-plate shear tests on Japanese cedar and published similar DIC strain maps for BS with tight radius growth rings, BS with flat growth rings and QS with pith. Olsson et al. (2023) conducted 4 point bending testing on CLT panels made from Scots pine and published DIC strain maps of transverse layers in CLT containing BS, SQS and QS with pith. These also show similar strain distribution to this study except where multiple cracks are present in their samples. This shows the 2 plate shear test gives similar strain distributions to the transverse layers in CLT under transverse loading.

Table 4. 2D strain maps of specimens just prior to initial crack formation. Brown lines indicate growth ring patterns. Red lines show initial cracks just prior to failure. Blue lines indicate the higher strain regions.

BS flat growth rings			
	(1a)	(1b)	(1c)
BS tight growth rings			
	(2a)	(2b)	(2c)



3.4. Crack formation and failure behaviour

The images collected by the DIC system to produce the 2D strain maps provided the opportunity to also look for initial crack formation in the images just prior to sample failure. Due to frame rate of 50 frames per second, the camera did not catch the initial cracks of every sample. Some typical examples of what were captured are given in Table 4 with initial cracks marked in red. These cracks were typically between 30° and 60° and occurred prior to abrupt brittle failure

As can be seen in Table 4, there are a variety of crack types between and within samples just prior to failure. Nie (2015) identified RS, tension perpendicular to grain or combinations of both were the causes of initial failures. They found the majority of failure cracks were perpendicular to growth rings. Also, tension failures were more likely to occur when RS stresses were perpendicular to growth rings, while shear failures were more likely when RS stresses were tangential to growth rings. Ehrhart and Brandner (2018) noted that decreasing aspect ratios resulted in increasing tensile stresses perpendicular to grain which helps to explain the many initial failure cracks occurring as tension perpendicular to grain in this study. Wang et al. (2018) noted three major initial failure modes being RS failure along the growth ring, tension perpendicular to grain either

through the pith or along the wood ray. These align well with the findings of this study. The initial and ongoing failure crack propagation is a complex process and not all initial cracks formed part of the major failure plane or are even obvious in the failed sample.

The BS examples given in Table 4 show initial cracks in RS typically in the earlywood zone which aligns with other studies (Cao et al., 2019; Li, Ashraf, et al., 2021; Wang et al., 2018; Wu & Ren, 2021; Zhou et al., 2014). Examples 1a and 2c have small RS cracks at angles approximately 60° and 30°, respectively, which remained in the earlywood zone. A slight disruption to the RS crack path can be seen in examples 1c and 2b as they crossed the latewood band. Examples 1b and 2a both have cracks that are a combination of RS and tension perpendicular to grain. These cracks start as RS at 30° in the earlywood, transitioning to tension perpendicular to grain aligning with the direction of wood rays at 60° and then back to RS at 30°. Zhou et al. (2014) describe similar occurrences with cracks initiating in the earlywood zone, propagating along the growth ring and then along a wood ray and Reiterer et al. (2002) found that wood rays hindered the propagation of cracks in the tangential plane. Images of failed samples by Li, Ashraf, et al. (2021) and Cao et al. (2019) also show transitions from RS failure to perpendicular to grain failure at wood rays. The parenchyma cells found in wood rays can create a weak zone where cracks form due to tension perpendicular to grain (Wang et al., 2018) and are the likely cause of this change in crack direction.

The SQS examples 3a, 3b and 3c all show multiple initial cracks in tension perpendicular to grain that are in line with the wood rays and at 45°. Wu and Ren (2021) saw the same crack type and layout in SQS boards in spruce-pine-fir. The QS examples 4a and 4c show similar initial crack patterns with multiple short cracks adjacent to the glueline while example 4b shows RS failure in line with the wood rays. Aicher, Christian, and Hirsch (2016) research also show multiple short cracks near the glue line for QS samples. For pith samples, the initial cracks formed as tension perpendicular to grain at the pith and radiated out from the pith as tension perpendicular to grain in line with wood ray direction.

3.5. Effect of Density

Increase density is often associated with increase structural performance and used as an indicator for structural properties of timber. This study focuses on a resource that comes from the corewood zone of the tree which has a lower cellulose content but higher lignin and increased resin content (Moore & Cown, 2017) compared to outerwood which add to density but not necessarily to structural properties and may affect this relationship. The correlation between density and RS MOE and RS strength in this study is very low with R^2 values <0.1 for all sample types separately and in combination. Other research has also reported low to no correlation between density and RS properties of pine (Aicher et al., 2016; Kumar et al., 2023). While Ehrhart and Brandner (2018)

and Nero, Christopher, and Ngo (2022) both found strong correlation and a positive relationship between density and RS properties when multiple species of hardwoods and softwoods were combined, they found poor correlation for softwoods individually. Moreover, Gu and Pang (2016) researched a much higher density (850 to 1000 kg/m^3) population of southern yellow pine and found a lower RS strength (2.0 MPa). The findings of this study align with other research in that density is not a suitable indicator for RS properties of softwood (Ehrhart & Brandner, 2018; Kumar et al., 2023; Nero et al., 2022) and growth ring pattern has more influence over RS properties than density (Ehrhart & Brandner, 2018; Nero et al., 2022).

3.6. Correlation between RS MOE and RS strength

There is a positive but poor correlation between RS MOE and RS strength for out-of-grade PEExPCH hybrid pine with clear samples at R^2=0.177 (Figure 8). This is low compared to that found by Ukyo, Shindo, and Miyatake (2019) for Japanese Larch at R^2=0.74 but similar to other softwoods in the literature. As with the correlation between density and RS properties, Ehrhart and Brandner (2018) and Nero, Christopher, and Ngo (2022) found that the correlation between RS MOE and RS strength was strong when multiple species were combined but the correlation for softwood species were poor when considered individually. Norway spruce and Scots pine show little to no correlation with R^2 values of 0.03 and 0.14, respectively (Ehrhart & Brandner, 2018) and Radiata and Norway Spruce <0.05 (Nero et al., 2022). A slightly higher correlation exists for knot and pith samples individually in this study, with R^2 values of 0.339 and 0.393, respectively. Aicher, Christian, and Hirsch (2016) also found a low correlation of R^2=0.24 for beech wood but when pith samples were excluded, there was a moderate correlation R^2=0.40 which may be linked to the pre-existing cracks in the pith samples affecting RS strength but not RS MOE.

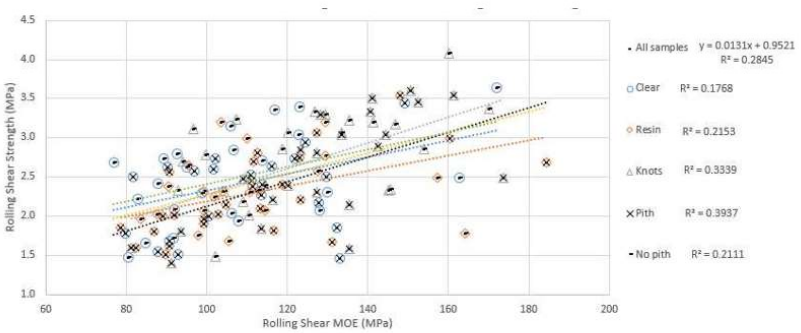


Figure 8. Correlation between RS MOE and RS Strength

4. Conclusions

This study investigated the RS MOE and RS strength of low-stiffness out-of-grade PEExPCH in the common cross sectional framing size of 90 mm x 35 mm and compared these to other common softwoods some of which are already used or being considered in the manufacture of CLT. The effect of resin, knots, pith and growth ring pattern on RS properties were evaluated. The strain distribution of the different growth ring patterns and cracks formations were discussed. The following conclusions can be drawn from the completed 135 2-plate shear tests:

- Out-of-grade PEExPCH proved to have good RS properties which are higher than some other softwood species already in use for the commercial manufacture of CLT. The clear samples achieved 108 MPa and 2.4 MPa RS MOE and strength, respectively, and is similar to southern yellow pines, including populations of higher grade timber. It performed mid-range compared to other softwoods in the literature.
- The relationships of RS properties with longitudinal MOE and shear strength provided in the literature and CLT standards are conservative. Rather than longitudinal MOE/160 or longitudinal shear MOE/10, the rolling shear MOE relationship proved to be 2.5 times higher at longitudinal MOE/64 and 1.8 times higher at longitudinal shear MOE/5.5. The rolling shear strength proved to be 42% of longitudinal shear strength, rather than in the range 18% to 33%.
- The effect of resin on RS properties was not significant and the correlation between RAR and RS properties was very low. Resin samples were 3% higher in RS MOE and 5% lower in RS strength.
- The effect of knots on RS properties was found to be positive and significant. Knot samples were 17% and 13% higher in RS MOE and strength, respectively.
- The effect of pith on RS properties was not significant. Pith samples were 2% higher in RS MOE 8% lower in RS strength when all sample types are combined.
- Growth ring pattern had an effect on RS properties. SQS, BS followed by QS was ranked higher to lower for RS MOE and RS strength. The difference between QS and the other two growth ring categories was significant while the difference between SQS and BS was not significant. BS was 4.1% and 3.8% less than SQS for RS MOE and RS strength, respectively while QS was 12.3% and 11.5% less than SQS, respectively.
- The 2D strain maps show high strain in the earlywood bands of growth rings. The SQS showed high strain regions along earlywood band but also perpendicular to growth rings that were diagonal to the sample. The flat BS growth ring pattern has higher peak strain

through an earlywood band while in the tight radius BS growth ring pattern closer to the pith, the strain is more evenly distributed across the sample.

- Initial cracks were either tensile perpendicular to grain in line with wood rays, tensile through the pith, RS or a combination of these.
- The correlation between density and RS MOE and RS strength was very low. Similar correlation exists between RS MOE and RS strength.
- This study has focused on limited characteristics found in this low-stiffness out-of-grade PEExPCH resource. Other characteristics found in this resource, such as resin shake, checking and distortion also need to be investigated to determine their RS properties and understand potential for their inclusion in transverse layers of CLT. Moreover, the evaluation for the inclusion or limitation of characteristics of out-of-grade timber in CLT needs to consider factors outside of RS structural performance alone. Cherry et al. (2023) looked at the impact of resin, knots and pith and recommended some restriction on their inclusion in CLT under the current test procedure and acceptance criteria due to negative impacts on bond performance. Further research is also required on creep, acoustic and fire performance of CLT made from low-stiffness out-of-grade PEExPCH pine.

5. Author contributions:

Author Contributions: Conceptualization, R.C., W.K. and A.M.; methodology, R.C.; validation, R.C.; formal analysis, R.C.; investigation, R.C.; resources, R.C.; data curation, R.C.; writing—original draft preparation, R.C.; writing—review and editing, W.K. and A.M.; visualization, R.C.; supervision, W.K. and A.M. All authors have read and agreed to the published version of the manuscript.

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4.3. Links and implications

The study in Chapter 4 evaluated the rolling shear MOE and strength of out-of-grade PEExPCH hybrid pine. It revealed that out-of-grade PEExPCH has as good, or in some instances better, rolling shear properties compared to other softwood species already used in the commercial manufacture of CLT. Resin and pith had no significant effect while knots significantly increased rolling shear properties. Growth ring pattern also had an effect with quartersawn significantly lower than semi-quarter and back-sawn. Semi-quartersawn was the highest performing growth ring pattern but not significantly different to backsawn. This information is critical in the evaluation of out-of-grade PEExPCH for the transverse layers in CLT. The evaluation of bond performance and bond quality is also essential to evaluate the suitability of this timber resource in CLT and is investigated in Chapter 5.

CHAPTER 5: PAPER 4 - MAXIMIXING THE USE OF OUT-OF-GRADE HYBRID PINE IN ENGINEERED WOOD PRODUCTS: BOND PERFORMANCE, THE EFFECT OF RESIN STREAKING, KNOTS AND PITH

5.1. Introduction

Chapter 2 identified the need to understand the bond performance and bond quality of out-of-grade pine and the extent to which current standards and guides address out-of-grade timber and its commonly occurring characteristics. This thesis investigates out-of-grade timber for use in sustainable building systems and while CLT is used and investigated as a good option and is the main example and focus throughout this research, the outcomes can be attributed to many applications including other engineered wood products such as glulam. EN16351 CLT standards allows for testing to be carried out on both CLT orientation and glulam orientation for evaluation of CLT bond performance. The opportunity was taken to extend this chapter to include evaluation for glulam orientated samples because these different orientations give different results and information. Therefore, both CLT and glulam orientations are included to provide a more complete study for CLT, but with the added benefit of also providing bond performance information for glulam.

Engineered wood products such as CLT and Glulam rely heavily on the integrity of their bond lines to perform safely and reliably in service over time. There needs to be suitable test methods and criteria that reliably and consistently evaluate this performance not only for clear defect free component of a timber resource but also for the commonly occurring characteristics such as resin, knots and pith as is seen in out-of-grade PEExPCH.

The objectives of this chapter are to investigate the bond quality and performance of out-of-grade PEExPCH hybrid pine and the effect of resin, knots and pith. This will be done using three common CLT standards. Additionally, to discuss the extent to which current standards and guides address out-of-grade PEExPCH and its common characteristics on bond performance.

5.2. Published Paper

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Article

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

Rebecca Cherry [1,2], Warna Karunasena [1,*] and Allan Manalo [1]

[1] Centre for Future Materials, University of Southern Queensland, West Street, Toowoomba, QLD 4300, Australia; rebecca.cherry@hyne.com.au (R.C.); allan.manalo@usq.edu.au (A.M.)
[2] Hyne & Son Pty Ltd., Kent Street, Maryborough, QLD 4650, Australia
* Correspondence: karu.karunasena@usq.edu.au

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].

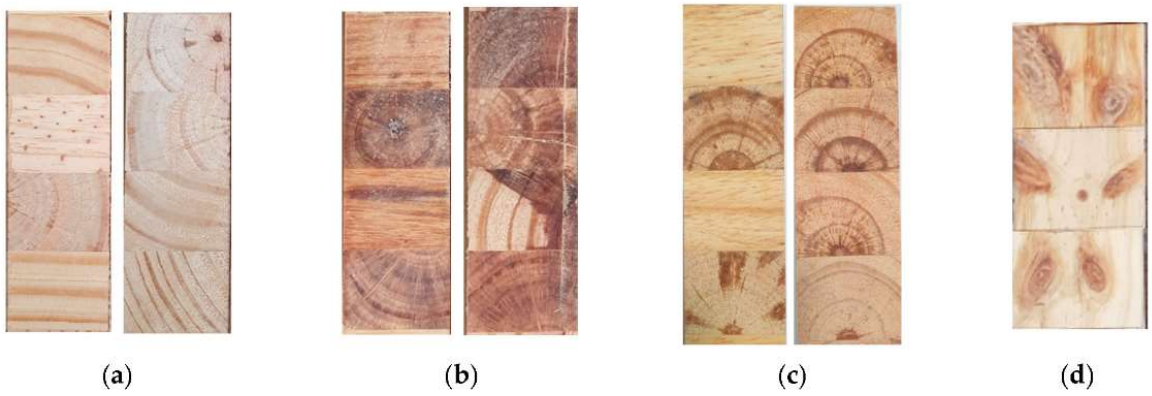


Figure 2. Examples of (**a**) clear, (**b**) resin, (**c**) pith, and (**d**) knot types.

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.

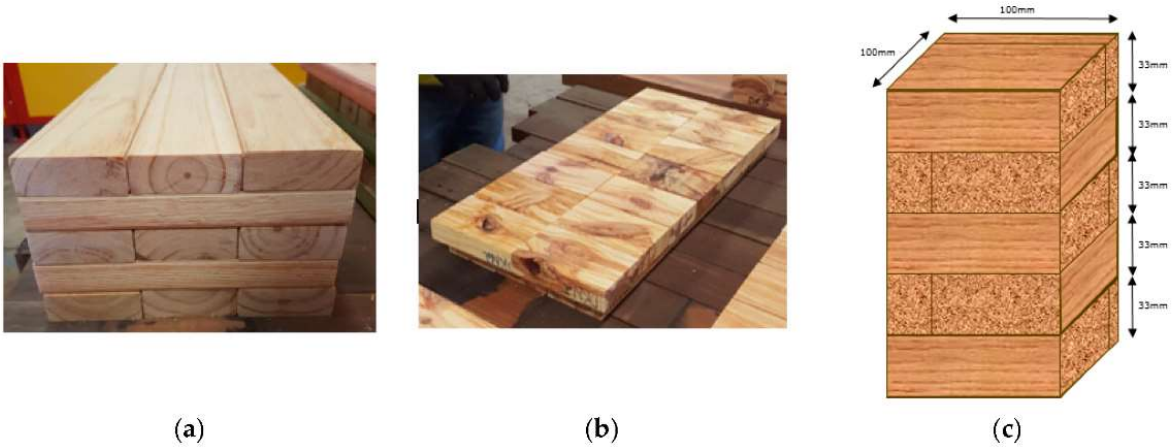


Figure 3. CLT delamination samples (**a**) are 5 layers deep, (**b**) knot samples are made from small lengths containing knots, and (**c**) 100 × 100 mm^2 samples are cut from these.

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.

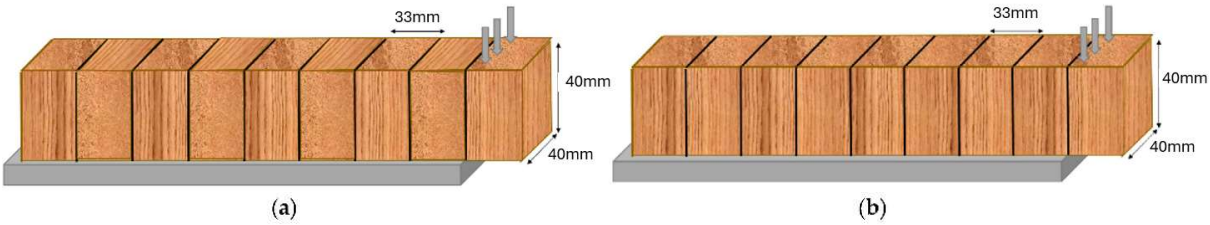


Figure 4. (**a**) Shear CLT and (**b**) shear glulam test sample dimensions and grain orientation.

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). $\text{Delam}_{\text{max}}$ is the percentage of the longest delamination within a single glue line. $\text{Delam}_{\text{tot}}$ 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. $\text{Delam}_{\text{max}}$ and $\text{Delam}_{\text{tot}}$ 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.

$$\text{Delam}_{\text{max}} = 100\frac{\text{l}_{\text{max,delam}}}{\text{l}_{\text{glueline}}} \quad (1)$$

$$\text{Delam}_{\text{tot}} = 100\frac{\text{l}_{\text{tot,delam}}}{\text{l}_{\text{tot,glueline}}} \quad (2)$$

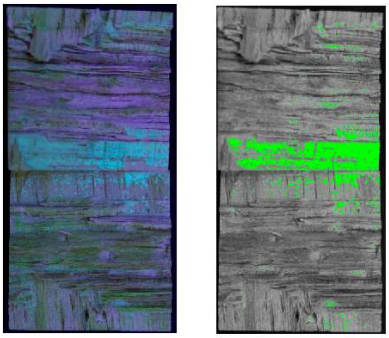
$$\text{Delam}_{\text{GL}} = 100\frac{\text{l}_{\text{tot,delamGL}}}{\text{l}_{\text{glueline}}} \quad (3)$$

where $\text{l}_{\text{max,delam}}$ is the maximum delamination length; $\text{l}_{\text{glue line}}$ is the perimeter of one glue line in a specimen; $\text{l}_{\text{tot,delam}}$ is the total delamination length; $\text{l}_{\text{tot, glue line}}$ 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.

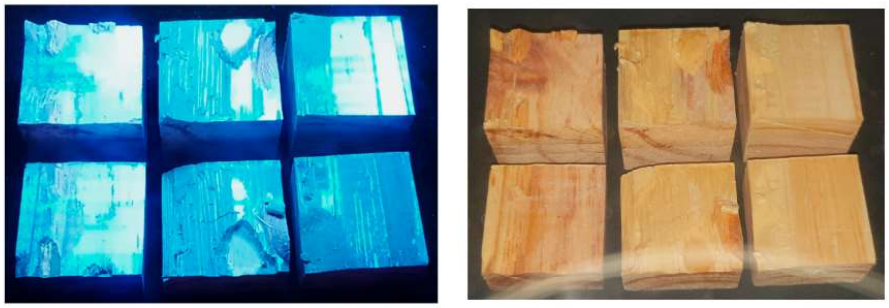
$$f_v = k\frac{F_u}{A} \tag{6}$$

$$k = 0.78 + 0.00044t \tag{7}$$

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 $\leq$10%, a second test specimen can be extracted and tested for a limit of $\leq$5% to pass. To achieve a passing result, the average WF_{tot} of all sheared specimens combined must be $\geq$80% and at least 95% of all specimens $\geq$ 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 $\leq$40% and $\leq$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 $\geq$50%, and the sum of wood failure on all split glue lines is required to be $\geq$70% for a passing result.

For EN16351:2015, to achieve a passing result, the shear samples required a population characteristic shear strength of $\geq$1.25 MPa and $\geq$1 MPa for each glue line for crosswise bonded layers, while parallel bonded layers require a characteristic shear strength of $\geq$3.5 MPa and $\geq$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.

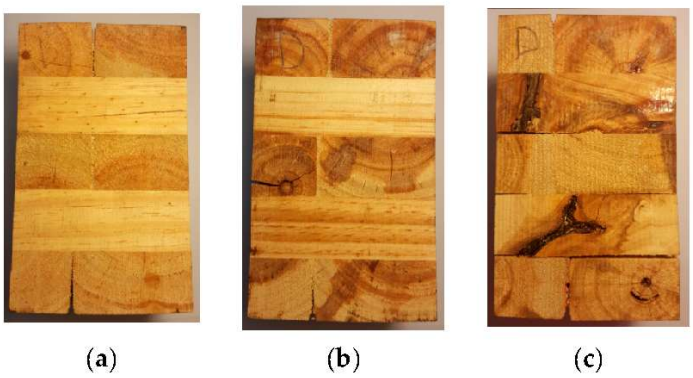


Figure 8. Typical samples post-delamination test for (**a**) clear, (**b**) resin, and (**c**) knots.

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.

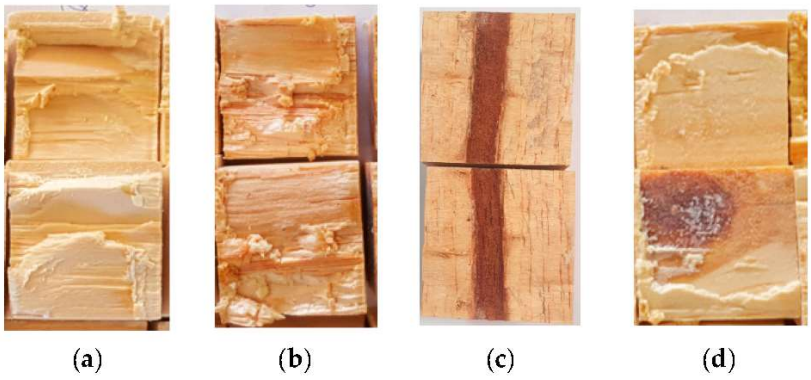


Figure 10. Examples of shear failures: (**a**) clear, (**b**) resin, (**c**) pith, and (**d**) knot samples.

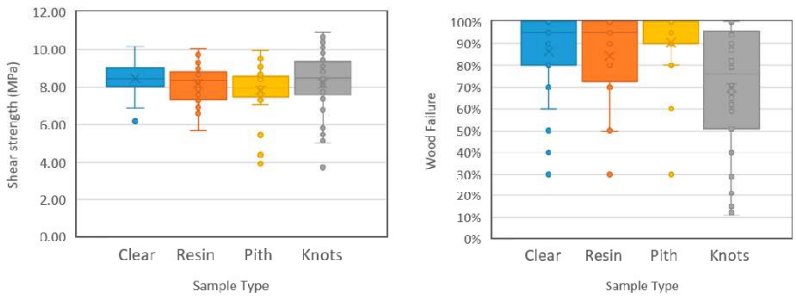
Clear Glulam

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



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

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

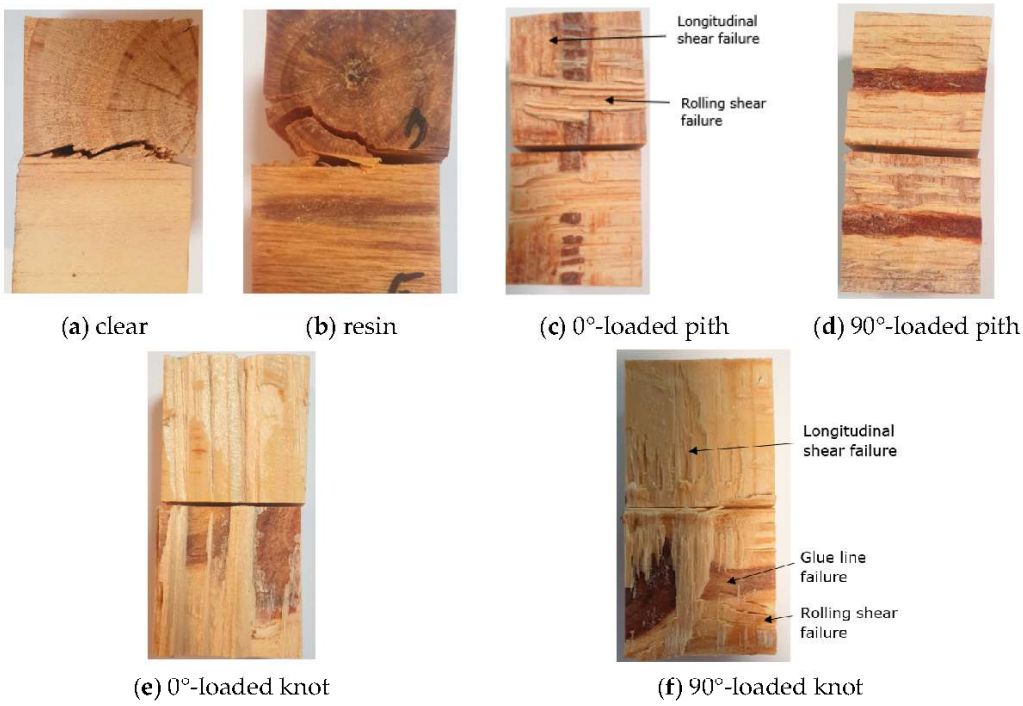
There is no significant difference in glue line shear strength ($p = 1.986$) between knots and clear glulam samples, but there is a significant difference in wood failure percentage ($p < 0.001$). Knots are 3.5% lower in glue line shear strength than clear, have the lowest 5th percentile at 5.0 MPa, 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.

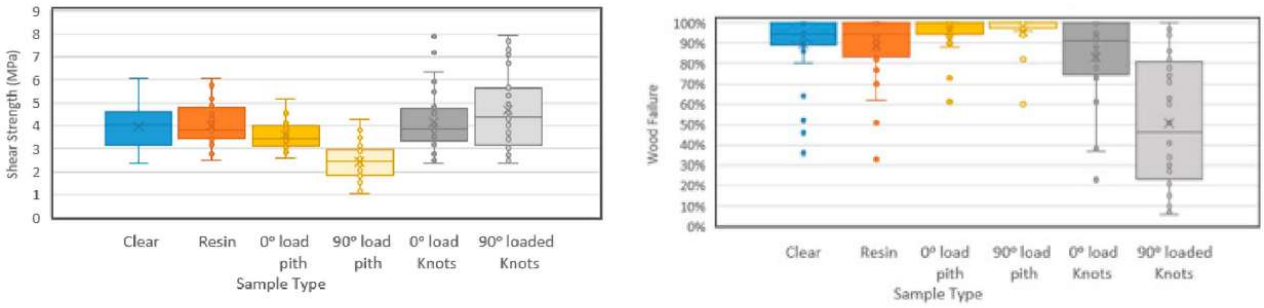
Clear CLT

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.

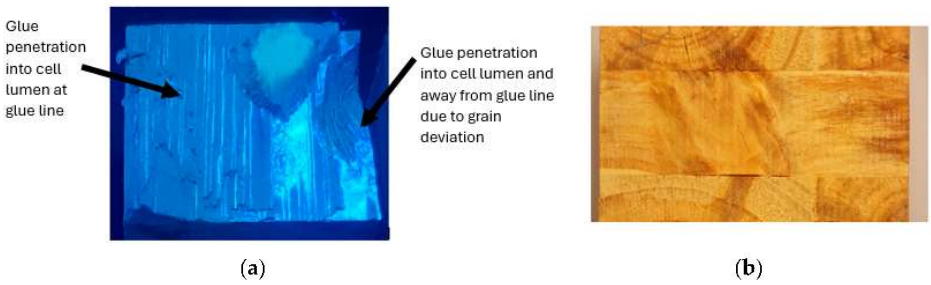


Figure 14. (**a**) A sample under UV light showing glue penetration into the cell lumen; (**b**) an example of delamination and wood failure on opposite glue lines of the same knot.

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.

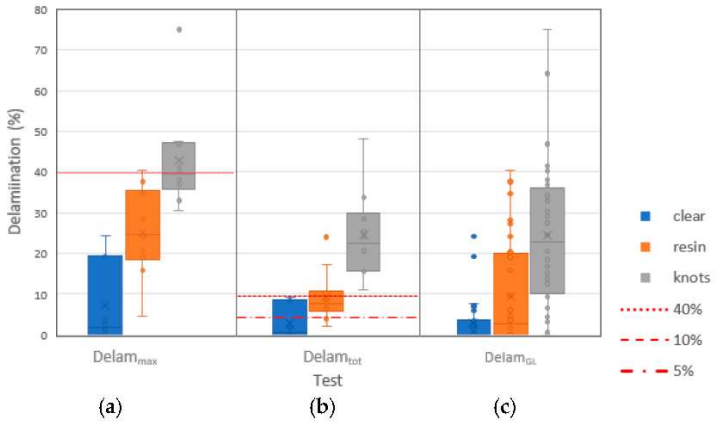


Figure 15. Percent of delamination in (**a**) the glue line of each sample with the maximum delamination, (**b**) each test sample, and (**c**) each of the 40 glue lines for each sample type.

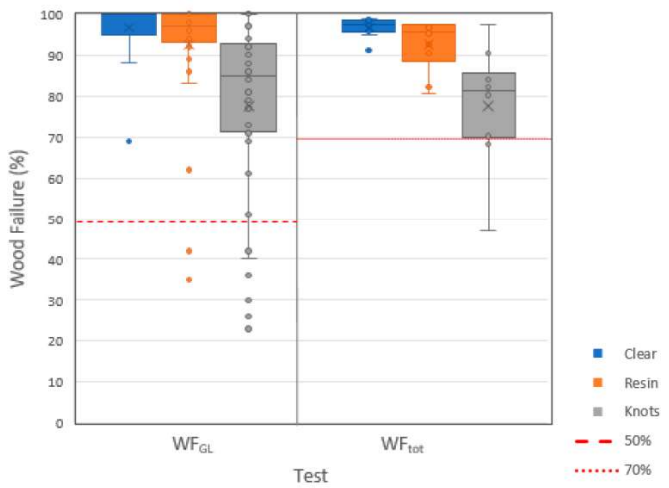


Figure 16. Wood failure of individual glue lines and total wood failure within a sample.

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 $\geq$ 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.

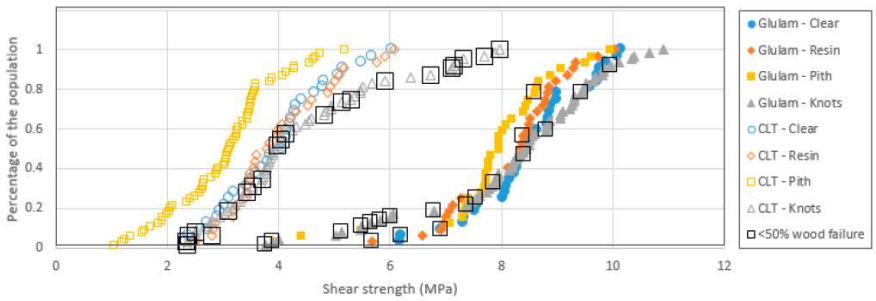


Figure 17. Glulam and CLT bond line shear strengths. Black boxes represent samples with less than 50% wood failure, the majority of which are knot sample types.

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% $\times$ 0.2 + 5% $\times$ 0.4 + 10% $\times$ 0.6 + 10 $\times$ 1 = 19%) and, therefore, meet the criteria of $\geq$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$\times$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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5.3. Links and implications

The study presented in Chapter 5 investigated the bond performance and bond quality of out-of-grade PEExPCH hybrid pine. The pass/fail criteria of three national CLT standards were used and compared. Clear out-of-grade PEExPCH performed well with very little delamination, high average wood failure percentage and good bond line shear strength results with 100% pass rate of the criteria in the European and International standards. Resin, knots and pith had a negative effect on bond performance and quality and were not addressed in the evaluation of delamination or shear strength in any standard. PRG320 was the only standard to restrict these characteristics over and above structural grading rules. This is a critical issue for the use and evaluation of out-of-grade timber in engineered wood products. A proposed modification to the PRG320 effective bond area was presented as a proactive solution. With the evaluation of the mechanical properties and bond performance of out-of-grade PEExPCH gained from chapters 3, 4 and 5, the potential for its use in CLT has been further confirmed, with some restrictions required on inclusion of knots for structural performance and resin, knots and pith for bond performance and quality requirements. Using these mechanical properties, analytical models can be used to further evaluate and optimise CLT layup to maximise out-of-grade PEExPCH inclusion. Chapter 6 investigates the bending MOE and strength of CLT manufactured from out-of-grade PEExPCH and effect of wood-based reinforcements.

CHAPTER 6: PAPER 5 - STRUCTURAL PERFORMANCE AND EVALUATION OF CROSS LAMINATED TIMBER MANUFACTURED FROM LOW-STIFFNESS OUT-OF-GRADE HYBRID PINE, THE EFFECT OF WOOD-BASED REINFORCEMENTS

6.1. Introduction

CLT has many benefits including environmental performance, large market opportunity, design flexibility, structural performance, lighter faster construction, cost competitiveness and liveability (Crespell & Gagnon, 2010). The unique design and intrinsic lamination effect of CLT, offers opportunity to incorporate large volumes of this out-of-grade PEExPCH in place of in-grade timber. The bending, compressive, longitudinal shear and tension properties of out-of-grade PEExPCH and the effect of resin, knots and pith were evaluated in Chapter 3. The rolling shear properties and effect of resin, knots, pith and growth ring pattern were evaluated in Chapter 4. The bond performance properties and the effect of resin, knots and pith were evaluated in Chapter 5. From the results and information gained from these studies, it was confirmed that out-of-grade PEExPCH is suitable for the manufacture of CLT, especially for the inner and transverse layers with some restrictions needed on knots for structural performance, and on knots, resin and pith for bond performance. The low bending properties of the out-of-grade PEExPCH indicate the CLT manufactured from it will also have low bending properties. Where out-of-grade PEExPCH is used in all layers of CLT it is expected there will be a need for reinforcement to increase bending properties to meet the performance requirements and minimum spans of building applications. The study in Chapter 6 investigates the bending MOE and strength performance of CLT manufactured from out-of-grade PEExPCH and the effect of wood-based reinforcements. It also verifies the accuracy of the shear analogy method to predict the bending MOE based on the structural properties of out-of-grade PEExPCH as determined in Chapters 3 and 4.

6.2. Paper Ready for Submission

Structural Performance of Cross Laminated Timber Manufactured from Low-stiffness Out-of-grade Hybrid Pine; Effect of Wood-based Reinforcements.

Rebecca Cherry [1,2], Warna Karunasena [1,*], and Allan Manalo [1]

[1] Centre for Future Materials, University of Southern Queensland, West Street, Toowoomba, QLD 4300, Australia; rebecca.cherry@hyne.com.au (R.C.); allan.manalo@unisq.edu.au (A.M.)
[2] Hyne & Son Pty Ltd., Kent Street, Maryborough, QLD 4650, Australia
* Correspondence: karu.karunasena@unisq.edu.au

Abstract

Large volumes of out-of-grade timber can be incorporated in cross-laminated timber (CLT) because of the intrinsic lamination effect in CLT as well as in the inner and transverse layers which are exposed to lower compressive and tensile stresses. This study investigated the bending Modulus of Elasticity (MOE) and bending strength of 3-layer CLT manufactured from low-stiffness out-of-grade hybrid pine. It investigated the effect of high-grade timber and plywood as reinforcements and verified the accuracy of the shear analogy method to predict the bending MOE of these combinations. The 100% low-stiffness out-of-grade CLT achieved an average bending MOE of 6.2 GPa and an average flexural strength of 24.9 MPa. Frequently occurring knots that consequently aligned accross the bottom layer under tension, attributed to reduced performance. The high-grade reinforcement provided the largest improvement on both bending MOE and strength with increases of 53% and 93%, respectively. The plywood reinforcements also increased bending MOE between 6% and 13% and increased strength between 34% and 64%. CLT made only from timber failed in tension at knots located throughout the bottom layer, whereas the panels with plywood failed in a straight line aligning with the tensile failure plane of the plywood panel on the bottom layer. The shear analogy method predicted bending MOE with good accuracy.

Key Words

cross laminated timber, resin, knots, out-of-grade, low-stiffness, shear analogy method, reinforcement, PEExPCH hybrid pine, plywood.

1. Introduction

Cross Laminated Timber (CLT) is a mass engineered wood product, which due to its size, intrinsic lamination effect, extensive possible applications and increasing use in the construction and building industry, has potential to use large volumes of low value and out-of-grade timber that has fallen short of the requirements of the highly sought after structural grades. With the continued change toward smaller diameter and/or faster grown plantation trees, there is an increasing percentage of lower quality, low-stiffness juvenile and corewood (Fridley, 2002). CLT offers a highly sustainable construction solution throughout all stages of its life cycle (Sandoli & Calderoni, 2020). It was initially developed to value add sawn side boards (Brandner et al., 2016) but results of recent research show that it offers good potential to other low-value low-grade timber products. Negri et al. (2012) performed cyclic tests on CLT wall panels made from out-of-grade Spruce and found that 3-layered CLT panels made from out-of-grade timber had similar mechanical properties to those made from mid-grade timber. Concu et al. (2018) concluded that medium quality CLT panels could be produced from low-quality timber with CLT bending strength more than double that of the tensile strength of the individual boards. Baño et al. (2018) investigated CLT made from loblolly and slash pine with low mechanical properties and found the resulting CLT had characteristic bending strength up to 43% higher than the individual layers. Additionally, transverse layers of CLT must resist rolling shear stresses and several studies have identified that the rolling shear modulus of elasticity (MOE) is not linked to the grade of timber but rather the growth ring pattern has a significant effect with the closer to the pith the higher the rolling shear MOE (Ehrhart & Brandner, 2018). Moreover, knots which are frequent in out-of-grade timber have shown to improve rolling shear performance (Cherry et al., 2024). Researchers and industry are recognising the potential for low or out-of-grade timber in CLT and have begun the research into understanding the impacts and facilitation of this. Silva do Carmo, Englund, and Li (2022) investigated the pressure requirements to overcome distortion in low grade timber and its impacts on bond performance and found no significant difference between the average of the different pressure zones. Cherry et al. (2023) investigated the bond performance of out-of-grade timber and the impact of its common occurring characteristics of resin, knots and pith. They also discussed the standards lack of evaluation of these characteristics on the bond performance

and proposed a modified version of effective bond area as a proactive approach for their inclusion.

Production of CLT continues to grow around the world (Sandoli & Calderoni, 2020), in central Europe alone it is estimated to have doubled from 2020 to more than 2 million m^3 in 2023 (Olsson et al., 2023). As the demand and use of CLT increases in the construction and building industry, the number of CLT manufacturing plants built around the world increase and so too does the demand for feedstock volumes and options. The species of timber investigated for the manufacture of CLT is expanding with numerous softwoods and hardwoods being considered (Ehrhart & Brandner, 2018; Ukyo et al., 2019). Using locally and sustainably grown timber species reduces environmental impact and costs associated with transportation of timber, supports local jobs and the economy and has the convenience of local timber mills for supply. An ideal solution is to optimise CLT layup and feedstock to include abundantly available, local, low value feedstock that meets the requirements of CLT and can be substituted in place of high value high demand in-grade structural timber.

One of the by-products created during the processes of milling and grading in-grade timber is out-of-grade timber. Out-of-grade timber is an abundant and underutilised resource that is often sold at a loss (Dewbury, 2016) and saw millers around the world are faced with the challenge to find value add opportunities. In Queensland Australia, the predominant species has recently become *Pinus elliotti* var. *elliottii* (Engelm) x *Pinus caribaea* var. *hondurensis* (Sénéclauze) (PEExPCH) hybrid pine. The majority of out-of-grade PEExPCH is low-stiffness timber from the corewood zone of the tree and frequently contains resin, high-angled clustered conical-shaped knots and pith (Cherry et al., 2022). New research indicates that the low-stiffness out-of-grade PEExPCH is a good candidate for the manufacture of CLT but as Moore and Cown (2017) point out, very few studies have examined the impact of corewood on the performance of CLT.

C24 (EN 338, 2016) grade timber is common in homogenous CLT layups and as outer layers in combined CLT layups which use C16 or C18 as the transverse layers (Brandner et al., 2016) with some manufacturers also using C14 (Wieruszewski & Mazela, 2017). The design characteristic properties were

calculated from the results of Cherry et al. (2022) using AS4063.2:2010 Characterisation of structural timber: Part 2: Determination of characteristic values (Standards Australia/New Zealand Standards, 2010). It was found that clear and resin samples meet or exceed the strength class requirements of C14 and C16 (EN 338, 2016) apart from bending MOE, which on average, clear and resin samples combined are 7% and 13% lower than C14 and C16, respectively. They also meet C18 except for bending MOE and compression perpendicular to grain MOE. Knots fell short of C14 only on bending MOE and strength by 26% and 11%, respectively, and could be limited or excluded to increase these properties if necessary. Nevertheless, the transverse layers in CLT are required to resist rolling shear stresses and knots have been found to increase rolling shear performance. Moreover, the rolling shear MOE and strength of low-stiffness out-of-grade PEExPCH at 108 MPa and 2.4 MPa, respectively, were found to be mid range compared to other softwood timber species and in some cases higher than timber species already used in the production of commercial CLT (Cherry et al., 2024). Brandner et al. (2016) note that due to a change with CLT producers now using more boards cut close to the pith, current CLT products have higher rolling shear modulus. This demonstrates that there are many benefits and good opportunity to use low-stiffness out-of-grade PEExPCH in the manufacture of CLT. Individually, the properties of low-stiffness out-of-grade PEExPCH timber show good potential at least for inner and transverse layers of CLT and this needs to be confirmed with structural testing of CLT panels.

Reinforcements via addition or partial substitution can provide improved structural performance where required such as bending MOE and strength and can be used to facilitate the inclusion of lower performing timber. Several studies have investigated using different timber species and wood-based material and seen improvements in rolling shear performance (Yang et al., 2021). Valdes et al. (2020) externally reinforced CLT made from maritime pine with natural flax fibre fabrics and found three layer panels bending MOE and strength were significantly increased. Yang et al. (2023b) investigated plywood, laminated veneer board, oriented strand board and particle board as the inner longitudinal layers in 5-layer CLT and found they improved structural properties in bending, compression and shear with laminated veneer board and ply performing the best. Karmar, Barbosa, and Sinha (2013) investigated CLT as a

value add option for low density hybrid poplar not traditionally used for structural applications. They found good performance in bending and shear strength but low bending MOE for which they proposed a solution to use other higher grade timbers as reinforcements to achieve bending MOE targets. Sigrist and Lehmann (2014) investigated out-of-grade Radiata pine in CLT and found with optimisation of layup and the use of wing board or high grade timber reinforcements, bending MOE and strength increased by up to 100% and found performance similar to European CLT products could be achieved. One of the challenges with using lower quality timber is the likely need for increased depth of members to achieve the performance requirements. This in turn affects design and costs associated with the deeper member, such as lower clearances and/or additional building height and associated additional resources required to accommodate this, such as cladding and length of services. Baño et al. (2018) found the use of low grade loblolly and slash pine required between 14% and 26% additional thickness compared to CLT made from C24 (EN 338, 2016) grade timber to achieve the performance requirements for residential and office buildings. Wood and wood-based reinforcement products such as high-grade timber and structural ply are sustainable options, which may increase the bending performance of low-stiffness out-of-grade PEExPCH and facilitate its use in CLT while maintaining the smaller element depths similar to others on the market

As Olsson et al. (2023) point out, the timber boards that make up a population have varying structural properties and it is important to know if those properties relate to the final CLT product. While experimental methods are the most accurate for determining the structural properties of CLT, this is an expensive and time-consuming process. Analytical models are available and commonly used to estimate the strength of stiffness of CLT based on the timber properties used in their manufacture (Karacabeyli & Gagnon, 2019). The CLT handbook (Karacabeyli & Gagnon, 2019) provides details and recommendations on analytical models to determine CLT performance. Timoshenko beam theory, the shear analogy method and Gamma method are the most common. Of these, many have found the shear analogy method to be the most accurate for CLT (Karacabeyli & Gagnon, 2019; Li et al., 2021; Lim et al., 2020) and for ply-lam CLT (Yang et al., 2023b). The shear analogy method takes into consideration the

shear deformations of the transverse and longitudinal layers. It separates the multi-layer cross-section of the CLT into two virtual beams connected with infinitely rigid web members with equal deflection and the results for the entire cross section are obtained by overlaying the bending moment and shear forces of both beams (Karacabeyli & Gagnon, 2019). As pointed out by Li et al. (2020), the analytical modelling approaches have predominantly been used to investigate homogeneous CLT panels and more work is need to verify these models for heterogeneous CLT. The accuracy of the shear analogy method in predicting CLT with plywood and high-grade timber reinforcement needs to be verified.

CLT panels are typically lower in bending MOE and higher in bending strength compared to the timber they are manufactured from. Baño et al. (2018) investigated CLT made from small diameter logs of loblolly and slash pine from thinning operations and found the average bending strength of the CLT panels were 7% higher than the individual sawn timber boards while the average MOE of the CLT was 13% lower. Karmar, Barbosa, and Sinha (2013) investigated CLT made from low-density hybrid poplar and found the MOE of the finished CLT was 10% lower than the timber used in its manufacture. Sikora, McPolin, and Harte (2016) investigated CLT made from Irish Sitka Spruce and found MOE of the CLT panels were on average 10% lower for bending MOE than the feedstock used for their manufacture. Fortune and Quenneville (2011) investigated CLT made from radiata pine and found the MOE of the CLT panels were between 7% and 30% lower than that of the boards that made up their outer layers. Gong et al. (2019) investigated CLT made from Japanese larch and found the CLT was between 3.6% and 17.9% lower than the MOE of the outer layers. Understanding the effect of reinforcements on this difference will help inform decisions on optimising CLT layup solutions.

The main aim of this study is to evaluate the suitability of low-stiffness out-of-grade PEExPCH hybrid pine for the manufacture of CLT with and without wood based reinforcements. To achieve this, the following objectives will be completed:

a. Evaluate the bending MOE and strength of CLT made of low-stiffness out-of-grade PEExPCH through experimental testing
b. Compare the bending MOE and strength of the timber feedstock properties to that of the finished CLT panels.
c. Evaluate the effect of reinforcement on MOE and strength
    i. High grade timber
    ii. 6.5mm F17 plywood on one face
    iii. 6.5mm F17 plywood on both faces
    iv. 16mm F17 plywood on one face
    v. 16mm F17 plywood on both faces
d. Verify the accuracy of using shear analogy method to predict bending MOE of these various combinations of CLT with and without wood based reinforcements.
e. Examine the failure behaviour of CLT made from out-of-grade PEExPCH and the effect of high-grade timber and ply reinforcements.

The results of this study will provide valuable information for the timber and building and construction industries for design, product development, optimisation and manufacture utilising low-grade timber.

2. Materials and methods

2.1. Samples

3-layer CLT panels were manufactured using low-stiffness out-of-grade PEExPCH timber with and without reinforcements. 3-layer CLT panels were selected so that the span to depth ratio requirements of EN408:2012 of greater than 18 could be achieved for the majority of the sample types. Only the 2Ply16 fell short of this target. The ply thickness and grade was selected with the aim to

use commonly available and characterised resource with two different thicknesses to reveal if the thicker ply achieved a greater difference in results.

The PEExPCH was harvested from Cowra, Queensland, Australia at an age of 31 years and is the same resource used in other related studies (Cherry et al., 2022, 2023, 2024). It was a common framing size of 90x35 mm^2 and failed to meet the requirements of the Machine Graded Pine standards (MGP) as set out in AS1748 (Standards Australia/New Zealand Standards, 2011) and AS1720.1 (Standards Australia, 2010). More detail on the characteristics and structural performance of this timber can be found in Cherry et al., (2022), rolling shear performance in Cherry et al. (2024) and bond performance in Cherry et al., (2023). Basic visual grading rules were used to eliminate large sections of resin shake, undersize pieces that would not achieve a clean planed surface for gluing, and knots or other characteristics that could cause a processing issue such as breaking in the planer. The dynamic MOE of all boards were measured using Beam Identification by Non-destructive Grading system (BING) which is a non-destructive system that estimates properties of timber using vibration analysis (Paradis et al., 2017). The MOE was recorded on the end of each piece as seen in Figure 1(a). The population average MOE is 7.0 GPa and aligns closely with results for bending MOE of this feedstock in Cherry et al. (2022). This information was tracked through into the final CLT samples so that the MOE of each board in each location of each CLT sample is known and was used for predicting the apparent beding MOE. The size of the CLT panels were 1200 mm wide and 2400 mm long which was the maximum size that could be made in the panel press.

(a) (b)

Figure 1 (a) Low-stiffness out-of-grade PEExPCH labelled with dynamic MOE and ready for planing. (b) CLT panel showing common occurring characteristics of low-stiffness out-of-grade PEExPCH.

The reinforcement materials used were a high grade southern pine which had been graded in accordance with AS1748:2011 (Standards Australia/New Zealand

Standards, 2011) and AS1720.1:2010, or F17 structural grade ply made from hoop pine and graded in accordance with AS/NZS 2269:2012 (Standards Australia/New Zealand Standards, 2012). The material properties can be seen in Table 1.

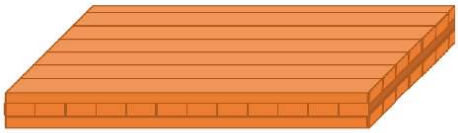
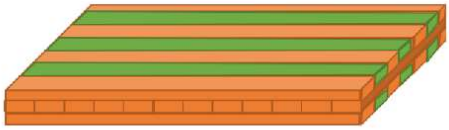
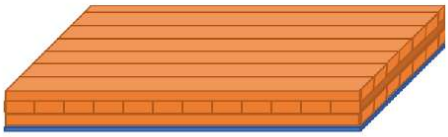
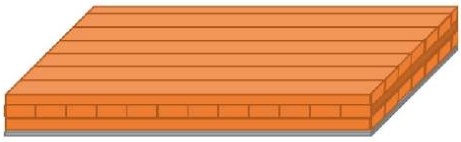
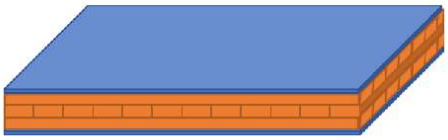
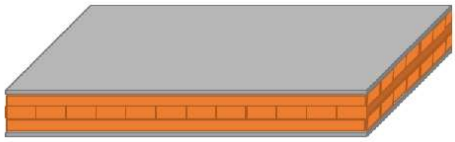
Table 1 Properties of materials

		Density (kg/m^3)	MOE_0 (GPa)	MOE_{90} (GPa)	G_0 (GPa)	G_{90} (GPa)	Ave F_b (MPa)
Out-of-grade	90 mm x33 mm	600	7.0	0.27[a]	0.590[a]	0.108[b]	Clear 45.8[a] Knots 26.7[a]
HGR	90 mm x 33 mm	650	16.1		1.010[c]		90.3[d]
Plywood	6.5 mm	600	11.2[e]		0.561[f]		82.1
Plywood	16 mm	600	10.7[e]		0.533[f]		75.3[f]

[a] Cherry et al. (2022)
[b] Cherry et al. (2024)
[c] AS1720.1 (Standards Australia, 2010)
[d] Sourced from the supplier
[e] Testing
[f] G_0 = MOE/20 (Standards Australia/New Zealand Standards, 2012)

The southern pine high-grade timber used for reinforcement were 90 mm x 35 mm and had a population average MOE of 16.1 GPa. It was alternated with out-of-grade PEExPCH in the outer layers of the CLT to make up every second piece as illustrated in Table 2(b) HGR. The plywood reinforcement was either 6.5 mm thick or 16 mm thick. The ply was either glued to the bottom of a 3 layer 100% low-stiffness out-of-grade CLT panel as illustrated in Table 2 c & d, or it was glued to both the top and bottom of the CLT panel as illustrated in Table 2 e & f. The 1Ply6.5 sample type has only one repetition because of resource constraints at the time of manufacture and therefore is not sufficient for reliability analysis of the result, but has been included throughout the discussions as an indication only.

Table 2 Test Samples

Sample Type	Layer and Description	No. Repititions	Depth (mm)	Width x Length: 1200 mm x 2400 mm
(a) (OOG)	1: 100% out-of-grade 2: 100% out-of-grade 3: 100% out-of-grade	3	99	
(b) (HGR)	1: out-of-grade/HGR alternating 2: 100% out-of-grade 3: out-of-grade/HGR alternating	3	99	
(c) (1Ply6.5)	1: 100% out-of-grade 2: 100% out-of-grade 3: 100% out-of-grade 4: 6.5 mm ply	1	106	
(d) (1Ply16)	1: 100% out-of-grade 2: 100% out-of-grade 3: 100% out-of-grade 4: 16 mm ply	3	115	
(e) (2Ply6.5)	1: 6.5 mm ply 2: 100% out-of-grade 3: 100% out-of-grade 4: 100% out-of-grade 5: 6.5 mm ply	3	112	
(f) (2Ply16)	1: 16 mm ply 2: 100% out-of-grade 3: 100% out-of-grade 4: 100% out-of-grade 5: 16 mm ply	3	131	

The wide face of the timber was planed resulting in a cross sectional size of 90 mm x 33 mm. The face of the ply being bonded was sanded using an orbital sander with 80 grit sandpaper just prior to glueing. The adhesive used was a

type 1, one-component polyurethane, Jowapur 681.40 which is primarily used for adhering wood. Jowapur 681.40 contains isocyanate and polyurethane and has a viscosity of between 13,000 cPs to 18,000 cPs, a density of approximately 1.15 g/cm^3. It is formaldehyde free, solvent free, emission-free and odorless when in cured state (Gluespec., n.d.). The adhesive was applied within the specifications given by the manufacturer at a spread rate of approximately 200 g/m^2 which results in 400 g/m^2 of completed panel for 3 layers, 600 g/m^2 for 3 layer with 1 ply sheet and 800 g/m^2 for 3 layers with 2 ply sheets. A Wagner L622 hand-held moisture meter (Wagner Meters, Rogue River, OR) was used to measure the moisture content of the timber. The moisture content was within the glue manufacturers' specified range of 8% to 18%, with an average of 12.4% and a standard deviation of 2%. The timber was not edge glued. An industrial panel press (Orma Macchine, Bergamo Italy) (Figure 2) was used to press each panel at a pressure of 0.8 N/mm^2 which is within the manufacturers specifications of between 0.6 N/mm^2 and 1.0 N/mm^2. Also in accordance with the adhesive manufacturer's specifications, assembly time was kept under 40 minutes and the panels were left in the press overnight, which exceeds the minimum press time of 60 minutes. The temperature ranged between 23°C and 29°C during the first 2 hours of each pressing. Finally, the eight 1200 mm x 2400 mm CLT panels were sawn longitudinally down the centre to create sixteen 600 mm x 2400 mm CLT samples that would fit in the bending test rig. The average density of the ply was 600 kg/m^3. The average of all the CLT panels types was 601 kg/m^3 and all were within the range of 571 kg/m^3 and 622 kg/m^3 with the OOG being the lowest density and the HGR being the highest.

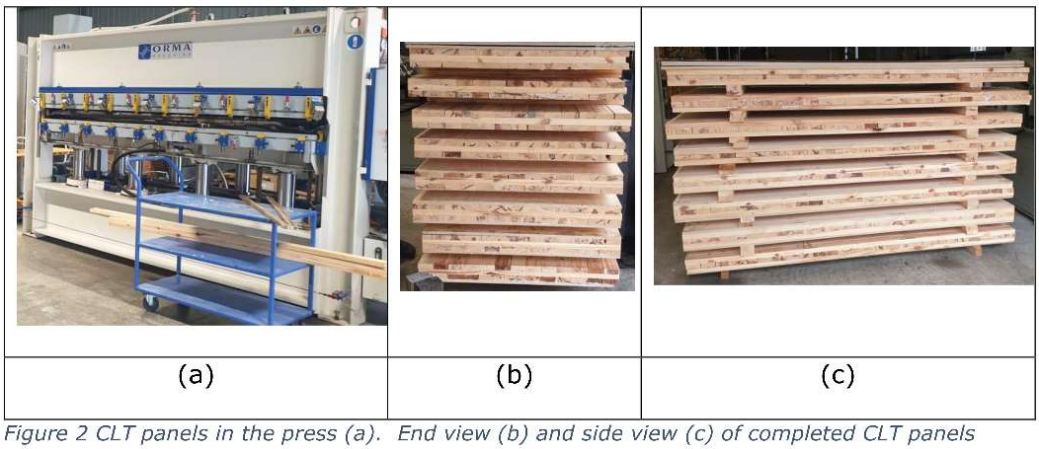


Figure 2 CLT panels in the press (a). End view (b) and side view (c) of completed CLT panels

2.2. Methods

2.3. Experimental tests – setup and procedure

To evaluate the bending MOE and strength of the CLT panels, four-point bending tests were carried out in accordance with EN408:2012 (European Committee for Standardization, 2012) as recommended in EN16351: 2021 (European Committee for Standardization, 2021). EN408:2012 requires a minimum sample length of 19 times the depth of the section. However, the size of the bed on the press used to manufacture the CLT panels was 2400 mm long which meant the 2Ply16 sample types were 100 mm short of their 2500 mm target. Additionally, the span/depth ratio for the 2Ply16 samples was 16.5, all other sample types achieved a span/depth ratio >=18.

The samples were tested for MOE, then flipped over and tested for MOE again with the opposite face up, which was done to determine if there was a difference in MOE performance based on orientation. All samples were then loaded to failure with the 1 ply sample types having the ply on the tensile face. The testing was completed on a custom test rig (Hyne, Maryborough, Australia) with a 100 tonne press (MetalMaster, China) at a load rate of 3 mm/minute and in the configuration shown in Figure 3. The deflection of the CLT panel was measured by two string transducers, attached to each side of the panel. EN16351:2019 requests local MOE rather than global MOE. The global displacement accounts for both bending and shear deformations whereas the local displacement only accounts for bending deformation. Several researchers found local and global bending stiffness to be similar and less than 3% of each other when using large span/depth ratios (Baño et al., 2018; He et al., 2021; Li et al., 2020). Li et al. (2020) stated that due to high span to depth ratio, shear deformation theory is not necessary where bending deformation dominates failure. O'Ceallaigh, Sikora, and Harte (2018) results show a larger difference, with on average 27% higher local compared to global MOE with global being much closer aligned to the theoretical bending stiffness. Sikora, McPolin, and Harte (2016) found greater scatter in the local bending MOE compared to Global and attributed this to variation in the MOE along the sample rather than the impact of shear. They also found good alignment between theoretical and experimental results using

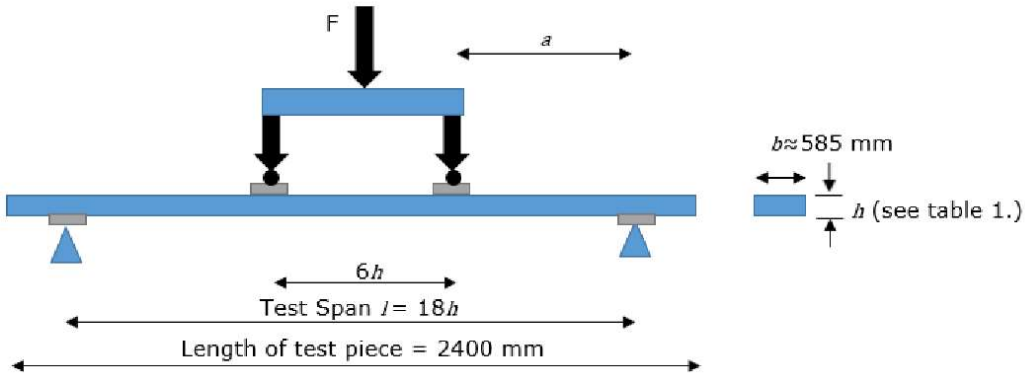
global MOE. For these reasons, the global MOE was measured rather than the local MOE.

The global bending MOE (GPa) and strength (MPa) from experimental tests are calculated using equations (1) and (2) as per EN408:2012.

$$E_{m,g} = \frac{3al^2 - 4a^3}{2bh^3\left(2\frac{w_2 - w_1}{F_2 - F_1} - \frac{6a}{5Gbh}\right)} \quad (1)$$

$$f_m = \frac{3Fa}{bh^2} \quad (2)$$

where, F_2-F_1 is an increment of load in newtons and was taken between $0.1F_{max}$ and $0.4F_{max}$, w_2-w_1 is the increment of deformation corresponding to F_2-F_1, in mm. F is the applied load initiating failure in the test piece in newtons (N), G is the shear modulus, in MPa, a is the distance between a loading position and the nearest support in a bending test, in mm, b is the width and h is the total height of the panel, in mm.



(a)

(b)

Figure 3. Four point bending (a) test configuration and (b) test rig

2.4. Apparent bending MOE using shear analogy method

The shear analogy method as recommended and set out in the CLT handbook (Karacabeyli & Gagnon, 2019) was used to calculate properties of the CLT panels using the structural properties of the feedstock and geometry of the panel. The apparent bending MOE (E_{app}) can be calculated using equation (3).

$$E_{app} = \frac{12EI_{app}}{bh^3} \qquad (3)$$

where, EI_{app} is the apparent bending stiffness.

The various versions of the CLT Handbooks provide different methods to calculate EI_{app} of CLT panels. Canadian 2011 edition (Gagnon & Pirvu, 2011) provides a formula based on the effective bending stiffness (EI_{eff}), effective shear stiffness (GA_{eff}) and uses a fixed factor of 11.52 with length as a variable. The USA version 2013 (Karacabeyli et al., 2013) replaces the fixed 11.52 value with a "K" factor which is based on the influence of shear deformation specific to different loading conditions and end fixity and range from 3.6 to 57.6. In the latest edition, Canadian 2019 version (Karacabeyli & Gagnon, 2019), the apparent bending stiffness formula has been replaced with a simplified shear free effective bending stiffness of 90% of the effective stiffness for ease of use in calculations for vibration.

The difference between the 2011, 2013 and 2019 version for calculating the EI_{app} for a CLT panel under 4 point bending configuration are illustrated in Figure 4(a). Crovella, Smith, and Bartczak (2019) specify a K-factor of 12.96 as suitable for four point bending configuration and has been used in the calculations for this comparison. The example given is of OOG.a sample. This comparison shows that for the four point bending configuration, the simplified Canadian 2019 version is non-conservative at short spans compared to the USA 2013 and Canadian 2019 versions but becomes conservative at spans longer than 4800 mm and 4200 mm, respectively. Figure 4(a) illustrates the effect of varying the K factor. It shows the highest K factor provided in the CLT Handbook (Karacabeyli et al., 2013) at 57.5, the lowest at 3.6 and the K factor used in this study of 12.96. Using the K factor relevant to the loading conditions and fixity has a considerable impact on the shorter spans.

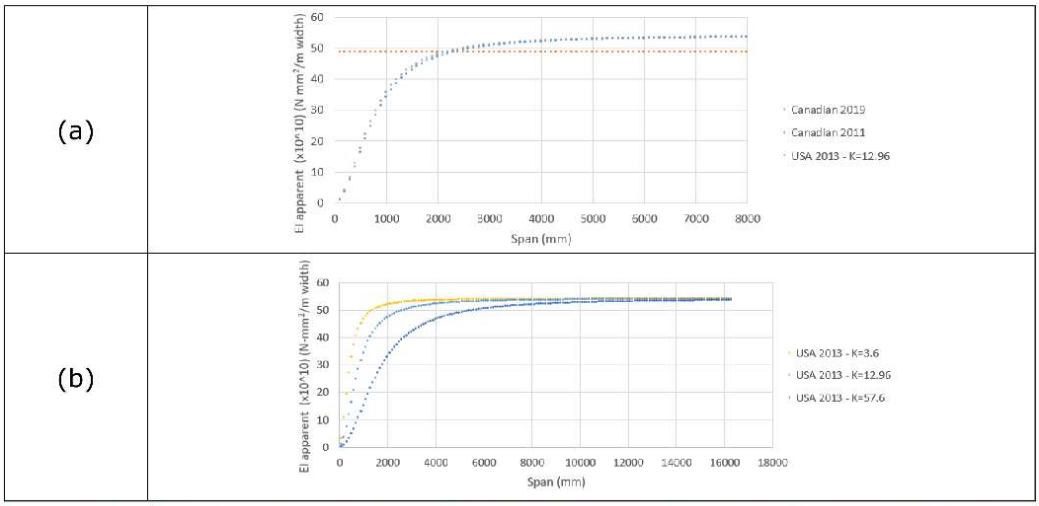


Figure 4 EI vs Span for sample OOG.a. (a) Shows the different CLT handbook editions and (b) shows the range of K factors for different loading and fixity conditions given in 2013 Edition.

The USA 2013 (Karacabeyli & Gagnon, 2019) CLT Handbook edition will be used in this study for calculating $(EI)_{app}$ using equation 4

$$(EI)_{app} = \frac{(EI)_{eff}}{1+\left(\frac{K_S(EI)_{eff}}{(GA)_{eff}L^2}\right)} \qquad (4)$$

where, K_s is a constant based upon the influence of shear deformation and for which the value of 12.96 is suitable for four point bending configuration

(Crovella et al., 2019). $(EI)_{eff}$ is the effective bending stiffness and was calculated using equation 5. $(GA)_{eff}$ is the effective shear stiffness and was calculated using equation 6

$$(EI)_{eff} = \sum_{i=1}^{n} E_i * b_i * \frac{t_i^3}{12} + \sum_{i=1}^{n} E_i * b_i * t_i * z_i^2 \qquad (5)$$

where, b_i is the width of the panel in mm, E_i is the MOE of laminations in the *i*-th layer, in MPa, taken as either longitudinal MOE for longitudinal layers and perpendicular to grain MOE for transverse layers. n is the number of layers in the panel, t_i is the thickness of lamination in the i-th layer, in mm, z_i is the distance between the centre point of the *i*-th layer and the neutral axis of the CLT panel, in mm

$$(GA)_{eff} = \frac{a^2}{\left[\left(\frac{t_1}{2*G_1*b}\right)+\left(\sum_{i=2}^{n-1}\frac{t_i}{G_i*b_i}\right)+\left(\frac{t_n}{2*G_n*b}\right)\right]} \qquad (6)$$

where, h is the thickness of the panel, in mm, G_i is the shear modulus of laminations in the i-th layer, in MPa, taken as either longitudinal shear MOE for longitudinal layers and rolling shear MOE for transverse layers and a is the distance between the neutral axis of the outer layers, in mm.

The neutral axis (Z) of the panel was calculated using equation 7.

$$Z = \frac{\sum_{i=1}^{n}(E_i A_i)*Y_i}{\sum_{i=1}^{n}(E_i A_i)} \qquad (7)$$

Where, A_i is the area of the i-th layer, in mm^2 and Y_i is the distance from the top of the panel to the centre of the i-th layer, in mm.

3. Results

The E_{app} and bending strength was determined through experimental testing for 16 CLT specimens with three repetitions of each sample type except for 1Ply6.5, which had 1 sample due to resource limits at the time of manufacture and therefore no conclusion can be made from the 1Ply6.5 sample due to insufficient reliability, but has been included in the discussions as an indication only. The shear analogy method (SAM) was then used to predict E_{app} using the properties of the feedstock and geometry of the panel. The results are listed in Table 3

Table 3 Bending properties of CLT with and without wood-based reinforcement

Sample ID	Eapp, exp (GPa)	Eapp, SAM (GPa)	Strength (MPa)
OOG.a	6.6	5.8	29.2
OOG.b	5.9	5.8	23.6
OOG.c	6.1	6.0	22.0
average	**6.2**	**5.9**	**24.9**
HGR.a	9.9	8.7	50.8
HGR.b	9.3	8.8	46.5
HGR.c	9.5	8.9	47.2
average	**9.5**	**8.8**	**48.2**
1Ply6.5.a	6.6	6.6	40.9
average	**6.6**	**6.6**	**40.9**
2Ply6.5.a	7.0	7.3	34.7
2Ply6.5.b	7.0	7.4	33.8
2Ply6.5.c	6.8	7.3	35.2
average	**6.9**	**7.3**	**34.6**
1Ply16.a	6.6	6.5	30.6
1Ply16.b	6.8	6.6	41.3
1Ply16.c	6.5	6.6	37.6
average	**6.6**	**6.6**	**36.5**
2Ply16.a	7.3	7.8	30.8
2Ply16.b	6.9	7.8	34.4
2Ply16.c	6.9	7.7	35.2
average	**7.0**	**7.8**	**33.4**

4. Discussion

4.1. Out-of-grade CLT

The OOG sample types achieved an average E_{app} of 6.22 GPa and average strength of 24.9 MPa. These results are similar to other studies that investigated CLT manufactured from low-grade and young timber feedstock. Baño et al. (2018) investigated CLT made from small diameter logs of loblolly and slash pine from thinning operations and found these panels achieved an average of 6.38

GPa and 21.2 MPa bending MOE and strength, respectively. Fortune and Quenneville (2011) investigated CLT made from radiata pine and found 5 layer CLT made from timber boards with an average MOE of 9.6 GPa achieved an average MOE of 7.63 GPa and strength of 27.6 MPa. However, the thinner 3 layer panels made from the same resource performed better with an average of 10.1 GPa and 36.1 MPa for MOE and strength, respectively. Sikora, McPolin, and Harte (2016) investigated 3 layer CLT made from C16 (EN 338, 2016) grade Irish Sitka Spruce with an average MOE of 8.16 GPa and 3 layer panels (thicknesses 60, 100 and 120 mm) achieved an average 7.52 GPa. The 100 mm panels had an average bending strength of 35 MPa compared to the thicker 120 mm panels with an average of 28 MPa. Concu et al. (2018) investigated maritime pine with average MOE of 8.2 GPa and average tensile strength of 11.7 MPa and found the CLT produced achieved average bending MOE of 5.97 GPa and average strength of 26.1 MPa. As expected, CLT made from low-stiffness out-of-grade PEExPCH has low bending and MOE performance.

4.2. CLT compared to timber feedstock structural properties

It is common to see CLT perform slightly lower in bending MOE and higher in bending strength than the feedstock used for its manufacture. The OOG CLT was on average 10.1% less than the average MOE of the clear and resin samples of out-of-grade PEExPCH, and 15.8% higher than the knot samples (Cherry, et al., 2022). The slightly lower average MOE compared to individual boards used for their manufacture is similar to other studies. Baño et al. (2018) reported a 13% reduction in MOE for loblolly and slash CLT, Olsson et al. (2023) found reductions of between 2% and 6% for Scots pine CLT,. Sikora, McPolin, and Harte (2016) found a 10% reduction for CLT made from C16 (EN 338, 2016) grade Irish Sitka Spruce and Concu et al. (2018) found a reduction of 27% in average MOE for maritime pine.

The bending strength of the OOG CLT was on average 45% lower than the clear and resin samples of out-of-grade PEExPCH, and 6.7% lower than knot samples (Cherry et al., 2022). This finding is different to most other studies apart from He et al. (2021) who also found reduced bending strength in CLT with decreases of between 25% and 45% for high visual grade larch. Other studies show an increase in bending strength which is attributed to the lamination effect of CLT. Baño et al. (2018) results show a 7% increase in average strength for loblolly

and slash CLT and Concu et al. (2018) found average strength of CLT to be 158% higher than the average tensile strength of the maritime pine boards it was made from.

While a lower bending strength of CLT compared to the clear and resin timber samples is expected given they were tested knot-free, the CLT performing lower than the knots samples was not expected. On further inspection, this low performance can be attributed to the frequently occurring knots in this out-of-grade resource, which consequently aligned across the entire width of the panel in the bottom layer under tension. CLTs unique design and intrinsic lamination effect enables incorporation of low performing timber pieces by providing reinforcement to low performing characteristics or regions. It creates alternative stress paths in adjacent timber meaning that lower performing characteristic have less negative impact however, this lamination effect is exercised more where greater difference of adjoining timber is used (Falk & Colling, 1995) as can be the case for out-of-grade features like knots. The frequency and alignment of knots that occurred in and across the width of the OOG panels would have undermined this benefit causing this low performance. This is because all surround boards that normally provide the alternative stress paths were likewise compromised by the presence of their own knots. This is an important point, as it is non-conservative to assume the lamination effect is independent of location and frequency of characteristics in timber. Furthermore, while the CLT strength was on average 10% lower than knot samples, they were on average 16% higher in MOE. This demonstrations that in CLT made from low-stiffness out-of-grade PEExPCH, knots have less impact on bending MOE than they do on bending strength. As was also the case in the test results for this out-of-grade timber feedstock (Cherry et al., 2022).

4.3. High-grade Reinforced CLT

The HGR sample type was manufactured by substituting every second piece of timber in the outer longitudinal layers of the CLT with a piece of high-grade timber. All other timber was out-of-grade PEExPCH resulting in 67% out-of-grade and 33% high grade by volume. These HGR panels achieved an average MOE of 9.54 GPa and average strength of 48.2 MPa. This is an increase from the OOG panel type of 53% and 93% for MOE and strength, respectively. These HGR panels are a good example of the lamination effect typically provided by

CLT that was compromised in the OOG sample type by multiple aligned knots. The high-grade reinforcement timber provided alternative stress paths around the low performing areas of the out-of-grade timber adjacent to it. The COV of the MOE in the outer layers of the HGR panels was much higher with an average of 44% compared to 11% for the OOG. The lamination effect of CLT is further exasperated when using timber with a higher COV (Olsson et al., 2023). The average MOE for the high-grade timber in the outer layers was 16.1 GPa and when combined with the out-of-grade timber that average was reduced to 11.2 GPa. The HGR CLT MOE was on average 40.7% and 14.8% lower, respectively, than the average MOE for the high-grade timber and the combined timber feedstock used in their manufacture. It was 46.6% less than the high-grade timber average strength. These results are similar to a study by Yang et al. (2023b) who investigated 3 layer CLT made from larch timber which had an average MOE of 10.3 GPa and average strength of 60.7 GPa. The CLT produced from this timber were on average 6% lower in MOE at 9.7 GPa and 35% lower in average strength at 39.4 MPa. Yang et al. (2023a) investigated 5 layer CLT made from larch with the MOE of the timber in the outer layers being in the range of 10 to 11 GPa. Knots were excluded from timber under tensile stresses. The CLT produced from this feedstock achieved an average of 11.8 GPa and 39.7 MPa in MOE and strength, respectively. Fujimoto et al. (2021) investigated CLT made from Japanese cypress for longitudinal layers and plywood for transverse layers and found the apparent bending MOE was within 1% of the MOE of the outer layers of timber. The timber that made up the outer layers had a bending MOE of >=11 GPa while the CLT achieved an average bending MOE of 10.9 GPa and average bending strength of 49 MPa. These results show that 3 layer CLT made from 67% out-of-grade PEExPCH hybrid pine with 33% high-grade timber reinforcement in the outer longitudinal layer achieve MOE and strength similar to panels made from timber with MOE >10GPa.

4.4. Plywood Reinforced CLT

The plywood reinforced CLT was manufactured using 6.5 mm or 16 mm plywood. The 1Ply sample types had the plywood glued to 1 face of an out-of-grade CLT panel and the 2Ply sample types had plywood glued to both top and bottom faces. The resulting CLT in the 1Ply6.5, 2Ply6.5, 1Ply16 and 2Ply16 CLT contain 94%, 88%, 86% and 76% of volume as out-of-grade timber,

respectively. The average MOE ranged from 6.57 GPa to 7.02 GPa and average strength from 33.4 MPa to 40.9 MPa. While the MOE is relatively low, the bending strength was similar to the findings in other studies. Yang et al. (2023b) investigated 5 layer CLT made from larch with plywood in the 1st, 3rd and 5th layer and the average MOE and strength were 13.2 GPa and 40.9 MPa. Choi et al. (2018) investigated CLT using plywood as transverse layers with average MOE of 3 and 5 layer panels at 10.8 GPa and 8.6 GPa, respectively. Average strength of 67.8 MPa and 43.9 MPa, respectively. These studies show that CLT made from out-of-grade PEExPCH wih plywood reinforcement has high bending strength relative to its bending MOE.

All plywood reinforced combinations resulted in an increase in bending MOE and strength as illustrated in Figure 5. Increases for MOE ranged between 6% and 13% and increases in strength ranged between 34% and 64%. Wang et al. (2017) investigated laminated veneer lumber for outer layers of CLT and found similar increases for MOE at 18% and lower increases for strength at 5%. Wang, Gong, and Chui (2015) investigated laminated strand lumber for outer layers of CLT and found bending MOE and strength were 19% and 36% higher.

The 1Ply6.5 panel had the largest increase in strength and the smallest increase in MOE, however due to resource limitations at the time of manufacture there was only 1 sample for this sample type. Therefore no conclusion can be made from the 1Ply6.5 panel results due to insufficient reliability, but it has been included in the discussions as an indication only. The 2Ply16 sample type had the largest increase in MOE, smallest for strength and the largest increase in panel depth of all the plywood reinforced panels. This trend is seen in other research, with the thicker the panel the higher the MOE and the lower the strength. Sikora, McPolin, and Harte (2016) investigated CLT made from C16 (EN 338, 2016) grade Irish Sitka Spruce and found that an increase of depth by 20%, from 100 mm to 120 mm resulted in a decrease of strength of 27% from 27 MPa to 37 MPa. They also found stiffness increased with increasing panel thickness. Fortune and Quenneville (2011) results show a decrease in strength of 23.5% with and increase of 66% in panel depth from 3 layer to 5 layer CLT. They also found that MOE decreased by 24.5% but this is likely due to the additional transverse layer as can also be seen in Choi et al. (2018).

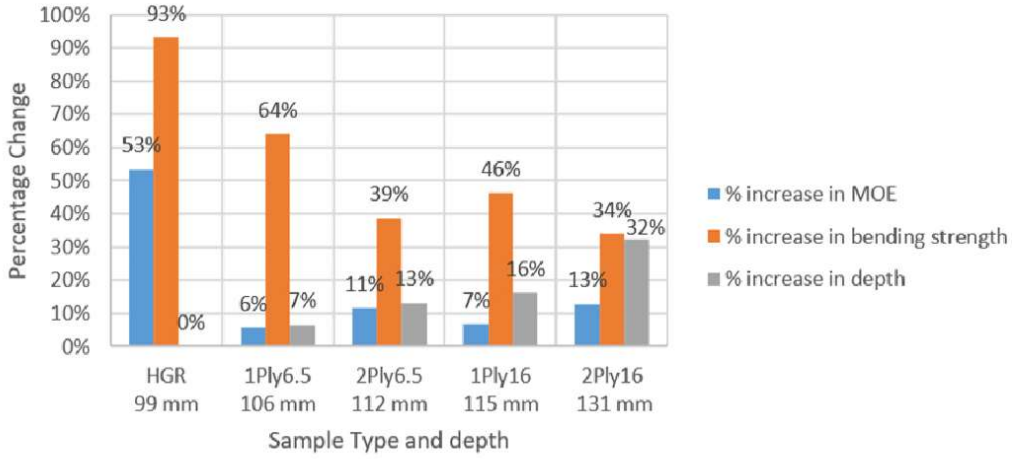


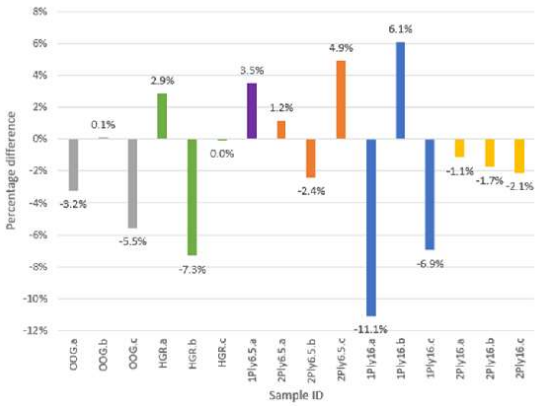
Figure 5 Percentage Change in MOE, bending strength and depth between OOG and reinforced CLT

The HGR increased the MOE and strength more than the plywood combinations and had the benefit of maintaining the same depth of panel. The HGR CLT also do not require the additional manufacturing process of handling, sanding and glueing large sheets of plywood. Yang et al. (2023b) compared CLT with plywood and timber and also found when timber was in the outer layers the best performance was achieved. They concluded that plywood used as outer layers impairs the bending properties; however, consideration needs to be given to the differences in structrual properties between the plywood and the timber being compared and reinforced.

4.5. MOE of different orientations

There are mixed results reported in the literature on the relationship between bending MOE, compressive MOE and tensile MOE. It is often assumed that these are the same (Dinwoodie, 2002) but this is not always proven to be the case (Bolza & Kloot, 1963; Guindos & Guaita, 2014; Shim et al., 2009). The CLT panels were tested for MOE with face 1 up and then flipped and tested again with face 1 down to determine if there was a difference in MOE depending on orientation of the panel. For the non-symetrical samples, 1Ply6.5 and 1Ply16, the plywood is on face 1. On average, the absolute difference is less than 4% of average MOE. The results are illustrated in Figure 6. The panel that had the largest difference of -11.1% was the 1Ply16.a sample which was 0.78 GPa lower in MOE when face 1 was down, so when the plywood was under tension. In this limited dataset, there are no conclusive trends that demonstrate consistently

that one orientation with or without plywood performed better or worse than the other orientation. So for example, no benefit could be guaranteed by placing plywood on the tensile side compared to the compressive side of the panel. It is reasonable to assume that the plywood would behave differently to the solid timber and have different relationships between compressive and tensile MOE. Therefore, it could anticipated that the non-symetrical panels would yield obvious different MOE values based on orientation. In fact, the 1Ply16 series did experience the largest differences but two had lower MOE while the third sample had higher MOE when the plywood was under tension. Moreover, the 2Ply16 samples were the most consistent and had the smallest differences. Given the scatter in the results, and the limited number of repetitions, more testing is needed to make better informed conclusions.



(a)

Figure 6 Percentage difference in bending MOE between face 1 up vs face 1 down

4.6. Shear analogy method predicted MOE

The MOE of each board and its location within each CLT panel was tracked. The average of each layer was used to predict the MOE of the CLT panels using the shear analogy method. The shear analogy method predicted bending MOE with good accuracy for all panel types and within 11% error. The all timber panel types of OOG and HGR were underestimated by 6% and 7%, the 1Ply6.5 and 1Ply16 were the closest and within 2% or experimental tested values, while the 2Ply6.5 and 2Ply16 were overestimated by 6% and 11% respectively. Other researchers have found the shear analogy method to be accurate for CLT (Karacabeyli & Gagnon, 2019; Li et al., 2021; Lim et al., 2020; Sikora et al.,

2016). Yang et al. (2023b) found that the shear analogy method was within 9% for pilot scale ply-lam specimens and concluded that the shear analogy method was the most suitable of the analytical methods as it was able to verify changes in predicted value to those in the composition of the inner layers.

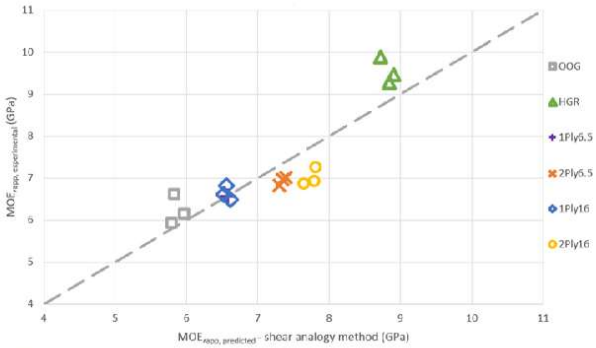


Figure 7 Predicted MOE_{app} using shear analogy method compared to experimental MOE_{app}

4.7. Failure behaviour

ASTM International (2022) describes bending (flexural) failures by the appearance of the fractured surface and the manner in which the failure develops. Bending failures in timber typically progress from compression failures at the top surface followed by a shift downward of the neutral axis and finally brittle failure within the tension zone (Dinwoodie, 2002). Fujimoto et al. (2021) and He et al. (2021) reported seeing this failure process with crushing on the compression side followed by fracture on the tensile site of CLT panels tested. Therefore failures are mainly described by the failure in the tension zone (Franke et al., 2015). The typical failure modes had some differences and are described for each panel type below, however, there were similarities between all the different sample types. Tension failures in the bottom layer were the most common occurring failure type and were typically accompanied by rolling shear failure in the transverse layer. This failure in CLT is common throughout the literature (Baño et al., 2018; Fujimoto et al., 2021; Gong et al., 2019; He et al., 2021; Sikora et al., 2016). Examples of CLT failures can be seen in Table 4.

The 3 layer OOG panels all failed mid span of the bending zone. As seen marked in red in Table 4(1b), the tensile failures typically occurred at knots in the timber of the bottom layer in tension. The cracks propagated through the transverse

layer, and in one sample, the crack at the edge of the panel continued into the top layer of timber, terminating after running along the grain for approximately 100 mm in both directions. Fortune and Quenneville (2011) reported similar crack propagation through CLT made from radiata pine. Due to the frequent occurrence of knots in the low-stiffness out-of-grade pine, there were knots in close proximity to each other across the panel as seen in Table 4(1a). Given the low MOE and strength performance of knots in this resource (Cherry et al., 2022), they would likely have negatively impacted structural performance reducing the benefit of the lamination effect usually seen in CLT. Concu et al. (2018) also reported failures occurring through aligned knots in the bottom layer and had similar poor bending strength results. After failure occurred at peak load, the top layer remained intact and sufficiently strong to hold the panel together as one piece.

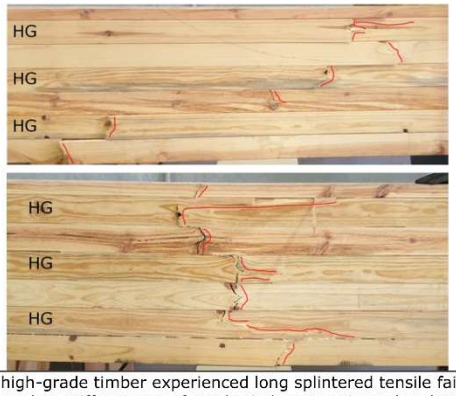
The HGR panels also failed in tension at knots in the bottom layer and the transverse layer experienced rolling shear failure with the failure plane running adjacent to the glue line in some regions. One of the HGR panels shown in Table 4(2b) is an example where knots are scattered along the length of the bottom layer of the panel. This resulted in timber failures scattered at these knot locations, reiterating the negative impact knots have in tension. The high grade timber reinforcement in the tension zone, as marked by "HG" in Table 4(2b), experienced splintered tension failures leaving a fibrous and long splintering fracture surface. On the other hand, the out-of-grade timber experienced brittle tension failures leaving a brash fracture surface with frequent short failures at the earlywood and latewood boundaries, as can be seen in examples given in Table 4(4b).

The ply panels experienced brittle bending failures with the failure plane occurring through the entire depth of the panels, creating two completely separate pieces. These panels failed in the bending zone with some being close to the loading points, apart from one of the 2Ply16 panels, which failed in rolling shear in the shear zone of the test span. The plywood and the longitudinal timber layer at the bottom of the panels failed in tension in an almost straight-line, perpendicular to the long face of the panel. An example can be seen in Table 4(3b). Different to the OOG and HGR panels, the failure location of the

timber in the tension zone was less influenced by knots but instead followed the tension failure plane of the plywood at the bottom of the panel.

The failure plane through the 1Ply6.5 panel was almost vertical. The piece of timber in the transverse layer adjacent to the bending failure plane experienced rolling shear failure but the crack did not propagate any further. The 1Ply16 panels showed longer rolling shear failure planes through the transverse layer compared to the 1Ply6.5 panel. On two of the three panels, rolling shear failures also occurred in the plywood within the transverse layer closest to the glue line in the tension zone. Yang et al. (2023b) also reported this occurrence of rolling shear failure in the plywood. There was rolling shear failures through the transverse layer of the 2Ply6.5 panels but no rolling shear failures in the plywood. The failure plane in the plywood at the bottom of the panel was straight, whereas the failure in the ply at the top was jagged as shown in Table 4(5b). One of the 2Ply16 panels experienced extensive rolling shear failures in the transverse layer and this failure occurred in the shear zone of the test span. Rolling shear failures also occurred within the plywood in the tension zone of the other two panels. He et al. (2021) found that CLT with more outer layer, was more likely to fail in rolling shear. Moreover, with increasing thickness of CLT, rolling shear strength decreases (Navaratnam et al., 2020; Sikora et al., 2016). Where pith was present, it frequently formed part of the failure plane as also found by Cherry et al. (2022, 2023, 2024). The rolling shear failure planes seen in these samples are similar to those seen in the results of the modified 2-plate shear test completed on this resource by Cherry et al. (2024). Sections of perpendicular to grain tension failures can be seen, as well as rolling shear failures that follow the earlywood growth rings. The ply in the tension zone changed the failure plane which became less influenced by knot location.

Table 4 Examples of Failures

OOG		
	1(a) typical failures of OOG panels showing tension failures in the bottom layer	1(b) frequent knots align across the width of the panel with tensile failure planes in the bottom layer of the panel marked in red.
HGR		
	2(a) typical failures of HGR panels showing tension failures accompanied by rolling shear failures.	2(b) high-grade timber experienced long splintered tensile failures whereas low-stiffness out-of-grade timber experience brash tensile failures. Failure of timber in the bottom of the panels marked in red.
1Ply6.5		
	3(a) failure in the 1Ply6.5 panel. The failure plane is almost vertical.	3(b) the bottom ply layer and timber in tension fail in a straight line while the failure of the timber on the compression side is jagged.
1Ply16		

	4(a) Failures of 1Ply16 panels showing tensile failures and some rolling shear failures in the transverse layer of the CLT and of the plywood.	4(b) Brash tensile failure plane of the low-stiffness out-of-grade pine showing frequent short failures at the earlywood and latewood boundaries.
2Ply6.5		
	5(a) Failures of 2Ply6.5 panels showing tensile and rolling shear failures.	5(b) The failure of the plywood in the bottom layer is straight while the failure in the plywood in the top layer is jagged. Some compression failures are visible in the top of the plywood.
2Ply16		
	6(a) failures of the 2Ply16 panels showing rolling shear failure in the timber in the transverse layer as well as in the plywood.	6(b) pith is frequently exposed in the failure plane.

5. Conclusions

An experimental study was conducted to determine the bending properties of CLT manufactured from low-stiffness out-of-grade PEExPCH hybrid pine and the effect of wood-based reinforcements were evaluated. The bending MOE and

strength of the CLT was completed according to EN16351 (European Committee for Standardization, 2021) and EN409 (European Committee for Standardization, 2012). From the experimental tests and data anlaysis, the following conclusions can be drawn:

- CLT manufacture from low-stiffness out-of-grade PEExPCH achieved a bending MOE and strength of 6.2 GPa and 24.9 MPa, respectively. Based on the properties of the timber used in their manufacture, the strength of the CLT was lower than expected. This was attributed to the frequently occurring knots that aligned in the bottom layer of the panel under tensile stress, at which failures occurred.
- CLT strength was on average 10% lower than knot samples and 16% higher in MOE. This demonstrations that in CLT made from low-stiffness out-of-grade PEExPCH, knots have less impact on bending MOE than they do on bending strength.
- All reinforced CLT panels experienced increased structural properties. The HGR panels experienced the largest increases of 53% and 93% for MOE and strength, respectively. HGR also had the benefit of maintaining the same panel depth and manufacturing processes without the need to sand and lay large sheets of plywood.
- 3-layer CLT made from 67% out-of-grade PEExPCH hybrid pine with 33% high-grade timber reinforcement in the outer longitudinal layers achieve MOE and strength similar to panels made from in-grade timber from other studies.
- 1Ply6.5, 2Ply6.5, 1Ply16 and 2Ply16 CLT contain 94%, 88%, 86% and 76% of volume as out-of-grade timber, respectively. The average MOE increases were 6%, 11%, 7% and 13%, respectively. The average strength increases were 64%, 39%, 46% and 34%, respectively.
- The panels with timber in the bottom layer under tension failed at knots whereas the plywood reinforced CLT panels were less influenced by knots in the bottom layer and the failure plane of the panels aligned with that of the plywood.

- The lamination effect typically provided by CLT was less effective in this out-of-grade PEExPCH in comparison to what is seen in other studies. This was attributed to the frequently occurring knots aligning across the width of the panel in the bottom layer under tension.
- As with solid timber, knots have a larger negative effect on bending strength than they do on bending MOE in CLT.
- There was no obvious trend seen in the differences between bending MOE with face 1 up compared to face 1 down. Although, on average the 2Ply16 panels experienced the least differences and 1Ply16 panels experienced the largest difference.
- The shear analogy method predicted MOE_{app} with good accuracy for all panel types with the largest error being 11%.

The results of this study demonstrates that it is possible to manufacture CLT from out-of-grade PEExPCH but due to their low MOE and strength performance, in un-reinforced CLT panels, this feedstock is best suited to the central and transverse layers allowing the stiffer stronger timber to be located in the high stress zones of the outer layers. High Grade timber reinforcement is highly effective at increasing MOE and strength. Plywood is also effective at increasing MOE and strength but to a lesser magnitude. The shear anaology method is suitable and accurate at predicting MOE of CLT made from out-of-grade PEExPCH hybrid pine with or without reinforcements when the mechanical properties of the feedstock are known.

6. Author contributions:

Author Contributions: Conceptualization, R.C., W.K. and A.M.; methodology, R.C.; validation, R.C.; formal analysis, R.C.; investigation, R.C.; resources, R.C.; data curation, R.C.; writing—original draft preparation, R.C.; writing—review and editing, W.K. and A.M.; visualization, R.C.; supervision, W.K. and A.M. All authors have read and agreed to the published version of the manuscript.

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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.

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6.3. Links and implications

The study presented in Chapter 6 investigated the bending MOE and strength of CLT made from out-of-grade PEExPCH and the effect of wood-based reinforcements. As expected, CLT without reinforcement had relatively low bending properties. High-grade timber and plywood were used as wood-based reinforcements and all increased bending properties with high-grade timber providing the largest improvement. The frequently occurring knots, which consequently aligned in the bottom layer under tension, attributed to lower than expected bending strength. Using the mechanical properties as determined in Chapters 3 and 4, the shear analogy method accurately predicted the bending MOE of these CLT panel combinations. The plywood reinforced panels experienced different failure compared to the 100% timber panels with the failure plane being less influenced by knots. Out-of-grade PEExPCH has good potential for the manufacture of CLT, in the transverse layers under rolling shear stresses, for inner layers under low longitudinal compressive and tensile stresses and in the outer layers where reinforcements are used. Some restrictions are required on knots to achieve strength requirements and on resin, knots and pith to achieve bond performance requirements.

CHAPTER 7: DISCUSSION AND CONCLUSIONS

7.1. Introduction

Out-of-grade PEExPCH hybrid pine is an abundant and underutilised material resource that is produced as a by-product of the structural grading process. Out-of-grade timber is often sold at a loss and value add opportunities are needed. All the while, the building and construction industry is looking for sustainable building solutions to meet increasing demand from a limited supply of in-grade structural timber. An ideal solution would use and value add large volumes of out-of-grade PEExPCH, be environmentally sustainable, competitively priced, perform satisfactorily and reliably in service, free up volumes of high value in-grade timber for other structural applications and continue to do so over time. Matching the strength and weaknesses of out-of-grade PEExPCH to the demands of the various applications in building systems and technologies is critical for success. Therefore, a thorough understanding of the structural properties and bond performance of out-of-grade PEExPCH and the effect of commonly occurring characteristics is needed.

7.2. Review of Out-of-grade Timber Characteristics, Opportunities, Challenges and Potential in CLT.

An in-depth critical review of the literature was completed and provided an understanding of the challenges, strengths and opportunities of out-of-grade PEExPCH through exploring the various characteristics found in this resource and matching these to applications in building systems that take advantage of strengths while avoiding weaknesses. The latest research and practices in building design methods, practices and technologies that would allow substitution of out-of-grade pine in place of in-grade were reviewed. Building design methods and technologies were identified to support the effective utilisation of out-of-grade pine in sustainable building systems.

The following conclusions were made:

- Out-of-grade sawn pine is an abundant resource that despite being rejected by structural grading rules would perform well in specific structural applications and lead to benefits for the environment, plantation managers, sawyers, designers, builders and customers.

- Substituting out-of-grade for in-grade where ever possible provides substantial benefits. It frees up the high demand in-grade timber while providing opportunity for otherwise under utilised out-of-grade timber. It is therefore essential to understand the mechanical properties of this out-of-grade PEExPCH resource and the effects of its major characteristics so that suitable custom grading rules can be developed to ensure the performance requirements of any application can be met.
- Low longitudinal bending stiffness, sloping grain, knots, distortion, resin shakes, splits and checks were the main characteristics of sawn out-of-grade timber. These perceived unfavourable properties can be overcome with a good understanding of their strengths and weaknesses, and through targeted placement in manufacturing building systems and utilisation of building technologies.
- Many options were identified including architectural designs that work with the properties and geometry of out-of-grade timber, reinforcements can be used to overcome deficiencies in structural performance, advanced adhesive technology can enhance bonding performance and durability and wood modifications can increase strength, stiffness, hardness and dimensional stability of timber.
- Fully integrated digital systems to make the use of out-of-grade timber easier and more efficient are possible. Data collected at every stage from milling to construction can be used to inform subsequent stages but this requires a high level of information sharing and communication throughout the entire timber and building industries.
- CLT's unique design and intrinsic lamination effect give it good potential to substitute out-of-grade in place of in-grade timber. However, significant research is still needed to confirm the suitability of each out-of-grade characteristic in all possible applications of CLT. It is argued that the work required for this research is warranted given the potential to utilise very large volumes of out-of-grade sawn timber in CLT.
- Based on analytical models, CLT made from very low stiffness timber can still achieve spans 80% of the equivalent CLT made from in-grade

timber. The rolling shear however is an important design consideration for CLT when using low stiffness out-of-grade timber due to the smaller span-to-depth ratios achievable.

7.3. Mechanical Properties of Out-of-grade PEExPCH and Effect of Resin, Knots and Pith

An extensive experimental study was carried out and evaluated the MOE and strength properties of out-of-grade PEExPCH hybrid pine in bending, compression parallel to grain (CParG), compression perpendicular to grain (CPerG), longitudinal shear, rolling shear (RS) and strength in tension. The structural performance and their ratio with bending MOE as an indicator property were compared to other PEExPCH hybrids and young, out-of-grade and average populations of similar pines. The effect of resin, knots and pith on these mechanical properties were evaluated. Correlations between RAR, KAR, density and structural properties were established. Changes in density were used in published models to predict changes in structural properties and compared to actual results. From the extensive experimental tests and data analyses, the following conclusions can be drawn:

- The out-of-grade PEExPCH hybrids from the lower-quality inner core of the tree are typically characterised with pith, high-angled clustered knots, resin streaking, resin shake, needle trace and tight-radius growth rings with high percentage of earlywood.
- The clear timber in this resource performed well in bending strength (45.8 MPa) and tension strength (32.4 MPa), mid-range in bending MOE (6.9 GPa), CParG strength (29.4 MPa), RS MOE (108 MPa) and RS strength (2.4 MPa) but poorly in CParG MOE (5.78 GPa), CPerpG MOE (0.27 GPa), CPerpG strength (6.7 MPa), longitudinal shear modulus (0.59 GPa) and shear strength (5.7 MPa) compared to other PEExPCH hybrids and young and low-grade similar pines. Bending strength and CPerpG strength were mid-range compared to average populations of similar pines, but all other structural properties were low which can be expected given the timber was out-of-grade and contains juvenile wood and pith.

- The ratios of structural performance for clear samples to bending MOE revealed high tensile strength, RS MOE and RS strength, mid-range bending and CParG strength, but all other structural properties were low relative to their bending MOE performance when compared to other PEExPCH hybrids and young and low-grade similar pines. Shear modulus, CParG and CPerpG strengths were mid-range, and all other properties were low relative to their bending MOE performance when compared to average populations of similar pines.
- The Poisson's ratio of the pooled clear and resin samples was found to be 0.4365 which is similar to slash pines as one of its parent species.
- Resin samples performed similar to and within a range of 98% to 116% of the clear samples. Resin significantly increased the density at 45% higher than clear but only CPerpG MOE performed significantly different; however, no clear relationship was found between RAR and CPerpG MOE. The resin in cell walls rather than in cell lumen is believed to have provided the increased performance. The increase in density due to resin caused large errors in predictive models that were based on density and should be subtracted from these equations. RAR showed low correlation with all structural properties with R2 values all below 0.2 and moderate correlation with density with R2 of 0.659.
- Knots performed significantly different to clear samples for all test types and within a range of 48% to 196%. Knots were high in CPerpG MOE and strength, RS MOE and strength, and lower for all other properties with the largest negative impact being on tensile strength followed by bending strength. The increase in density was similar to that seen in resin. Knot-associated resin streaking was common which would have added to density.
- KAR was moderately correlated with tension strength and CParG MOE with R2 of 0.48 and 0.35, respectively. All other correlations were low or non-existent with R2 below 0.2.
- Pith samples were within the range of 76% to 121% of non-pith samples.

- The density of clear samples at 500 kg/m3 was high compared to other PEExPCH hybrids and young and low-grade similar pines and mid-range compared to average populations of similar pines.
- The RS properties are as good as and better in some cases than high grade timber and other species that are already used in the manufacture of CLT.
- Growth ring pattern has a significant effect on RS properties.

While this resource has been rejected from MGP structural grade, it still possesses some good mechanical properties that can be matched to structural applications that do not need high strength or stiffness performance. This detailed information can be used to create custom grading rules and the opportunity for the optimal design and use of this material resource in various civil engineering applications. For example, with the exception of bending MOE, the clear and resinous out-of-grade PEExPCH has structural properties that meet or exceed the structural performance requirements of C14 and C16 (European Committee for Standardization, 2012) which are used in the manufacture of CLT (Brandner et al., 2016; Wieruszewski & Mazela, 2017). Clear and resin samples fall short on bending MOE, which on average, clear and resin samples combined are 7% and 13% lower than C14 and C16, respectively. They also meet C18 except for bending MOE and compression perpendicular to grain MOE. Knots fell short of C14 on bending MOE and strength by 26% and 11%, respectively, and could be limited or excluded to increase these properties if necessary. However, the transverse layers in CLT are required to resist rolling shear stresses and knots were found to increase rolling shear performance. Moreover, the rolling shear properties of this resource are as good as or in some cases, better than timber species already used in the commercial manufacture of CLT.

7.4. Bond performance of Out-of-grade PEExPCH

Bond performance is critical to engineered wood products, they must be durable and strong enough to perform sufficiently and predictably over time. An experimental study was completed which investigated the bond quality and performance of out-of-grade PEExPCH in CLT and glulam orientations using delamination and shear tests. The effect of resin, pith, and knots on bond

performance were assessed. The extent to which current standards and guides address out-of-grade PEExPCH and its common characteristics of resin, knots and pith on bond performance were discussed. The main findings are as follows:

- Clear samples performed well with little delamination and high 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;
- 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;
- 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;
- 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;
- 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;

- 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;
- 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;
- 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;
- 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;
- 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 provide valuable information about the bond performance of out-of-grade PEExPCH 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.

7.5. Bending Properties of CLT made from Out-of-grade PEExPCH and the effect of wood-based reinforcements

Cross laminated timber (CLT) is a mass engineered wood product that was identified as a good opportunity for large volumes of out-of-grade timber due to its size, intrinsic lamination effect, extensive possible applications and increasing use in the construction and building industry. An experimental study was conducted to determine the bending properties of CLT manufactured from low-stiffness out-of-grade PEExPCH hybrid pine and the effect of wood-based reinforcements were evaluated. The bending MOE and strength of the CLT was completed according to EN16351 (European Committee for Standardization, 2021) and EN409 (European Committee for Standardization, 2012). From the experimental tests and data analysis, the following conclusions can be drawn:

- CLT manufacture from low-stiffness out-of-grade PEExPCH achieved a bending MOE and strength of 6.2 GPa and 24.9 MPa respectively. Based on the properties of the timber used in their manufacture, the strength of the CLT was lower than expected. This was attributed to the frequently occurring knots that aligned in the bottom layer of the panel under tensile stress, at which failures occurred.
- CLT strength was on average 10% lower than knot samples and 16% higher in MOE. This demonstrates that in CLT made from low-stiffness out-of-grade PEExPCH, knots have less impact on bending MOE than they do on bending strength.
- All reinforced CLT panels experienced increased structural properties. The HGR panels experienced the largest increases of 53% and 93% for MOE and strength, respectively. HGR also had the benefit of maintaining the same panel depth and manufacturing processes

without the need to sand and lay large sheets of plywood. The results show that 3 layer CLT made from 67% out-of-grade PEExPCH hybrid pine with 33% high-grade timber reinforcement in the outer longitudinal layers achieve MOE and strength similar to panels made from in-grade timber from other studies.

- 1Ply6.5, 2Ply6.5, 1Ply16 and 2Ply16 CLT contain 94%, 88%, 86% and 76% of volume as out-of-grade timber, respectively. The average MOE increases were 6%, 11%, 7% and 13% respectively. The average strength increases were 64%, 39%, 46% and 34%, respectively.
- The panels with timber in the bottom layer under tension failed at knots whereas the plywood reinforced CLT panels were less influenced by knots in the bottom layer and the failure plane of the panels aligned with that of the plywood.
- The lamination effect typically provided by CLT was less effective in this out-of-grade PEExPCH in comparison to what is seen in other studies. This was attributed to the frequently occurring knots aligning across the width of the panel in the bottom layer under tension.
- As with solid timber, it was found that knots have a larger negative affect on bending strength than they do on bending MOE in CLT.
- There was no obvious trend seen in the differences between bending MOE with face 1 up compared to face 1 down. Although, on average the 2Ply16 panels experienced the least differences and 1Ply16 panels experienced the largest difference.
- The shear analogy method predicted MOE_{app} with good accuracy for all panel types with the largest error being 11%.

This study provides valuable information for the timber and building and construction industries for design, product development, optimisation and manufacture. It demonstrates that it is possible to manufacture CLT from out-of-grade PEExPCH but due to their low MOE and strength performance, in un-reinforced CLT panels, this feedstock is best suited to the central and transverse layers allowing the stiffer stronger timber to be located in the high stress zones of the outer layers. High Grade timber reinforcement is highly effective at increasing MOE and strength. Plywood is also effective at

increasing MOE and strength but to a lesser magnitude. The shear anaology method is suitable and accurate at predicting bending MOE of CLT made from out-of-grade PEExPCH hybrid pine with or without reinforcements when the mechanical properties of the feedstock are known.

7.6. Contribution and Summary of Conclusions

This study has provided a valuable contribution to the literature and the timber and building industry. The outcomes are useful to designers, product developers, timber mills, engineered wood product manufacturers, researchers and engineers, for evaluation, for further research and product development of out-of-grade PEExPCH into sustainable building systems. In summary, out-of-grade PEExPCH hybrid pine is an abundant, underutilised and low value material resource that has potential to be substituted in place of highly sought after and high value in-grade timber, in a range of applications with and without the use of reinforcements and/or technologies. To evaluate this resource for applications in sustainable building systems the mechanical properties need to be understood. In this study, the mechanical properties of out-of-grade PEExPCH were determined and were found to be comparable to other similar resources of young and/or low grade pines. Rolling shear MOE and strength performed well and better than some in-grade timber which was attributed to the growth ring patterns in this out-of-grade resource. To provide further detailed information and to inform the development of grading rules to optimise structural performance for specific applications, the effect of resin, knots and pith on these mechanical properties were evaluated. It was found that resin has minimal effect on most mechanical properties but did significantly increase density. Knots had mixed results with the largest negative impact on tensile strength but had a positive effect on rolling shear. Pith also had mixed results on structural performance and higher density than non-pith samples. Cross laminated timber was identified as a sustainable building system that had potential to utilise large volumes of out-of-grade PEExPCH, especially in its inner and transverse layers which experience lower tensile and compressive stresses. The stress distributions for the different growth ring patterns under rolling shear stresses were captured using DIC and presented. Engineered wood products such as CLT depend on the timber and adhesive to perform predictably and reliably as a system under service conditions and over the life of the structure. It is critical that good bond performance and bond

quality is achieved and that methods to evaluate this are available and used. In this study, the bond performance and quality of out-of-grade PEExPCH glued with PUR adhesive was evaluated and based on criteria in current CLT standards performed well with 100% pass rate except for the stricter PRG320 delamination requirement of =<5% total delamination in which a 70% pass rate was achieved but all failed samples qualified for retesting. The effect of resin, knots an pith were evaluated and all were found to have a negative impact on bond quality and/or performance. It was found the current CLT standards were lacking in addressing and evaluating characteristics such as resin, knots and pith. PRG320 is the only standard to restrict these characteristic over and above the structural grading requirements. A proposed modification to the PRG320 effective bond area was presented as a proactive solution. CLT made from out-of-grade PEExPCH were manufactured and experimentally tested to determine bending MOE and strength. The panels performed similarly to other CLT panels made from young and low-grade timber resources. The effect of high-grade timber and plywood reinforcements were investigated and it was found the high-grade timber had the largest positive impact with the added benefit of maintaining panel depth. The plywood also increased structural performance. The shear analogy method was found to be a good predictor of bending MOE for these CLT panel combinations with less than 11% error.

7.7. Limitations

This thesis studied the structural properties and bond performance of out-of-grade PEExPCH hybrid pine and its opportunity and performance in the sustainable building system of CLT. The approach taken was to evaluate the clear timber and then identify the effect of commonly occurring characteristics of resin, knots and pith. This provides information that is relevant to establishing grading rules for any end use application. In order to limit the scope of this study given the available resources and time, other characteristics also present in this out-of-grade resource have not been included, such as wane, resin shake and distortion, but could be considered in future studies. Knots, resin and pith were selected as they were found to be most predominant in this resource. The glue used for bond performance and durability assessments is one component polyurethane glue. The development of CLT from a new timber resource requires extensive research in a range of specialty areas that

are outside the scope of this research. These include fire performance, connections, durability and acoustic performance of the completed product.

7.8. Recommendations for future work

Further research is needed to evaluate the effect on structural performance of other characteristics found in out-of-grade PEExPCH such as resin shake, distortion and bark pockets. Also, to understand the effect of background resin compared to resin streaking on bond performance, as well as to find an easily measurable metric and set criteria to limit resin to an extent that it does not detrimentally effect bond performance. Verification for the proposed modified effective bond area on PEExPCH and other species of wood are required, as well as further optimisation and development and trials of characteristic identification and measurement systems are needed. Furthermore, the fire performance, connections, durability, acoustic performance and loading conditions other than out-of-plane bending are all areas needing further research on CLT made from out-of-grade PEExPCH.

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APPENDIX A: REFEREED CONFERENCE PAPER

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OPPORTUNITIES FOR OUT-OF-GRADE SAWN PINE IN SUSTAINABLE BUILDING SYSTEMS

R. CHERRY[1,2,3]*, A. MANALO[1,2], W. KARUNASENA[1,2] and G. STRINGER[3]

[1]School of Civil Engineering and Surveying, The University of Southern Queensland, QLD 4300, Australia

[2]Centre for Future Materials, University of Southern Queensland, QLD 4300, Australia

[3]Hyne & Son Pty Ltd, Maryborough QLD 4650, Australia

Email: rebecca.cherry@usq.edu.au, allan.manalo@usq.edu.au, karu.karunasena@usq.edu.au, geofstri@hyne.com.au

*Corresponding author

Abstract. *Sawyers across the world are challenged with the task of finding a profitable market for the large volumes of sawn timber which fail to meet the specifications of their chosen structural grading system, while also meeting the demands of the increasing structural timber market. As more people begin to see and discuss its many benefits, the use of structural timber in construction will continue to increase across the globe however, intrinsically this also means an increase in out-of-grade timber. It is time to take a 21st century look at the out-of-grade resource, at advances in building technologies and in sustainable building systems and bring these together to use out-of-grade to supplement the in-grade market in structural applications. This paper will briefly discuss what characteristics to expect in a pack of out-of-grade Australian structural pine. It will identify opportunity for incorporation into sustainable building systems and introduce a range of modern building technologies that could be used to facilitate the use of out-of-grade.*

Keywords: out-of-grade timber; structural pine; building technologies; sustainable building.

1 INTRODUCTION

Out-of-grade sawn pine is an abundant resource that despite being rejected by structural grading rules would perform well in specific structural applications and lead to benefits for the environment, plantations mangers, sawyers, designers, builders and customers. Australia has 1.036 million hectares of softwood (ABARES, 2017) of which 97.7% are managed to supply the Australian housing market with sawlogs (ABARES, 2016). The expansion of plantation area is considered a viable option to meet the increasing timber demand (Department of Employment Economic Development and Innovation, 2010). Using out-of-grade pine to supplement the increasing in-grade market would increase the structural yield from existing plantations reducing the need and costs involved to expand these plantations, value add to the out-of-grade resource, reduce strain on the in-grade market and would also be cost competitive.

The approach in Australia is to provide bulk packs of graded pine where each standalone piece is required to perform in a range of yet unknown applications but to achieve this, high demands are placed on the timber resulting in many pieces of out-of-grade having a range of good structural properties despite one or two shortfalls. Additionally, the focus of structural grading is on meeting grading standards rather than meeting the demands of the end use of the timber (Johansson, Kliger, & Perstorper, 1994) and not all applications require all mechanical

properties to perform to the level demanded by grading. There exists a mismatch between national grading standards and the needs of the building industry where some important properties are ignored while other demands are irrelevant (Johansson, Kliger, & Perstorper, 1994) leading to timber being unnecessarily rejected. Knowing the end use allows design to take advantage of strengths, avoid weaknesses and to enhance properties as required. Moreover, improved information sharing within the timber industry would lead to increased use of the timber resource including out-of-grade and a more competitive market.

Investigating the performance of out-of-grade characteristics systematically is key to making an informed decision about what roles each one can play in a building system. However, studies often look at in-grade clear timber samples or characterise general populations of a timber resource. What is missing is an understanding of what is in the out-of-grade packs. This paper will identify and briefly discuss common characteristics found in out-of-grade pine timber packs in Australia, looking for potential strengths and weaknesses. It will look at how building systems can provide opportunities to substitute out-of-grade in place of in-grade timber. Finally, it will present some building technologies that can either enhance the properties of the timber or make substitution effective and efficient.

2 OUT-OF-GRADE TIMBER

Machine graded pine (MGP) is the base grade for structural pine in Australia (Harding, 2008) for which criteria on minimum mechanical properties and maximum tolerances and characteristics are set out in AS1720.1 (Standards Australia, 2010) and AS/NZS1748 (Standards Australia/New Zealand Standards, 2011a, 2011b). There is high demand for timber that falls within MGP grading but little demand for the large volumes of out-of-grade that do not. Common characteristics found in out-of-grade timber packs are included below, it is important to note that the extent of any one or combination of these characteristics governs the capacity of a piece to perform satisfactorily and therefore an assessment of each piece is required.

Resin pockets, bark pockets, shakes, splits and checks are all separations of the timber fibre which disrupt stress transfer resulting in stress concentrations and a reduction in the strength of the timber. Shakes cause a reduction in shear strength (Laveielle, Gibier, & Stringer, 1996) and perpendicular to grain tensile strength, but may not impact bending stiffness or strength (Thelandersson, 2003). Bow, cup, twist and spring are all forms of timber distortion which have a range of contributing factors including the inherent properties of timber and processing methods. When wood is sawn, cutting through the fibre releases growth stresses within the timber cells leading to distortion (Plomion, Leprovost, & Stokes, 2001). Distortion also develops during drying as timber shrinks at different rates in the radial, tangential and longitudinal direction. This distorted shape can lead to eccentric loading, conflict with other building materials and cause weak glued connection (Forest Products Laboratory, 2010). However, it is not necessarily low performing, can simply be reduced by further processing and the internal shrinkage stresses could act like prestressing.

Low longitudinal stiffness and strength of timber can make design challenging and seemingly inefficient, capable of only relatively short spans and small longitudinal loads. Where the smaller framing sizes are cut from the center of a log, the high content of juvenile wood and minimal content of mature wood result in reduced mechanical properties (Dahlen et al., 2014). Juvenile wood is often associated with low stiffness of timber due to the high microfibral angle in the S2 layer of the cell walls (Plomion, Leprovost, & Stokes, 2001) however, high microfibril angle can be advantageous for some transverse properties (Astley, Stol, & Harrington, 1998;

Jager et al., 2011; Ramage et al., 2017) and longitudinal shear stiffness (Astley, Stol, & Harrington, 1998).

From most impacted, knots negatively influence longitudinal tensile strength, modulus of rupture, compressive strength parallel to grain followed by modulus of elasticity (Phillips, Bodig, & Goodman, 1981) and the extent of this negative impact depends on the knot location, shape and associated grain deviation (Green, 2001). Large knots are believed to be responsible for the limitation of tensile strengths of Australian softwoods despite their strong clear wood (Adam & Milner, 2012). Knots have no significant effect on longitudinal shear (Gupta, Basta, & Kent, 2004) and can in fact increase shear capacity, fracture energy (Jockwer et al., 2017) and perpendicular to grain strengths (Thelandersson, 2003). For non-conformance due to out of tolerance dimension, squareness, machine skip or wane, there is not necessarily a shortfall in structural properties where the limits are not excessively exceeded but instead the main issue stems from the interaction with other building materials required to perform alongside the timber. Some of these pieces can have good mechanical properties (Dahlen et al., 2014), they can be reduced by further processing and should not be an issue where size tolerance is large.

Only the more commonly occurring out-of-grade characteristics have been discussed here. From this it is clear that although out-of-grade may have some shortfalls, it has a range of good and in some cases improved structural properties that could be used in structural applications.

3 BUILDING SYSTEMS

Many building systems already in use today have opportunity to incorporate out-of-grade in one or multiple ways as a direct substitute for in-grade timber or coupled with enhancement from technologies however, a good understanding of timber and building system are key to success. A study by Hansson (2011) reiterates this as it revealed that failures in timber structures are mostly due to incorrect design and poor work practices rather than material performance. Direct substitution, customised design, lamination effect, large profile size and optimised design are all examples of opportunities building systems provide for out-of-grade.

Customised building systems is a targeted approach that takes a specific mechanical property and develops a building system that exploits that property, such as a stacking rather than spanning system which results in higher compression rather than bending stresses. In this application out-of-grade timber with low bending stiffness or strength but high perpendicular to grain properties such as knotted timber would be suitable. For example timber interlocking bricks such as Tumiki House timber bricks (Nakao, 1999) or large scale stacked engineered timber system used for the AWEL workshop shown in Figure 1.

Figure 1 Stacked engineered timber system (Rossetti+Wyss Architeckten, 2015)

The lamination effect fundamental to engineered laminated timber products provides alternative stress paths so that lower performing characteristics do not have to endure the full load and therefore, have less negative impact. The connection system used to connect the timber dictates the means and effectiveness of stress transfer in these building systems. Knowing the proficiency of the lamination effect would allow incorporation of out-of-grade characteristics to be maximised while remaining below capacity limits.

Larger profile sizes of engineered timber building systems have regions of lower stresses where out-of-grade could be incorporated. Central layers of a glue laminated beams or cross laminated timber under bending are an example where axial stresses are low but shear is greater compared to outer layers and therefore knots may be a suitable option.

Optimised design is an approach where a building system is altered to change or reduce the loading on the timber to facilitate out-of-grade and can be done by changing the layup of the building system. For example, CLT cross layers at angles other than 90° increasing dependence on longitudinal while reducing perpendicular to grain stresses (Buck et al., 2016) or varying CLT laminar depth changing the stresses throughout the depth of the panel (Erhart et al., 2015).

Methods to incorporate out-of-grade into building systems presented in this section require a good understanding of the demands within the building system and the structural performance capabilities of the out-of-grade timber. They require good product management and handling processes for manufacture but they also enable better use of the timber resource. For timber to remain competitive and to take best advantage of the current plantation resource it will be necessary to use timber in a much less wasteful and more optimised way. Moreover, advances in building technologies can be applied to automate and simplify these ideas.

4 BUILDING TECHNOLOGIES

The advances and uses of building technologies are and continue to be extensive and can be applied in applications to facilitate the use of out-of-grade timber. Building technologies for the purposes of this research are skills, knowledge, tools or materials that can be used to enhance or assist the structural performance, design, planning or construction of a building. A variety of technologies can be used throughout all stages from milling through to construction.

Improved utilisation of the data collected during the grading assessment process in the mill is vital to the ongoing advancement of timber in modern construction. As part of the grading process in modern sawmills, the mechanical and physical properties of each piece of timber are well investigated using wood imaging techniques (Figure 2) and non-destructive testing. Having this grading assessment data for the population of out-of-grade timber prior to design and assembly would inform the project earlier allowing better utilisation, placement and planning of out-of-grade into a range of building systems. It would prove invaluable for informing computer aided design (CAD), engineering (CAE) and manufacture (CAM) as the uncertainty associated with highly variable populations of out-of-grade timber is diminished.

CAD, CAE and CAM offer opportunity to optimise design and automate processes to increase the use of out-of-grade timber and their use is increasing in the construction industry along with the wider acceptance and utilisation of building information modelling. Advanced digital design, automated manufacture and robotic timber construction offer unique advantages allowing timber to keep up with the rapidly spreading world of digital and automated construction (Willmann et al., 2015). Moreover, the development of fabrication-orientated design systems that are more easily accessible and user friendly are currently of high interest

(Lipton et al., 2018). These integrate with robotic assisted carpentry which are now being developed and researched (Lipton et al., 2018). Challenges that variations in timber, but especially out-of-grade timber, bring to this digital and automated world are also being addressed, for example, the need for self-analysis and adjustment of original dimensions to overcome the natural variations of timber often not found in manmade materials (Willmann et al., 2015). The data collected as part of the grading assessment process would inform CAD, CAE and CAM which would then optimise the design and automate manufacturing while ensuring rules are adhered to without double handling and reassessment involved in manual assembly that would otherwise be essential for out-of-grade.

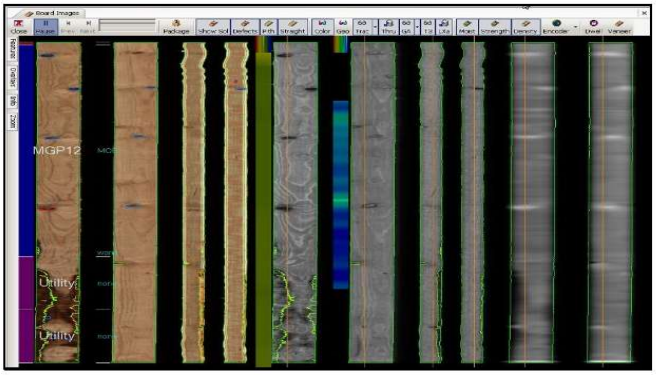

Figure 2 Lucidyne GradeScan® wood imaging

Reinforcement and composite systems can be used with out-of-grade timber increasing mechanical properties and overcoming insufficiencies in performance. Increases in bearing capacity, tensile strength perpendicular to grain, flexural strength, flexural stiffness, shear strength and creep in timber have all been accomplished (Schober et al., 2015). Proper adhesive systems for timber plays an important role for enabling out-of-grade to be connected with reinforcement materials and other timber within engineered timber products but out-of-grade can present additional challenges for adhesives with higher longitudinal shrink swell behavior of juvenile wood, knotted fibre and associated variations of grain angle, high resin content and chemical variations or in the case of reinforcement, connecting low MOE wood with high MOE non-wood materials. Numerous wood adhesives are available today that can be chosen to meet the needs of the adherents (Stoeckel, Konnerth, & Gindl-Altmutter, 2013). Additionally, nanomaterials are increasingly being studied for their benefits in wood adhesives with many positive results for mechanical properties being found (Jiang et al., 2018; Saleem et al., 2016; Stoeckel, Konnerth, & Gindl-Altmutter, 2013). Moreover, primers are now available for these adhesives that improve adhesion, shear strength and reduce delamination (Amen-Chen & Gabriel, 2014; Clerc et al., 2018). The range of adhesives and our ability to target specific properties is vastly improved in recent years and a more targeted approach can be taken for incorporating out-of-grade.

Wood modification aims to change the properties of wood at the cell wall level via chemical, physical or biological methods (Hill, 2006) and from a structural perspective provides opportunity to strengthen, stiffen, harden and influence the dimension stability of out-of-grade timber. Chemical, thermal and impregnation methods are increasingly being commercially used today (Hill, 2006; Mantanis, 2017) and can be used separately or in combination. Chemical modification involves a reaction of the chemical and wood achieving a covalent bond between the two, thermal involves the application of heat while impregnation involves filling the cell walls with a chemical or mix of chemicals to achieve a change in wood performance (Hill, 2006).

Acetylation was found to reduce shrink swell behavior by as much as 75%, increase hardness by up to 30% with no effect (Mantanis, 2017) or an increase on the strength properties depending on variables used (Hill, 2006; Xie et al., 2013). Furfurylation has been found to reduce shrinkage by 60% and increase hardness, modulus of elasticity and modulus of rupture (Mantanis, 2017; Xie et al., 2013). Impregnation with resins such as N-methylol, formaldehyde-based resins and vinyl monomer resins can achieve an assortment of change in properties such as increased tensile, compressive and bending strength and stiffness and reducing moisture sorption and deformation (Hill, 2006; Xie et al., 2013). Impregnation with wax increased hardness, impact strength, compressive stiffness, bending stiffness and strength (Xie et al., 2013). Heat is often applied to assist other modification processes, however, thermal modification itself improves dimensional stability and reduces hygroscopicity nonetheless, care needs to be taken as temperatures above 200°C lead to reduced mechanical properties (Hill, 2006; Xie et al., 2013). Densified wood through means of heat, steam and pressure increase tensile and bending strength and stiffness and reconcile splits in veneers (Fang et al., 2012). Delignification followed by compression achieved significant increases in bending stiffness and bending, compressive (Song et al., 2018) and tensile strengths (Frey et al., 2018). Moreover, delignified wood is very moldable (Figure 3) allowing customisation of shape and redirection of strong longitudinal fibre prior to compression (Frey et al., 2018).

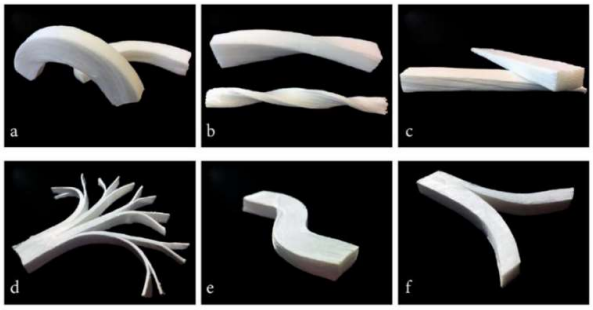

Figure 3 Molded delignified wood (Frey et al., 2018)

Only a limited number of technologies available have been presented here. However, those mentioned are seen to have high opportunity to facilitate the use of out-of-grade timber. Digital technologies allow a better understanding of the out-of-grade resource, and data sharing provides efficiency by linking the material to end use via design, engineering and construction digital technologies. Adhesive technologies facilitate reinforcement and engineered timber products while wood modification can enhance properties of out-of-grade. Most of these technologies are already in use today for other materials or for in-grade timber however, with modification to meet the needs of out-of-grade timber they also provide excellent opportunity.

4 CONCLUSION

The key to using out-of-grade timber is understanding the strengths and weaknesses of each piece and assigning each piece to a task that exploits these, but to do this we must know the end use of the timber. By matching the properties of timber to the expectations and needs of the end user, optimisation is possible. Characteristics of out-of-grade structural sawn pine and some of their structural strengths and weaknesses have been identified. It is clear that out-of-grade possesses many good properties and is underutilised in structural applications. A range of opportunities to incorporate these out-of-grade characteristics into building systems have been presented. Some building technologies that enhance the ability of out-of-grade timber to achieve high structural performance have been discussed. Moreover, it is argued that digital

technologies provide an excellent opportunity to maximise the use of out-of-grade. While some of these could be adopted as standalone solutions for applications of out-of-grade, the best benefit comes from a unified system which requires communication and information sharing throughout the entire timber industry. While market penetration, public awareness and expense are all challenges that may need to be addressed in some examples given, there are many benefits to the environment, plantations mangers, sawyers, designers, builders and customers from increased use of out-of-grade in structural applications.

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