CZECH UNIVERSITY OF LIFE SCIENCE IN PRAGUE

FACULTY OF FORESTRY AND WOOD SCIENCE

Mechanical and physical properties of CLT from hardwoods

DISSERTATION THESIS

Prague 2023 **Ing. Sumanta Das**

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I declare that I have written a dissertation on the topic of “Mechanical and physical properties of CLT from hardwoods” independently, with the use of literature and based on consultations and supervisor recommendations. I agree to the publishing of the dissertation pursuant to Act no. 111/1998 Coll., on schools, as amended, regardless of the outcome of its defense.

In Prague on …………………...   Ing. Sumanta Das

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CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Forestry and Wood Sciences

Ph.D. THESIS ASSIGNMENT

Sumanta Das

Forestry Engineering
Wood Processing and Forest Machinery

Thesis title

Mechanical and physical properties of CLT from hardwoods

Objectives of thesis

- Select the appropriate CLT composition from selected hardwoods and adhesives
- Test the CLT properties of hardwoods glued with different types of exterior adhesives according to standards
- Complex evaluation of CLT from hardwoods in terms of physical and mechanical properties
- Comparison of CLT from hardwoods with currently produced CLT from softwoods

Methodology

The following methodology is proposed for fulfilling the objectives of the thesis:

1. Analysis of literary review about CLT (Cross Laminated Timber).

2. Design of CLT compositions from hardwoods, serving as suitable alternatives to currently used softwood species, and suitable adhesives for external use.

3. On the basis of selected standardized tests, verify the physical and mechanical properties of individual CLT compositions using different types of adhesives.

4. Data evaluation using statistical methods (ANOVA, correlation) and evaluation of the most suitable CLT composition.

5. Results and discussion.

6. Conclusions and recommendations for science and practice.

The proposed extent of the thesis

90 – 120

Keywords

CLT, hardwoods, adhesives, physical properties, mechanical properties

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Abstract

Hardwood species have recently been the focus of a growing number of studies for use in manufacturing Cross-laminated timber (CLT). This research evaluates the viability of using lower-grade, fast-growing poplar and aspen lumber for both homogenous CLT and hybrid configuration with outer Norway maple layer with core poplar layer by examining the bonding properties (delamination and shear) and bending and rolling shear properties. Two types of adhesives, namely one-component polyurethane (1C-PUR) and melamine adhesive (ME), were utilized in the process. Samples were prepared from spruce for comparison. The wood species and manufacturing pressure significantly affect the CLT panels' water absorption (WA) and thickness swelling (TS). The observed WA and TS values in aspen, poplar, and hybrid CLT were comparatively greater than spruce CLT. Both homogenous and hybrid maple-poplar CLT bonded with 1C-PUR adhesive with 1 MPa pressure passed the delamination test, demonstrating excellent bonding. However, ME adhesive exhibited satisfactory performance in homogenous CLT panels, while only 50% of the hybrid maple-poplar CLT samples met the delamination test criteria. The CLT panels prepared with 0.6 MPa pressure experienced significant failure due to insufficient adhesive penetration. Both homogeneous and hybrid CLT panels met the minimum glue line shear strength. Nevertheless, it is worth noting that hybrid maple-poplar CLT exhibits significantly greater shear strength when compared to its homogeneous CLT counterparts. Compared to the delamination testing method, the performance of ME bonding indicates a slight advantage over 1C-PUR bonding in all CLT panels, regardless of the species and composition. Moreover, the primary determinant contributing to shear failure in shear testing was predominantly attributed to wood failure, accounting for more than 80%. The adhesive type did have any significant impact on global bending stiffness (EI_{mg}), bending strength (f_m) and rolling shear strength (f_r). The wood species employed in manufacturing significantly influence these outcomes. According to theoretical methods, the bending stiffness of CLT panels was underestimated by 5% for polar CLT and 10% for hybrid CLT. The Modified Gamma (MG) hypothesis demonstrated the highest accuracy in predicting bending stiffness values by incorporating the connection efficiency factor to account for shear effects, while both Shear Analogy (SA) and Timoshenko Beam Theory (TBT) exhibited a high degree of similarity. Furthermore, the strength predictions of

SA were found to be more accurate regarding bending and shear compared to other theoretical methodologies. The finite element technique can be utilized to accurately forecast the bending stiffness, with a minimal variance of 7%. Both aspen and poplar CLT panels demonstrated comparable results to spruce CLT panels. Incorporating maple as the outer layer of the hybrid CLT panels led to improved flexural and shear performance.

Keywords: Aspen, Bending stiffness and strength, Cross-laminated timber, Delamination, Hybrid CLT, Rolling shear strength, Shear strength, Water absorption

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1. Motivation

The rapidly rising population and forced relocation due to war or natural disasters like floods, earthquakes, fires, etc., need solutions for quickly supplying large residential units. Moreover, due to environmental deterioration and global warming, there is a growing demand to enhance the utilization of construction materials that are carbon-neutral, renewable, and possess long-lasting properties (Green et al., 2023). Gu et al. (2023) have shown that around 13% of global greenhouse gas (GHG) emissions may be attributed to manufacturing materials used to construct buildings and infrastructure. Further human activity, such as deforestation and industrialization, has also increased carbon dioxide (CO_2) emissions into the Earth's atmosphere, thus leading to global warming (Green et al., 2023). The operating activities of buildings account for 28% of global CO_2 emissions, with an additional 11% of emissions being attributable to the construction industry (Hart et al., 2021). Due to their durability and strength, concrete and steel are utilized in commercial buildings, but their manufacturing and transportation require a lot of energy and emit a lot of GHGs. Mass timber products, including cross-laminated timber (CLT) and glue-laminated timber (glulam), exhibit similar structural properties, making them suitable substitutes in residential and commercial construction. Compared to steel and concrete, mass timber products need less energy throughout manufacturing, work as natural carbon storage, and can be recycled (Greene et al., 2023).

The global forest cover currently encompasses approximately 30.8% of the Earth's surface (FAO and UNEP, 2020). However, this coverage is experiencing a significant decline due to human activities and natural disasters, such as converting forests into agricultural, residential, and industrial areas, forest fires, and unsustainable industrial wood extraction. In response to the depletion of natural forest resources, several nations have implemented the cultivation of plantation-grown species to preserve forest distribution. Since 1990, there has been a notable increase in the extent of planted forests, with a substantial expansion of 123 million hectares. As a result, the total area of planted forests now stands at 294 million hectares (FAO and UNEP, 2020). Approximately 45% of the overall woody areas comprise plantation forests, constituting around 3% of the total forested area (FAO and UNEP, 2020). In the last two decades, short-rotation coppice plantations, including poplar trees, have become noteworthy species in plantation forestry (Oliveira et al., 2020). Poplar plantations have a widespread geographical distribution and are predominantly cultivated in China, western Europe, and North America because of their notable wood quality, accelerated growth rate, and comparatively short rotation period (Oliveira et al., 2020). Commercial poplar plantations primarily focus on producing pulp, paper, and plywood. However, there is a growing inclination towards using poplar wood for more valuable commodities such as fibre planks, particle planks, oriented strand planks (OSB), and furniture (Brandner et al., 2016).

The naturally regenerated forest contains wood species that grow slowly but have higher market value than plantation species. The harvesting of timber is a vital forest management practice. However, there are many limitations in efficiently using low-grade wood in structural applications due to the limited market size (Adhikari et al., 2020). Furthermore, low-grade hardwoods may compete significantly with softwood lumber for structural purposes, which would result in the availability of CLT panels at a price comparable to the existing alternatives available for softwood (Beagley et al., 2014; Adhikari et al., 2021). Further, it has been reported that low-quality, underutilized hardwoods could provide an additional economic contribution of US$4.9 billion and create about 29,252 employment opportunities (Palacio-Betancur et al., 2023). Moreover, as poplar is well distributed globally, its rapid growth may offer a compelling opportunity to explore its potential uses in load-bearing structures like CLT. CLT is a prefabricated engineered panel product composed of at least three layers (Schickhofer et al., 2016). The orientation of the grain direction in one or more of these consecutive layers is orthogonal. Using this plantation lower grade wood in manufacturing CLT might provide potential benefits owing to its notable efficacy in minimizing adverse effects such as higher shrinkage and swelling, drying defects, and lower mechanical strength. Additionally, Hematabadi et al. (2020) reported that poplar is another suitable hardwood species for CLT manufacturing due to its much faster growth rate, moderate swelling and shrinking, and density comparable to spruce.

In Europe, broadleaved (hardwoods) make up about 37% of the forest, whereas conifers (softwoods) make up about 46% of the total, with mixed stands accounting for approximately 17% of the total forest area (Köhl and Linser, 2020). The prevalence of coniferous trees is primarily observed in Northern Europe (66.9%), where boreal forests are prevalent (Köhl and Linser, 2020). Finland and Sweden reported the highest proportions of coniferous trees, corresponding to 78.7% and 73.9%. However, South-West Europe showed the most significant proportion of broadleaved stands, accounting for 61.4%, primarily ten European countries reporting around 60%. The countries exhibiting the highest broadleaved trees are the Republic of Moldova, Croatia, and Hungary, with percentages of 100%, 82%, and 80.3% (Köhl and Linser, 2020). Central-West Europe exhibited the highest proportion of mixed forests, constituting 24.1% of the total forested area. Over the past three decades, the growing stock of broadleaved trees has had significant annual rise of approximately 1.6%, while coniferous plants have exhibited a comparatively lower growth rate of around 1.2% (Köhl and Linser, 2020). The hardwood forests' rise could be due to persistent afforestation with coniferous trees, bark beetle crisis, and climate changes (Glavinić et al., 2020). Pine, spruce, fir, beech, oak, and birch are the six species that account for 83.8% of the growing stock (Köhl and Linser, 2020). The dominant tree species in terms of proportion are pine (29.6%) and spruce (23%), with beech (11.9%) and oak (10%) following closely behind. Based on contemporary forest management trends, there is a notable shift towards converting spruce and pine forests into mixed forests characterized by a substantial presence of deciduous hardwood trees, with a particular emphasis on beech trees (Glavinić et al., 2020). Moreover, maple is a vital hardwood widely distributed over Canada, the United States of America, and Europe. Maple is used for furniture, musical instruments and floorings because of its durability and attractive grain patterns (known as "quilted" or "curly" grain patterns). When compared to beech, maple wood dries more slowly and exhibits minimal drying faults, while beech is prone to cracking, checking, and warping due to its rapid drying process (Avramidis et al., 2023). Further, both maple (*Acer spp.*) and poplar (*Populus spp.*) are two crucial fast-growing species contributing about (18.82%) and (5.83%) of the roadside planted species in the Czech Republic (Mácová et al., 2022).

2. Hypothesis and Objectives

Problem statement

Due to rising CLT demand, softwood timber supply and consumption are out of balance. The softwood timber market requires an alternative method to reduce imports. Hardwood CLT is one option. Using hardwood lumber to make structural CLT panels is difficult. The American standard ANSI/APA PRG-320 (2019) does not acknowledge hardwoods as a pioneer species for CLT; however, the recent version of European standard EN 16351 (2021) lists only poplar (*Populus spp.*) as a suitable material. Testing methods, standard values, and adhesive systems with technical aspects apply to softwood species. Presently, the production of CLT is governed by material characteristics and variabilities rather than being regulated following the standards (Fink et al., 2018). Further, hardwoods require drying to 15% moisture content, surface on all four sides, and trimming and ripping to a specified width thickness. These procedures may increase lumber production costs (Adhikari et al., 2020). Hardwood lumbers were mainly used to make furniture, but producers have paid little attention to their structural efficiency. Most hardwoods have higher market values due to their slower growth rate, making CLT panel manufacture economically unfeasible (Espinoza and Buehlmann, 2018). Lower-grade and plantation-grown hardwoods could be used for CLT, offering a market opportunity for traditional hardwood lumber (Beagley et al., 2014; Mohamadzadeh and Hindman, 2015). Another economic benefit of using lower-grade hardwoods is that they have better aesthetic value than strength grades (Adhikari et al., 2021).

Moreover, compared to softwoods, hardwoods have various anatomical properties. According to Meier (2007) and Ross (2010), hardwoods with low density, such as aspen, poplar, and high-density maple, exhibit higher shrinkage and swelling coefficients than softwoods, which raises concerns about their bond durability in CLT panels, particularly in situations with varying moisture levels. Further, sanding the surface of poplar wood reduced the roughness and raised the contact angle, which are indicators of poor wettability (Qin et al., 2014). Additionally, Mantanis and Young (1997) observed that the wettability of maple wood was comparatively lower when compared to aspen and spruce. The lower surface wettability of wood species makes adhesive penetration difficult (Alade et al., 2022). Moreover, previous studies (Zhang et al., 2013; Szadkowska et al., 2021) have shown the extractive content of various poplar species, including aspen and poplar, to range from 2.1% to 2.7%, while maple was observed to have an extractive content ranging from 3.1% to 3.2%. The increased extractive content in the wood species was a significant obstacle in achieving improved bonding performance. Poplar wood is generally available at a lower price for its short rotation and global cultivation. However, maple's curly grain makes it ideal for flooring and has a higher market price. Maples are planted as roadside plants in Europe and America and have not been used for structural purposes. Despite these issues with hardwood CLTs, the study was designed to discover some applicable solutions and contribute to efficiently using hardwoods for load-bearing CLT preparation. It has been observed that conventional softwood CLTs, such as spruce or pine CLTs, are prone to rolling shear failure due to lower shear strength along the grain (Gong et al., 2015; Wang et al., 2017). These softwood CLTs' relatively longer wood fibres are more susceptible to sliding or shearing along their length than hardwood (Aicher et al., 2016 b). According to Ross (2010), low-density wood species, such as poplar, have excellent shear performance in the radial-tangential plane (RT Plane) compared to spruce, although they have identical densities.

Even though one-component polyurethane (1C-PUR) adhesive occupied the market as a potential adhesive for CLT manufacturing, formaldehyde-based adhesives such as Melamine Formaldehyde (MF), Melamine Urea Formaldehyde (MUF) and Phenol Resorcinol Formaldehyde (PRF) are also being used by some manufacturers. However, many countries have issued stringent legislative regulations to reduce the emission of formaldehyde and other volatile organic compounds from wood-based panels due to environmental and human health problems (Chrobak et al., 2022). Additionally, using 1C-PUR adhesive is associated with a lower amount of wood failure percentage (WFP) during the bonding test, which challenges satisfying the requirements outlined by the CLT standards (Kläusler et al., 2014 a). In contrast, the formaldehyde-based adhesives (MF, MUF, PRF) demonstrate a WFP generation of at least 80% in the mentioned standards.

Goal

The main goal of this study is to examine the suitability of plantation-grown lower-grade underutilized hardwood poplar (*Populus spp.*) for manufacturing the CLT panels by analysing its physical, bonding, and mechanical properties. The study was further designed to examine the suitability of poplar (*Populus* spp.) as the core lamellas in preparing hybrid CLT panels with the high-density maple (*Acer platanoides* L.) as the outer lamellas. Maple is selected in this research for its curly or quilted grain pattern, which will improve the aesthetic property of the hybrid CLT panel. Moreover, maple is abundant as a roadside plantation species in the Czech Republic, which has not been studied as a structural material. This research will aid in identifying plantation-grown hardwoods for use in CLT production and provide concrete considerations for policymakers considering the inclusion of hardwoods in the standard.

Hypothesis

- The plantation-grown, low-grade, underutilized hardwood (*Populus spp.*) could be effectively utilized for CLT production, with properties like spruce CLT.
- In hybrid composition with poplar, high-density maple (*Acer platanoides* L.) wood may be utilized as the outer layers to improve the bonding and mechanical performance.

Objectives

❖ Select the appropriate CLT composition from selected hardwoods (poplar, aspen, and maple) and adhesives (1C-PUR, ME)

❖ Test the CLT properties (water absorption, thickness swelling, delamination, shear strength, bending, and rolling shear performance) of hardwoods glued with different types of exterior adhesives (1C-PUR, ME) according to standards

❖ Complex evaluation of CLT from hardwoods in terms of physical (wood species, adhesives, and pressure) and mechanical properties (theoretical to experimental)

❖ Comparison of CLT from hardwoods with currently produced CLT from softwoods (spruce and woods with similar densities)

3. Theoretical overview

3.1. Engineering Wood Products (EWPs)

Since the dawn of civilization, wood has played a crucial role in human culture. Employing solid wood components with restricted spans in traditional wooden buildings was customary. The accessibility, versatility, and sustainability of wood have contributed to its continued significance as a fundamental element in the construction industry (Jones and Brischke, 2017). Wood is recognised for its ecological compatibility and capacity for long-term use. Its advantages include its ability to withstand heavy loads, higher strength to weight, ease of workability, effective thermal insulation, and commendable fire resistance. In addition, wood exhibits the benefit of being both recyclable and reusable (Ross, 2010). However, wood poses difficulties in construction due to its intrinsic properties. Ross (2010) reported that the anisotropic property of wood causes its transverse mechanical properties to be much inferior to its longitudinal qualities. Moreover, it is essential to note that wood qualities can exhibit substantial variations even within the same species and tree, primarily influenced by grain angle, distribution of knots, and the proportion of latewood. Moisture also creates dimensional changes that may challenge wood's bonding and mechanical properties (Sandberg et al., 2021). Recently, researchers have acknowledged the potential of wood products as a feasible substitute for traditional construction materials such as concrete and steel. The environmental and climate change implications of timber have been investigated in recent studies.

Wood has been reported to help the environment and slow climate change due to its capacity for carbon sequestration (Heräjärvi, 2019). Furthermore, wood exhibits reduced levels of CO_2 emissions across several stages, including material production, building, and consumption (Lu et al., 2018; Myllyviita et al., 2022). Based on the information above, it can be inferred that significant reductions in greenhouse gas (GHG) emissions or improvements to the construction industry are essential to achieving national and international climate change targets, which can be achieved by using wood as construction material rather than steel or concrete. Wood is also a natural, recyclable material. Higher wood wastage from demolition projects is suitable for construction reuse (Arbelaez et al., 2019). Furthermore, the increasing demand for timber and the substantial rise in its current market value should catalyse the promotion of the adoption of timber reuse practices in the context of demolished structures. The waste generated during demolition is often processed into wood chips, which are then utilised for energy generation or wood panel production (Llana et al., 2022). Minimal waste is generated when wooden floors, doors, and windows are produced. Any remaining wood chips can be used as a renewable energy source through combustion or repurposed as sawdust in manufacturing. The waste demonstrates complete biodegradability, meaning it will eventually deteriorate and be reincorporated into the natural ecosystem, improving its environmental compatibility. Due to its cellular structure, wood naturally maintains heat better than other materials; it does so seven times better than ceramic tiles. The air chambers embedded inside the wood material facilitate heat absorption, resulting in a naturally warmer indoor atmosphere. Consequently, this characteristic reduces the energy demand for heating, promoting environmental sustainability. The benefit above has led to the heightened focus on wood as a construction material, fostering the expansion of multi-story timber construction in diverse nations (Johanides et al., 2020).

Thanks to technological advancements and the industrial revolution, high-rise wooden buildings now use engineered wood products (EWPs), which provide alternatives to traditional construction methods (Kremer and Symmons, 2015; Tupenaite et al., 2023). EWPs are commonly considered superior construction materials due to their remarkable environmental sustainability. The items are fabricated efficiently during production, using renewable resources. EWPs demonstrate a diverse range of sizes and dimensions in the context of their evolution (Harte, 2017). The benefits associated with EWPs include improved dimensional stability, the capacity to manufacture more significant and more complex structural elements, a reduction in the negative impact of common defects such as knots, increased toughness, and enhanced uniformity in mechanical properties (Stark et al., 2010). The development of structural wood composites has significantly improved their overall performance, making them a more suitable material for constructing diverse structures. As a result, the range of potential applications for these composites is expanded. Developing EWPs has enabled the utilisation of wood in situations where solid timber is not suitable, resulting in the creation of specialised goods that cater to a broader range of applications. According to Stark et al. (2010), EWPs have improved performance in their specific structural applications compared to conventional sawn timber. Moreover, they function as a feasible substitute for traditional engineering materials. Engaging in collaboration with engineered wood products presents several additional benefits. These factors encompass lowering costs in the building industry by using more cost-effective materials and accelerating the construction process. In addition, this collaborative effort reduces the release of ozone-depleting compounds by circumventing the utilisation of materials that need high energy levels. Furthermore, it promotes structural flexibility to withstand seismic stresses and optimises energy performance and efficiency. According to Harte (2017), mass timber construction is distinguished by the predominant utilisation of timber in the structural framework of a structure. The advantages of mass timber include enhanced and predictable physical and mechanical features, such as a more uniform structure, higher dimensional stability, and increased strength and stiffness (Harte, 2017).

3.2. Introduction to Cross-Laminated Timber

Cross-laminated timber (CLT) is an advanced EWP that first evolved in Europe in the 1990s and revolutionised the usage of wood in structural applications (Schickhofer et al., 2016). CLT has better mechanical property consistency than solid-sawn wood, which enables the use of smaller, lower-grade, and underutilised wood, assuring market competitiveness (Cherry et al., 2019). A conventional CLT panel typically comprises a minimum of three layers of structural wood planks or structural composite lumber (SCL) arranged in a perpendicular orientation and joined together using structural glue (Chen, 2011; Schickhofer et al., 2016), as shown in Figure 1. The lamellas utilised in the panels are either machine stress-graded or visually graded and kiln-dried to a moisture content of 12%. All knots or other faults are eliminated, and the planks are joined together using finger joints to get the desired lengths and efficiently use smaller wood pieces. CLT panels exhibit higher prefabrication, facilitating efficient transportation and swift installation. Moreover, these panels manifest a reduced ecological footprint at the construction site, rendering them a compelling substitute for conventional construction materials (Zhang et al., 2017). Additionally, CLT panels commonly consist of an odd number of layers, typically ranging from three to a maximum of nine layers (Schickhofer et al., 2016). CLT panels exhibit size variations contingent upon the manufacturer, with the potential to attain dimensions of up to 18 metres in length, 5 metres in width, and a thickness of 500 millimetres. This characteristic renders them highly suitable for flooring, wall construction, and roofing (Abed et al., 2022).

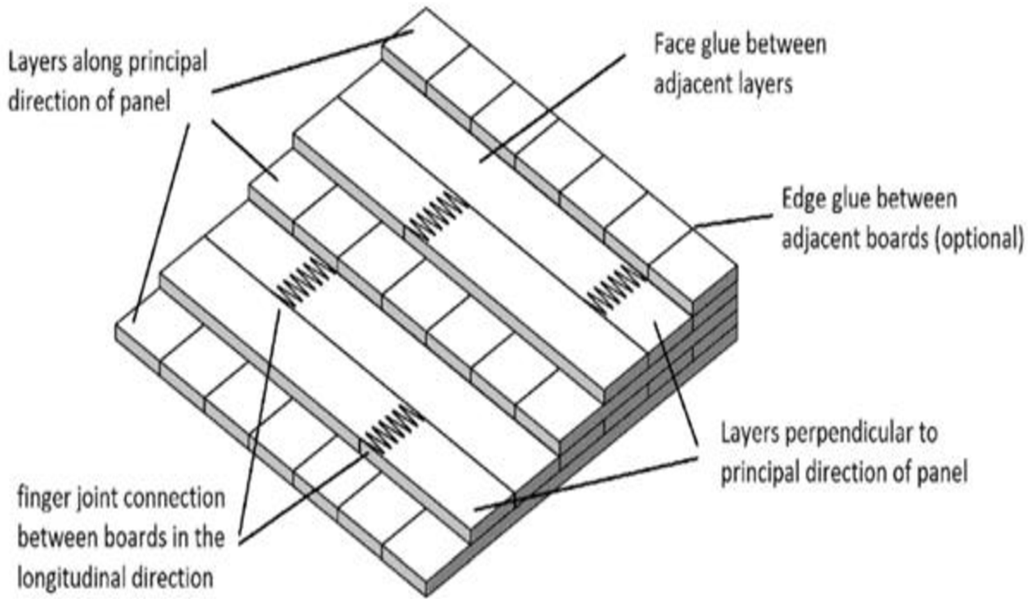


Figure 1: Construction detail of CLT panels (Christovasilis et al., 2016)

CLT permits the construction of huge or multi-story buildings in contrast to conventional light-timber frame construction. The production of CLT on a global scale is experiencing rapid growth and is projected to reach a volume of 3,000,000 m^3 by 2025, as stated by Muszynski et al. (2017). Furthermore, Europe is anticipated to account for a significant portion of this expansion, with a production volume of 2,000,000 m^3 expected by 2023 (De Araujo and Christoforo, 2023). The rapid growth and demand for CLT have sparked attention among researchers and professionals in global contexts, leading to standardised design principles for CLT construction. According to a national survey conducted among members of the architectural community in the United States, it was observed that over 50% of the respondents considered CLT as a suitable material for residential constructions (Mallo and Espinoza, 2015). Additionally, a consistent annual increase in the production and utilisation of CLT panels in several countries, including the United States, Canada, Australia, Japan, and New Zealand, can be observed (Pei et al., 2016; Goto et al., 2018; Iqbal, 2018). The global CLT productions are primarily concentrated in Europe and America, mostly from traditional softwoods, as indicated in Figure 2. Specifically, these regions are home to 70 and 18 producers, respectively. Eight firms have established operations in the Asia-Pacific region; additionally, one company has been observed in Oceania and another in Africa.

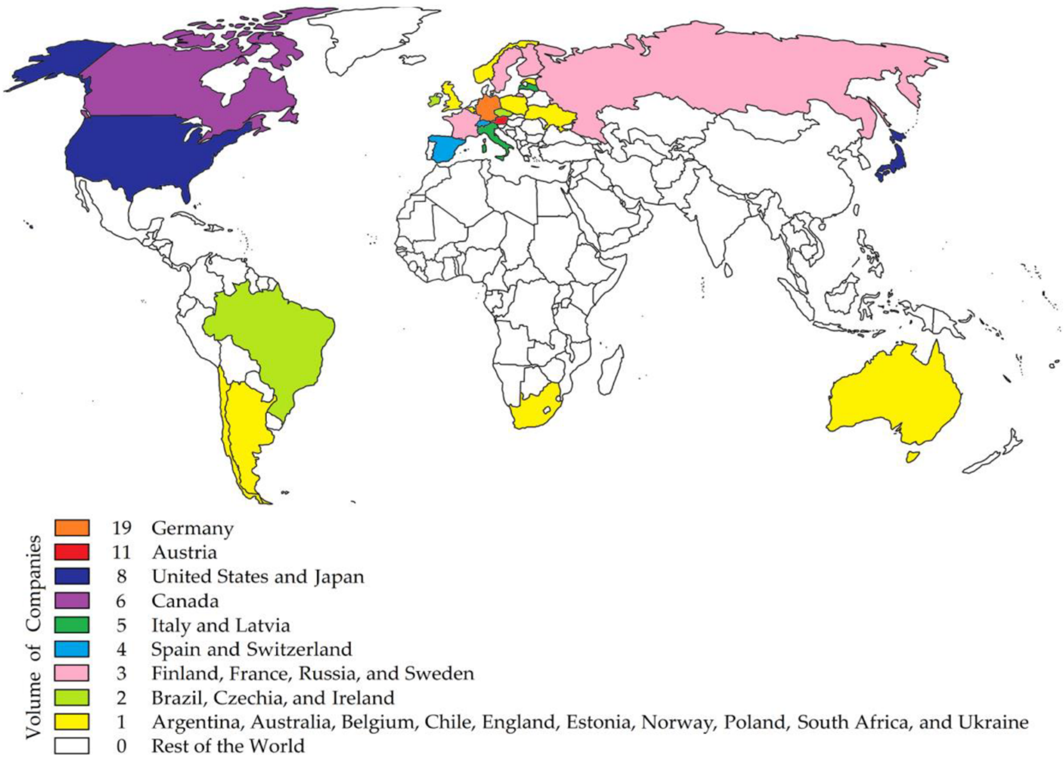
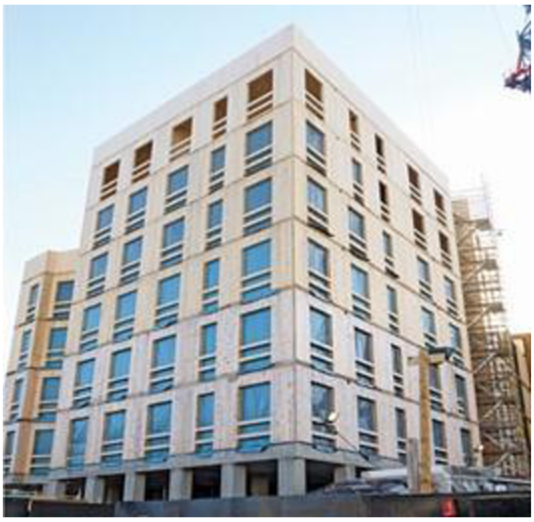


Figure 2: Active CLT manufacturers worldwide in 2023 (De Araujo and Christoforo, 2023)

Due to its superior sustainability, prefabrication, efficiency, and strength-to-weight ratio compared to those of conventional construction materials such as concrete and steel (Liu et al., 2016; Guo et al., 2017), CLT is becoming more and more popular in the application of prefabricated low-rise (three to four storeys) and mid-rise (five to eight storeys) structures along with significant opportunities for building high-rise structures (Svatoš-Ražnjević et al., 2022). Recently, there has been a global trend in constructing multistorey buildings utilising CLT. Notable examples include the Stadt Haus in London, England, a 9-story structure, the Forte building in Australia, Treet in Norway, and the Brock Commons Tallwood House at the University of British Columbia in Canada, as shown in Figure 3. These constructions demonstrate CLT's viability for developing mid- and high-rise wooden buildings (Mai et al., 2018; Siddika et al., 2021). Furthermore, it is noteworthy that the recent edition of the International Building Code (IBC, 2021) has three new construction types allowing the use of mass timber or non-combustible materials (Thornburg and Kimball, 2022). These activities have effectively increased awareness of cross-laminated timber (CLT) as a desirable construction material due to its cost-effectiveness and ecologically favourable characteristics.

Treet, Norway (Mallo et al., 2016)



Stadthaus, London (Reina, 2015)

Brock Commons, Canada (Hasan, 2017)

Forte, Australia (Parkes, 2023)

Figure 3: Some notable CLT buildings

The growing acceptance of CLT as a building material is probably due to its numerous advantages, including its low environmental impact (especially its low carbon footprint), ease of installation, aesthetic value, higher fire resistance and many more. The dimensions of CLT panels possess the capacity for convenient modification, allowing for both expansion and reduction (Jiang and Crocetti, 2019). This characteristic renders CLT a promising material for various structural components such as walls, floors, and roofs. Compared to glulam, CLT exhibits greater structural rigidity and reduces dimensional changes, specifically in shrinkage and swelling, over its length and width due to the cross-laminating within CLT. Moreover, both glulam and NLT demonstrate superior structural efficiency in a unidirectional manner due to the exclusive orientation of wood fibres along the span, while CLT reported bidirectional structural efficiency. In contrast to traditional building materials like concrete and steel, which contribute significantly to CO_2 emissions during their manufacturing, CLT, as a natural wood source, has the inherent ability to extract around two tonnes of CO_2 from the atmosphere to produce one tonne of their dry mass (Harte, 2017). According to Younis and Dodoo (2022), it has been revealed that wooden structures built using CLT panels can function as carbon sinks, effectively storing carbon throughout their operational lifespan, which leads to a reduction in global warming compared to conventional steel or concrete constructions. Moreover, Hammond and Jones (2008) reported that the CO_2 emissions from CLT buildings are significantly lower, amounting to less than 50% of the emissions produced by conventional concrete structures. In a separate investigation, Dong et al. (2019) also noted that CLT buildings exhibit lower energy consumption than reinforced concrete constructions. In addition, utilising CLT panels in the context of reuse and recycling can mitigate buildings' carbon emissions (Passarelli, 2018). Santi et al. (2016) also reported that utilising CLT can reduce environmental emissions by approximately 59% compared to traditional brickwork construction methods. Further, it is crucial to analyse the economy of CLT panels compared to that of steel and concrete to examine their suitability in the construction industry. Several recent studies have compared the material costs associated with the structural frame CLT buildings and traditional concrete buildings, yielding varying outcomes. Silva et al. (2016) asserted that using CLT can significantly decrease construction time by as much as 30%. This reduction in time not only leads to a decrease in labour expenses but also contributes to overall economic efficiency. An extensive cost analysis of a hypothetical seven-story office building observed that mass timber would save 13.6% of money over concrete (Abed et al. 2022). Additionally, CLT structures are often 40 - 50% lighter than equivalent concrete structures due to the lightweight nature of wood (Harte, 2017). As a result, it can be observed that CLT buildings necessitate a reduced amount of foundation, which substantially impacts the reduction of earthworks and foundation expenses. The curing period for CLT can vary from 4 to 7 days, whereas ordinary concrete buildings typically require 21 to 30 days (Mallo and Espinoza, 2015). Fire safety is a crucial construction component regardless of the building material type. Fire hazards associated with wood continue significantly contributing to implementing stringent constraints and building code regulations for wooden structures globally. Several investigations (Frangi et al., 2009; Wang et al., 2020) have observed the superior fire performance of CLT panels with a higher number of layers (five or seven) and greater thickness, particularly when utilising 1C-PUR adhesives and suggested the use of thicker CLT panels for fire resistivity. Ensuring the structural resilience of buildings is a vital aspect of architectural design, particularly in regions prone to frequent seismic activity. Ceccotti et al. (2013) conducted a study investigating the seismic performance of a seven-storey prototype CLT structure by Eurocode 8. The structure was subjected to a simulated load caused by an earthquake. The experimental structure displayed no observable residual displacement and remained devoid of significant structural damage, except for nail and metal fastener loosening or removal. In contrast, traditional structures constructed with reinforced concrete are more susceptible to catastrophic failure due to their inherent brittleness. Similarly, Shahnewaz et al. (2017) examined the seismic behaviour of a hypothetical six-storey CLT platform building in Vancouver using the Incremental Dynamic Analysis method. The study reported that CLT building is likely to experience any damage during a maximum-considered earthquake, with a calculated probability of collapse below 0.1%. Furthermore, due to the high in-plane stiffness of CLT panels, they can resist lateral distortion and ductile connections can yield without endangering the building's structural integrity (Izzi et al., 2018). Mallo and Espinoza (2015) revealed that 94% of US architects are deeply concerned about the aesthetics of CLT panels in buildings. Using natural materials such as wood has been shown to affect human health positively (Fell, 2010). More recently, Zhang et al. (2017) compared the physiological impacts of wooden and non-wooden interiors of a building and reported that exposure to wood reduces tension and creates a visual relaxing effect by acting on the autonomic nervous, respiratory, and visual systems.

3.3. Suitable wood species for CLT

The majority of the wood species utilised in the production of CLT consist of softwoods, specifically Norway spruce (*Picea abies* (L.) H. Karst.), Scots pine (*Pinus sylvestris* L.), and white fir (*Abies* alba Mill.), collectively referred as SPF. Simultaneously, additional species like Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), European larch (*Larix decidua* Mill.), and Western larch (*Larix occidentalis* Nutt.) were also getting used by some of the manufacturers. (Adnan et al., 2021; Musah et al., 2021). Table 1 is a compilation of noteworthy study findings.

Table 1: Some notable research on softwood CLTs

Species	**Comments**	**References**
Norway spruce (*Picea abies* (L.) H. Karst.)	Bending strength (MOR): 38.2 N/mm^2, Modulus of elasticity (MOE): 11625 N/mm^2 Rolling shear strength (f_r): 1.4 - 1.88 N/mm^2	Ehrhart and Brandner (2018); Corpataux et al. (2020)
Radiata Pine (*Pinus radiata* D. Don)	MOR: 26.61 - 28.86 N/mm^2 f_r: 1.76 - 2N/mm^2	Navaratnam et al. (2020)
Pine (*Pinus sylvestris* L.)	f_r: 1.7 - 2.29 N/mm^2	Ehrhart and Brandner (2018)
Black spruce (*Picea mariana*)	MOR: 29.6 - 30.9 N/mm^2 f_r: 1.7 - 1.83 N/mm^2	He et al. (2020)
Western hemlock (*Tsuga heterophylla* (Raf.) Sarg) and Amabilis fir (*Abies amabilis* (Dougl.) Forbes)	Bond shear strength (F_v): 2.86 - 3.89 N/mm^2 Delamination (%): 8.6 - 24.2 (50% failure)	Wang et al. (2018)
Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco)	MOR: 34.72 N/mm^2, MOE: 8690 N/mm^2, f_r: 1.24 N/mm^2	Wang et al. (2014)
Irish Sitka spruce (*Picea sitchensis*)	MOR: 36.7 - 37.8 N/mm^2 MOE: 7584 N/mm^2	Sikora et al. (2016 a)

3.3.1. Evolution of hardwoods for CLT

The decline of natural forest resources and the rise of fast-growing wood species are forcing many developing countries to switch to hardwood. Hardwood CLTs need more investigation than softwood CLTs due to their higher cost, bonding issues, and industry rejection (Adnan et al., 2021; Musah et al., 2021). Hardwood availability has increased in Europe due to increased softwood felling and its environmental impact, prefer drought-resistant hardwoods (Glavinić et al., 2023). In Europe, 37% of forests are deciduous, 17% are mixed, and 46% are coniferous (Glavinić et al., 2023). Thus, hardwoods are preferred over softwoods for construction (Van Acker, 2021). The European standard EN 16351 (2015) principally defines species with a density greater than 0.42 g/m^3 for CLT manufacturing (Hematabadi et al., 2020). Beech is a vital hardwood species observed abundantly in Europe and has excellent mechanical properties, prompting the researcher to investigate its use in CLT manufacturing, either homogenous beech CLT or hybrid CLT with softwoods or hardwoods (Aicher et al., 2016 a, b; Franke, 2016; Brunetti et al., 2020). Due to its increased density, beech CLT has better mechanical properties such as bending, rolling shear, and compression strength (Aicher et al., 2016 a, b; Franke, 2016). Due to higher swelling/shrinking values, Brunetti et al. (2020) observed that nearly all beech CLT specimens bonded with polyurethane (1C-PUR) adhesive failed the delamination test. Size also affected delamination (%); larger specimens had more surface area with higher delamination. Its higher load-bearing capacity makes it an effective cross or core layer in hybrid CLT systems (Aicher et al., 2016 a, b; Hematabadi et al., 2021; Scimoneta et al., 2021). Oak is also significant for CLT (Llana et al., 2022; Purba et al., 2022). Due to the higher density of oak, Purba et al. (2022) observed that homogeneous oak and hybrid oak-poplar CLT have higher shear strength. Oak CLT panels constructed from freshly cut and salvaged timber have an identical bending modulus of elasticity and are higher than the softwood CLTs (Llana et al., 2022). Birch is also appropriate for CLT manufacture (Jeitler et al., 2016; Eriksson and Karlsson, 2020). Birch CLT prototypes had higher load-carrying capacity.

The North American and Canadian standard ANSI/APA PRG-320 (2019) suggested wood species have a 0.35 g/m^3 or higher density for CLT manufacturing. Most hardwoods in North America and Canada have higher densities (Ross, 2010), prompting many researchers to study CLT from locally grown hardwood species. On that note, American tulipwood's (*Liriodendron tulipifera* L.) abundance and lower market price have made it a viable species for CLT production among researchers (Kłosińska, 2021). Using tulipwood CLT panels, the American Hardwood Export Council (AHEC) produced Endless Stair at the London Design Festival in 2013, Maggie's Centre in Oldham (the first hardwood CLT building), and The Smile (Espinoza and Buehlmann 2018). Furthermore, researchers like Beagley et al. (2014) and da Rosa Azambuja et al. (2022) reported that the No. 2 and 3-grade tulipwood CLT panels have higher mechanical strength higher than the required value suggested by the standard ANSI/APA PRG-320 (2019), while Mohamadzadeh and Hindman (2015) observed similar results with visually graded V1 grade lumbers. Further, maple wood evolved as a suitable material for CLT manufacturing, like tulipwood. Previous studies (Crovella et al., 2019; Ma et al., 2021 a, b; Musah et al., 2021; Rara, 2021; Palacio-Betancur et al., 2023) have examined maple's bonding and mechanical properties for CLT manufacturing. Ma et al. (2021 a, b) suggested using maple in homogeneous and hybrid CLT for superior bending performance (strength and stiffness) than the present norm. The estimated bending stiffnesses for red maple (*Acer rubrum* L.) CLT were 25% lower than experimental values (Crovella et al., 2019). Palacio-Betancur et al. (2023) observed that sweetgum CLT panels have the highest mean compressive strength, followed by red maple, sycamore, Douglas fir, and southern yellow pine. Rara (2021) observed maple CLT had twice the rolling shear strength of poplar. Musah et al. (2021) observed that homogeneous maple (red and sycamore) CLT passed the delamination test with about 80% of the sample showing higher than the standard required value, while their hybrid configuration with other hardwoods failed because of their differing anatomical structure and behaviour.

Further, domesticated and plantation-grown hardwood species have arisen in tropical countries like Malaysia, China, Korea, and Indonesia. Hamdan et al. (2016) created the first tropical hardwood CLT from sesendok (*Endospermum malaccensis*). These studies observed sesendok timber CLT to be strong. Several studies (Liao et al., 2017; Pangh et al., 2019; Nero et al., 2022) examined the bonding, bending (strength and stiffness), and rolling shear performance of several *Eucalyptus* species for CLT manufacturing. These researchers observed *Eucalyptus* can make load-bearing CLT panels. Acacia species (*Acacia mangium* Willd.) can be used to make CLT, according to Yusof et al. (2019 a, b). The authors reported that Acacia CLT has better bending and rolling shear performance than the minimum required by requirements. Corpataux et al. (2020) also studied Indonesian Sengon (*Falcataria moluccana*), Red Jabon (*Anthocephalus macrophyllus*), and Acacia hybrid (*Acacia mangium* and *Acacia auriculiformis*) for CLT performance. In addition, Adnan et al. (2021) examined several wood species, namely Batai, sesendok, rubberwood, and kedondong, while rubberwood, coconut, and oil palm (*Elaeis guineensis* Jacq) were examined by Srivaro et al. (2019, 2021 a, b) while Muñoz et al. (2021) focused on *Gmelina arborea* and *Tectona grandis* while Batai (*Paraserianthes falcataria*) by Liew and Maining (2021).

In contrast to the wood above species, the suitability of poplar (*Populus spp.*) has been the subject of many studies. Kramer et al. (2014) examined the bending parameters of CLTs made from hybrid poplar (*Pacific albus*). They observed that poplar CLT met the shear and bending strength for Grade E3 from ANSI/APA PRG-320 (2019) but fell short of the stiffness criterion. Similar results were reported by Marko et al. (2016) in their study with hybrid poplar (*Populus euramericana* cv. 'I214') CLT. Despite the comparatively low MOE values, both authors recommended that poplar could be an excellent raw material for CLT if only high-grade timber is selected and used (by non-destructive testing). Hematabadi et al. (2020) observed similar results. They further noted that poplar CLT had a lower load-carrying capability in bending tests due to the core layer's susceptibility to rolling shear failure. However, Vetsch (2015) observed aspen (*Populus tremula* L.) CLT with a higher MOE (8,068 N/mm^2) than the studies above and a very low MOR (13.26 N/mm^2), significantly below the minimum requirement with complete delamination failures. Several researchers (Wang et al., 2014; Lu et al., 2019; Hematabadi et al., 2021) have reported poplar to be employed as core layers in a hybrid CLT arrangement. Lu et al. (2019) observed that poplar (*Populus euramericana* (Dode) Guinier) could be effectively used as a core layer with Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) and Monterey pine (*Pinus radiata* D. Don) in a hybrid configuration increased the bending stiffness by 8-22% compared to homogenous poplar CLT. Poplar is also a suitable species for hybrid CLT configuration, which distributes stress equally to both outer layers, as Hematabadi et al. (2021) reported. These researchers observed that hybrid poplar-beech CLT's bending, shear strength, and stiffness were approximately 70% higher than pure poplar CLT. Poplar has been observed to have higher rolling shear strength (f_r) and modulus (G_R) than Norway Spruce. Gong et al. (2015) reported a mean G_R and f_r of 177 N/mm^2 and 2.88 N/mm^2 for aspen (*Populus tremuloides* Michx.), while Ehrhart and Brandner (2018) reported 127 N/mm^2 and 2.88 N/mm^2 and Wang et al. (2018) report 177 N/mm^2 and 3.06 N/mm^2 for poplar (*Populus spp.*). In addition, despite the density difference, Li and Ren (2022) observed that the interlaminar shear strength of hybrid larch poplar CLT is higher than that of pure larch CLT. The reported rolling shear modulus poplar CLT was higher than the stranded suggested values (50 N/mm^2) as per both ANSI/APA PRG-320 (2019) and EN 16351 (2021). Several researchers (Weidman, 2015; Musah et al., 2020; Li and Ren, 2022; Purba et al., 2022) claim that poplar has superior bonding capability. According to Weidman (2015), 70% of poplar CLT glued with 1C-PUR adhesive failed the delamination test, while the failure rate for specimens bonded with Phenol Resorcinol Formaldehyde (PRF) was 20%. Both types of glue have shear strengths that exceed the standard required value. Since homogeneous oak CLT and glulam delaminated more than mixed oak-poplar CLT, Purba et al. (2022) conclude that poplar is an excellent alternative for oak in a hybrid configuration. Additionally, Musah et al. (2021) reported that homogeneous aspen (*Populus tremuloides* Michx.) CLT showed higher delamination than their hybrid configuration due to low adhesive penetration. Table 2 summarises the performance of hardwoods in CLT manufacturing.

Table 2: Overview of some notable performance of hardwood CLTs compared to softwoods

Species	**Comments**	**References**
Eucalyptus *(Eucalyptus urophylla, Eucalyptus grandis, Eucalyptus nitens)*	Improved load-bearing performance with higher MOE, MOR and f_r than spruce CLT	Liao et al. (2017); Pangh et al. (2019); Nero et al. (2022)
Poplar (*Populus alba* L.; *Populus tremula* L.; *Pacific albus*; *Populus euramericana* cv. 'I214')	Lower MOR and MOE than the standard requirement, delamination failure	Kramer et al. (2014); Vetsch (2015); Marko et al. (2016); Ehrhart and Brandner (2018); Hematabadi et al. (2020)
Birch (*Betula pendula* R.)	Multi-storey building in Graz	Jeitler et al. (2016); Ehrhart and Brandner (2018); Eriksson and Karlsson (2020)
Beech (*Fagus sylvatica* L.)	Higher MOE, MOR and f_r and complete delamination failure	Aicher et al. (2016 a); Franke (2016); Brunetti et al. (2020)
Oak (*Quercus robur* L.; *Quercus petraea* (Matt.) Liebl)	Higher MOE, MOR and F_v	Llana et al. (2022); Purba et al. (2022)
European ash (*Fraxinus excelsior* L.)	Higher f_r	Ehrhart and Brandner (2018)
White ash (*Fraxinus americana* L.)	Higher MOE, MOR and f_r	Crovella et al. (2019)
Red maple (*Acer rubrum* L.)	Higher MOE, MOR and f_r	Crovella et al. (2019)
Sugar maple (*Acer saccharum*)	Higher MOE, MOR, f_r, compression strength (F_C) than Douglas fir and southern pine, majority delamination failure	Ma et al. (2020 a); Musah et al. (2021); Rara (2021); Palacio-Betancur et al. (2023)
Sengon (*Falcataria moluccana*)	Lower MOE, MOR	Corpataux et al. (2020)
Red jabon (*Anthocephalaus macrophyllus*)	Higher MOE, MOR	Corpataux et al. (2020)
Batai (*Paraserianthes falcataria*)	Higher F_v and passed the delamination test	Adnan et al. (2021); Liew and Maining (2021)

Gmelina arborea and *Tectona grandis*	Higher water absorption and thickness swelling, delamination failure	Muñoz et al. (2021)
Sesendok (*Endospermum malaccensis*)	Higher F_v and passed the delamination test	Adnan et al. (2021)
Kedondong (*Canarium sp.)*	Higher F_v and passed the delamination test	Adnan et al. (2021)
Acacia (*Acacia mangium, Acacia auriculiformis*)	Higher MOE, MOR, F_v, with delamination	Yusof et al. (2019 a, b); Corpataux et al. (2020)
Yellow poplar (*Liriodendron tulipifera*)	Endless Stair, Maggie's Centre in Oldham, Higher MOE, MOR	Beagley et al. (2014); Mohamadzadeh and Hindman (2015); Espinoza and Buehlmann (2018); da Rosa Azambuja et al. (2022)
Rubberwood (*Hevea brasiliensis*)	Higher water absorption (WA), F_v and passed the delamination test	Adnan et al. (2021); Srivaro et al. (2021 a); Yusoh et al. (2021)

3.3.2. Advantages of CLT made of hardwoods

It has been observed that the lower-grade plantation-grown, underutilised hardwoods possess superior mechanical properties compared to softwoods, which contributes to their acceptance as materials for CLT manufacturing. The advantages of hardwood CLTs over traditional softwood CLTs are shown in Figure 4. High-density hardwoods have more load-bearing capability than softwood, making them ideal for stressed wooden buildings, particularly for large spans (Šuhajdová et al., 2023). Another important consideration is that hardwoods' higher density and strength could meet mechanical qualities with less material than softwoods. Due to their higher strength, hardwood CLT is typically used in high-load-bearing constructions with longer spans. Hardwood CLT has these advantages over softwoods, according to several studies. Jeitler et al. (2016) found that birch CLT had higher bending strength, modulus of elasticity, compressive strength, and double the rolling shear strength of spruce CLT. They also found that birch timber required 10–15% less volume than softwood CLT to obtain strength. Franke (2016) found that beech CLT has 4.8 times higher shear strength, 1.7 times bending strength, and 4.9 times higher compressive strength perpendicular to the grain than spruce CLT. Further, hardwood has a more intricate and diverse grain pattern than softwood, making it more distinctive and attractive. However, softwood has a more straightforward and consistent grain pattern (Ross, 2010). Hardwood CLTs add more aesthetic value to timber buildings than softwood CLTs.

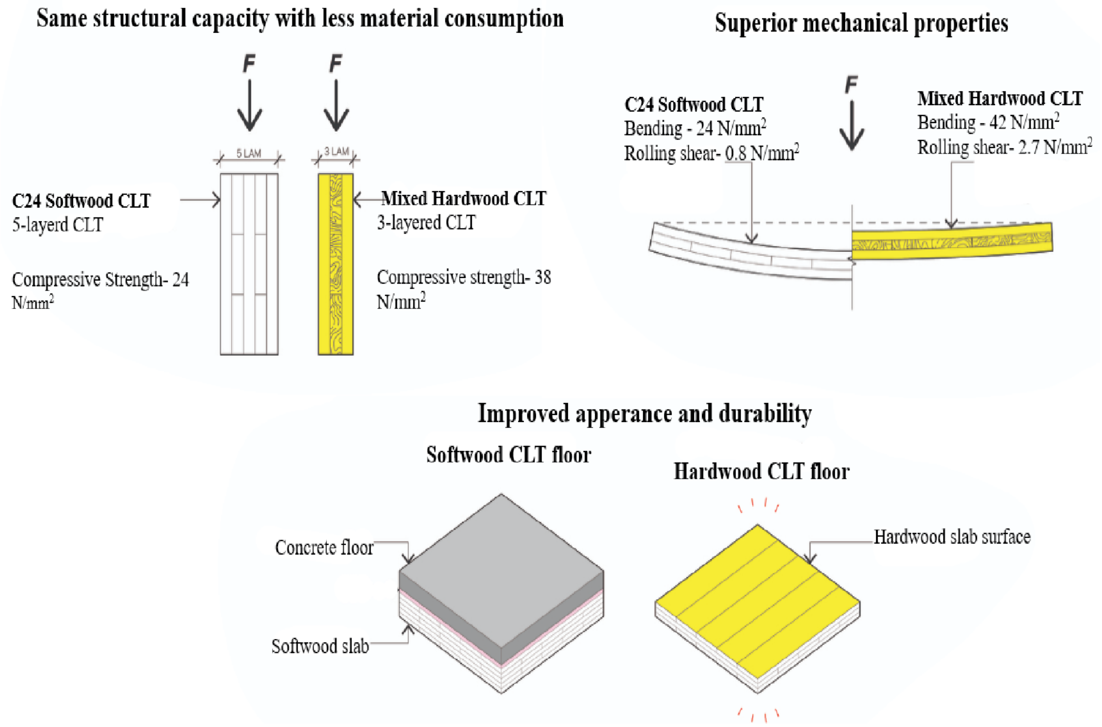


Figure 4: Advantages of hardwood CLTs

3.3.3. Limitations of hardwood CLT

Although hardwood CLT has many benefits, there are also some drawbacks. Furthermore, it is essential to acknowledge that the current edition of the European standard EN 16351 (2021) explicitly accepts poplar as the solitary hardwood species suitable to produce CLT, while the current edition of the North American and Canadian standard ANSI/APA PRG-320 (2019) has not yet recognised hardwoods as a viable option for the fabrication of CLT. Evaluating the bonding efficiency of an EWP is consistently important as bonding is an essential component of the wooden joints. However, insufficient bonding between the lamellas in hardwood CLT was observed in prior investigations conducted by Knorz et al. (2017), Musah et al. (2021), and Yusoh et al. (2021). Typically, the hardwoods demonstrate greater density and substantially higher shrinkage and swelling coefficients (Ross, 2010; Šuhajdová et al., 2023). As a result, variations in moisture levels during the delamination test may induce increased stress on the adhesive bonds of the wood, leading to the collapse of the bonds (Marra, 1992). The bonding efficiency is influenced by various factors such as wood density, porosity, strength, swelling, shrinkage, and anatomical features (Frihart and Hunt, 2010). There are significant variations between hardwoods and softwoods regarding their microscopic structure and chemical content (Walker, 2006). According to Hänsel et al. (2022), softwoods possess longitudinal tracheids with bordered pits, facilitating the adhesive flow and tangential and radial movement. In contrast, hardwoods exhibit porous end walls on thin-walled longitudinal channels, facilitating adhesive penetration into the end grain. Furthermore, various anatomical variations in hardwoods can be observed, particularly the presence of multiple pore systems, such as diffuse-porous and ring-porous topologies (Musah et al., 2021).

The limited adhesive penetration can be attributed to the low porosity and permeability (Leggate et al., 2022). Moreover, the porosity of wood varies depending on its grain orientation. In contrast to radial or tangential surfaces, end-grain surfaces exhibit a significantly higher density of pores. In some instances, the bonding of end-grain surfaces may result in excessive penetration, as the adhesive rapidly infiltrates the exposed lumens. Nevertheless, adhesives exhibit minimal penetration perpendicular to the wood grain (Frihart and Hunt, 2010). Proper adhesive penetration is crucial (Konnerth et al., 2016). Nevertheless, it should be noted that not all adhesives can penetrate deeply into the wood. Existing research indicates that cell wall penetration is accomplished mainly by in-situ polymerized adhesives with low molecular weight fractions, such as RF and PRF (Frihart, 2009). However, pre-polymerised adhesives, such as polyurethane (PUR), reported poorer penetration ability (Jakes et al., 2018). Moreover, low-density hardwood is characterised by its thin cell walls and wide lumina, whereas high-density wood is distinguished by its thick walls and small lumina. The dimensional changes generated by moisture absorption and desorption may affect the bond quality, leading to potential strain on the bond line due to increased density (Frihart and Hunt, 2010). Furthermore, it is worth noting that fluctuations in bonding efficacy can be attributed to alterations in the surface chemistry of the wood and their impact on establishing an interface with an adhesive system (Ammann et al., 2015). Based on their research findings, multiple characteristics, including surface pH, quantities of acidic and fatty acid extractives, and the accessibility of functional groups on the wood surface, influence the bonding efficacy of hardwood bonding. Furthermore, the chemical composition of wood (Ammann et al., 2015; Bockel et al., 2019) and the presence of extractives (Bourreau et al., 2013; Ammann et al., 2015; Messmer et al., 2018) significantly impact the bonding performance of hardwoods. Hardwoods have less hydrophobic lignin and more hydrophilic carbohydrates like cellulose and hemicellulose (Schroeder 1972; Tarasov et al. 2018), which affect their absorption, swelling, shrinkage, and bonding. Moreover, it is essential to acknowledge that the chemical compositions of those extractives of wood display differences between diverse species (Frihart et al., 2023). Further, the impact of adhesive components' chemistry (Frihart, 2009) and molecular size on cell wall penetration is more significant, leading to alterations in cell wall characteristics (Gindl et al., 2002; Konnerth and Gindl, 2006). Consequently, this resulted in lower swelling, potentially exerting a substantial influence on the adhesive strength in high humidity conditions. Yelle and Stirgus (2016) examined the impact of pore density and distribution on the efficacy of wood adhesive bonding in diffuse-porous hardwoods, such as basswood, soft maple, and sugar maple, during wet-dry cycle testing. Their findings show that the bond shear strength exhibits an upward trend with the specific gravity (SG) values by observing higher bond shear strength in sugar maple followed by soft maple and basswood. Similarly, Koch (1970) observed that those with higher specific gravity showed higher delamination than those with lower specific gravity. Further, Sikora et al. (2016 b) reported a negative correlation between wood density and bond durability and a positive correlation between wood density and rolling shear strength. Furthermore, it is essential to acknowledge that hardwoods have been known for their slower growth rate and have a higher price than softwoods due to their slower growth rate (Adhikari et al., 2020; Rahman et al., 2020). The long drying period of hardwoods might impose excessive stress on the bonds, leading to a deterioration in the integrity of the bonding and the subsequent separation of layers (Konnerth et al., 2016; Knorz et al., 2017). Delamination primarily arises from the inherent dimensional changes of wood, resulting in stress accumulation inside the adhesive interface during the delamination phenomenon (Frihart, 2009; Sikora et al., 2016 b; Purba et al., 2022). The water absorption can disrupt the bond between particles or layers, resulting in irreversible swelling (Winandy and Morell, 2017). Hardwoods have also been reported to have a higher price than softwoods due to their slower growth rate (Adhikari et al., 2020; Rahman et al., 2020).

3.3.4. Hybrid/mixed species CLT

Softwood CLT panels were susceptible to rolling shear failure and excessive deflection during bending tests due to their lower shear strength along the grain (Wang et al. 2017) or their longer wood fibres, which could slide or shear (Aicher et al. 2016 b). Several researchers (Gong et al., 2015; Ehrhart and Brandner, 2018; Lu et al., 2019; Hematabadi et al., 2021; Sciomenta et al., 2021) have proposed using high-density wood as outer layers and low-density wood as core to improve bending and rolling shear performance and efficiently use lower-grade woods for CLT as shown in Table 3.

Table 3: Summary of hybrid CLT performance

Species	**Comments**	**References**
European spruce (*Picea abies* L. Karst.) and beech (*Fagus sylvatica* L.)	Higher MOE, MOR, f_r	Aicher et al. (2016 b)
Sugar maple (*Acer saccharum*) and white spruce (*Picea glauca*)	Higher MOE, MOR, f_r than the E1 grade (ANSI/APA PRG-320)	Ma et al. (2020 b)
Douglas fir (*Pseudotsuga menziesii*), and Poplar (*Populus euramericana* cv. 1-214)	Lower MOE, MOR, f_r than poplar CLT	Wang et al. (2014); Lu et al. (2019)
Monterey Pine (*Pinus radiata* D. Don) and Poplar (*Populus euramericana* cv. 1-214)	Equivalent MOE, MOR, f_r like Monterey Pine CLT	Wang et al. (2014)
Poplar (*Populus alba L.*) and beech (*Fagus orientalis* Lipsky)	Higher MOE, MOR, f_r by the core beech	Hematabadi et al. (2021)
Beech (*Fagus sylvatica* L.) and Corsican Pine (*Pinus nigra* subsp. laricio)	Higher MOE, MOR, f_r than beech and Corsican Pine	Aicher et al. (2016 b); Bruneti et al. (2020); Hematabadi et al. (2021); Scimoneta et al. (2021)
Beech (*Fagus sylvatica* L.) and spruce (*Picea abies* L.)	Higher F_v, with delamination failure	Bruneti et al. (2020); Scimoneta et al. (2021)
Oak (*Quercus petraea* (Matt.) Liebl) and poplar (*Populous alba* L.)	Higher F_v, with delamination failure	Purba et al. (2022)

3.4. Adhesive system for CLT

Adhesives are just as crucial for the performance of EWPs like CLT and GLT as the type of wood is. The adhesives employed in the EWPs effectively distributed and transmitted the loads and stresses across several laminations, hence maintaining the structural integrity of the timber construction (Frihart et al., 2023). The resilience and strength of bond lines significantly impact the longevity and serviceability of timber buildings. According to Sikora et al. (2016 b), several types of adhesives, such as melamine urea formaldehyde (MUF), melamine formaldehyde (MF), one-component polyurethane (1C-PUR), phenol resorcinol formaldehyde (PRF), and emulsion polymer isocyanate (EPI), have been employed as structural adhesives. Lehringer and Gabriel (2014) and Muszynski et al. (2017) have reported that the predominant adhesive used for producing CLT panels worldwide involves using moisture-curing, 1C-PUR adhesives. According to Muszynski et al. (2017), about 66% of CLT panels were prepared with 1C-PUR, compared to the 24% usage of melamine-based adhesives like MUF/MF globally. Compared to 1C-PUR, PRF requires a longer pressing time and has a greater glue spread, more than three times that of 1C-PUR, as reported by Sikora et al. (2016 b). Moreover, the darker colour and intricate manufacturing procedure render it inappropriate (Čolić, 2021). EPI can connect edges, surfaces, and even finger joints. However, according to Sikora et al. (2016 b), EPI is unsuitable for larger finger joints and CLT. The prevalence of EPI is primarily noticed in Asia-Pacific countries, including Japan and Malaysia, where it is utilised for manufacturing CLT panels (Passarelli and Koshihara, 2017). The failure in epoxy-based adhesives such as EPI and formaldehyde-based adhesives like MUF, MF, and PRF is increased due to the dimensional changes in the wood resulting from the variations in moisture content (Issa and Kmeid, 2005; Stoeckel et al., 2013). Further, one of the most detrimental characteristics of EWPs is the release of formaldehyde, a toxic gas, from traditional formaldehyde-based thermosetting adhesives like PF, MUF, MF, and PRF. This emission is particularly concerning in indoor situations. This emitted formaldehyde primarily enters the human body through inhalation and has been linked to human cancer development (Song et al., 2015). Formaldehyde is known to be emitted by wood naturally, and levels have been observed to increase during processing processes like pressing, drying, and thermal hydrolysis in the treatment of pulp mill sludge; however, these emissions remain relatively low by occupational standards, are known to be impermanent, and rapidly decrease after these processes (Salem and Böhm, 2013). Several variable factors, such as wood species, adhesive type, resin addition level, manufacturing conditions, and hot press type, were reported to influence the formaldehyde emissions of wood-based panels (Roffael, 2006; Kumar and Pizzi, 2019). However, the environmental circumstances, the temperature and relative humidity (RH), in which the panels are subjected to testing also influence the formaldehyde emissions (Roffael, 2006). Formaldehyde-based wood composites may be exposed to additional exogenic factors, such as heating or vibration during grinding, sanding, cutting, and sawing (Kovatchev, 2018). Further, as toxic fumes are released, formaldehyde-based adhesives are also problematic during the burning of CLT panels (Čolić, 2021). Recycling products containing formaldehyde-based adhesives, including plywood and other wood-based components, is particularly challenging (Risholm-Sundman and Vestin, 2005). Consequently, the utilisation of formaldehyde-based adhesives has been limited by the World Health Organisation and categorised as a hazard within the wood industry (Salem et al., 2012; Čolić, 2021). Moreover, most wood adhesives have a primary resin component and a secondary hardening agent. Several studies have examined plant-based or other low-formaldehyde-emitting adhesives that will reduce formaldehyde emissions (Kumar and Pizzi, 2019). In addition, some researchers have begun experimenting with formaldehyde scavengers, also known as formaldehyde catchers (Kumar and Pizzi, 2019), to modify existing formaldehyde-based adhesive systems and meet the low formaldehyde limitations mandated by the new stricter environmental legislation.

3.4.1. One-component polyurethane (1C-PUR) adhesive

The formaldehyde-free, moisture-curing, 1C-PUR adhesives are widely employed in most CLT manufacturing on a global scale (Lehringer and Gabriel, 2014; (Muszynski et al., 2017). The 1C-PUR adhesive is simple and requires no hardener or supplementary chemical compounds. 1C-PUR finds application in diverse structural and non-structural contexts, exhibiting a wide array of mechanical properties that can be modified by molecular design. The utilisation of polyurethane reactive in producing structural materials such as CLTs has emerged as a relatively recent advancement (Frihart et al., 2023). Several researchers (Marra et al., 2012; Lehringer and Gabriel, 2014; Sikora et al., 2016 b) have conducted extensive investigations to examine the mechanical strength, thermal stability, and hydrophobic properties of the 1C-PUR adhesive. However, limited studies have explored its efficacy in gap-filling (Miyazaki et al., 2023). Nevertheless, the molecular weight of 1C-PUR hinders their ability to effectively infiltrate the cell wall of wood, limiting their penetration to the pores and cell lumens only (Pröller et al., 2018). According to Konnerth and Gindl (2006), 1C-PUR adhesives have a greater wetting capacity than amino-plastic adhesives, which facilitates adhesive penetration and enhances the stiffness of the glue line. Furthermore, Horváth and Csiha (2016) observed that 1C-PUR has the potential to infiltrate adhesive-coated surfaces to a greater extent than uncoated surfaces. Wood extractives hinder 1C-PUR adhesive bonding by preventing adhesive penetration and access to the hydroxyl groups due to their hydrophobic nature (Nuopponen et al., 2003). Additionally, 1C-PUR was reported to have lower water resistance if not treated with an appropriate priming solution (Hass et al., 2013; Luedtke et al., 2015). Furthermore, several researchers (Hass et al., 2013; Luedtke et al., 2015; Konnerth et al., 2016) observed lower tensile shear strength and wood failure in 1C-PUR bonded panels compared to adhesives such as MF or MUF in A4 testing EN 302-1 (2023).

Wood extractives have been observed to negatively impact the bonding effectiveness of 1C-PUR adhesive by preventing adhesive penetration and access to the hydroxyl groups due to their hydrophobic nature (Nuopponen et al., 2003). Furthermore, it should be noted that the extractives and chemical elements present in wood can alter the pH of the wood, which in turn has a direct impact on the curing process of 1C-PUR as well as its strength (Bockel et al., 2019). Moreover, it has been observed that 1C-PUR adhesive has the potential to undergo a reaction with extractives, increasing its viscosity. This increase in viscosity can impact both the adhesive's penetration and curing process, ultimately modifying the kinetics of the curing process, as shown in Figure 5 (Shirmohammadi et al., 2023).

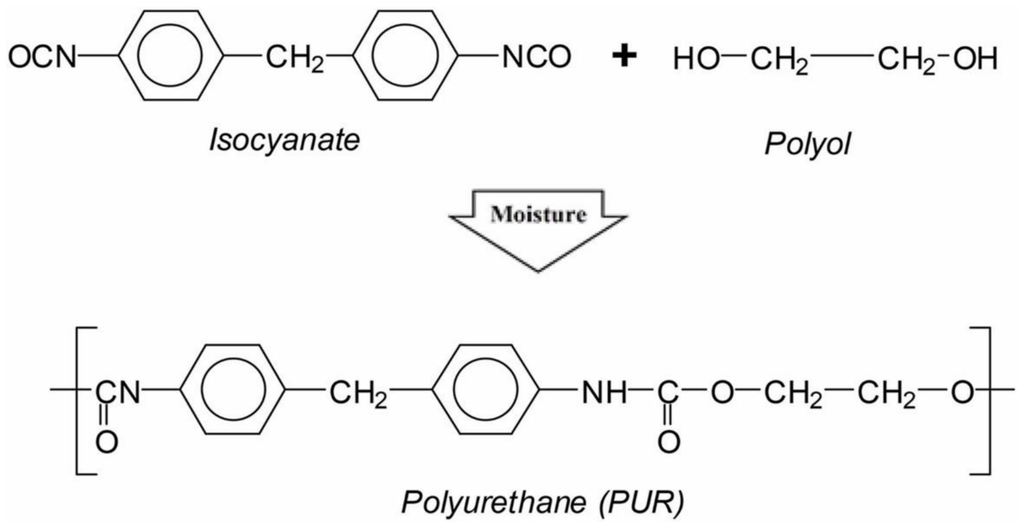


Figure 5: Synthesis of 1C-PUR adhesive (Shirmohammadi et al., 2023)

Further, primers with 1C-PUR adhesives can enhance the bonding performance of high-density wood with high extractive contents (Kläusler et al., 2014 a; Shirmohammadi et al., 2023). Moreover, surface priming with 1C-PUR adhesive might improve the bonding ability of fast-growing hardwoods like eucalyptus, which have more juvenile woods and greater levels of internal stress (Lu et al., 2018). The primers primarily increased the bonding performance by enhancing the wood surface's wettability and reducing swelling (Kläusler et al., 2014 a). The appearance of bubbles during the curing process can be attributed to the chemical reaction between water and isocyanate, producing carbon dioxide (Šebenik and Krajnc, 2007). These bubbles play a crucial role as a gap-filling agent. Therefore, applying adequate manufacturing pressure is necessary to avoid the entrapment of air bubbles within the glue line and their subsequent escape from the margins. The presence of bubbles in the adhesive glue line can generate areas of reduced strength, hence initiating the degradation of the glue line, delamination, and creep phenomena (Vella et al., 2019).

3.4.2. Melamine Formaldehyde (MF) adhesives

As one of the thermosetting adhesives, melamine formaldehyde (MF) adhesives are amino-plastic. MF adhesives possess several advantages that make them highly desirable for various industrial applications. These properties include higher moisture resistance, excellent thermal stability, high scratch resistance, superior abrasion resistance, remarkable boil resistance, surface smoothness, and exceptional transparency (Pizzi, 2003; Despres et al., 2007; Ullah et al., 2014). Besides wood adhesives, MF adhesives are utilised in many applications, such as flooring and ornamental laminates, moulding compounds, and coatings (Gindl et al., 2002; Merline et al., 2013). MF adhesives are commonly utilised as adhesives in the manufacturing of wood-based panels, including plywood, MDF, and oriented strand board (OSB), due to superior adhesion performance and reduced formaldehyde emission when compared to Urea Formaldehyde (UF) adhesives (Tohmura et al., 2001; Pizzi, 2003). The curing process of these adhesives involves using hardening agents such as ammonium salts or acids (Pizzi, 2003). Previous research has indicated that melamine reactivity primarily influences the tendency of MF adhesive to undergo hardening. The chemical process involving the interaction of the amino group observed in melamine with up to three molecules of formaldehyde, as illustrated in Figure 6, leads to the production of hydroxymethyl amines. This chemical compound has been the subject of much research. The interaction between melamine and formaldehyde is typical in an aqueous solution inside pure MF adhesives, which resembles UF adhesives (Pizzi, 2003). Due to its thermosetting properties, MF is typically utilised with hot presses, resulting in increased expenses due to the energy consumption associated with heat production. According to Merline et al. (2013), the curing temperature range for MF is reported to be between 140 and 160 °C. Moreover, throughout the heat treatment procedure employed to produce wood composites, the emission of formaldehyde, either from adhesives or the wood itself as a raw material, may occur, posing a potential hazard (Salem et al., 2012; Ferdosian et al., 2017). Additional studies have also reported that the principal drawback of MF adhesive is its significantly reduced water resistance, limiting its use solely to indoor services (Kristak et al., 2023). The aromatic ring structure of melamine imparts increased resistance to hydrolysis in MF resins by stabilising the C-N bonds inside the methylene linkages of the MF adhesive (Kristak et al., 2023). According to Shirmohammadi et al. (2023), the phenolic and melamine-based adhesives can effectively penetrate the cellular structure of wood, resulting in a strong bond formation. Additionally, these adhesives can stop water movement within the wood and make it waterproof.

Additionally, the lower formaldehyde-emitting MF adhesives are often influenced by the molar ratio of melamine and formaldehyde monomers (Dunky and Mittal, 2023). An increased molar ratio of both monomers led to elevated reactivity and viscosities, accompanied by higher formaldehyde concentration. A lower molar ratio is characterised by reduced reactivity, lower viscosities, and decreased formaldehyde content. The unbound formaldehyde inside the resins will affect the quantity of formaldehyde emitted from the final wood-based panels.

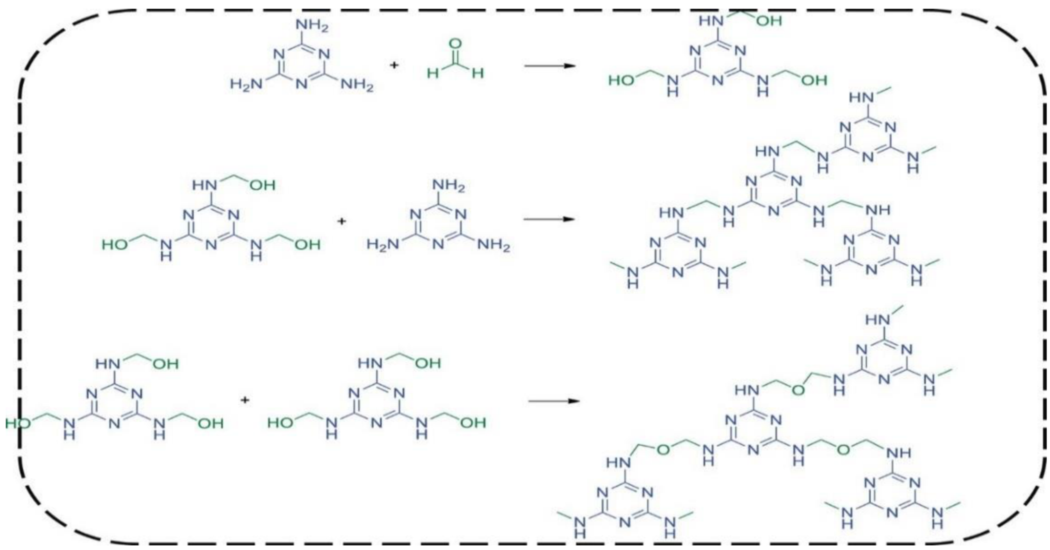


Figure 6: Addition-condensation reaction of melamine-formaldehyde adhesive (Kristak et al., 2023)

3.5. Wood adhesive bond formation process

Understanding the bond formation process in laminated wood products and how various factors can affect the quality of bonding and the wood-adhesive interaction is necessary. Thus, as shown in Figure 7, bond strength depends on ach linked properties like wood, adhesive and their interaction (Frihart, 2009). The adhesive holds the wood together, including mechanical and chemical elements. Links 2 and 3 show the adhesive boundary layer, cured under the substrates' effect, whereas link 1 is the pure adhesive phase unaffected by substrates (Marra, 1992). In these link zones, the adhesives must have been held together by attractive intermolecular forces, such as Van der Waal's, dipole-dipole, and hydrogen bonding, having a significant influence on bond strength, especially in adhesives with large contact surfaces (Frihart and Hunt, 2010). The adhesion mechanism is represented by links 4 and 5, which act as the contact between the boundary layer and the substrate. There could be the covalent bonds between the adhesive and wood substrate, or they held by the mechanical interlocking process (Frihart and Hunt, 2010; Ülker, 2016). Effective mechanical interlocking occurs when an adhesive penetrates deeper into the wood, forming a strong bond. The wood cells in links 6 and 7 have been changed during bonding or surface preparation, whereas links 8 and 9 show natural wood with lower structural integrity limitations (Frihart and Hunt, 2010; Ülker, 2016).

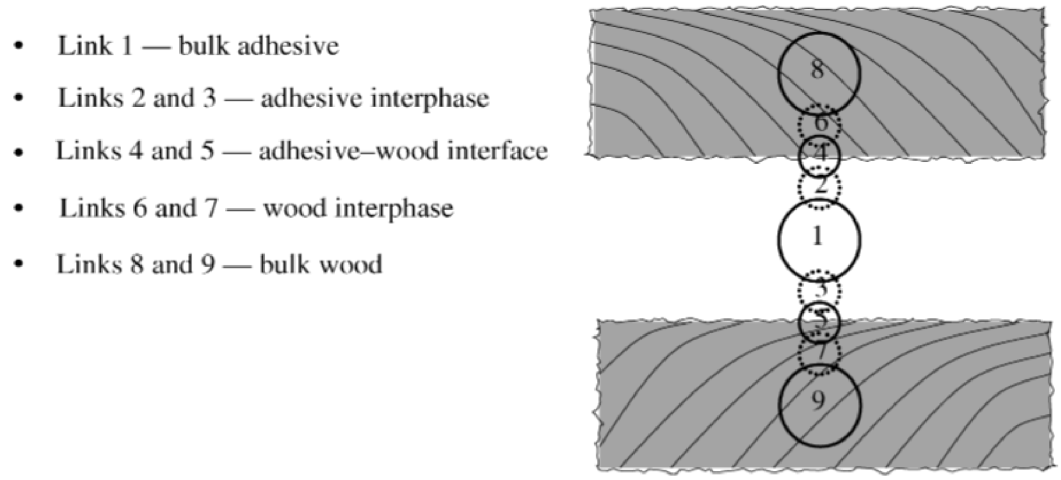


Figure 7: Chain link analogy for an adhesive bond in wood (Frihart, 2009)

Moreover, the capacity of an adhesive to penetrate the wood is limited by the porosity of the wood. The vascular structures observed in hardwoods are most important in allowing adhesive flow throughout the wood. Hardwoods exhibit distinctive characteristics such as strong cell walls, narrow cell lumina, tiny pores, and small earlywood vessels. These features contribute to a lower adhesive permeability than softwoods and ring-porous hardwoods (Kamke and Lee, 2007). The uniform dispersion of adhesive across the whole glue line is ascribed to the porous nature of the structure. The observed occurrence is a consistent glue line, characterised by limited and constant extrusion. Further, due to their unique characteristics, high-density hardwoods are challenging to bond. The narrow cell lumens observed in these cells can be attributed to thick cell walls, which pose a significant challenge for adhesive penetration, significantly limiting the depth of mechanical interlock (Frihart and Hunt, 2010). Woods with high density exhibit higher concentrations of extractives, which can impede adhesive curing and hinder the subsequent creation of bonds (Frihart and Hunt, 2010).

Further, gross and cell wall penetration contributes to adhesive penetration into the wood cell structure. Gross penetration refers to the process by which adhesive is compelled into the lumina of cells through compression clamping, while cell wall penetration refers to the process by which glue diffuses into the cell walls (Kamke and Lee, 2007). This phenomenon occurs due to the presence of charged components in the adhesive and wood, which strive to achieve a state of neutrality (Kamke and Lee, 2007). The viscosity of the adhesive is an additional variable that influences the extent of bond penetration and the longevity of the connection (Chandler et al., 2005; Kamke and Lee, 2007). The degree of adhesive penetration plays a crucial role in wood bonding due to its impact on both the adhesive composition and the conditions under which bonding occurs. An appropriate equilibrium is necessary to prevent inadequate bonding from insufficient or excessive penetration. Poor penetration leads to diminished interactions between wood and adhesive. In contrast, extreme penetration leads to bad bonds that effectively bridge the gaps between wood surfaces, resulting in connections lacking sufficient adhesive material. Firhart (2005) reported that an adhesive with lower viscosity can penetrate to a greater depth than an adhesive with higher viscosity. Simultaneously, a coarse wooden surface facilitated enhanced adhesive penetration, allowing for a more superficial penetration on smoother surfaces (Cheng and Sun, 2006). According to Musah et al. (2021), the lower viscosity of melamine adhesive allows excellent adhesive penetration, resulting in a bonding process lacking sufficient adhesive. Conversely, Cheng and Sun (2006) and Ren and Frazier (2012) observed that 1C-PUR exhibits shallow penetration due to its higher contact angle and viscosity.

Foams may be generated on the wood surface due to the surplus of 1C-PUR adhesive, resulting in decreased bonding strength (Kläusler et al., 2014 b; Lu et al., 2018).

The effectiveness of bonding is influenced by various factors, including the type of adhesive used, its formulation, composition, and viscosity. The adhesives can broadly be classified as water soluble and water insoluble. The water-soluble adhesives are MF, UF, MUF, PRF, PVAc, and EPI, and can include up to 50% water content, as indicated by Pizzi (2003) and Hänsel et al. (2022). On the other hand, the 1C-PUR adhesive does not contain any water content. Introducing water into adhesives causes the wood to expand, resulting in subsequent modifications to the pore structure. Consequently, this leads to a shift in the adhesive's capacity to infiltrate the wood subsurface (Hänsel et al., 2022). Furthermore, it is essential to acknowledge that the bonding performance may be affected by the different primers utilised during the bonding procedure since studies have shown that specific primers can generate greater swelling levels than water (Ammann et al., 2015). The interconnected structure of the adhesive enables the efficient transportation of water from the adhesive to the wood throughout the drying process. When UF, MUF, MF, and PRF adhesives are used, the observed behaviour causes the swelling of the wood while the adhesive layer decreases (Sonderegger, 2011). As a result, the bonded connection experiences the formation of cracks, leading to the gradual degradation of the material (Hass, 2012). Another consequence of moisture absorption by wood is the modification of surface roughness caused by the swelling phenomenon. Hänsel et al. (2022) reported that using 1C-PUR in wood bonding showed no signs of swelling or shrinking.

According to Gindl et al. (2001), additional elements such as glue spread, glue line thickness, and the adhesive mixture formulation play a crucial role in achieving mechanical stability in bonding. Using more rigid adhesives is associated with an increased incidence of wood failure (Hass, 2012; Knorz et al., 2016). The magnitude of stress applied to the wood, and consequently the rate at which wood failure occurs, is influenced by the adhesive's stiffness at the bonded joint (Hass et al., 2013). The flexibility of the glue line significantly affects the fatigue properties of the adhesive system's components. The manufacturing parameters under consideration include the closed assembly time (Ohnesorge et al., 2010; Schmidt et al., 2010), the thickness of lamellae in the final glued product (Ohnesorge et al., 2010), the utilisation of multiple primers before the application of a one-component polyurethane adhesive (Ohnesorge et al., 2010; Kläusler et al., 2014 b; Luedtke et al., 2015; Casdorff et al., 2018), the impact of the angle of the growth rings of the lamellae (Ohnesorge et al., 2010), and the surface preparation before glueing (Kläusler et al., 2014 b; Luedtke et al., 2015).

3.6. Physical and mechanical properties of CLT

3.6.1. Water absorption (WA) and thickness swelling (TS) of CLT

When CLT is exposed to liquid, such as leaks, rain during construction, or high relative humidity, the wood may experience increased moisture above the fibre saturation point. Schmidt et al. (2019) reported that increased wood moisture content decreases stiffness and increases viscoelasticity and plastic deformation. Moisture-induced stresses and strains, including differential swelling and shrinkage, can produce checking, warping, and delamination (Glass and Zelinka, 2010; Schmidt et al., 2019). Different lamellas used in CLT panel production and their cellular composition and dimensions significantly affect WA and TS properties (Shirmohammadi, 2023). Numerous prior investigations (Peng et al., 2015; Cai et al., 2020) have examined the relationship between pore size and diverse characteristics, including porosity, permeability, and treatability of products on WA and sorption isotherm in mass timber constructions. McClung et al. (2014) have reported a correlation between the porosity of timber species and their susceptibility to moisture flow, indicating that timber species with higher porosity tend to display reduced resistance to moisture. Due to the greater porosity exhibited by hardwoods, both the WA and TS values may be expected to be higher than softwoods. Moreover, the anatomical structure of wood species was predominantly ascribed to the WA and TS of the panels. It is further reported that the diffusivity of the bound water in wood species depends upon its porosity (Shirmohammadi, 2023) and the proportion of voids present within the wood structure (Suleiman et al., 1999). Higher porosity can enhance the sorption process, attributing to the higher proportion of voids serving as conduits for liquid migration (Slovackova et al., 2021). Srivaro et al. (2021 a) have observed a positive correlation between the density of lamella utilised in CLT and the resulting panel density and the WA and TS of the CLT panels. However, Aisyah et al. (2023) reported that the different lamellas in the production of CLT panels had a significant impact only on TS values. On the other hand, the WA seen in CLT panels was determined to result from the combined influence of the various lamellae used in the manufacturing process. Nevertheless, the individual contributions made by the lamellas do not demonstrate statistical significance (Aisyah et al., 2023). The CLT panels' porosity was greatly affected by the edge gaps resulting from non-edge glueing (Shirmohammadi, 2023). According to Shirmohammadi (2023), the number of glue lines in CLT panels can act as a barrier to water circulation. The CLT's holes, cracks, and fissures enable water circulation and absorption. Humidity levels affect CLT's load-bearing dimensional stability in timber buildings. Since CLT is orthogonal, its dimensional expansion coefficient differs from solid wood or glulam in all three directions (radial, tangential, and longitudinal) (Gereke et al., 2010). CLT has a width-wise swelling coefficient of less than one-fifth compared to solid wood or glulam (Pang and Jeong, 2020). Table 4 shows the WA and TS of CLT panels from several wood species.

Table 4: Reported water absorption (WA) and thickness swelling (TS) of several CLT panels from various research

Species	Comments	WA (%)	TS (%)	References
Acacia mangimum	1C-PUR PRF	7.808 7.028	1.053 0.696	Yusof et al. (2019 a)
Radiata pine	1C-PUR	29.35	4.30	Maithani et al. (2023)
Gamhar (*Gmelina arborea*) Teak (*Tectona grandis*)	EPI	8.61 8.90		Muñoz et al. (2022)
Rubberwood	MUF	24-33	1.5-3.1	Srivaro et al. (2021 a)
Coconut	MUF	12-20	2.2-2.8	Srivaro et al. (2021 b)
Oil palm (*Elaeis guineensis* Jacq)	PVA	70-160	15-27	Srivaro et al. (2019)
SPF Hybrid SPF-OSB Hybrid OSB-SPF	1C-PUR, EPI and PRF	13.2-16.8 10.4-13.8 10.2-11.1	2.3-3.8 2.2-2.4 2.6-3.6	Liang et al. (2022)
Sumatran pine (*Pinus merkusii*) Coconut (*Cocos nucifera*) Hybrid pine-coconut Hybrid coconut-pine	1C-PUR	38.79 17.21 30.65 28.12	7.15 3.69 6.08 4.11	Baskara et al. (2023)

According to Liang et al. (2022), the WA and TS properties of CLT panels are influenced by several factors, including the wood species employed, the thickness of the laminations, and the adhesive utilised. According to Yusof et al. (2019 a), the mean TS values for *Acacia mangium* CLT manufactured with PRF and 1C-PUR were 1.053% and 0.696%, respectively. Srivaro et al. (2019) observed a correlation between the manufacturing pressure and TS and WA in oil palm (*Elaeis guineensis* Jacq.) CLT, reporting higher manufacturing pressure resulted in lower WA and TS. Liew and Maining (2021) investigated the mechanical and physical properties of Batai (*Paraserianthes falcataria*) CLT panels with varying glue spreads, specifically 150, 200, 250, and 300 g/m^2. They reported lower WA and TS in the CLT panels with a higher glue spread. Srivaro et al. (2021 a) reported that the resin content and clamping pressure had no significant impact on the WA and TS of rubber wood CLT panels. According to the study conducted by Gereke et al. (2010), it was observed that glue lines experienced the highest strains due to tangential and radial changes in shrinkage. The study also revealed that the annual ring angle, intermediate layer features, and layer thickness ratios significantly impacted panel warpage and induced stresses.

3.6.2. Bonding performance of CLT

In EN 16351 (2021) and ANSI/APA-PRG 320 (2019), delamination and shear tests are recommended to assess CLT panel bond performance. Delamination between lamellae may diminish CLT mechanical strength due to inferior bonding or manufacturing faults (Sikora et al., 2016 b; Brunetti et al., 2020). Delamination can happen at a single spot or throughout entire lamellas, leading to total glue line collapse. It is primarily produced by natural dimensional changes in wood, which result in stress accumulation at the wood-adhesive interface during the delamination process, which is predominantly swelling and shrinkage (Frihart, 2009; Sikora et al., 2016 b; Purba et al., 2022). Due to the diverse anatomical structures, density, chemical components, porosity, strength, swelling, and shrinkage, hardwoods are especially prone to this issue (Frihart and Hunt, 2010). The longitudinal tracheid with bordered pits in softwoods allows transverse fluid flow, whereas, in hardwoods, the porous end walls on thin-walled longitudinal vessels allow adhesive penetration (Hänsel et al., 2022). Furthermore, the orthotropic nature of wood and grain orientation significantly impact its mechanical properties, and the porosity of wood varies depending on grain orientation. This influenced the wood's water absorption, swelling, and shrinkage behaviour (Ammann, 2015; Arzola-Villegas et al., 2019). Wood swells by 10% along the tangential direction (T), 5% along the radial direction (R), and 0.1% along the longitudinal direction (L) (Arzola-Villegas et al., 2019). The reduced swelling and shrinkage in the longitudinal direction is attributed to the alignment of the rigid cellulose microfibrils, which are predominantly oriented parallel to the longitudinal axis and exhibit minimal changes during moisture adsorption (Arzola-Villegas et al., 2019). Furthermore, the porosity of end-grain surfaces is greater than that of radial or tangential surfaces, resulting in overpenetration since the viscous adhesive can easily permeate the open channels inside the grain structure. Wood density determines water absorption and swelling (Koddenberg, 2016; Niemz et al., 2023). The swelling coefficient of high-density wood with thick cell walls and tiny cell lumina is greater than that of low-density wood with thin and big cell lumina. The stress on the bond line induced by greater density caused by dimensional changes caused by moisture absorption and desorption might impair the bond quality of hardwoods. Furthermore, the higher the hydrophilic carbohydrates in hardwoods, such as cellulose and hemicellulose, the lower the hydrophobic lignin content, positively influencing swelling (Schroeder, 1972). Wood swelling differences are most likely due to intra-cell wall structures with shorter scales (Schulgasser and Witztum, 2015; Arzola-Villegas et al., 2019). Additionally, because of their thicker cell walls and smaller lumens, mechanical interlocking of high-density woods is limited to depths of less than two cells, which may necessitate higher pressure to effectively compress these timber components and promote their bonding with the adhesives (Frihart and Hunt, 2010). Wood's extractive content has also been shown to reduce the bonding performance (Luedtke et al., 2015; Konnerth et al., 2016; Bockel et al., 2019). When many domestic and tropical wood species have significant amounts of extractives, the challenges connected with adhesion become apparent. Furthermore, the ratio and chemical makeup of the extractive component differs between the sapwood and heartwood of these specific species (Frihart et al., 2023).

Moreover, the moisture difference between layers of the CLT panels' orthogonal arrangement potentially results in delamination (Bobadilha et al., 2020). Further delamination occurs when wood and glue do not expand or contract together during swelling or shrinking, causing stress in the glue line and delamination (Frihart and Beecher, 2016). Winandy and Morell (2017) reported that the absorbed moisture potentially disrupts the wood-adhesive bonding, resulting in irreversible swelling caused by the release of compressive tension induced during the hot-pressing process. Watson et al. (2013) reported that delamination was significantly influenced by the swelling and shrinking of the wood lamellas in both parallel and perpendicular orientations to the panel plane. The variations in the drying characteristics of different wood species might potentially lead to the development of internal stress inside wood-adhesive bonds, which may cause the bonds to fail and result in delamination (Knorz et al., 2014). Konnerth et al. (2016) reported a notable variation in the drying time among different wood species, with certain species requiring a much longer period to reach the initial mass threshold after impregnation. Further, delamination is also induced by the orthogonal arrangement in CLT, which causes a greater stress level in the glue line due to the sandwich configuration comprising the outer and core layers. The increase is also attributed to the orthotropic nature of the wood material. When the resultant swelling and shrinkage stresses within the CLT panels exceeded the threshold, cracks developed in the bond. These cracks can propagate, posing a potentially disastrous consequence for the remainder of the structure. Further, Gereke et al. (2009) observed that the wood species used in the outer layers play a significant role in moisture-induced stresses, while the core layer does not significantly impact and acts as an effective barrier against moisture. They further reported that moisture-induced cupping is most likely to occur in radial-tangential (RT-plane). Furthermore, it is crucial to recognise that the adhesives utilised in this context can function as a diffusion barrier, potentially amplifying internal tensions (Ammann, 2015).

The bond shear test is widely regarded as an easy and efficient technique for assessing the adhesive properties of bonded composites. Nevertheless, several researchers have previously modified their experimental methodology to investigate the bond shear test of CLT panels. According to Steiger et al. (2010, 2014), it has been observed that shear testing can lead to rolling shear and glue line shear failures. These failures can be attributed to various factors, such as the testing method employed, the specimen's arrangement, and the loading direction. Betti et al. (2016) observed increased shear strength when specimens with sides oriented at a 45° angle with each panel. Furthermore, Gao et al. (2022) revealed that using a compressive double shear test effectively reduced the variability in shear stress measurements of CLT panels by neglecting the influence of rolling shear and promoting a more uniform distribution of shear stress across the panel.

By conducting delamination and shear tests, Sikora et al. (2016 b) compared the bonding performance of Sitka spruce (*Picea sitchensis* (Bong.) Carrière) CLT bonded with 1C-PUR and PRF. They discovered that 1C-PUR specimens provided greater shear strength while failing in the delamination test, whereas the PRF specimens excelled in the delamination test. In another study, Yusoh et al. (2021) analysed bond shear strength and delamination test results to determine the bonding performance of four fast-growing tropical timbers: Batai (*Paraserianthes falcataria*), Rubberwood (*Hevea brasiliensis*), Sesendok (*Endospermum malaccensis*), and Kedondong (*Canarium spp.*). The study revealed that the glue spread significantly affected the bond shear strength and wood failure percentage (WFP), while the delamination (%) was unaffected significantly. According to their findings, the best results were achieved with a glue spread of 200 g/m^2. Similarly, Liao et al. (2017) examined the effects of manufacturing pressure, pressing time, and glue spread on bond performance and mechanical properties of *Eucalyptus* CLT bonded with 1C-PUR. They reported that higher manufacturing pressure and pressing time slightly increased block shear strength and wood failure percentage (WFP) and reduced delamination significantly. Further, they suggested an optimal manufacturing pressure of 0.8 MPa, with a pressing time of 200 minutes with a glue spread of 160 g/m^2 for better bonding of eucalyptus CLT. Lu et al. (2018) used four different types of adhesives, including epoxy resin (EP), emulsion polymer isocyanate (EPI), phenol resorcinol formaldehyde (PRF), and polyurethane (PUR), to investigate the effect of adhesives on bonding performance to produce *eucalyptus* CLT and observed that PUR bonded CLT showed best results for both delamination and shear strength. Wang et al. (2018) examined the effect of adhesive and clamping pressure on the bond quality and durability of hem-fir CLT panels. The study revealed that higher bonding pressure positively influenced shear strength, concurrently reducing delamination (%) and increasing the proportion of wood failure. Gong et al. (2016) conducted an orthogonal test to investigate critical aspects of Japanese larch CLT, including adhesive type, glue spread, and clamping pressure. The optimal manufacturing circumstances encompass a one-component polyurethane (1C-PUR) adhesive with a glue spread of 200 g/cm^2 and a manufacturing pressure of 1.2 MPa. Yusof et al. (2019 a, b) examined the delamination of *Acacia mangium* CLT bonded with PRF and one-component polyurethane (1C-PUR) and observed that PRF was more water-resistant than PUR, resulting in less delamination of PRF-bonded CLT specimens. Luedtke et al. (2015) investigated delamination and block shear tests. Furthermore, microscopic glue line thickness measurements were used to acquire information concerning bonding quality. Due to the high density of hardwoods, hardwood CLT shear strength values were higher than softwood values; however, WFP values were somewhat lower than softwoods. Hindman and Bouldin (2015) evaluated the bonding performance of southern pine CLT by performing delamination, shear tests, and compression loads to compare the findings to the values stated in the product specifications. They reported that applying glued laminated timber standards to CLT products necessitates clarity in loading direction orientation for shear resistance by compression loading. Purba et al. (2022) examined the bonding properties of both CLT and glulam made from oak (*(Quercus petraea* (Matt.) Liebl*)*) and hybrid poplar-oak (*Populus alba L.*), and they observed that manufacturing pressure, glue type, and their interactions with species all had a significant impact on the bonding quality. The researchers noted a decrease in delamination in the hybrid configuration compared to the homogeneous oak CLT. In another study, Musah et al. (2021) employed a delamination test to examine the bond durability of various hardwood and softwood species native to Northern America, including aspen (*Populus tremuloides* Michx.), white ash (*Fraxinus americana* L.), white pine (*Pinus strobus* L.), yellow birch (*Betula alleghaniensis* Britton), and their hybrid configurations. The bonding was achieved using melamine formaldehyde (MF) and phenol resorcinol formaldehyde (PRF) resin. In contrast to mixed species CLT, the homogeneous CLT exhibited higher delamination failure. In another study, Li et al. (2023) examined the bonding performance of homogenous Shining gum, radiata pine CLT and their hybrid configuration with core Shining gum and outer radiata pine in both parallel and perpendicular directions bonded with 1C-PUR adhesives. The study observed delamination failure in most of the hardwood CLTs. However, due to their higher density, the hardwood samples showed greater shear strength and stiffness regardless of bond direction. On the other hand, the orientation of bonds significantly impacted the properties of hybrid structures.

Given the limitations of the two test methods (delamination and bond shear) specified by the standards for evaluating adhesive bonding quality, it is evident that neither test method can provide essential information on the bonding quality of the CLT panels (Schmidt et al., 2010). Therefore, the standards suggested visually evaluating the WFP by breaking down the bonds with the help of a hammer and chisel. Further, several previous research has already identified the delamination test as the most critical test method for examining the bonding performance of CLT panels, specifically for hardwoods, due to their higher swelling and shrinkage coefficients (Betti et al., 2016; Sikora et al., 2016 b; Knorz et al., 2017). However, in the bond shear test, the hardwoods showed prominent results. Further, the calculation of WFP is very efficient in determining whether the failure is attributed to the wood or glue. However, the WFP evaluation is reported to be ineffective as it is challenging to convey the specific behaviour of the failure visually (Steiger et al., 2014; Betti et al., 2016). Further, several previous studies (Xiao et al., 2008; Lehringer and Gabriel, 2014) observed higher bond shear strength and lower WFP due to the exceptionally higher ductility nature of 1C-PUR adhesive. Similarly, Purba et al. (2022) reported higher shear strength and WFP in MUF-bonded CLT panels manufactured with higher manufacturing pressure. Similarly, Sikora et al. (2016 b) reported higher WFP in spruce CLT, which is as much as 100% with higher manufacturing pressure (1 MPa) compared to the WFP of approximately 40% with a low manufacturing pressure (0.4-0.6 MPa). Further, Pröller et al. (2018) raised concerns over utilising WFP to evaluate the bonding quality of the CLT panels bonded with 1C-PUR adhesives. Further, Luedtke et al. (2015) examined the bond performance of hardwoods using the block shear test. They reported higher shear strength values of hardwoods compared to softwoods, which may be attributed to the higher density of hardwoods. However, the WFP values of hardwoods were somewhat lower compared to softwoods.

3.6.3. Bending properties of CLT

Recently, the usage of CLT as both interior and exterior elements in tall buildings has increased exponentially due to its advantages (Song and Hong, 2018). This material's primary advantages include its dimensional stability, superior strength in both in-plane and out-of-plane orientations, enhanced stiffness properties resulting from cross-laminating, and improved fire performance (Sharifnia and Hindman, 2017). However, there are numerous concerns regarding the bending performance of CLT panels in various applications, both short- and long-span (Sikora et al., 2016 a). The rolling shear in the CLT is mainly attributed to out-of-plane bending, resulting in shear stress on the radial-tangential plane perpendicular to the grain within the cross-layer (Wang et al., 2014; Wang et al., 2015; Davids et al., 2017). According to Hosseinzadeh et al. (2022), when a CLT panel is subjected to out-of-plane bending, the deflection of the panel is attributed to both bending and shear deformation. The presence of inadequate rolling shear behaviour within the cross-layer of the panel would result in an increased deflection, accompanied by a reduction in the overall bending stiffness and strength. When evaluating the suitability of CLT for structural applications, it is imperative to consider its exceptional bending characteristics, particularly with floor systems. Consequently, it is essential to allocate additional attention to the rolling shear characteristics of the material to prevent it from becoming a constraining factor in the structural design process (Wang et al., 2017). The deformation behaviour of CLT is relatively complex due to wood's orthotropic properties and the arrangement of layers in a crosswise lay-up (Marjanović et al., 2020). The higher ratio of the modulus of elasticity in the longitudinal direction (E_L), along with the corresponding transverse shear modulus of the cross layers (G_{RT}), induces significant shear deformations across the thickness of the plate. The transverse shear stress exhibits significant discontinuities at the interfaces between layers, whereas the transverse shear stresses remain continuous and exhibit a substantial nonlinearity across the thickness (Marjanović et al., 2020). The primary structural concern on the bending characteristics of CLT is the relatively low transverse shear strength exhibited by the layers perpendicular to the grain. This deficiency results in the rotation of wood fibres and the occurrence of a brittle failure mechanism (Franzoni et al., 2016). The bending strength (MOR), modulus of elasticity (MOE) and rolling shear strength (f_r) are the primary mechanical properties utilised to evaluate its structural performance (Ma et al., 2021 a, b). The bending performance of CLT panels can be influenced by various factors, such as wood species and its density, adhesive type, and the thickness and orientations of the lamella.

Franke (2016) observed that beech (*Fagus* spp.) CLT has superior bending strength, stiffness and elastic modulus compared to spruce (*Picea* spp.) CLT as the density of beech (690 kg/m^3) is much higher compared to spruce (470 kg/m^3). Similarly, Pereira and Calil (2019) observed higher bending performance in *Eucalyptus* CLT than in pine CLT. Further, *Eucalyptus nitens* and *Eucalyptus globulus* performed better than other *eucalyptus* species, according to Pangh et al. (2019). They also observed that the wood species significantly influence the MOE and MOR of CLT panels constructed from both species. Ma et al. (2021 a) examined the bending and shear properties of sugar maple (*Acer saccharum*) CLT with two distinct grade combinations: high-low-high and low-high-low. The CLT panels were bonded using melamine-formaldehyde (MF) and resorcinol-formaldehyde (RF) adhesives. The research findings indicate that sugar maple CLT has a significantly higher MOE, around 50-80%, and double the MOR compared to the E1 grade of CLT suggested by ANSI/APA PRG-320 (2019). Additionally, Ma et al. (2021 b) reported that sugar maple (*Acer saccharum*) in a hybrid configuration with white spruce (*Picea glauca*) increased the MOE by 100% to 110%

compared to the E1 grade CLT. Both investigations observed that wood species greatly affected CLT panels' bending and shear performance, whereas adhesive type did not. Hematabadi et al. (2020) observed that homogeneous poplar (*Populus alba* L.) CLT had a lower MOE than pine and larch CLT due to its lower density. However, they reported higher MOE in a hybrid arrangement with a beech (*Fagus orientalis* Lipsky) core layer than the spruce CLT. Additionally, Park et al. (2003) reported higher MOR in CLT derived from oriental oak, followed by tulipwood, Japanese larch, chestnut, Japanese cypress, and Japanese cedar. They further observed a positive correlation between the CLT panels' density and MOE and MOR. Sciomenta et al. (2021) observed that hybrid beech-Corsican pine CLT and homogeneous beech CLT have better bending and rolling shear performance than Corsican pine CLT.

Moreover, Yusof et al. (2019 a) investigated the bending performance of *Acacia mangium* CLT panels bonded with polyurethane (PUR) and phenol-resorcinol-formaldehyde (PRF). They observed that adhesive had a significant effect on both MOE and MOR of CLT panels, with an MOE of 12639 N/mm^2 for PRF-bonded panels compared to 10740 N/mm^2 for PUR-bonded panels and a similar trend for MOR. Sikora et al. (2016 a) studied the bending properties of Irish Sitka Spruce CLT panels. They discovered an inverse relation between panel thickness and bending and shear strength, with thicker CLT panels having lower bending and shear strength. Li et al. (2020) and Navaratnam et al. (2020) showed similar results in their Australian radiata pine CLT investigations. Rostampour Haftkhani and Hematabadi (2022) studied the effect of layer configuration on the bending capabilities of poplar (*Populus deltoides* L.) CLT with five different configurations: 0/30/0, 0/45/0, 0/90/0, 45/0/45, and 45/45/45. The best orientations for CLT construction, as indicated by average MOE values, were discovered to be 0/30/0, 0/45/0, and 0/90/0 based on their research findings. Similarly, Buck et al. (2016) observed that CLT panels with 45° transverse layer arrangements outperformed typical CLT panels with 90° transverse layers. Furthermore, manufacturing pressure, glue spread, and pressing time have been shown to influence the bending capabilities of CLT panels (Sharifnia and Hindman, 2017; Liao et al., 2017). The core layer is widely known as the neutral axis during the bending test, while the top and bottom layers experience compressive and tensile forces due to their cross-laminating feature (Nero et al., 2022; Silva et al., 2023). A comparative overview of the bending performance of different CLT panels is presented in Table 5 concerning wood species, the thickness of the lamella, and their arrangements.

Table 5: Bending performance of some notable CLT panels from various research

Species	Comments	MOR (N/mm^2)	MOE (N/mm^2)	References
Irish Sitka Spruce	20/20/20 40/40/40	36.8 - 37.6 24.5 - 25.1	7584 7563	Sikora et al. (2016 a)
Irish Sitka Spruce	20/20/20 20/20/20/20/20	35.7 - 35.9 34 - 34.4	7319 - 9552 6310 - 8404	O'Ceallaigh et al. (2018)
Beech		43.8	12306	Franke (2016)
Norway spruce	0/90/0 0/45/0	35.2 47.5	8243 9517	Buck et al. (2016)
Acacia		27.7 - 36.5	10740 -12693	Yusof et al. (2019 a)
Eucalyptus *(Eucalyptus nitens*) (*Eucalyptus globulus*)		34.5 - 55.5 52. - 64.1	8900 - 12100 11000 - 13700	Pangh et al. (2019)
Eucalyptus urograndis *Pinus taeda*			11740 5461	Pereira and Calil (2019)
Australian Radiata pine	35/35/35 35/20/35/20/35	23.4 26.8		Navaratnam et al. (2020)
Southern SPF and LSL	35/35/35	33.6		Davids et al. (2017)
Black spruce	35/35/35 35/25/35/25/35	30.9 29.6		He et al. (2020)
Canadian hemlock	35/35/35/35/35	21.6	7670	He et al. (2018)
Sugar maple		77.1 - 86.9	17880 -18620	Ma et al. (2021 a)
Poplar (*Populus alba* L.)		26	7356	Kramer et al. (2014)
Poplar (*Populus alba* L.)		35	7031	Hematabadi et al. (2020)
Beech Corsican pine Hybrid Beech-Corsican pine		85 44.9 61	13620 10010 15237	Sciomenta et al. (2021)

3.6.4. Rolling shear performance of CLT

Rolling shear (RS) refers to the shear stress that acts perpendicular to the direction of the grain, potentially resulting in substantial shear deformation due to the relatively low stiffness associated with rolling shear (Fellmoser and Blaß, 2004). The anisotropy of the material can influence the design of CLT panels and their load-bearing behaviour, as it allows for the control of rolling shear strength and stiffness in the cross layers (Mestek et al., 2008). The low value of the shear modulus in the direction orthogonal to the grain, namely the rolling shear modulus (G_R), results in significant shear deformations in the transverse layers, which are oriented perpendicular to the direction of the tangential stresses (as depicted in Figure 8).

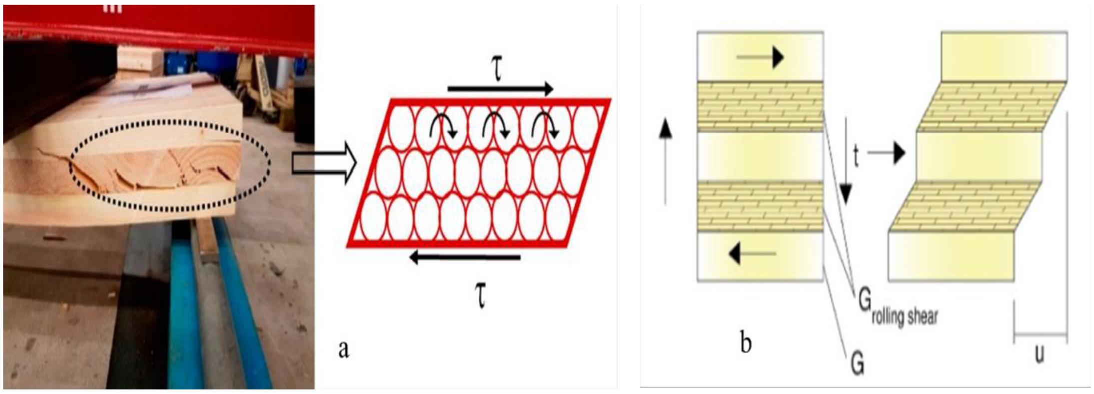


Figure 8: (**a**) Rolling shear stress in wood fibres (Fellmoser and Blaß, 2004)
(**b**) Rolling shear stress and deformation in 5 layers of CLT panel (Karacabeyli and Douglas, 2013)

Rolling shear (RS) influences the out-of-plane panel stiffness of the CLT panels, further impacting the design and functionality of CLT floor and wall systems (Kumar et al., 2022). Due to the orthotropic nature of the wood, they have different mechanical properties in the three mutually perpendicular directions: longitudinal (L), radial (R) and tangential (T), as shown in Figure 9 (a). During the bending test, the longitudinally oriented lamellas slip off one another instead of being crushed individually, as shown in Figure 9 (b) and 9 (c), causing RS failure (Ehrhart and Brandner, 2018). Due to the low shear modulus and strength, the shear properties affect CLT panels' overall deflection and shear capabilities. Therefore, RS, particularly in short-span bending tests, can lead to failure in CLT; hence RS is essential when choosing wood species for structural applications (Wang et al., 2018; Silva et al., 2023). According to Li et al. (2021), the most frequent reason for CLT beam specimen failure was the RS failure of the transverse layer in the flatwise bending test. Because RS is so important to CLT design, it's essential to understand both its fundamental characteristics and the factors that affect them.

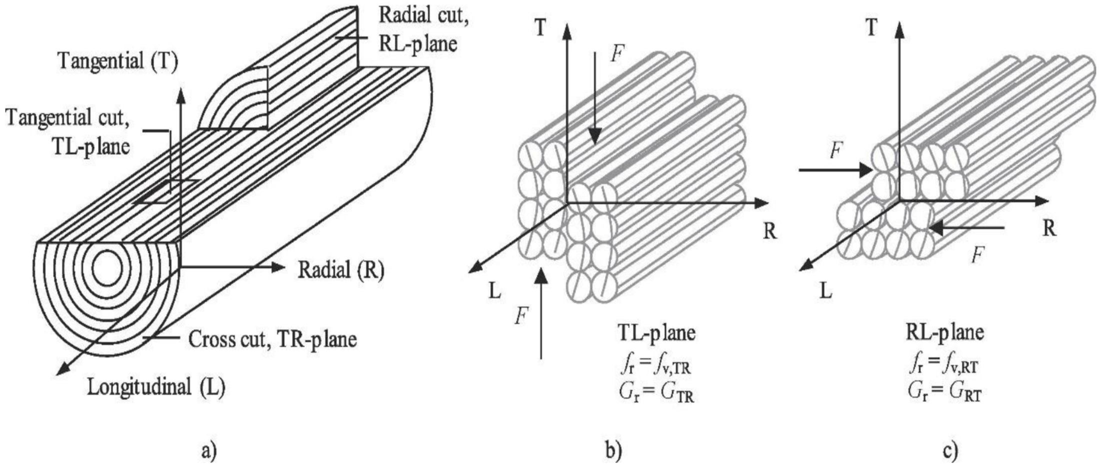


Figure 9: (**a**) principal material axes in a log (**b**) tangential-longitudinal RS plane and (**c**) radial-longitudinal RS planes (Ehrhart and Brandner 2018)

Similar to bending performance, the CLT panels' RS properties were also affected by several factors, including wood species, density, sawing pattern and lamellas orientation, edge glueing, and aspect ratio (width/thickness ratio). Wood has a diverse microstructure as a naturally occurring material that produces various mechanical characteristics depending on the species. These variations may also be affected by growth ring, density, fibre orientation, and the presence or absence of inherent defects. European woods, including Norway spruce, Irish Sitka spruce, and European beech, have been the focus of most studies. The average RS strength of regularly used spruce species was 1.30 - 2.13 N/mm^2, while the RS modulus varied from 28 - 110 N/mm^2 (Kumar et al. 2022). Recent studies have shown that European beech has an RS strength of 6.0 N/mm^2 and a modulus of 370 N/mm^2 (Aicher et al., 2016 a; Sciomenta et al., 2021). Zhou et al. (2014) researched Canadian black spruce CLT and observed that its mean RS strength and modulus were 1.09 N/mm^2 and 136 N/m^2, respectively. They further observed that the RS modulus is significantly affected by the growth ring orientation, while the RS strength is unaffected. The semi-quarter-sawn planks had the highest recorded RS modulus, while the flat-sawn planks had the lowest. Ehrhart and Brandner (2018) examined the RS properties of CLT panels manufactured from six different wood species such as Norway spruce (*Picea abies* (L.) Karst.), pine (*Pinus sylvestris* L.), European beech (*Fagus sylvatica* L.), European ash (*Fraxinus excelsior* L.), poplar (*Populus tremula* L.) and European birch (*Betula pendula* R.). According to their findings, Norway spruce has an RS strength around 85% lower than that of birch, pine, and poplar, while ash and beech have outstanding RS strength around 250-300% higher than spruce due to their variations in anatomical characteristics rather than its density. Li et al. (2019) also observed similar outcomes. Aicher et al. (2016 a) observed that the RS modulus of semi-quarter-sawn planks was highest (420 N/mm^2), and that of quarter-sawn planks was lowest (390 N/mm^2). The average RS modulus for flat-sawn planks was 380 N/mm^2, while for planks with pith, it was 370 N/mm^2. They further reported that the pith had no significant effect on the RS modulus of the CLT panels. The RS strength of Australian radiata pine CLT was measured to be between 1.55 and 2.18 N/mm^2 by Navaratnam et al. (2020). In contrast, Li et al. (2020) reported values of 2.0 N/mm^2 and 65.5 N/mm^2 for the RS strength and modulus, respectively. In addition, Li et al. (2019) also observed that the higher density radiata pine CLT showed higher RS properties than Douglas fir despite having equal aspect ratios. Using dynamic analytic approaches, Fellmoser and Blaß (2004) observed a positive relationship between density and RS modulus. Ukyo et al. (2019) examined the effect of annual ring patterns and lamina geometry on the RS properties of CLT both experimentally and numerically. They observed that the annual ring structure significantly impacts the RS characteristics. They further observed that increasing the radial distance from the pith decreased RS strength and modulus. The aspect ratio was shown to influence the RS strength of CLT significantly; a higher aspect ratio would result in higher RS properties (Sikora et al., 2016 a; Li, 2017; Li et al., 2019). European standard EN 16351 (2021) proposed lamella with a minimum width/thickness ratio of 4 or greater to limit the influence of rolling shear stress on the core lamella, whereas ANSI/APA PRG-320 (2019) indicated a minimal ratio of 3.5. Wang et al. (2018) used a modified planar shear test technique to analyse the RS properties of samples with and without edge glueing and with gaps of 2 mm, 4 mm, and 6 mm. Using a modified planar shear test, they discovered that edge glueing and gap size influenced RS strength rather than apparent RS modulus. The testing method also impacts the rolling shear properties of CLT. Cao et al. (2019) report that the RS strength observed in the planar shear test method is higher than that of a short-span bending test method. However, Zhou et al. (2014) observed higher RS strength in the short-span bending test method. Experimentally, these two methods provide comparable findings in other studies (Li., 2017; Li et al., 2019). Table 6 shows the comparative rolling shear strength of CLT panels from different species.

Table 6: Rolling shear properties of CLT panels correspond to the wood species, testing methods and other related parameters

Specimen	Testing method	Comment	RS strength (N/mm^2)	Reference
Irish Sitka spruce	4-point short-span bending	20/20/20 20/20/20/20/20	2.14 - 2.22 1.39 - 1.40	O'Ceallaigh et al. (2018)
Black spruce	Two-plate shear Variable span bending		2.57 - 2.84 2.02 - 2.13	Zhou et al. (2014)
Radiata pine	Short-span bending Modified planar shear	20/20/20 20/20/20	1.97 - 2.45 1.99 - 2.33	Li (2017)
Norway spruce European beech European birch Poplar European ash Pine	Modified planar shear	w/t=4	1.88 5.37 3.45 2.88 5.57 2.29	Ehrhart and Brandner (2018)
European beech	Compression shear	w/t = 4.09	5.5	Aicher et al. (2016 a)
SPF Hybrid SPF-aspen Hybrid SPF-white birch Hybrid SPF-white birch	Modified planar shear	Outer SPF layer	0.92 - 1.29 2.88 3.10 2.66	Gong et al. (2015)
White pine Red maple White ash	Bending	w/t= 4.29, no edge-glueing	1.34 3.0 3.1	Crovella et al. (2019)
Hybrid maple-spruce Hybrid spruce-maple	3-point short-span bending		1.75 2.11	Ma et al. (2021 b)
Poplar	3-point short-span bending		2	Kramer et al. (2014)

Both the cross-layer and the outer-layer characteristics affected the rolling shear performance. Hardwoods (Gong et al., 2015; Aicher et al., 2016 b; Ehrhart and Brandner, 2018), laminated strand lumber (LSL) (Wang et al., 2015), and laminated veneer lumber (LVL) (Wang et al., 2017) are examples of that have been explored as potential replacements for hybrid CLT. Aicher et al. (2016 b) discovered that adding a core beech layer to hybrid CLT with spruce increased its shear modulus thrice. Multiple studies (Wang et al., 2015; Davids et al., 2017) have reported that LSL cross-layers can increase RS by 1.8 times, and they suggested using high-density species as outer layers to improve structural integrity. In another study, Xu et al. (2021) evaluated the RS properties of hybrid CLT with exterior SPF layers and inner layers of birch, compressed wood (CW), LVL, PSL, plywood, OSB, and GLB. GLB, as the core layer, had over twice the RS strength of SPF CLT, while SPF and birch were roughly equal. They observed that CW is flexible and can be used as an alternate material to prevent core layer failure before the outer layer bends. In another study, Rara (2021) evaluated the RS properties of soft maple, yellow-poplar, and southern pine. Wood species affected RS characteristics, with soft maple having the highest (5.93 N/mm^2) and southern pine CLT the lowest (2.51 N/mm^2).

3.7. Theoretical approach for bending performance

The flexural characteristics of the CLT element are determined experimentally; however, theoretical approaches and numerical models are utilized to forecast the strength and stiffness of the CLT panels based on the geometry and lamination features (Ettelaei et al., 2022 a). An experimental method is based on testing the actual test specimen, which precisely evaluates the mechanical properties of CLT panels. However, the experimental process is time-consuming. However, the theoretical methods are less expensive alternatives, less time-consuming, and reported to have a good accuracy compared to experimental findings. Further, we can easily alter the manufacturing characteristics for a new product without laboratory testing, such as layup configuration, material type, and qualities in the theoretical methods. For studying bending elements, the conventional Euler-Bernoulli beam theory is frequently utilized; however, it is not directly utilised in the case of CLT due to the presence of shear deformation during CLT bending (Li et al., 2020). Alternative methods have been used to ascertain the bending characteristics of CLT panels to get over this restriction, including the Timoshenko Beam Theory (TBT), composite method (k-method), modified gamma (MG) method, and shear analogy method (SA). Understanding the mechanical characteristics of each lamella is necessary for the theoretical approaches.

It should be emphasized that these methods have primarily been used with homogenous CLT panels made of laminae with equivalent strengths.

3.7.1. Shear analogy method (SA)

Kreuzinger is credited with the shear analogy technique (Niederwestberg et al., 2018). The shear analogy (SA) approach is the most accurate way of finding the out-of-plane bending stiffness of the CLT panels. It is adopted by the American standard ANSI/APA PRG-320 (2019). Almost all system configurations (such as the number of layers and span-to-depth ratios) are considered by the approach, which considers the individual layers' various elasticity and shear moduli. The SA approach divided the multi-layer CLT into two virtual beams (A and B) with equal vertical distance, and the bending stiffness is the sum of the layer's stiffness and Steiner's stiffness close to the neutral axis (Bogensperger et al., 2012). According to ANSI/APA PRG-320 (2019), the shear modulus perpendicular to the grain (G_0) is 1/16 of the modulus of elasticity for softwood timber. Depending on the type of wood, this shear modulus to elasticity ratio (G/E) will change. Furthermore, it says that the rolling shear modulus, abbreviated G_R, is taken to be 1/10 the shear modulus perpendicular to the grain. These hypotheses depend on the wood's characteristics, such as density and yearly ring orientation. E and G ratios are cautious about accounting for the variation in wood specimens because these properties might vary significantly from panel to panel (Schultz, 2017). The assumption to determine the effective shear stiffness is that the glue line between neighbouring layers is rigid and does not slide deform. Commonly, the effective shear resistance is computed using the separation between the centre points of the two layers that are oriented parallel to the direction under consideration.

3.7.2. Timoshenko beam theory (TBT)

Timoshenko beam theory is frequently employed when shear deformation is considered to calculate beam deflection. The Timoshenko beam theory uses a shear form factor (k) to address shear deformation. The shear form factor makes up for the assumption of a constant shear strain across the cross-section. The average shear strain within a section to the shear strain at its centroid is the definition of the shear correction factor, which is the reciprocal value of the shear form factor (Niederwestberg et al., 2018). For isotropic solid homogeneous isotropic beams with rectangular cross-sections, Timoshenko proposed a shear correction factor of 2/3 (Niederwestberg et al., 2018). However, this is not applied to CLT because the lay-up of CLT with its alternating grain orientation results in a more complex transverse shear strain distribution. Further, Li et al. (2020) reported that as the transverse layers in CLT panels shear deform during bending, the cross-section of CLT panels does not remain perpendicular to the deformed axis. This feature is considered in Timoshenko's theory, making it applicable to CLT elements. This theory is observed on the assumption that "plane sections remain plane," just like Euler-Bernoulli beams, which makes manual computation and practical application straightforward and adaptable to any systems or stresses. The bending stiffness is calculated similarly to that mentioned in the SAM method. However, the shear stiffness (GA_{eff}) is adjusted with the so-called shear correction factor to determine the effective shear stiffness (Niederwestberg et al., 2018).

3.7.3. Modified gamma (MG) method

The modified gamma (MG) method, also known as mechanically jointed beams theory, published in Annex B of Eurocode 5, observes a standard analytical strategy adopted for CLT across Europe (Bogensperger et al., 2012). The effective stiffness is introduced in this theory, and a connection efficiency factor (γ) is utilized to account for the shear deformation of the perpendicular layer, with γ=0 indicating no connection at all and γ=1 signifying a bonded component. This connection is made possible by the internal transverse layers' shear stiffness (those parallel to the beam length). The technique may be applied to 3- or 5-layer CLT panels but can also be expanded to 7 and 9-layer panels (Christovasilis et al., 2016). The shear stiffness is calculated similarly to that of the TBM method.

3.7.4. Finite element method

According to Ottosen and Petersson (1992), the finite element method is a numerical technique for solving differential equations roughly. The differential equations are considered valid for a given region, which might be a one, two or three-dimensional region. The finite elements inside the defined area are subjected to differential equations, which are then approximated for each component. If the linearity is only assumed inside the individual elements, then linear or other approximations that might not be remarkably accurate throughout the entire region will be more accurate when the part is divided into finite pieces. This implies that once the elements have been bound, each element has an estimate that, while it may not be exact for the component itself, will provide a reasonable approximation for the entire region (Svensson Meulmann and Latifi, 2021).

In their investigation of the stiffness and strength properties of CLT panels, Christovasilis et al. (2016) observed that the findings of the experimental and theoretical studies were in good agreement. They further reported that the shear analogy approach, with a connection efficiency factor, calculates the most accurate value. He et al. (2018) investigated the bending characteristics of Canadian hemlock using theoretical methods and finite element analysis. They discovered that local bending stiffness (EI_l) could be estimated using the shear analogy method ($EI_{eff,shear}$). They further reported that with a 10-20% variation, the FEM could predict the stiffness and strength of CLT panels. Navaratnam et al. (2020) reported that theoretically predicted bending and rolling shear strengths were slightly higher than actual results for Australian radiata pine CLTs. The experimental data and corresponding values for bending stiffness were anticipated by the finite element model, with a 20% difference. According to Crovella et al. (2019), compared to the experimental results, their theoretically predicted bending stiffnesses using the shear analogy approach resulted in a 25% lower value for white ash (*Fraxinus americana* L.) and red maple (*Acer rubrum* L.) CLTs while a 5% reduced value for white pine (*Pinus strobus* L.) CLT. The shear analogy method yielded the best results for bending and rolling shear strength, whereas the modified gamma approach predicted the best for bending stiffness, according to Li et al. (2020). Additionally, they discovered that the FEM approach overestimated maximum load capacity in thicker panels by 20% while underestimating it for thinner panels. Sikora et al. (2016 a) reported that the bending strength values predicted by shear analogy and layered beam theories varied by 0.5%, while the variation in gamma theory was 2-4% lower. Additionally, according to Sikora et al. (2016 a) and Navaratnam et al. (2020), the shear modulus can be assumed to have an infinite shear strength for maximum accuracy in bending stiffness calculations. Niederwestberg et al. (2018) observed good agreement between the apparent and effective bending stiffness values predicted by the shear analogy approach and those measured in experimental bending tests for innovative multi-layer composite laminated panels. Mahamid and Torra-Bilal (2019) studied the analysis and design of CLT mats and observed that the finite element predictions corresponded well with experimental results for maximum displacement, shear, and normal stresses in bending. Li et al. (2021) examined the engineering performance of 3-ply composite CLT panels made from bamboo mat-curtain panels (BMCP) and hem-fir lumber. They observed that the modulus of elasticity (MOE) and bending strength in the minor strength direction were 96.0% and 104.0% of those in the major strength direction, respectively, for composite CLT with an outer layer of bamboo and an inner layer of hem-fir lumber (BWB-CCLT). Xiao et al. (2021) examined the flexural behaviour of cross-laminated bamboo-timber (CLBT) beams and observed that CLBT specimens made with locally available poplar wood had equivalent or higher mechanical properties than those made with spruce-pine-fir (SPF) wood. Hematabadi et al. (2021) investigated the structural performance of hybrid poplar-beech CLT in major and minor strength directions. They compared the findings to hybrid CLT made entirely from poplar species. Based on experimental and theoretical results, hybrid poplar-beech CLT's bending and shear performances were superior to those of poplar CLT in all span-to-thickness ratios and orientations.

4. Material and methodology

This chapter describes the different wood species and adhesives and their properties employed in this study and will provide a brief idea about the CLT manufacturing process.

4.1. Wood species

This comprehensive investigation utilized four distinct wood species, namely aspen (*Populus tremula* L.), poplar (*Populus nigra* L.), Norway maple (*Acer platanoides* L.), and Norway spruce (*Picea abies* (L.) H. Karst.). The selected hardwoods, maple (*Acer* spp.) and poplar *(Populus* spp.) are crucial fast-growing species that provide 18.82% and 5.83% of roadside-planted species in the Czech Republic (Mácová et al., 2022). The distribution of the selected species in this research around Europe is shown in Figure 10.

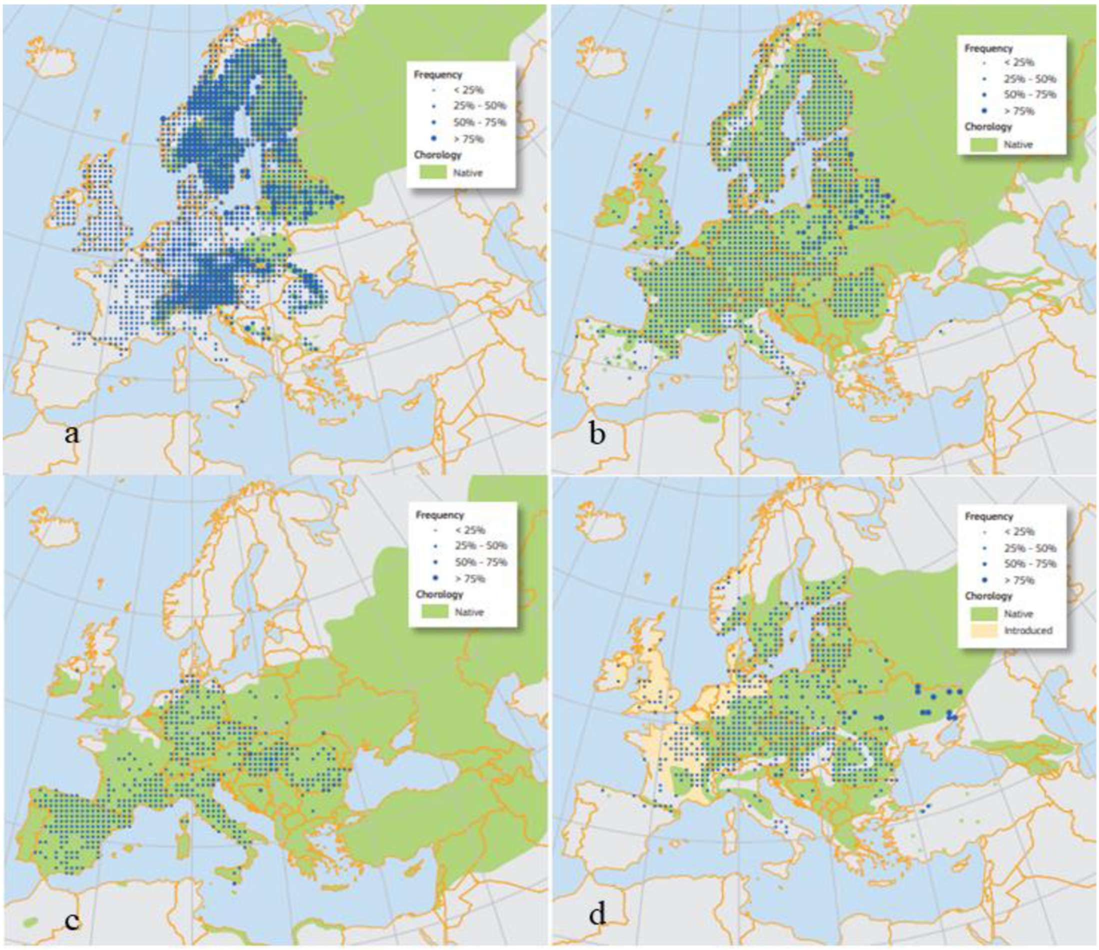


Figure 10: Distribution of the selected wood species: (**a**) spruce, (**b**) aspen, (**c**) poplar, (**d**) Norway maple (De Rigo et al., 2016)

4.1.1. Aspen

Aspen (*Populus tremula* L.) is a fast-growing broadleaf tree native to colder temperate Europe and Asia's boreal regions. This economically valuable species is widespread globally, mostly in northern and central Eurasian regions (Singer et al., 2019). Aspen, the second most common tree after the Scots pine (*Pinus sylvestris* L.), is observed in Iceland and Ireland through Kamchatka, Fennoscandia and Russia above the Arctic Circle, Spain, Turkey, North Korea, and northern Japan (De Rigo et al., 2016). Multiple regional races are sub-species due to their global distribution (Rogers et al., 2020). Aspen is a keystone species because it supports herbivorous creatures, saprophytic invertebrates, fungi, lichens, birds, and others (Singer et al., 2019; Rogers et al., 2020). Because of the colouration of the leaf, it is an appealing plant for decorative purposes (Ross, 2010). The wood is thinner than other poplars and is used for veneer, pulp, high-quality charcoal, and chipboards (De Rigo et al., 2016). Due to its rapid growth, it is used as a shelterbelt plant due to its wind resilience and a pioneer species for afforestation of arid or degraded terrain. The grain is often straight and has a homogeneous medium texture with poor lustre and diffuse-porous, solitary, and radial pore arrangements (Meier, 2007). The species is easy to work with hand and machine equipment. Due to twisting and deformation during drying, the wood has poor nail-holding strength. Wood glues easily.

4.1.2. Poplar

Poplar (*Populus nigra* L.), a pioneer wind-pollinated tree, grows in Europe, Asia, and northern Africa. It is observed across Europe, from the British Isles to the Mediterranean, North Africa, and the Middle East, predominantly towards the southern extent of its distribution (De Rigo et al., 2016). The distribution of the species extends towards the east, encompassing regions such as Kazakhstan and China and some parts of India as well. The wood has several excellent properties; it is generally fire-resistant and shockproof and has a delicate, fine texture despite its lack of strength. It is presently used to create pulp and paper, and its rapid growth rate makes it an ideal bioenergy crop (De Rigo et al., 2016). The heartwood is usually light brown, while the sapwood tends to be pale yellow to white. However, this species is mainly known for its distinctive burl, increasing its market value. Further, the mechanical and machining properties are almost identical to aspen.

4.1.3. Norway maple

Norway maple (*Acer platanoides* L.) is a large tree in central Europe and the Ural Mountains. The natural distribution of this species encompasses Greece, the Balkans, northern Italy, the Pyrenees, and southern Fennoscandia and extends to Russia in the eastern region (De Rigo et al., 2016). It was introduced to the US in the 18th century and naturalized across much of the central-east US and southeast Canada, overlapping the native sugar maple (*Acer saccharum* Marshall) (Ross, 2010). Norway maples are popular ornamental, shade, and roadside trees due to their beauty, colourful leaves, enormous, spreading crowns, and urban tolerance (Mácová et al., 2022). The wood is used to produce furniture, marquetry, turned objects, and other small wood products. Heartwood ranges from white to light golden or reddish brown and is darker than sapwood. Norway maple's wavy or quilted grain pattern, used for guitars and violins, increases its value. Maple burns when machined; thus, special care is needed.

4.1.4. Norway spruce

Norway spruce (*Picea abies* (L.) H. Karst.), an essential European softwood, grows from central Russia to the Ural Mountains, where it mixes with Siberian spruce, often considered a subspecies (De Rigo et al., 2016). It exhibits dominance within the Boreal and subalpine coniferous forests. The wide distribution is mainly attributed to its inherent patterns of variation. This tree holds great importance in Europe, with enormous economic and ecological value, and boasting a rich history of cultivation. According to the MZP (2019), Norway spruce accounts for 50.0% of coniferous tree species, while Scotch pine comprises 16.2% of the forest cover. The utilization of solid wood in the construction of wooden structures and pulpwood for paper production constitutes a significant focus within the business sector, notably in countries located in northern Europe (De Rigo et al., 2016). The wood is utilized for a diverse range of items, such as joinery timber, furniture, and veneer, as well as for constructing the bodies of guitars and violins and sound planks for pianos (Ross, 2010; De Rigo et al., 2016).

All the wood species used in this study were purchased from a commercial supplier (woodstore.cz) from the Czech Republic. The aspen (*Populus tremula* L.) planks were purchased in green condition, while poplar (*Populus nigra* L.), maple (*Acer platanoides* L.), and spruce (*Picea abies* (L.) H. Karst.) were kiln-dried to a moisture content of 12% at the time of purchasing. After purchasing, the aspen planks were air dried for 3 months to achieve a moisture content (MC) of 12%. Other planks were conditioned for four weeks at 20°C and 65% relative humidity (RH) before processing for lamellas. The purchased lumbers had nominal dimensions of 150 mm in width, 3 m in length, and a thickness of 30 mm. The physical and mechanical properties of the wood species are listed in Table 7.

Table 7: Physical and mechanical properties of the examined wood species (Meier, 2007; Ross, 2010; Zhang et al., 2013; Ammann, 2015; Szadkowska et al., 2021)

Properties	**Direction or Comments**	**Species**			
		Spruce	**Aspen**	**Poplar**	**Maple**
Density (kg/m^3)		410	381	394	650
Elastic modulus *(E)* (N/mm^2)	*L*	11000	8100	9900	12600
	R	800	745	910	1633
	T	450	348	425	819
Shear modulus *(G)* (N/mm^2)	*LR*	650	607	742	1398
	LT	600	558	683	793
	RT	50	89	108	298
Bending strength (N/mm^2)		63	62	63.7	115
Compression parallel to grain (N/mm^2)		38.19	29.30	36.54	46.05
Compression perpendicular (N/mm^2)		3.79	2.55	3.10	7.03
Shrinkage (%)	*L*	0.3	0.39	0.41	0.45
	R	3.6	4.8	4.0	4.8
	T	7.8	8.2	9.3	9.9
	V	12.9	13.2	12.9	14.7
Composition (%)	Cellulose	50	45.58	45.58	44.6
	Hemicellulose	27.8	27.91	27.91	35.5
	Lignin	26.5	24.15	24.15	24.9
	Extractive	1.0	2.7	2.1	3.1
pH		4.79	5.8	5.8	4.65

(Note: L- longitudinal, R- radial, T- tangential while LR- longitudinal-radial plane, LT-longitudinal-tangential plane and RT – radial-tangential plane)

4.2. Adhesives

The present study employed two distinct commercially available adhesives: one-component polyurethane (1C-PUR) and liquid melamine adhesive (ME) to examine their suitability for CLT manufacturing and to investigate the impact of adhesives on the assessed characteristics of the CLT panels. A commercial supplier, M/s Akzo Nobel (Netherlands), provided both adhesives. As per the manufacturer and the product list, the melamine adhesive contains no formaldehyde, while some reports claim it only has the least amount of formaldehyde, which is negligible (At'ome WTI, 2023). Therefore, melamine adhesive was denoted as ME in the whole dissertation. More information regarding both the adhesives are shown in Table 8. According to the manufacturer, both adhesives were specially designed for load-bearing wood constructions such as laminated beams, CLT, and duo and trio beams.

Table 8: Properties of both the adhesives

Properties	**One component polyurethane**	**Liquid melamine adhesive**	
Commercial Name	2010	Plus Adhesive A011	Plus Hardener H011
Product	Isocyanate MDI-based pre-polymer	Melamine adhesive	Hardener
Delivery Form	Liquid	Liquid	Liquid
Colour	White	Opaque white	White
Viscosity (mPas)	6000 - 19000	1500 - 9000	1700 - 2700
pH (production)		8.5 - 9.6	1.3 - 2.0
Dry content (%)	100	Appr. 65	Not applicable
Density (kg/m^3)	1160	Appr. 1290	Appr. 1070
Adhesive to hardener mixing ratio	100	50	50
Assembly time (min) (Open + Close)	10	25	
Pressing time (min)	60	60	
Pressure (MPa)	0.6 and 1	0.6 and 1	

4.3. Preparation of CLT

The planks were selected randomly to make up each panel. Planks with a significant crook, wane, end-splitting, or checking were discarded from the manufacturing process to minimize the material defects affecting the overall performance of the CLT panels. After discarding the defective planks, the rest were visually graded according to EN 14081+A1 (2016) and grouped into two groups. The defect-free planks were grouped into Grade A, and planks with permissible defects such as knots, pin holes, cracks and wane were grouped into Grade B. The Grade A planks were further processed for the outer lamellas, and those in Grade B were processed for core lamellas, as the outer lamellas were primarily responsible for the load-bearing capacity of the CLT. The manufacturing of CLT panels follows the procedure as shown in Figure 11.

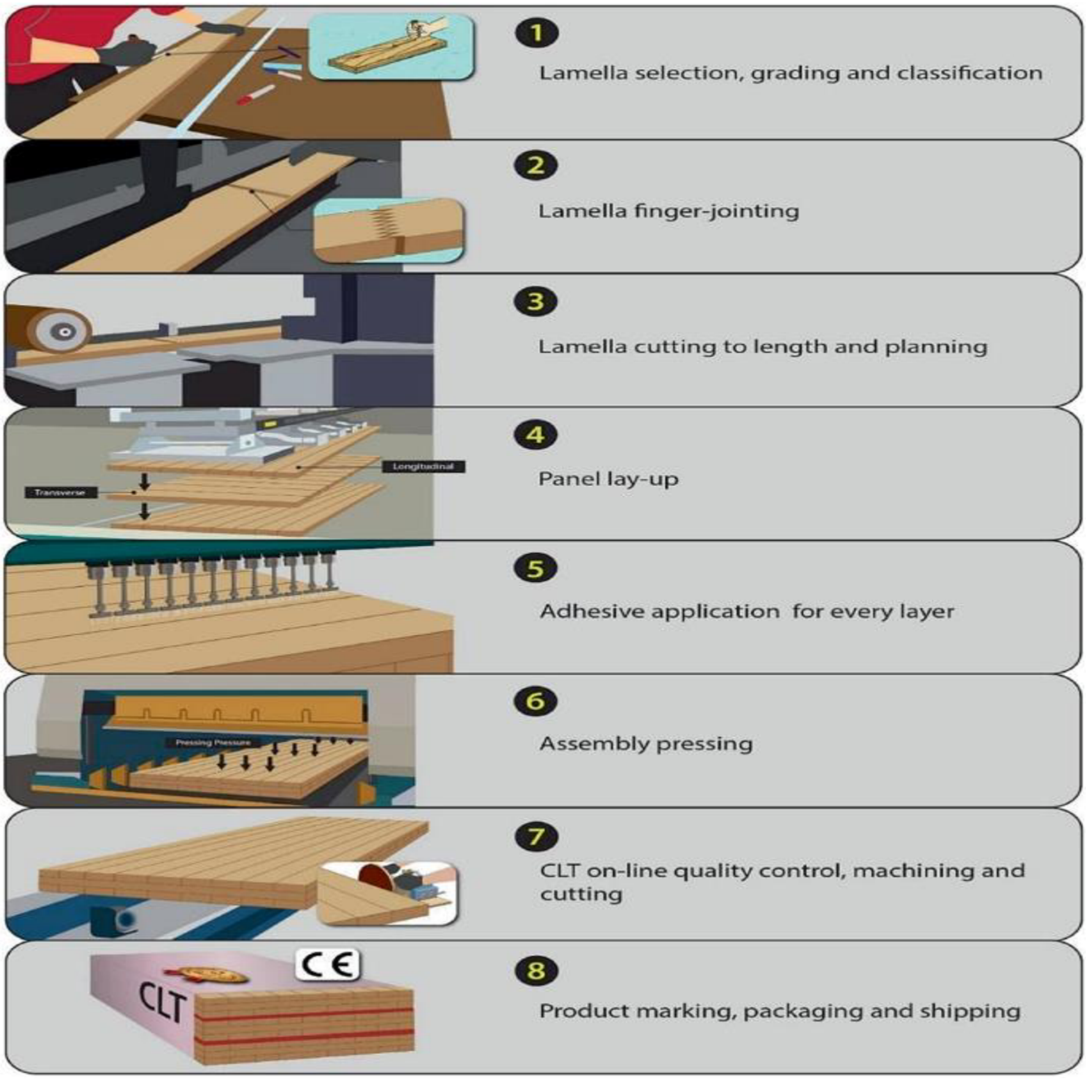


Figure 11: Flow chart of the CLT manufacturing process (Lum et al., 2022)

The CLT panels were manufactured in two different phases for this research. In the first phase, the lumbers were processed to examine the physical properties (water absorption, thickness swelling) and bonding properties (delamination and bond shear test). In the second phase of the manufacturing process, the lumbers were processed for bending and rolling shear performance of the CLT panels. The planks in Grade A were processed for the outer lamellas with a final dimension of 2750 mm × 75 mm × 20 mm ($l \times w \times t$), while Grade B planks were processed for the core lamellas to a dimension of 300 mm × 75 mm × 20 mm ($l \times w \times t$). In the first phase, the outer Grade A lamellas were processed to a dimension of 300 mm × 75 mm × 20 mm ($l \times w \times t$), while in the second phase, the outer lamellas were processed to a dimension of 2000 mm × 75 mm × 20 mm for bending and rolling shear performance of the CLT panels. In both phases of manufacturing, the Grade B lamellas were processed to a dimension of 300 mm × 75 mm × 20 mm ($l \times w \times t$). Planing and sanding were carried out on all four sides of the planks to provide a smooth, clean surface for a better glueing process, which was carried out within 4 hours of glueing and assembling (Yeh et al., 2013). Before glueing and assembling, the surfaces were cleaned with compressed air to remove the dust processed during the processing and improve the glueing.

Two different compositions of CLT panels were prepared for the whole study. The first composition of CLT panels consisted of homogeneous CLT panels made from aspen (A), poplar (P) and spruce (S) wood, while the second composition was hybrid CLT (M+P) composed of outer maple (M) layers with core poplar layers (maple-poplar-maple). In the first phase of the manufacturing process, eight lamellas from Grade A were randomly selected for the outer layers, 4 for each outer layer, and four from Grade B were chosen randomly for the core layer. The selected Grade A lamellas were placed over a long table for the glue application, as shown in Figure 12. Similarly, for the bending and rolling shear test, eight lamellas from Grade A were selected randomly, having dimensions of 2250 mm × 75 mm × 20 mm for the outer layers; 4 for each outer layer, while 30 lamellas from Grade B were chosen randomly for the core layer, as shown in Figure 13. Much care was taken because there shouldn't be an edge gap between the lamellas; however, the European standard EN 16351 (2015) allows for an edge gap of up to 6 mm between non-edge-glued lamellas. The two outer lamellae were positioned parallel to the main strength direction. At the same time, the single central lamella was orientated perpendicular to the major strength direction.

The adhesive was applied on one-surface of the lamella was performed using a roller coater. The adhesive used for this process was 1C-PUR, with a glue spread of 180 g/m^2, while 300 g/m^2 for ME adhesive. The ME adhesive was applied using a mixture of adhesive and hardener in a weight-to-weight ratio of 100:100, following the guidelines provided by the manufacturer. Edge glueing was not performed during the production process, as reported to have less impact (Brandner et al., 2016).

After the glueing, each panel were subjected to a hydraulic press for assembling and pressing. The outer lamellas (Grade A) were positioned parallel to the main strength direction, while the core lamellas (Grade B) were orientated perpendicular to the Grade A lamellas. Using a hydraulic press Leopida GS 6/90 (SCM LEOPIDA SERGIANI, Poland), the CLT panels were pressed for 1 hour with two different manufacturing pressures, 0.6 MPa and 1 MPa, according to the manufacturer. In the first phase of the manufacturing process, for examining the effect of manufacturing pressure on the water absorption (WA), thickness swelling (TS), delamination (*Delam*) and bond shear strength (F_v), the CLT panels were prepared with 0.6 MPa and 1 MPa pressure according to the manufacturer. In the second phase of the manufacturing process, the CLT panels were prepared with 1 MPa pressure to evaluate bending and rolling shear properties, as predominant bonding failure was observed with the lower manufacturing pressure of 0.6 MPa. Both the adhesive application and the pressing were done at normal room temperature (around 20°C). A total of 120 CLT panels were prepared for the whole study.

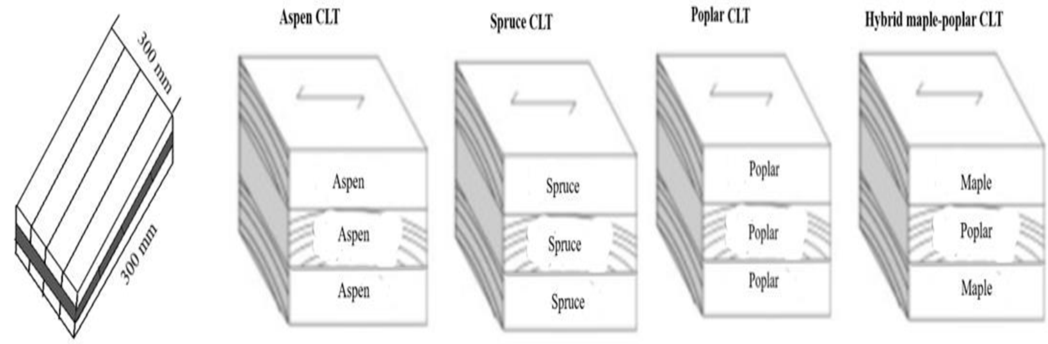


Figure 12: Composition of CLT panels for physical and bonding performance test

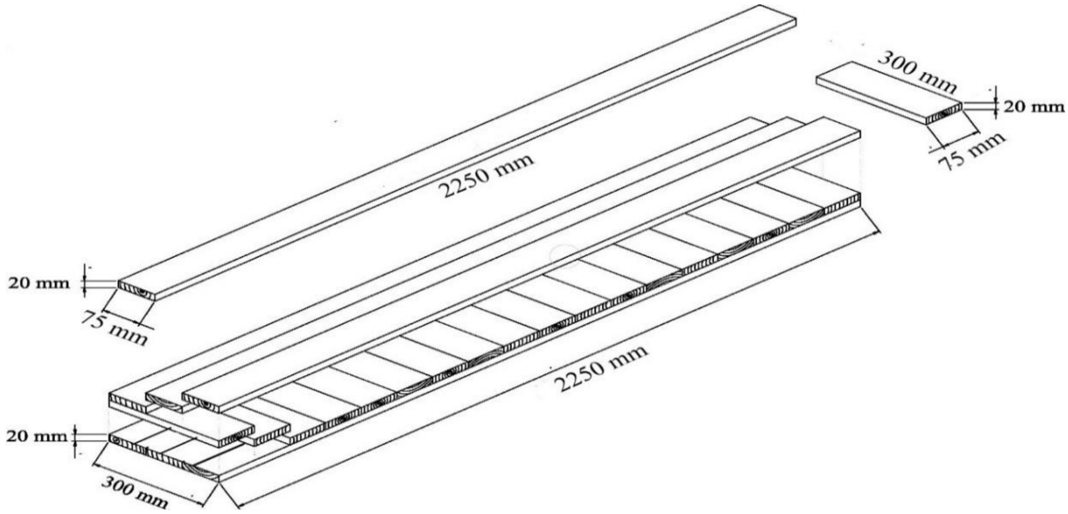


Figure 13: Panel layup and assembly for bending and rolling shear test during manufacturing

After pressing, the manufactured CLT panels were kept at room temperature for almost two days to cure the excessive adhesives. After two days, the prepared CLT panels were trimmed from all sides and conditioned at 65 ± 5% RH and 20 ± 2 °C for three weeks in the conditioning chamber before cutting into specimens for physical and mechanical testing.

4.4. Experimental methods

4.4.1. Water absorption (WA) and thickness swelling (TS)

The WA and TS tests for the CLT panels were performed using the same sample (Yusof et al., 2019 a; EN 16351, 2015). Twelve examples of each type of CLT panel, measuring 70 mm × 70 mm× 60 mm ($l \times w \times t$), were cut from the CLT panels before the test, as shown in Figure 14. Each sample was conditioned to a moisture content of 12%. The samples were weighed, and the dimensions were measured with a vernier calliper before immersion in distilled water at normal room temperature. After 2 hours of immersion, the samples were collected by a wire screen and dried with a cotton cloth, and the weight and dimensions of the samples were recorded. After the measurement, the samples were again immersed in distilled water for 22h. After that, the samples were taken out and dried with a cloth.

Figure 14: Water absorption and thickness swelling test

The final weight and dimension were measured. The following equations were used to calculate the percentage of WA and TS from the obtained data.

$$WA\ (\%) = \frac{W_2 - W_1}{W_1} \times 100 \quad (1)$$

$$TS\ (\%) = \frac{T_2 - T_1}{T_1} \times 100 \quad (2)$$

where W_1 - initial weight of the sample before immersion (g), W_2 - final weight of the sample after 2h and 24h after immersion (g), T_1 - initial thickness of the sample before immersion (mm), T_2 - final thickness of sample after 2h and 24h after immersion (mm).

4.4.2. Delamination

The samples for the delamination test were taken by making a quadratic cut from the CLT panels. Ten specimens were tested per EN 16351 (2015) with a dimension of 100 mm× 100 mm× 60 mm (l × b ×h). The test pieces were weighed first and then placed in a pressure vessel. Then, water was added to the pressure vessels at an ambient temperature of 20 °C until the samples were submerged. Care was taken to expose the end grains of each test sample to water. Then, a vacuum of 70 kPa was drawn and held for 30 min. Subsequently, the vacuum was released, and a pressure of 550 kPa was applied for 2 h. After 2h, pressure was released, and the test pieces were dried for 15 h in a circulating oven at a temperature of 70 ± 5 °C. Delamination in the test pieces was examined when the mass of the test pieces was between 100% to 110% of the original mass. The delamination of the glue lines was observed upon removal from the oven. The length of the delamination was recorded by inserting a thin metal sheet between the two delaminated surfaces and with the help of a Vernier calliper, as shown in Figure 15 (c). Measurements were recorded when the delamination depth was less than 2.5 mm and more than 5 mm from the nearest delamination. The following equations calculated the total delamination and maximum delamination.

$$Delam_{tot} = \frac{L_{tot.delam}}{L_{tot.glueline}} \times 100 \quad (3)$$

$$Delam_{max} = \frac{L_{max.delam}}{L_{glueline}} \times 100 \quad (4)$$

where $Delam_{tot}$ - total delamination (%), $Delam_{max}$ - maximum delamination (%), $L_{tot.delam}$ - total delamination length (mm), $L_{tot.glue\ line}$ - sum of the perimeter of all glue lines in samples (mm), $L_{max.delam}$ - maximum delamination length (mm), $L_{glue\ line}$ - perimeter of one glue line in a delamination sample (mm).

Figure 15: Delamination test; (**a**) vacuum-pressure cycle, (**b**) drying of specimen in hot air oven, (**c**) measurement of delamination, (**d**) wood failure evaluation

After evaluating the quantity of delamination, the wood failure percentage (WFP) was calculated by breaking the two glue lines with a hammer and chisel, as shown in Figure 15 (d), and comparing the amount of wood failure to adhesive failure for each glue line. Each glue line's WFP was calculated visually to the nearest 5%, and the average was used to calculate the sample's average WFP. Areas with wood defects were excluded from the overall bonding surface area and weren't considered for WFP.

$$WFP = \frac{Area\ with\ wood\ failure}{Total\ glued\ area\ before\ splitting} \times 100 \tag{5}$$

4.4.3. Shear strength

The bond shear test is one of the simplest and quickest methods for assessing the bonding effectiveness of CLT panels. The bond shear test was recommended by the European standard EN 16351 (2015); however, due to the lack of shearing tools and testing equipment, a double shear test technique was adopted for the research recommended by Annex A of the draft standard BSI FprEN 14732 (2011). In addition, Gao et al. (2022) reported that the double shear test reduced the influence of rolling shear and distributed the shear stress evenly over the panel to estimate the shear stress of the CLT panels with slight variance. A 70 mm × 70 mm × 60 mm block was carved out of the CLT panels. A band saw was then used to carefully take 30 mm from both sides of the outer lamellas, and a circular saw was used to gently remove 30 mm from the core layer, as illustrated in Figure 16, with a shear area of 40 mm × 40 mm. Ten samples from each species and each adhesive were evaluated altogether. The samples were preconditioned at 20 °C temperature and 65% relative humidity until they attained a consistent mass before testing. The universal testing system UTS 50 (TIRA, Germany) was used for the compression loading. The load was applied so the failure would occur within 30 - 90 seconds. The samples were tested while carefully monitored to prevent sample movement under loading. After failure, compression (shear) forces were recorded by the PC connected to the testing machine. Using Eq. 6, the shear strength was determined following Annex A of the draft standard BSI FprEN 14732 (2011).

$$F_v = \frac{F_u}{2 \times A} \tag{6}$$

where F_v - shear strength (N/mm^2), F_u - the ultimate load (N), A - total sheared area.

Following the shearing of each glue line, the amount of wood failure was visually assessed and represented as a percentage (5%) of the sheared area.

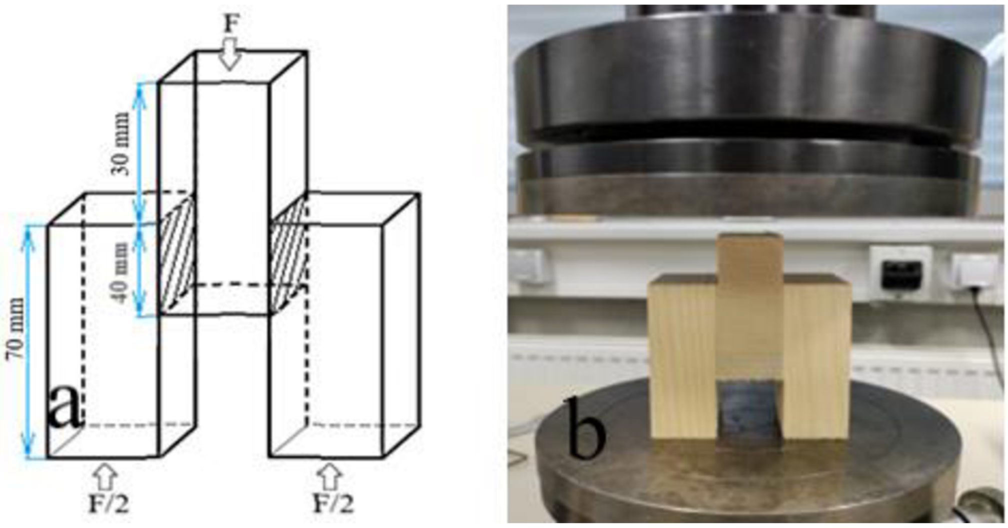


Figure 16: Shear test sample; (**a**) shape and dimensions of sample, (**b**) sample during testing

4.4.4. Bending characteristics

A standard 4-point bending test following EN 16351 (2015) was conducted to evaluate the bending performance. The sample length (l) was 18 times the panel thickness (18h). As shown in Figure 17, the CLT panels were placed over the two supports at both ends. Two-point loads were applied to the CLT panels at the centre and placed apart from each end of the other support by a distance equal to six times the thickness of the panel (6h). The load was applied constantly so that the maximum load would reach 300 ± 120 seconds. The test was carried out using a universal testing machine (TIRA 2850 S E5, Germany). The overall deflection was calculated using an extensometer connected to the testing equipment. The computer attached to the testing device recorded the maximum load and deflection. For each adhesive and layup, ten replicate samples were examined.

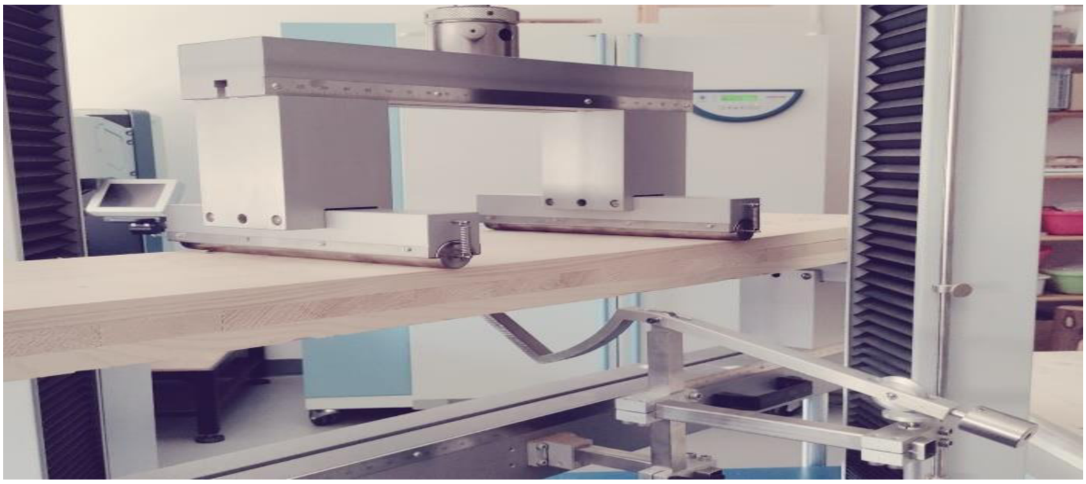


Figure 17: 4-point bending test CLT panels

The recorded measurements were used to calculate the global modulus of elasticity (E_{mg}), global bending stiffness (EI_{mg}) and bending strength (f_m) of the CLT panels. From the results, the global bending stiffness (EI_{mg}) was calculated using Eq. 7 with shear deformation according to Li et al. (2020) and Navaratnam et al. (2020),

$$EI_{mg} = \frac{3al^2 - 4a^3}{48\left(\frac{(W_2 - W_1)}{(F_2 - F_1)} - \frac{3a}{5Gbh}\right)} \tag{7}$$

where a - loading point distance to the nearest support (mm), l - specimen length between supports (mm), h and b - panel thickness and width (mm), $F_2 – F_1$ - increase in of load corresponds to 10% and 40% of maximum load (N), $W_2 – W_1$ - increase in displacement proportional to load F_2 - F_1 (mm), G - shear modulus (N/mm^2).

It is crucial to note that in EN 408 (2010), the suggested value for the shear modulus of G for softwoods is 650 N/mm^2. However, according to He et al. (2018), the shear modulus of the hardwoods was calculated as ($G_0 = E_0/16$, $G_{90} = G_0/10$) respectively.

The bending strength (f_m) can be calculated using Eq. 8 according to EN 408 (2010),

$$f_m = \frac{3Fa}{bh^2} \tag{8}$$

where F - load (N), a - the distance between the load point and the nearest support during the bending test (mm), h and b - panel thickness and width (mm).

According to He et al. (2018), the global modulus of elasticity (E_{mg}) of the CLT panels can be determined from the resultant division of bending stiffness (EI_{mg}) with the second moment of inertia (I).

$$E_{mg} = \frac{EI_{mg}}{I} \tag{9}$$

where E_{mg} - global modulus of elasticity (N/mm^2), EI_{mg}- global bending stiffness (EI_{mg}), I- moment of inertia.

4.4.5. Rolling shear

A short-span 4-point bending test was carried out following EN 16351 (2015), as illustrated in Figure 18, to examine the RS strength of the CLT panels. As shown in the figure, both loading points were positioned in the centre at an equal distance of three times the panel thickness (3h) from each end of the supports. The specimens' span was nine times the panel's thickness (9h). Instron 5882 testing machine (Illinois Tool Works Inc., USA) was used to perform the test. The load was applied at 10 mm/min, and the computer attached to the testing machine recorded the load vs displacement curve.

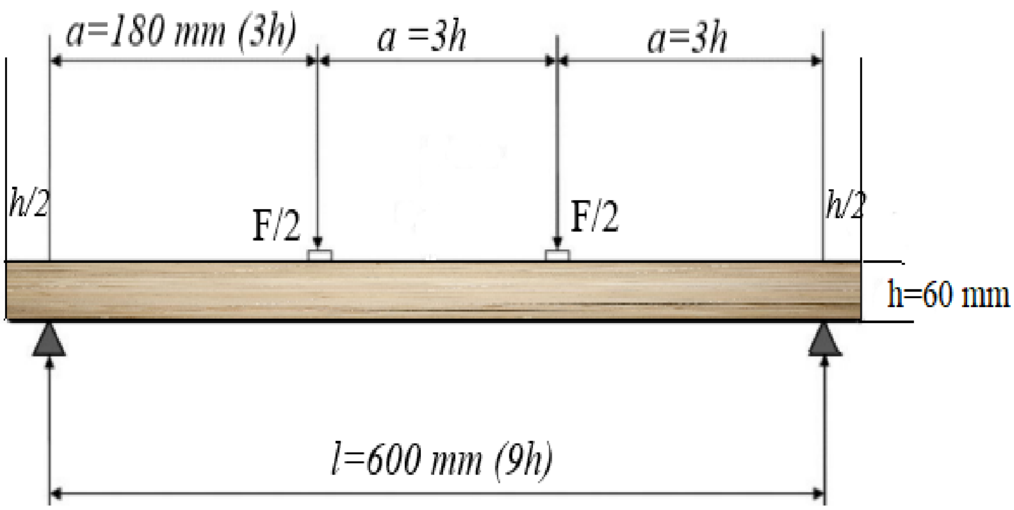


Figure 18: Rolling shear test set-up of CLT panels

Eq. 9 was used to calculate the RS strength (f_r) of the CLT panels according to Li et al. (2020),

$$f_r = \frac{3F_{max}}{4bh} \tag{10}$$

where F_{max} - maximum load (N), h and b - panel thickness and width (mm).

4.5. Theoretical calculation

The shear analogy (SA), Timoshenko beam theory (TBT), and modified gamma (MG) were used in this study to examine the theoretical bending stiffness, bending strength, and rolling shear strength of the CLT panels. SA, TBM and MG calculated the bending stiffness (EI) using Eq. 11, 12 and 13 (Brandner et al., 2016).

$$EI_{eff,shear} = \sum_{i=1}^{n} E_i * b_i * \frac{{h_i}^3}{12} + \sum_{i=1}^{n} E_i * A_i * {Z_i}^2 \tag{11}$$

$$EI_{eff,timo} = \sum_{i=1}^{n}(E_i * I_i) + \sum_{i=1}^{n} E_i * A_i * {e_{si}}^2 \tag{12}$$

$$EI_{eff,gamma} = \sum_{i=1}^{n}(E_i * b_i * \frac{{h_i}^3}{12}) + \sum_{i=1}^{n} E_i * A_i * {Z_i}^2 * \gamma_i \tag{13}$$

where E_i - Young's elastic modulus of ith-layer (N/mm^2), h_i and b_i - respective thickness and width of ith layer (mm), A_i - area of ith layer (mm^2), Z_i - ith layer's centre and the neutral axis distance (mm), I_i - ith layer's moment of inertia, e_{si} - similar Z_i (mm), γ_i - connection efficiency factor.

The connection efficiency factor (γ_i) was calculated by using Eq. 14, suggested by Brandner et al. (2016)

$$\gamma_i = 1 + \left(\frac{\pi^2 E_i b_i h_i}{{L_{eff}}^2 * (G * b_j / h_j)}\right)^{-1} \tag{14}$$

where L_{eff} - effective specimen length, $_j$ - transverse layer.

The theoretical bending and shear strength were calculated from Eqs. 15 and 16, according to He et al. (2018),

$$f_m = \frac{M_{max}}{S_{eff}} \tag{15}$$

$$\tau_m = \frac{V_{max}}{I_{eff}} \times \frac{Q}{b} \tag{16}$$

where f_m and τ_m - theoretical bending and rolling shear strength (N/mm^2), V_{max} and M_{max} - maximum shear force (kN) and bending moment (N/mm), Q - the moment of area of the specimen (mm^3), S_{eff} - the section modulus and calculated by EI_{eff} by E_1*h_i/2.

4.6. Finite element modelling

The finite element models for the CLT panels were created using the software program ANSYS 2019 R13, as shown in Figure 19. Individual layers of CLT panels were modelled as an orthotropic material with variable elastic properties in each perpendicular direction like longitudinal, tangential, and radial directions. Wood defects (knots and fractures), annular rings, and other factors were ignored in the model. The mechanical response of orthotropic CLT panels is governed by nine separate elastic constants such as three elastic moduli in the three mutually perpendicular directions: longitudinal (L), radial (R) and tangential (T) (E_L, E_R, E_T), three Poisson's ratios in the three planes such as longitudinal-radial (LR), longitudinal-tangential (LT) and radial-tangential (RT) (ν_{LR}, ν_{LT}, ν_{RT}), and three shear moduli (G_{LR}, G_{LT}, G_{RT}). Table 9 shows the various wood properties required for modelling.

Table 9: Elastic constant of both poplar and maple wood used for the FEM analysis at 12% moisture (Hajdarević and Busuladžić, 2015; Hematabadi et al., 2020)

Species	***E_L* *(N/mm^2)***	***E_R***	***E_T***	***ν_{LR}* *(-)***	***ν_{LT}* *(-)***	***ν_{RT}* *(-)***	***G_{LR}* *(N/mm^2)***	***G_{LT}***	***G_{RT}***
Poplar	8900	739	418	0.34	0.42	0.875	676	463	134
Maple	13810	1311	678	0.46	0.50	0.82	1013	753	255

The model was prepared like the poplar and hybrid maple-poplar CLT prepared for the experimental tests. Bonded contact zones do not allow sliding or separating faces or edges. The outer and core layer lamellas were not edge bonded to one other; hence, their contact is described as friction. It denotes that the contact pair can move and detach from one another on the target's surface. Tangential motions are influenced by friction coefficients (f). The friction coefficient in our situation is f = 0.5. SOLID186 elements represented the CLT panels and auxiliary components, such as steel loading rollers and supports. Each of the 20 nodes comprising the element has three degrees of freedom, allowing for translations in all three directions. The element is capable of plasticity, hyperelasticity, creep, stress stiffening, deflection, and strain. Using mixed formulations, it also provides the ability to model deformations of entirely incompressible hyperelastic and almost incompressible elastoplastic materials. The loads and supports are also shown as a single, homogenous unit at both ends and in the centre, corresponding to a hinge and a roller at the ends of the components.

Like the experiment, boundary conditions were used in this simulation, according to the finite element model in Figure 19. The load was applied to the top layer with two rollers, while two roller supports (a hinged or pin support and a roller support) were replicated for each CLT panel at the beam's end, like in the experiment. Each model used loads and boundary conditions like the test method. One of the supports is fixed with displacement inhibition; the other is defined as displacement, with movement in the X-axis direction enabled. The finite element mesh was created automatically by the program. The model of the CLT panel was loaded with the average force determined in the experiment F_A = 21500 N, F_B = 21500 N.

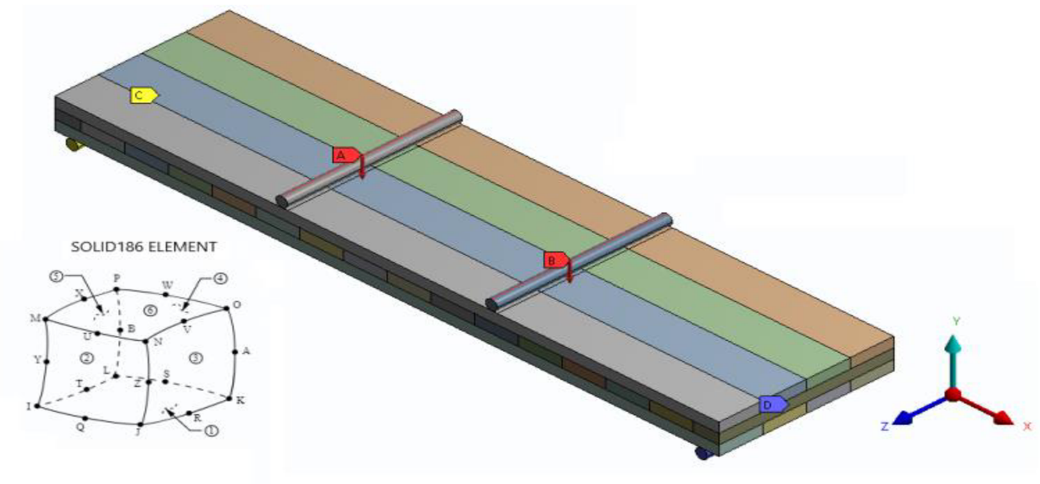


Figure 19: Finite element models for CLT panels

4.7. Statistical analysis

Results from the delamination test were evaluated as passed/failed according to the minimum required value specified in Annex C of EN 16351 (2015). Further, the samples which did not pass the minimum required value of the delamination criteria were evaluated according to the minimum required values of wood failure percentage (WFP) value specified in Annex C of EN 16351 (2015). The bond strength was sufficient and "Pass Delam" if:

a. total delamination ($Delam_{tot}$) of both glue lines was less than 10% of their length.
b. maximum delamination ($Delam_{max}$) of each glue line was less than 40% of the total length.
c. samples with a WFP of more than 70% will be considered as pass; otherwise, fail.

Further, the bond shear test results were evaluated according to Annex D of EN 16351 (2015). According to the required value, glue lines should have shear strengths (F_v) greater than 1 N/mm^2 that were deemed to pass; otherwise, they fail.

The whole experiment was conducted in a completely randomized design (CRD) to examine the effect of wood species and adhesive type on the examined properties. Aspen, spruce, poplar, and maple were the four wood species, while the two adhesive types were ME and 1C-PUR, and the manufacturing pressures were 0.6 MPa (L) and 1 MPa (H) for physical properties like WA and TS, bonding properties like total delamination, maximum delamination, shear strength, and WFP were tested using a factorial analysis (three-way ANOVA) to determine the effect of wood species, adhesive and manufacturing pressure on the examined properties. Similarly, a two-way analysis of variance (ANOVA) was conducted to investigate the impact of wood species and adhesives on the CLT panels' bending and rolling shear properties. Statistica 13 (TIBCO Software Inc., USA) was used for the statistical analysis. If the observed factor is statistically significant, this test will tell you based on your chosen significance level (the 'P' value). The assessed factor is ranked following the magnitude of P. In that case, the impact of the factor is statistically significant if the P value is less than 0.05 and insignificant if the value is more than 0.05. The vertical bars in the statistical graphs in the results section show a 95% confidence interval.

5. Results and discussion

This chapter gives a detailed idea about the results obtained from the various tests performed and discussed in Chapter 4 and their relative causes.

5.1. Water absorption (WA)

The potential water absorption, swelling or shrinkage of individual structural elements within tall structures can significantly influence the overall structural integrity of mass timber construction. Figure 20 illustrates the variation in WA (%) of the CLT panels as a function of wood species, adhesive, and pressure throughout 2 and 24 hours of immersion. The WA (%) spruce CLT bonded with ME and 1C-PUR adhesive at a pressure of 0.6 MPa were observed to be 14.5% and 13.3%, respectively, after 2h immersion period and 24.8% and 23.6%, after 24h of immersion. In comparison, WA (%) for aspen CLT were observed to be 33.8%, 32.3%, 58.2%, and 57.8%, respectively, while 32.3%, 31.4%, 54.5%, and 53.4% for poplar CLT. However, in hybrid maple-poplar CLT, the WA (%) were reported to be 27.5%, 26.8%, 43.8% and 41.6% after 2h and 24h immersion for 1C-PUR and ME, respectively. Similarly, the WA (%) of spruce CLT bonded with 1 MPa pressure were 13.7% and 13.27% after 2h of immersion and 23.6% and 23.2% after 24h of immersion, respectively. Comparingly, the reported WA (%) for aspen CLT were 33.3%, 31.2%, 54.62%, and 54.4%, while poplar CLT were reported to be 31.04%, 30.64%, 52.9%, and 52.4%. For hybrid maple-poplar CLT, the reported WA (%) were 25.02% and 24.47% after 2h and 40.8% and 41.6% after 24 hours, respectively.

Statistical analysis revealed that the WA (%) of the CLT panel were most affected by the wood species ($p=000$) and the pressure applied ($p=0.010$), while the adhesive had no significant effect ($p=0.332$). The statistical analysis showed the interaction effect of species and adhesive ($p=0.99$), species and pressure ($p=0.715$)., adhesive and pressure ($p=0.702$)., and species and adhesive and pressure ($p=0.989$) were statistically insignificant. Aisyah et al. (2023) and Baskara et al. (2023) observed similar results. They reported that the lamellas used in manufacture considerably affected the WA (%) of homogeneous and hybrid CLT panels. The results showed that all CLT panels had a rapid increase in WA (%) values during the first 2h of immersion and, after that, a steady fall. This behaviour can be ascribed to the inherent characteristic of wood to absorb moisture from the ambient environment and sustain a uniform moisture level. During the initial 2h of immersion, the pores of the wood exhibit a fast absorption of water due to the open voids present in the wood and the hydrophilic nature of wood to saturate the wood with water (Shukla and Pascal, 2008; Glass and Zelinka, 2010). After the initial 2h, when a significant proportion of wood pores achieved complete saturation with water, a gradual decrease in absorption rate was observed. When wood encounters water, the wood's moisture content may change quickly due to the gradual changes due to water vapour sorption. Further, Glass and Zelinka (2010) reported that the rate of absorption drops in wood above the fibre saturation point. Moreover, as the CLT panels' transverse portion or end grain encounters water, absorption occurs more quickly than in the longitudinal direction; therefore, rapid absorption in the first 2h was observed.

The WA (%) of the CLT panels were primarily affected by the wood species' anatomical structure, hygroscopicity, porosity, permeability, and cellular constituents (Srivarao et al., 2019). It has been observed that diffused porous or semi-diffused porous hardwoods (aspen, poplar, maple) exhibit higher permeability compared to ring-porous species such as red oak or white ash due to the presence of tyloses, which close the earlywood channels and drastically reduce the permeability and comparatively higher than spruce (Ross, 2010; Musah et al., 2021). The higher permeability resulted in a higher WA (%) in hardwood CLTs (aspen, poplar, and hybrid maple-poplar) than spruce CLT. Moreover, permeability is influenced by various factors, including vessel properties (such as vessel diameter, frequency, and specific area), the type and size of pit openings, and the presence of extractive contents (Koutsianitis et al., 2021). As shown in Table 7, the extractive contents in hardwoods such as aspen, poplar and maple were comparatively higher than spruce, which also resulted in higher WA (%) in the hardwood CLTs (Koutsianitis et al., 2021). Further, the anatomy of wood plays a crucial role in governing its water absorption (Hansmann et al., 2002). Tracheid lumina, pit apertures, and pit membrane pores collectively contribute to axial flow in softwoods, as observed by Hansmann et al. (2002). The size and quantity of open channels, rather than tyloses, significantly determine the longitudinal flow of fluids in hardwoods (Nguyen et al., 2021). The pit membranes of hardwoods exhibit a continuous structure, lacking the torus observed in softwoods. In contrast to softwoods, the pit membranes of hardwoods are not surrounded by cellulose strands that extend radially from a central torus (Hansmann et al., 2002). The hygroscopic properties of wood are subject to the influence of its chemical compositions, such as cellulose, hemicellulose, lignin, and extractive contents (Zhang et al., 2020). In addition, spruce's higher lignin content than hardwoods like aspen, poplar, and maple may have hindered water absorption due to its hydrophobic nature (Zhang et al., 2020). Moreover, the WA (%) was also reported to be higher in the tangential direction (Michalec and Niklasova, 2006). This phenomenon can be attributed to the higher presence of pits on the radial surface of the tracheid, hence rendering the influence of wood rays and resin canals on the flow negligible. Further, higher swelling and shrinkage values were observed in hardwoods than in spruce, as shown in Table 7, which also attributed to their higher WA (%) hardwood.

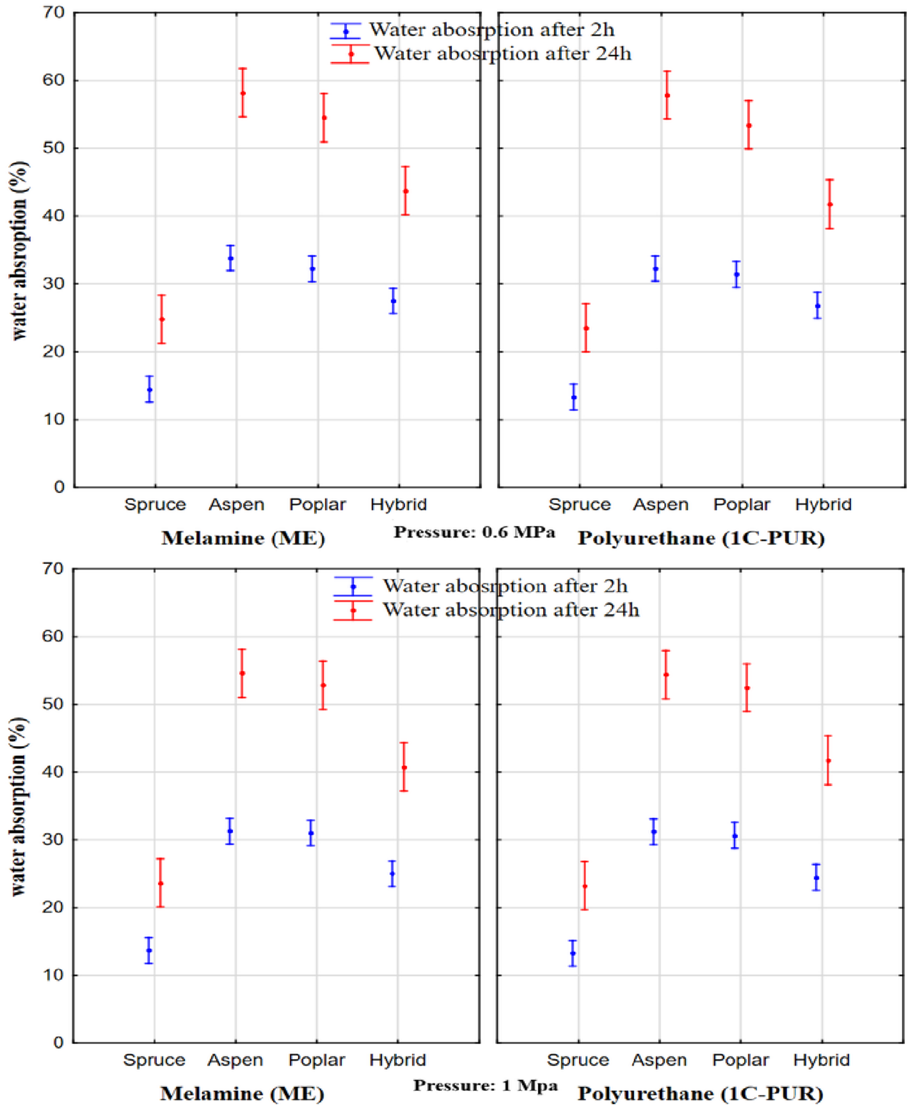


Figure 20: Effect of wood species, adhesive, and manufacturing pressure on water absorption (%) of the CLT panels

Moreover, according to Glass and Zelinka (2010) and Srivaro et al. (2021 a), low-density wood has increased water penetration due to its higher porosity. The findings in Table 7 indicate that aspen and poplar wood exhibit higher shrinkage than maple. Bal (2016) showed that poplar LVL absorbed more water than *Eucalyptus* LVL because of its higher permeability and lower density. Since aspen and poplar are from the same genus and have similar densities and anatomical characteristics, their WA (%) would be similar. Additionally, hybrid maple-poplar CLT had lower WA (%) values than aspen or poplar and higher than spruce CLT. This difference could be attributed to the distinct variations in swelling and shrinking properties exhibited by the two species. Furthermore, the WA (%) in hybrid CLT is also significantly affected by the overall density of the CLT panels (Aisyah et al., 2023; Baskara et al., 2023). So, the outer maple lamellas may have densified the low-density poplar in the core (Aisyah et al., 2023; Baskara et al., 2023), which significantly reduced the density of the hybrid CLT panels and hence lower WA (%).

The manufacturing pressure also plays a significant role in the WA (%) of the CLT panels. Similarly, Shukla and Pascal (2008) reported that higher manufacturing pressure caused lower WA (%) than low manufacturing pressure. Frihart and Hunt (2010) also reported that higher manufacturing pressure is necessary to establish intimate contact between the layers of wood and the adhesive. The 0.6 MPa manufacturing pressure may restrict adhesive penetration and thicken the glue line, leaving more wood pores for water absorption, while with 1 MPa, the adhesive penetrates cell lumens deeper, reducing water absorption (Wang et al., 2018). The thick glue lines also contain cavities caused by CO_2, which can increase water absorption (Sterley and Gustafsson, 2012). Further, the higher manufacturing pressure of 1 MPa could result in compression (Aisyah et al., 2023; Baskara et al., 2023), reducing the presence of cavities and WA (%). The absence of edge glueing in the tested CLT panels resulted in a gap between each lamella. Consequently, this gap likely increased the surface area of the CLT panels exposed to water absorption. The findings of Schmidt et al. (2019) align with the present study, as they observed that the gaps between the lamellae in a CLT panel facilitated higher water infiltration and accumulation owing to the increased exposed surface area.

5.2. Thickness swelling (TS)

Figure 21 shows the variation in (TS) (%) of the CLT panels as a function of species, adhesive, and pressure after 2 and 24 hours of immersion. Like WA (%), the TS (%) follows similar trends. From the statistical analysis, it was observed that the TS

(%) of the CLT panels entirely depended upon the wood species ($p=000$) and the pressure applied ($p=0.000$), and the interaction effect of species and pressure ($p=0.04$), while the adhesive had no significant impact ($p=0.218$). Further, the interaction effect of species and adhesive and species ($p=0.988$), adhesive and pressure ($p=0.775$) was statistically insignificant.

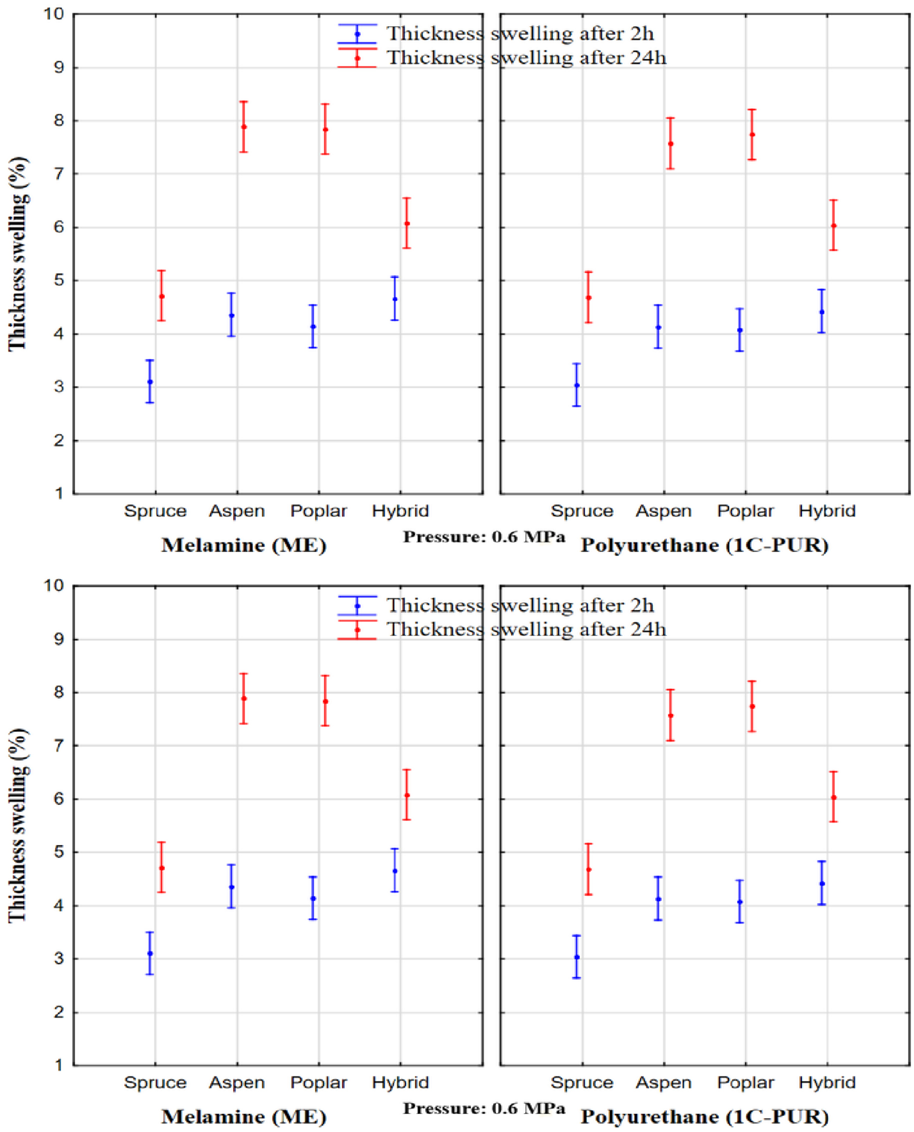


Figure 21: Effect of wood species, adhesive, and manufacturing pressure on thickness swelling (%) of the CLT panels

As shown in Figure 21, the TS (%) of spruce CLT bonded with ME and 1C-PUR adhesive at 0.6 MPa pressure was 3.11% and 3.04 %, respectively, after 2h, while the values were reported to be 4.72% and 4.69%, respectively, after 24h. Comparatively, the TS (%) for aspen CLT was 4.36%, 4.14%, 7.89%, 7.57%, while for poplar CLT it was 4.14%, 4.08%, 7.84%, 7.74%. Additionally, the TS (%) for hybrid maple-poplar

CLT were 4.67%, 4.43% after 2 hours of immersion and 6.08%, and 6.04% after 24 hours, respectively. Similarly, the TS (%) of spruce CLT bonded with ME and 1C-PUR adhesive at 1 MPa pressure was 3.63% and 3.52%, respectively, after 2h, while 5.98% and 5.48%, respectively, after 24h. Comparatively, the TS (%) for aspen CLT was 5.39%, 5.10%, 8.65%, 8.17%, while for poplar CLT it was 4.27%, 4.25%, 7.95%, 7.88%. Additionally, TS (%) for hybrid maple-poplar CLT were 4.86%, 4.67% after 2h and 6.75% and 6.74% after 24h, respectively.

Like WA (%), the spruce CLT exhibited lower TS (%) compared to both homogenous CLT (aspen, poplar) and hybrid maple-poplar CLT, whereas aspen and poplar CLT had higher values. This phenomenon could be attributed to the higher levels of absorption and porosity exhibited by aspen, poplar, and maple compared to spruce. Moreover, TS (%) of aspen, poplar, and hybrid maple-poplar CLT were approximately 1.5 times greater than that of spruce CLT. Pang and Jeong (2020) also reported a similar result, reporting that larch CLT has a swelling about 1.5 times greater than pine CLT due to their density variations and the variation in the swelling and shrinkage coefficients. Spruce has the lowest extractive content compared to maple and poplar (Table 7); hence its TS (%) will be lowest and higher in aspen, poplar, and hybrid maple-poplar CLT (Sheshmani et al., 2012; Wang et al., 2018). The response of wood to water infiltration differs significantly depending on whether the water enters by the end grain or the longitudinal grain (Wang et al., 2020). Furthermore, it should be noted that the TS (%) is greatly influenced by the lamellas employed during their production process and the overall density of the CLT panels (Aisyah et al., 2023; Baskara et al., 2023). The overall panel density of aspen and poplar CLT is lower than spruce CLT and the hybrid maple-poplar CLT. Thus, the higher density may result in lower TS (%). Further, Pang and Jeong (2020) also reported that the TS in CLT panels was 8.6-11.7 times higher than the swelling along the length and width. Additionally, they noted that the dimensional changes of wood perpendicular to the grain direction are approximately 24 times larger than those occurring parallel to the grain direction. The TS (%) for the panels made with 1 MPa pressure were slightly higher than 0.6 MPa pressure, as shown in Figure 21. Higher TS (%) of CLT panels with 1 MPa pressure was caused by the wood cell wall compression, causing internal stress, which is released as the compressed wood absorbs moisture and relaxes (Obataya and Chen, 2019). Srivaro et al. (2021) also reported similar results, noting that the increase in manufacturing pressure from 0.5 MPa to 1 MPa and 2 MPa correspondingly increases the TS (%) in rubberwood CLT.

Furthermore, compared to homogenous CLT, the core poplar may have compressed more with 1 MPa manufacturing pressure than 0.6 MPa in hybrid maple-poplar CLT, resulting in lower TS (%) (Feng and Chiang, 2020).

The results showed that 1C-PUR and ME adhesives exhibited nearly equivalent WA and TS values without statistical significance for adhesive type; however, 1C-PUR reported lower values than ME. Additionally, 1C-PUR has a 100% solid content, whereas the water-soluble adhesive ME contains 65% solid content and 35% water. So, further introducing water into adhesives results in wood expansion, hence inducing alterations in the pore structure. This alteration in the pore structure and the adhesive's water content also affected the adhesive's penetration behaviour (Hänsel et al., 2022).In another study, similar results were reported by Konnerth et al.(2008). The study observed a notable increase in swelling explicitly in PRF, while no significant swelling was observed in either 1C-PUR or epoxy (EP). The study also reported that most swelling observed in spruce wood samples treated with PRF adhesive is attributable to water within the liquid PRF adhesive, while the absence of swelling in 1C-PUR and EP specimens serves as reliable evidence for better bonding as well as lower WA and TS. In another study, Mannes et al. (2012) reported that emulsion-polymer-isocyanate (EPI) and 1C-PUR adhesives are barriers to water absorption in wooden joints. According to Wimmer et al. (2013), aminoplastic adhesives like MF/MUF are prone to partial hydrolysis, and MUF-bonded joints are considered appropriate for constructions with limited exposure to weathering and water. They further reported that thermosetting adhesives like MUF or PRF reported around 18% and 22% WA compared to a relatively low value of 3.5% in 1C-PUR. According to Wimmer et al. (2013), desorption causes the polymer to contract in MUF adhesive, bringing them closer to their water-holding sites and lowering the material's ability to hold water while the curing process of 1C-PUR is initiated by the presence of moisture, either from the substrate itself or from the surrounding environment. Due to all these, a lower WA and TS were reported in 1C-PUR bonded CLT panels compared to ME.

The reported WA (%) and TS (%) of the homogenous poplar and aspen CLT and hybrid maple-poplar CLT with 1 MPa pressure had similar results to that of radiata pine CLT (Maithani et al., 2023), Sumatran pine CLT and hybrid pine-coconut CLT (Baskara et al., 2023) as shown in Table 10.

Table 10: Comparison of the obtained water absorption (%) and thickness swelling (%) with various other results

CLT specimen	WA (%)	TS (%)	Adhesive	Reference
Spruce	13.27 - 23.6 13.7 - 24.8	3.04 - 5.48 3.11 - 5.98	1C-PUR ME	This study
Aspen	31.2 - 57.8 33.3 - 58.2	4.69 - 7.88 4.76 - 7.99	1C-PUR ME	This study
Poplar	30.64 - 53.4 31.04 - 54.5	4.14 - 8.57 4.36 - 8.19	1C-PUR ME	This study
Hybrid maple-poplar	26.8 - 40.8 27.5 - 41.73	4.67 - 6.78 4.43 - 6.76	1C-PUR ME	This study
Acacia mangimum	7.80 7.02	1.83 1.29	PUR PRF	Yusof et al. (2019 a)
Radiata pine (*Pinus radiata*)	29.35	4.30	PUR	Maithani et al. (2023)
Gamhar (*Gmelina arborea*) Teak (*Tectona grandis*)	8.61 8.90		EPI	Muñoz et al. (2022)
Rubberwood *(Hevea brasiliensis)*	24 - 33	1.5 - 3.1		Srivaro et al. (2021 a)
Sumatran pine (*Pinus merkusii*) Coconut Hybrid pine-coconut Hybrid coconut-pine	38.79 17.21 30.65 28.12	7.15 3.69 6.08 4.11	1C-PUR	Baskara et al. (2023)
Spruce-Pine-Fir (SPF) Hybrid SPF-OSB Hybrid OSB-SPF	13.2 - 16.8 10.4 - 13.8 10.2 - 11.1	2.3 - 3.8 2.2 - 2.4 2.6 - 3.6	1C-PUR, EPI and PRF	Liang et al. (2022)

5.3. Delamination properties

A pass/fail analysis was carried out regarding total delamination ($Delam_{tot}$), maximum delamination ($Delam_{max}$), and wood failure (WFP) for the delaminated sample according to the minimum required value specified in EN 16351 (2015). Figure 22 illustrates the pass/fail analysis of the CLT panels bonded with 1 MPa (top) and 0.6 MPa (bottom) manufacturing pressure. The homogenous CLT panels (spruce, poplar, aspen) bonded with both adhesives (1C-PUR and ME) passed the delamination test (both $Delam_{tot}$ and $Delam_{max}$) with 1 MPa manufacturing pressure, while hybrid maple-poplar CLT samples bonded with 1C-PUR only passed the delamination test. However, only 30% of hybrid maple-poplar CLT bonded with ME adhesive passed the $Delam_{tot}$ requirement with a mean value of 15.2%. Still, all passed the minimum standards requirement for $Delam_{max}$ with 28.2%. Unfortunately, most CLT panels bonded with 0.6 MPa failed miserably in the delamination test. About 60% of spruce CLT panels with 1C-PUR passed the delamination test, while the passing rate decreased to 50% in ME-bonded panels. Similarly, both aspen and poplar CLT panels reported a 60% passing rate with 1C-PUR adhesive, while the CLT panels bonded with ME failed miserably with an 80% failure rate. Compared to the homogenous CLT panels, the hybrid maple-poplar CLT exhibited the worst result, with a passing rate of only 30% with 1C-PUR adhesive and a mere 20% with ME adhesive. The pass/fail analysis showed that the hardwood CLT panels (aspen, poplar, and hybrid maple-poplar) performed well with a higher manufacturing pressure of 1 MPa than the lower 0.6 MPa pressure. Further in the delamination test, it was further observed that the CLT panels manufactured with lower pressure (0.6 MPa) mostly failed in a single glue line.

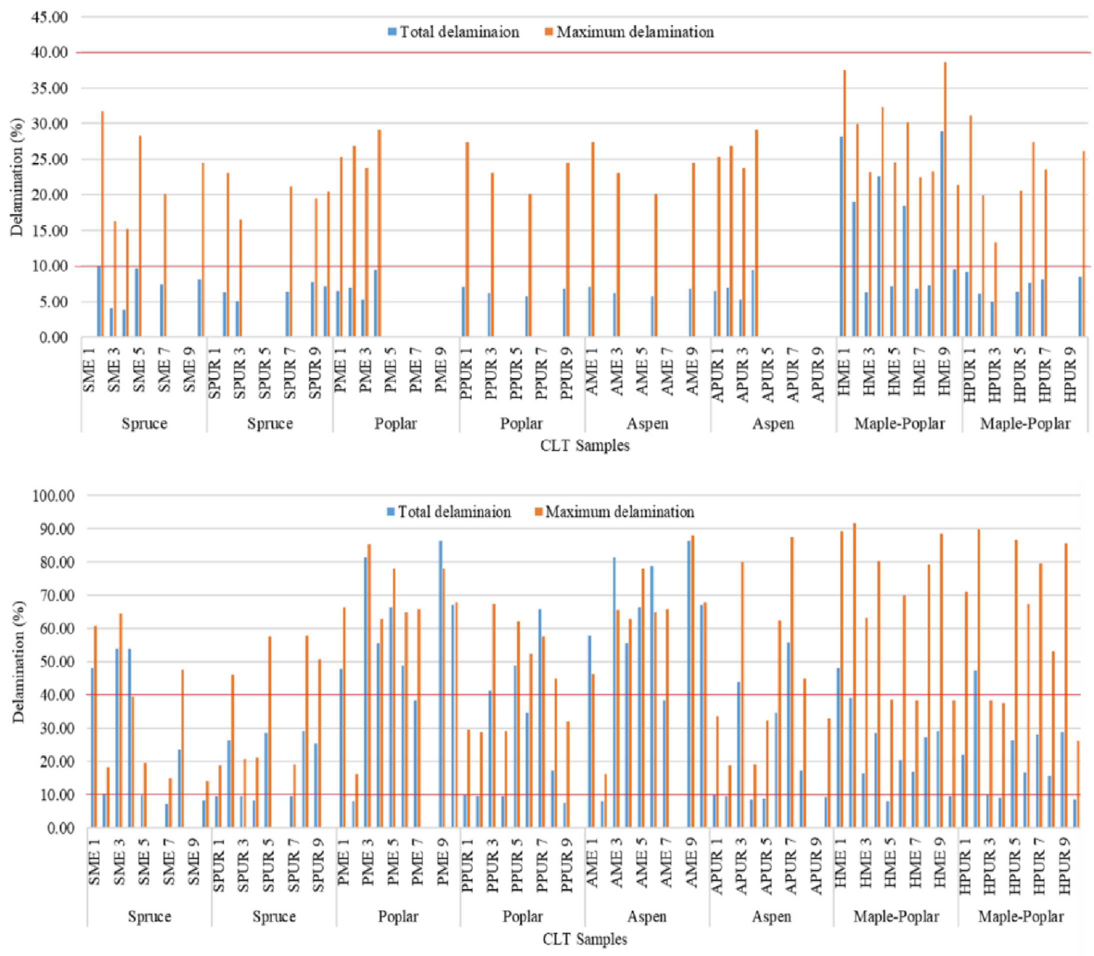


Figure 22: Pass/fail analysis results of the CLT specimens

After the pass/fail analysis, the failed specimens were broken with the help of a hammer and chisel to examine visually the WFP requirements suggested in EN 16351 (2015). The WFP calculation was purely conducted on the samples prepared with 0.6 MPa pressure, as the specimens manufactured with 1 MPa pressure met the minimum requirement. From the WFP analysis, it was observed that all the homogenous CLT panels from spruce and poplar from both adhesives (1C-PUR and ME) successfully met the minimum needed value for WFP, as depicted in Figure 23. The mean WFP in spruce CLT bonded with ME adhesive was reported to be 80%, while 81.5% in 1C-PUR. The mean WFP was reported as 75% and 78% in poplar CLT. However, the WFP performance of aspen CLT was miserable. Only 50% of aspen CLT bonded with ME adhesive passed the WFP requirements with a mean WFP of 69%, while 60% of the sample passed with 1C-PUR adhesive with a mean WFP of 71%. The hybrid maple-poplar CLT bonded with ME adhesive was the worst, with only 20% of the specimens passing the requirements, exhibiting an average WFP value of 66%. However, all the hybrid maple-poplar specimens bonded with 1C-PUR adhesive successfully met the WFP requirement, displaying an average WFP value of 77%. This may be because the low viscous ME adhesive may not penetrate deeper into the hardwoods, specifically the high-density maple wood, causing an inferior bonding (Musah et al., 2021). Different swelling and shrinkage coefficients of the outer maples and the core poplar may increase strains during vapour-pressure impregnation and quick drying, which may have led to the total breakdown of a single glue line to release the accumulated stress.

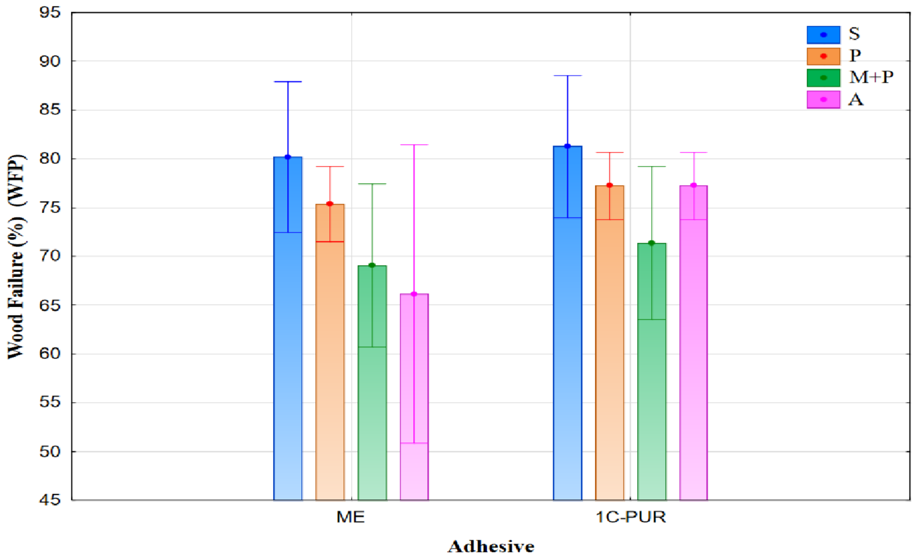


Figure 23: Effect of wood species and adhesive on the wood failure (%) of the delaminated CLT samples with 0.6 MPa pressure

The statistical analysis of the effect of wood species, adhesive and manufacturing pressure on $Delam_{tot}$ and $Delam_{max}$ values of the CLT samples is shown in Table 11. The analysis showed that all the tested parameters, i.e., wood species, adhesive and manufacturing pressure, as a single factor, are highly significant ($p=0.00$) for both $Delam_{tot}$ and $Delam_{max}$. Further, their interaction effects, such as species and pressure ($p=0.00$), adhesive and pressure ($p=0.006$), were observed to be significant, while the interaction effect of species and adhesive ($p=0.055$), and species, adhesive and pressure were insignificant ($p=0.010$). Purba et al. (2022) also reported a similar result in their study with oak and hybrid poplar-oak CLT and glulam bonded with 1C-PUR and MUF adhesives.

Table 11: Statistical analysis of the effect of wood species, adhesive and manufacturing pressure on delamination (%) ($Delam_{tot}$, $Delam_{max}$) of the CLT panels

Effect	**F value**	**Degree of freedom (df)**	**error**	**p-value**
Intercept	219.0742	2	143	0.000000
Species	15.6631	6	286	0.000000
Adhesive	13.2001	2	143	0.000005
Pressure	63.8358	2	143	0.000000
Species*Adhesive	2.0817	6	286	0.055393
Species*Pressure	12.1902	6	286	0.000000
Adhesive*Pressure	10.4274	2	143	0.000059
Species*Adhesive*Pressure	2.8629	6	286	0.010058

Figure 24 depicts the effect of wood species, adhesive and manufacturing pressure and their interaction effects on the CLT panels' delamination ($Delam_{tot}$, $Delam_{max}$). The mean $Delam_{tot}$ in spruce CLT bonded with ME adhesive with 1 MPa manufacturing pressure was observed to be 4.6%, with 1C-PUR reported to be 4%, while the mean $Delam_{max}$ were 14.2% and 12%, respectively. Similarly, the mean $Delam_{tot}$ *and Delammax* were reported to be 3%, 2.5 %, 10.2%, and 9.6% in poplar CLT and 5% and 20% in aspen CLT, respectively. In the hybrid maple-poplar CLT, all the specimens bonded with 1C-PUR adhesive passed the delamination test with a mean $Delam_{tot}$ of 5% and a $Delam_{max}$ of 16.4%. While with ME adhesive, only 30% of specimens met the $Delam_{tot}$ requirement with a mean value of 15.2%, but all passed the $Delam_{max}$ requirement with a mean $Delam_{max}$ of 28.2%. Furthermore, with the low manufacturing pressure (0.6 MPa), most specimens showed delamination. In spruce

CLT bonded with 0.6 MPa, the $Delam_{tot}$ and $Delam_{max}$ were reported to be 21.48%, 27.89% and 14.61%, 29.17% for both ME and 1C-PUR adhesives with 60% samples failing in both $Delam_{tot}$, $Delam_{max}$ requirements. However, both poplar and aspen CLT panels showed similar results. The mean $Delam_{tot}$ and $Delam_{max}$ were reported to be 50.05%, 58.8% and 24.4%, 41.39% for both ME and 1C-PUR adhesives, while 55.04%, 58.05% and 17.09%, 41.20% for aspen CLT panels bonded with for both ME and 1C-PUR adhesives. Compared to the homogenous CLT panels, in hybrid maple-poplar CLT bonded with 0.6 MPa, a higher mean $Delam_{tot}$, $Delam_{max}$ was reported. The mean $Delam_{tot}$ and $Delam_{max}$ were reported as 24.33%, 68.82% and, 21.21%, 63.39% for both ME and 1C-PUR adhesives.

The wood species mainly caused the variation and delamination of the CLT panels. As different wood species have different coefficients of swelling and shrinkage, the glue line's stress and delamination vary. Moreover, the porosity of wood and its differential coefficients of shrinkage and swelling in different directions are influenced by the orthotropic nature of wood (Ammann, 2015; Arzola-Villegas et al., 2019). The swelling and shrinkage variations among the lamellas of CLT panels might generate stresses within the glue line, leading to warping and subsequent delamination (Silva do Carmo et al., 2022). Based on the data presented in Table 7, it is evident that spruce's swelling and shrinkage coefficients are comparatively lower than those of the hardwood species, namely aspen, poplar, and maple. Additionally, maple exhibited higher swelling and shrinkage coefficients among the hardwoods in the longitudinal, radial, and tangential directions. The observed variation can be ascribed to the inherent porosity of the materials (Koddenberg, 2016; Niemz et al., 2023). Furthermore, it should be noted that the porosity of end-grain surfaces is higher compared to radial or tangential surfaces (Arzola-Villegas et al., 2019). It can be stated that, during the vacuum-pressure delamination process, the exposure of the end grains to the water vessel potentially facilitated a higher infiltration of water into the lamellas. This outcome may have been influenced by the combined effects of vacuum and pressure and the higher porosity exhibited by the end grain. Furthermore, it should be noted that swelling resulting from water absorption indicates a direct correlation with the density of the wood, which induces stress inside the glue line, ultimately leading to delamination (Niemz et al., 2023; Morin-Bernard et al., 2020). Moreover, it can be stated that tree species such as poplar and aspen, characterized by low density and enhanced porosity, exhibit a larger space. This void space is a conduit for the adhesive to penetrate the cell lumen, resulting in a better bond formation (Plötze and Niemz, 2011), while the high-density maple's thick cell walls and tiny cell lumina may not be penetrated well. It is possible that the tension exerted on the bonds of homogeneous spruce, aspen and poplar wood bonded with 1C-PUR and ME was considerably lower than the threshold limit. Nevertheless, it was observed that in the case of hybrid maple-poplar CLT, the core poplar layer exhibited higher stress than the outer maple layer when subjected to the vapour-pressure delamination test. This might be attributed to the substantial variance in density and the anisotropic nature of wood (Silva do Carmo et al., 2022). Additionally, the delamination in the core lamellas of CLT can be mainly attributed to the sandwich effect of stress resulting from variations in the swelling and shrinkage coefficients of both the outer and core lamellas. Moreover, the higher delamination in the hybrid maple-poplar CLT can be ascribed to variations in permeability among the wood species. Maple exhibits more permeability than poplar. Consequently, the increased permeability of maple allows for a higher accumulation of adhesive, leaving less adhesive for core poplar wood and causing inferior bonding. Similar results were reported in hybrid poplar-oak CLT (Purba et al., 2022) and hybrid beech-spruce CLT (Brunetti et al., 2020). Additionally, Koch (1970) reported that wood's density/specific gravity is directly related to delamination; wood with higher specific gravity had higher delamination than wood species with lower specific gravity.

The various extractives in the wood may also contribute to the variation in delamination and CLT panel failure, as previous studies have shown to impact bonding negatively (Luedtke et al., 2015; Konnerth et al., 2016; Bockel et al., 2019). The chemical composition of wood, especially wood extractives, determines wood surface pH and buffer capacity (Bockel et al., 2019). Thus, wood extractives affect the bonding through surface contamination (Nussbaum and Sterley, 2002), wettability, penetration, and adhesive curing (Bockel et al., 2019). Table 7 shows that spruce (1%) has less extractive content than the hardwoods, poplar (2.1-2.7%), and maple (3.1%). Hardwoods with higher extractive content had higher adhesion deficits when moisture fluctuations stressed the interface area during delamination (Bockel et al., 2019). Moreover, excessively high or low surface pH may change the wood-adhesive interface and bond line, according to Huang et al. (2010). A lower pH on the wood surface may counteract the effects of hardeners in formaldehyde-based adhesives like MF and PRF, preventing adhesive hardening (Pizzi and Mittal, 2017), while did not affect the hardening of 1C-PUR (Kol and Özbay, 2016). Internal stresses within wood-adhesive bonds have been highlighted as a component that could contribute to bond breakdown and subsequent delamination due to the varied drying qualities of various wood species (Knorz et al., 2014). Konnerth et al. (2016) discovered a considerable variation in the duration of drying time across diverse wood species in their investigation. Standard testing methodology recommends limiting the drying period to 16 hours to achieve the initial mass, primarily suited for softwoods like spruce. However, hardwoods such as beech, birch, and hornbeam require a longer drying period of 40-45 hours, whilst ash, oak, and poplar require 50-70 hours (Konnerth et al., 2016) and maple to 48-60 hours (Bergman, 2021).

Adhesives also strongly affect delamination (Sikora et al., 2016 b; Musah, 2021; Purba et al., 2022). The lower delamination in 1C-PUR could be attributed to its improved gap-filling characteristics (Lehringer and Gabriel, 2014). The adhesive viscosity is critical for bonding performance (Musah et al., 2021). As ME has a lower viscosity (varying from 1500 to 9000 mPas) than 1C-PUR, it may penetrate deeper into the cell lumina of the hybrid CLT, perhaps leading to the creation of starved junctions. However, according to Vick (1997), thermosetting adhesives such as MUF and MF lack adequate bonding strength to withstand extensive delamination testing. Knorz et al. (2014) discovered similar results with MUF adhesives compared to others. Furthermore, the solvents used in stiff structural adhesives, such as melamine-formaldehyde, phenol, and resorcinol, have been reported to cause shrinkage and the formation of gaps during the curing process (Frihart and Hunt, 2010). The higher formaldehyde content in formaldehyde-based adhesive also increases cross-linking inside the solidified glue, generating a strong adhesive bond (Knorz et al., 2014). The lack of formaldehyde in the glue employed in our study may result in less cross-linking and cause poor bonding. A longer closed assembly time is always required for deeper penetration of melamine adhesives into the wood to establish a strong bonding that resists delamination (Knorz et al., 2014; Brunetti et al., 2020; Musah et al., 2021). According to the manufacturer's recommendations, the closed assembly time for both glue types was limited to 1 hour in our experiment. This observation implies that the 1-hour time given for the closed assembly of the ME adhesive may be insufficient to sufficiently penetrate deeper into the dense structure of the maple wood and produce a strong connection. Furthermore, it was discovered that the water content and solid content of the adhesives played a role in the swelling of wood, resulting in changes in the pore structure and the adhesive's ability to penetrate the wood's subsurface (Hänsel et al., 2022; Dunky and Mittal, 2023). Table 8 shows that the 1C-PUR glue has a 100% solid composition, whereas the ME adhesive has a 65% solid content. Furthermore, the ME adhesive is water soluble. The higher water content of the ME adhesive may have contributed significantly to the increased swelling of the CLT panels, possibly causing stress inside the adhesive bond and consequent delamination.

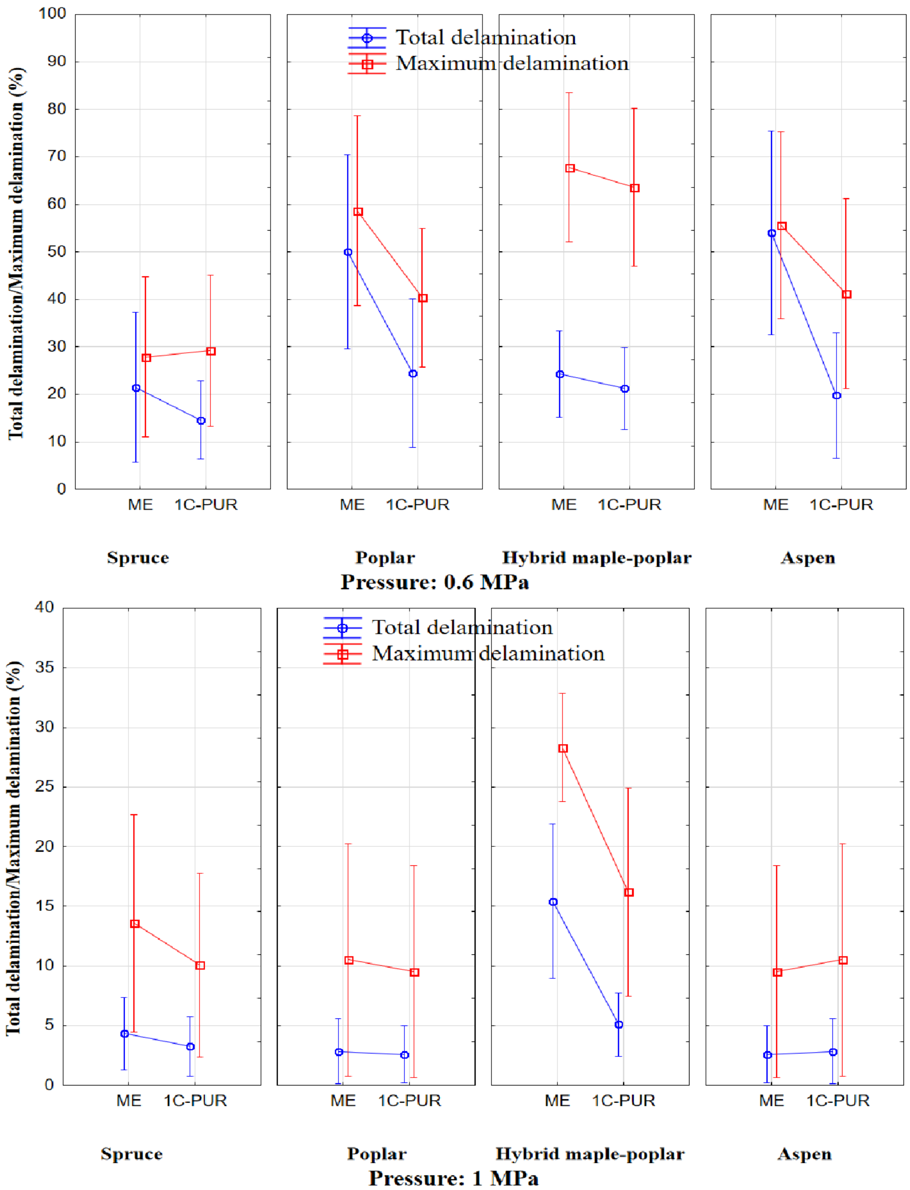


Figure 24: Effect of wood species, adhesive, and manufacturing pressure on the CLT panels' delamination ($Delam_{tot}$, $Delam_{max}$)

The pressure was also highly predictive and statistically significant in determining $Delam_{tot}$ and $Delam_{max}$. The higher pressure caused less delamination as the higher pressure resulted in higher adhesive penetration and caused an extremely thin glue line, while the lower pressure caused a thicker glue line by shallow adhesive penetration. The shallower the adhesive penetration, the more the adhesive surface is directly exposed to water (Wang et al., 2018) and causes poor bond. Higher pressure appears to be favoured for hardwood CLT, particularly high-density hardwoods, to overcome board distortion or deformation during pressing while bringing the lamellas together for bonding (Li et al., 2022; Purba et al., 2022). According to Li et al. (2022), 1C-PUR had a greater bonding strength when bonded with a bonding pressure of 1 MPa. Because ME adhesive has a lesser viscosity than 1C-PUR, a pressure of 1 MPa, regarded best for 1C-PUR, may not be strong enough to penetrate ME further into maple wood, creating starved junctions. The findings are consistent with the findings of Musah et al. (2021), who observed that the failure rate of MF-bonded hybrid maple-aspen CLT exceeded 50% with around 30% delamination. According to Martins et al. (2017), poplar glulam bonded with 1C-PUR adhesive had a delamination value of 73%, dropping to 68% when the pressure was increased from 0.8 MPa to 1 MPa. The lower pressure might not bring the high-density maple material to make a strong connection and might even lessen the adhesive's capacity to pierce the narrower cell lumens (Knorz et al. 2017). Furthermore, compared to the lower pressure (0.6 MPa), the higher manufacturing pressure (1 MPa) may have significantly densified the core poplar lamellas in the hybrid maple-poplar CLT. This densification of core lamellas may have dramatically reduced the number of voids in the core and enhanced bonding strength.

5.3.1. Delamination failure

During the delamination test, it was observed that the glue lines exhibited an increase in length and underwent a transition from their initial linear configuration to a curved morphology due to Poisson's effect and the variations in radial and tangential swelling of the lamellas. Delamination is caused mainly by variations in swelling and shrinkage of the lamellas and drying defects like cupping, twisting, warping, checking, and honeycombing (Nairn, 2019). According to Gereke et al. (2009), moisture-induced swelling and strains are primarily responsible for the delamination failure in the three-layered CLT. Delamination was mostly found in a single glue line in CLT panels with 1 MPa manufacturing pressure. The failure in the hybrid maple-poplar CLT mainly occurred at the interface between the two layers of high-density maple and the core poplar layer, as shown in Figure 25 (a). The failure is mainly caused by variations in density, swelling and shrinkage coefficients, and the bonding capabilities of the poplar material employed in the core layer. Liang et al. (2022) discovered similar results in the hybrid SPF-CSOB (Construction Oriented Strand Board) CLT panel. End-splitting was seen in the homogeneous poplar CLT panels, which might be attributed to vacuum impregnation and quick drying, as shown in Figure 25 (b). Figure 25 (c) also indicates fracture at the wood-adhesive contact in spruce CLT. However, in Aspen CLTs, only a small amount of rupture was observed in both glue lines as in Figure 25 (d).

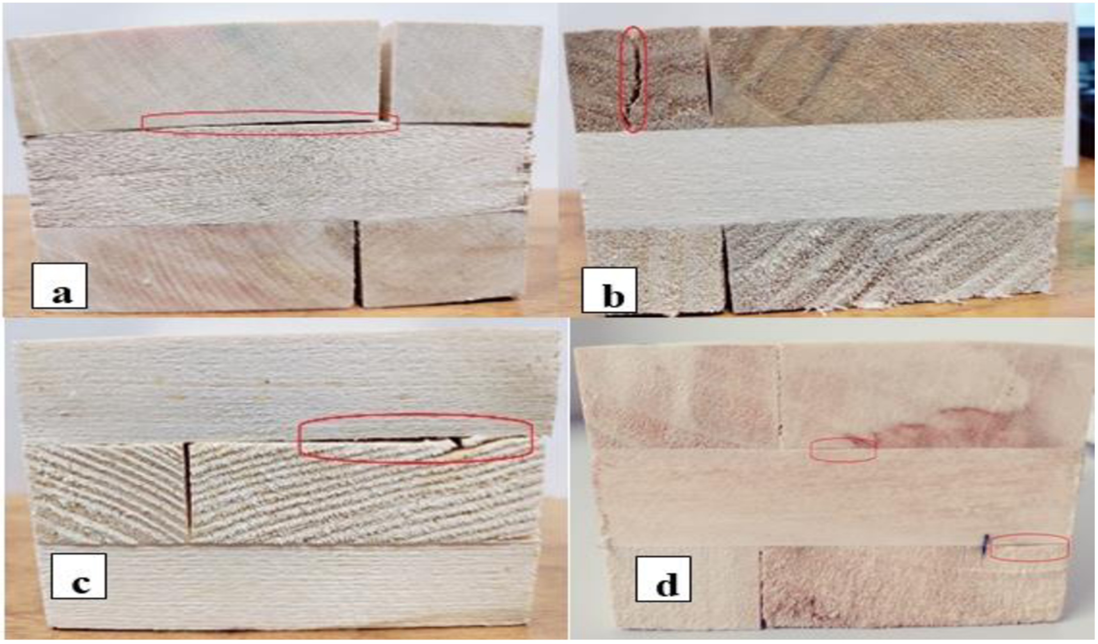


Figure 25: Delamination failure of CLT samples with 1 MPa manufacturing pressure

Compared to the CLT panels with 1 MPa pressure, the CLT panels bonded with 0.6 MPa pressure reported delamination failure in both glue lines, as depicted in Figure 26. Due to their lower bonding strength, when the samples were placed in the water vessel with a vacuum, higher water penetration may have occurred, rupturing the bonding. Similarly, the entrapped water in the samples evaporated quickly during the rapid drying. Because of the quick impregnation and drying, the resulting stress allows fracture propagation, leading to complete delamination failure. Another possible reason is the gaps caused by the lack of edge-glueing in the lamellas, which makes them more susceptible to water penetration. The cross-laminating feature also created a sandwich effect of stress in the glue lines as the outer lamella's variation in swelling and shrinkage caused tensile stress in the glue line, leading to partial lamella separation, while the core lamellas induced shear stress separating the lamellas along the glue line (Lim et al., 2020). Further, the rapid drying of the hardwoods above 60 °C during the initial phase of hardwood drying resulted in considerable surface checks, cupping, twisting, warping, and end splits (Vermaas, 1995). Hassani et al. (2016) also reported that stiffer adhesive stiffness like MUF increases the CLT panels' warping compared to 1C-PUR and PVAc.

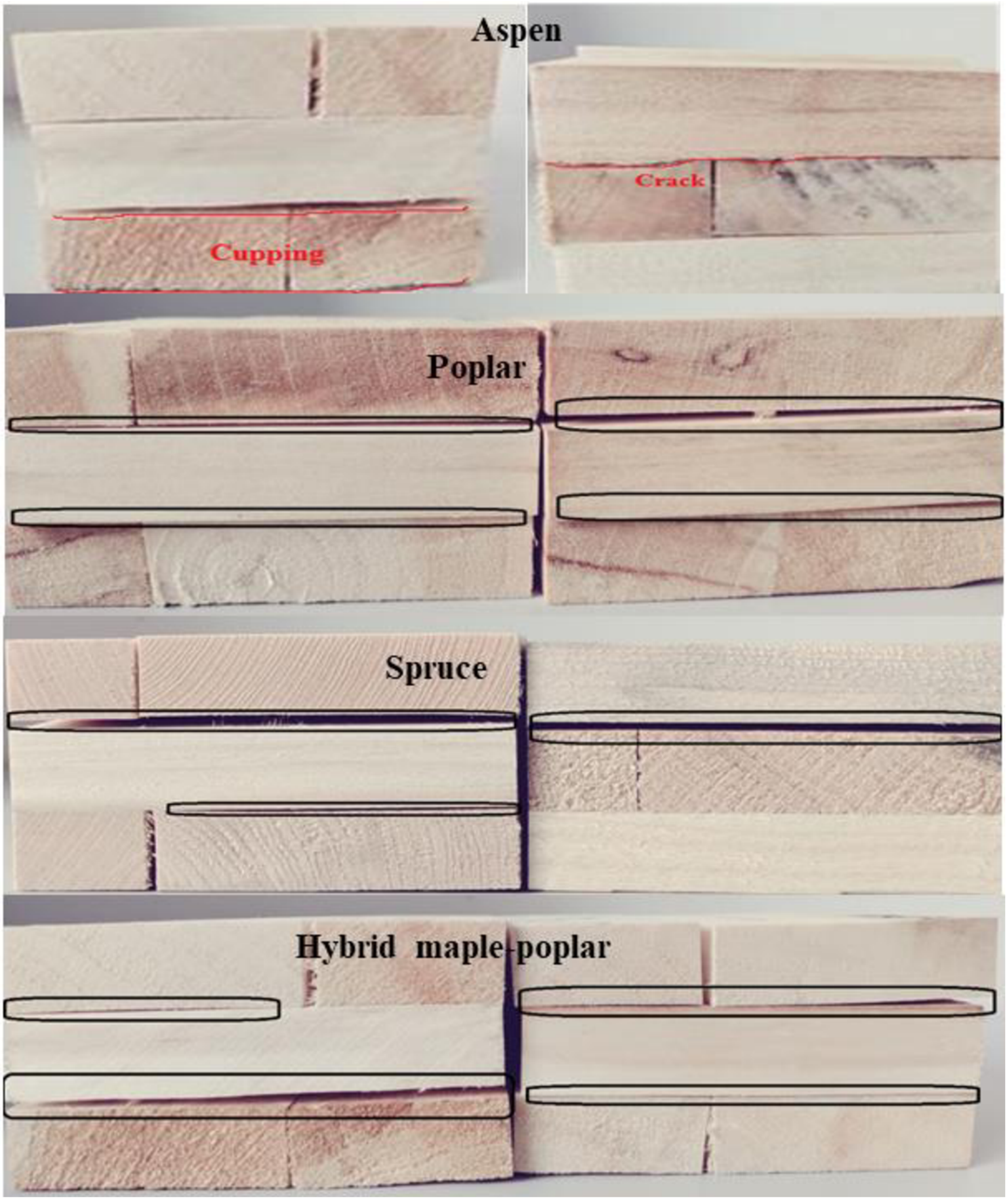


Figure 26: Delamination failure of CLT samples with 0.6 MPa manufacturing pressure

As shown in Table 12, low-density hardwoods like aspen and poplar bond well when bonded with an adequate manufacturing pressure (1 MPa) and pass the delamination test, which also coincided with the findings of Musah et al. (2021) in both homogenous aspen and hybrid aspen-maple CLT. Like our study, Sikora et al. (2016 b) reported that the lowest manufacturing caused severe delamination failure in the CLT panels. The table shows that the delamination test is one of the most critical.

Table 12: Comparison of the obtained result with the delamination (%) of other results

Specimen	Adhesive	Delamination (%)	Comments	References
Spruce	1C-PUR ME	4 and 18 5 and 27	1 MPa pressure passed	This study
Aspen	1C-PUR ME	7 and 41 8 and 52	1 MPa pressure passed	This study
Poplar	1C-PUR ME	3 and 24 4 and 41	1 MPa pressure passed	This study
Hybrid maple-poplar	1C-PUR ME	8 and 50 13 and 56	1 MPa pressure passed	This study
Sitka Spruce	1C-PUR PRF	24.3 - 68.8 21.2 - 63.3	1 MPa better performance	Sikora et al. (2016 b)
Beech Hybrid beech-spruce	PUR MUF PUR+P PUR MUF PUR+P	98.5 55.7 47.3 55.2 44.3 29.2	Majority failed PUR + Primer showed good performance	Brunetti et al. (2020)
Oak Hybrid Oak-poplar	PUR MUF PUR MUF	55.60 27.00 12.70 27.00	Hybrid oak-poplar good bonding with PUR	Purba et al. (2022)
Eucalyptus	EP EPI PRF PUR	10.25 16.5 12.5 7.8	PUR passed	Lu et al. (2018)
Aspen Sugar Maple Hybrid aspen-maple	MF PRF MF PRF MF PRF	10% 0% 6% 4% 4% 18%	PRF passed Hybrid CLT with MF passed the test	Musah et al. (2021)

5.4. Shear strength

Table 13 shows the statistical analysis of how different kinds of wood species, adhesives and manufacturing pressure affect the bond shear strength (F_v) and WFP of the CLT panels. The study revealed that the effect of wood species, adhesive and manufacturing pressure was highly significant ($p=0.00$) on shear strength and WFP when taken as a single factor. However, the interaction effect of both species and adhesive, adhesive and pressure and species, adhesive and pressure were statistically insignificant, while the interaction effect of species and pressure was highly significant.

Table 13: Statistical analysis of the effect of wood species, adhesive and manufacturing pressure on bond shear strength (F_v) and wood failure percentage (WFP) of CLT panels

Effect	**F value**	**Degree of freedom (df)**	**error**	**p-value**
Intercept	237666.2	2	143	0.000000
Species	256.8	6	286	0.000000
Adhesive	18.7	2	143	0.000000
Pressure	299.5	2	143	0.000000
Species*Adhesive	1.2	6	286	0.325777
Species*Pressure	10.4	6	286	0.000000
Adhesive*Pressure	0.4	2	143	0.701107
Species*Adhesive*Pressure	0.8	6	286	0.539912

The effects of wood species, adhesives, and manufacturing pressure on the shear strength of CLT panels made of homogeneous spruce, poplar, aspen, and hybrid maple-poplar are depicted in Figure 27. The study indicated that the mean shear strength of spruce CLT with 1 MPa was 4.3 N/mm^2 and 3.6 N/mm^2 for both ME and 1C-PUR. Similarly, the bond shear strength was 5.6 N/mm^2 and 5.2 N/mm^2 for poplar CLT, while 5 N/mm^2 and 4.6 N/mm^2 for aspen CLT, respectively. The mean shear strength in hybrid maple-poplar CLT was also observed to be 10.9 N/mm^2 and 10.7 N/mm^2 for both ME and 1C-PUR. The results showed that all CLT panels bonded with 0.6 MPa manufacturing pressure had 20-30% lower bond shear strengths than 1 MPa. However, the shear strengths for all CLT panels are reported to be comparatively higher than the specified threshold (1 N/mm^2) outlined in Annexe D of EN 16351 (2015). According to Frihart (2005), the wood species and density significantly impact CLT panels' bond shear strength and durability. The reported densities observed in our studies, spruce (0.389 g/cm^3), poplar (0.401 g/cm^3), aspen (0.391 g/cm^3), and maple (0.650 g/cm^3), indicate a possible association with shear strength. However, the shear strengths of spruce, aspen, and poplar were expected to be similar because their densities were almost equivalent. Similar results were reported by Sikora et al. (2016 b) in Irish Sitka spruce CLT and poplar CLT by Kramer et al. (2014). However, the hybrid maple-poplar CLT panels have increased shear strength due to the higher density maple in the outer layers (Chen et al., 2019). In another study, Adnan et al. (2021) observed that hybrid rubberwood-sesendok CLT panels have stronger bond shear strength due to the density and arrangement of the outer lamellas. Additionally, high-density woods like maple have higher contact angles and reduce moisture, which will hold the adhesive longer (Adnan et al., 2021), while low-density poplar absorbs adhesive quickly due to its low density, low contact angle, and higher wettability (Oberhofnerová and Pánek, 2016). This may have resulted in higher shear strength in hybrid maple-poplar CLT. Additionally, regardless of CLT panel composition, Srivaro et al. (2022) observed that the core lamella had a stronger effect on perpendicular shear strength than parallel shear strength. Notably, regardless of the density of the core lamella, Mohamad et al. (2019) observed that the mixed sesendok-merpauh glulam's shear strength was higher than that of the mixed jelutong-merpauh glulam.

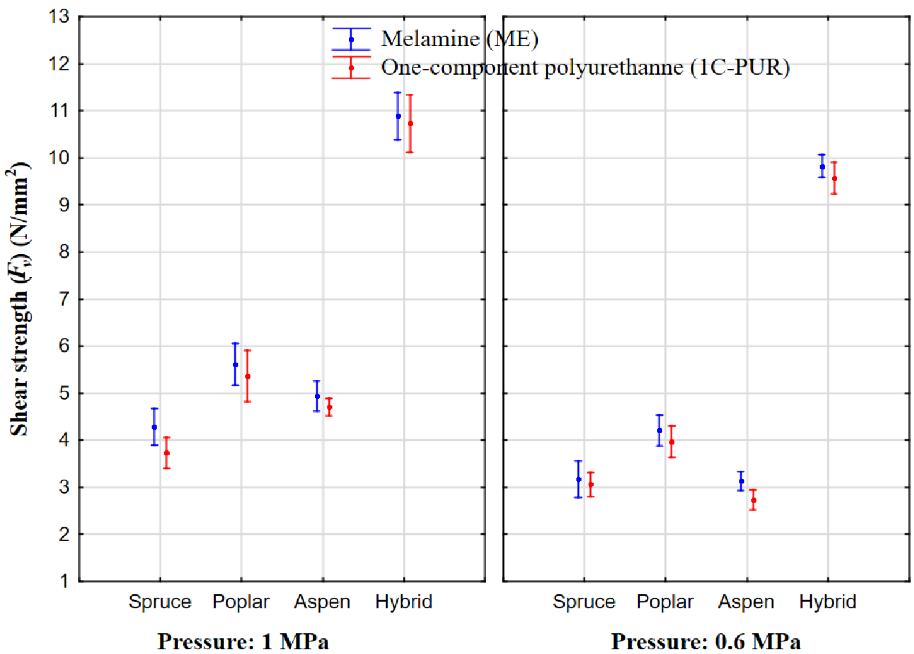


Figure 27: Effect of wood species, adhesive, and manufacturing pressure on bond shear strength (F_v) of CLT panels

Regardless of wood species, ME-bonded panels had higher mean shear strength than 1C-PUR bonded panels. Other researchers observed similar findings (Knorz et al., 2014; Brunetti et al., 2020; Purba et al., 2022). According to Musah et al. (2021), it has been observed that MF bonds exhibit enhanced resistance to shear deformation under higher pressure conditions, leading to higher bond shear strength in comparison to PRF. The observed differences in shear strength can be ascribed to the adhesive's viscosity and its ability to adhere, as discussed by Chandler et al. (2005) and Kamke and Lee (2007). The viscosity range of 1C-PUR falls between 6000 and 19000 mPas, while 1500 to 9000 mPas for ME. Several studies (Cheng and Sun, 2006; Ren and Frazier, 2012;

Musah et al., 2021) have reported that 1C-PUR exhibits limited penetration because of its higher contact angle and viscosity in comparison to alternative adhesives, including MF, PRF, and EPI. Moreover, it has been observed that during the pressing, the extractives present in the wood could migrate towards the wood's surface, which has a detrimental effect on the adhesive penetration and shear strength of 1C-PUR adhesive (Shirmohammadi et al., 2023). In addition, it has been observed that the curing process of 1C-PUR leads to the formation of bubbles, which can be attributed to the generation of carbon dioxide (CO_2), which also lowers the shear strength (Shirmohammadi et al., 2023). To reduce foam production in 1C-PUR during curing, carbon dioxide-absorbing, de-foaming, and curing agents have been suggested. However, the preliminary trials and the glue manufacturer reported higher performance with 1C-PUR. Consequently, the study was conducted without primers or curing agents in the 1C-PUR adhesive. Further, the formic acid hardener in ME catalyzes the curing process, decreasing the adhesive's pH and viscosity and increasing the CLT's shear strength (Tran et al., 2022). The higher hardener concentration within the adhesive mixture also increases the shear strength (Knorz et al., 2014). In our investigation, the adhesive and hardener mixture were created in a 100:100 ratio, potentially contributing to the observed increase in shear strength. Further study by Zhou et al. (2017) revealed that the wood bonded with MUF adhesive in a 2% (w/w) formic acid solution had a stable shear strength of 10.6 N/mm^2 at 12% MC and 10.0 N/mm^2 at 18% MC, which is around 17% and 16% higher than PRF adhesive under the same conditions.

The statistical analysis also reported that the manufacturing pressure had a highly significant effect on the shear strength of the CLT panels. Several prior studies (Gong et al., 2016; Liao et al., 2017; Wang et al., 2018; Dong et al., 2023) produced similar findings. Higher pressure could have resulted in deeper adhesive penetration, increasing the bond strength of the CLT panels (Sikora et al., 2016 b). During the CLT production process, sufficient pressure is always required. Low manufacturing pressure might cause air bubbles, which get trapped in the glue line during the curing process, resulting in delamination and low shear strength (Shirmohammadi et al., 2023). According to Liao et al. (2017), a higher manufacturing pressure (1 MPa) with a longer time improves the bond performance by lowering the delamination rate and enhancing shear strength and WFP in *Eucalyptus* CLT. Further, the interactions between species, adhesive, and pressure were statistically insignificant, whereas the interaction between species and pressure was highly significant. Wang et al. (2018) showed similar results in hem-fir (*Tsuga heterophylla* (Raf.) Sarg - *Abies amabilis* (Dougl.) Forbes) CLT panels bonded with 1C-PUR and EPI. Furthermore, Knorz et al. (2014) also discovered that variations in shear strength might be attributed to the testing methodology used by each researcher in their study and changes in shearing equipment, which could significantly impact the results of shear tests. Fu et al. (2020) discovered that shear stress is equally distributed in specimens with shorter glue lines. Furthermore, they reported that while the double shear test technique predicted the actual shear strength of the bond line, the compression shear strength approach predicted a shear strength that was 5-10% lower than the real shear strength.

The WFP was calculated after the bond shear test since bonding performance is affected by both shear strength and WFP. Figure 28 illustrates the impact of wood species, adhesive types, and manufacturing pressure on the WFP of the CLT panels. The WFP, like shear strength, is significantly affected by wood species, adhesive type, manufacturing pressure, and the interaction effect of wood species and pressure. The WFP values of poplar CLT and aspen CLT exhibit similarity, as evidenced by their mean WFP of 90% in ME-bonded CLT panels and 87.5% in 1C-PUR bonded CLT panels manufactured with 1 MPa pressure. In contrast, the mean WFP for spruce CLT bonded with ME adhesive was 89% and 88.3% for 1C-PUR. Furthermore, a decrease in WFP was seen in the hybrid maple-poplar CLT. The WFP of hybrid maple-poplar CLT bonded with ME adhesive was 89%, while it was 84% with 1C-PUR adhesive. The observed decrease in WFP in hybrid maple-poplar CLT could be due to the exceptional resistance of the high-density outer maple layer, which effectively mitigates WFP. Nevertheless, with 0.6 MPa manufacturing pressure, only a marginal increase was observed in the WFP of both spruce CLT and aspen CLT. The mean WFP of spruce CLT was 91.6% and 89.8% for both ME and 1C-PUR, respectively. In comparison, the WFP of aspen CLT was 91% and 89.4%. The WFP in poplar CLT were very similar in both pressures. However, a significant reduction in WFP was seen in hybrid maple-poplar CLT bonded with 0.6 MPa pressure rather than 1 MPa pressure. The average WFP for both adhesive kinds was reported to be 80%. Regarding both pressures of 0.6 MPa and 1 MPa, the study observed a slight variation (2%) in WFP for homogeneous CLT panels and a higher variation (approximately 10%) in hybrid maple-poplar CLT. The manufacturing pressure of 0.6 MPa may have been sufficient to produce a strong link between the poplar, aspen, and spruce species, as their densities are similar and comparably lower than maple. On the other hand, a pressure of 0.6 MPa may not have been sufficient for a strong bonding between the high-density maple and the core poplar.

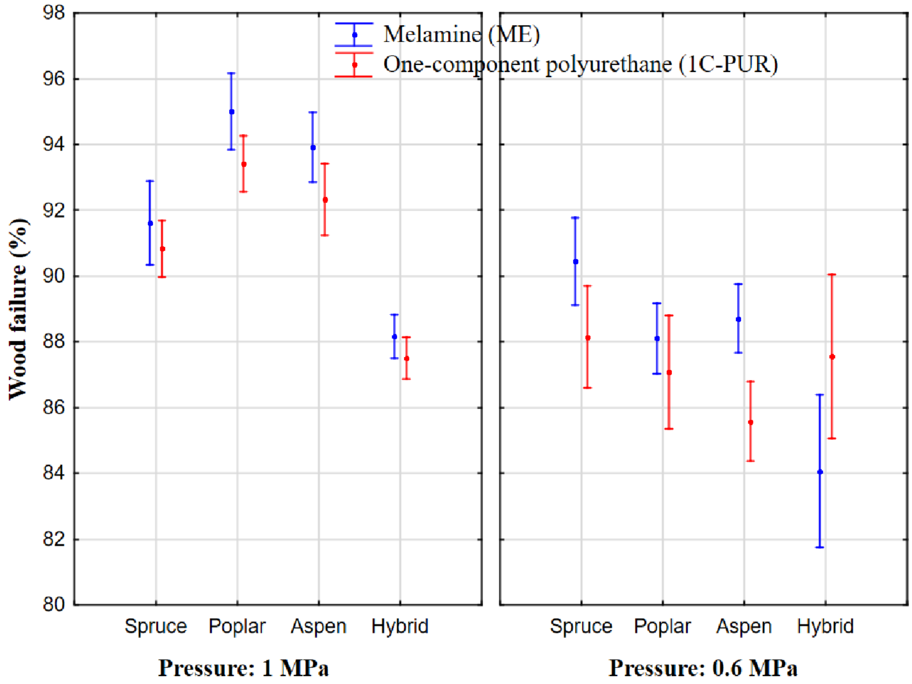


Figure 28: Effect of wood species, adhesive, and manufacturing pressure on wood failure (%) (WFP) of CLT panels after shear test

Additionally, the lower WFP of the hybrid maple-poplar CLT may be due to the higher strength of hardwood fibres to hold stronger with each compared to the adhesive used, resulting in glue failure (Frihart and Hunt, 2010). Further, the high-density maple in the outer layer may have also contributed to less mechanical glue anchoring, which reduces the likelihood of wood fibre pull-out from the stronger wood matrix and results in lower WFP (Aicher et al., 2018). Aicher et al. (2018) also observed that glulam produced from tropical hardwoods, including keruing (*Dipterocarpus spp.*), melagangai (*Potoxylon melagangai*), meranti (*Shorea spp.*), and teak (*Tectona grandis*), exhibited higher WFP (93-96%) compared to European hardwoods such as ash (*Fraxinus excelsior*), beech (*Fagus sylvatica*), sweet chestnut (*Castanea sativa*), and oak (*Quercus robur/petraea*) (79-89%). Frihart (2005) also observed superficial bonding in maple, which decreased the WFP. Therefore, including maple in the hybrid design lowered the WFP, presumably due to its increased permeability and reduced parenchyma content (Frihart, 2005). The variation in the anatomical characteristics of both species in the hybrid arrangement may have also resulted in lower WFP. Furthermore, because the wood has lower density and strength, the higher manufacturing pressure (1 MPa) may have caused microstructural cracking within the wood, resulting in a weak bond, or it may have caused a bleeding phenomenon, causing the adhesive to ooze out and lowering WFP (Gharbi and Sikora, 2022). However, applying an appropriate manufacturing pressure for improved bonding is crucial since low and high pressure will result in poor bonding (Sikora et al., 2016 b; Gharbi and Sikora, 2022). The glue line thickness also strongly influences WFP and shear strength (Kläusler et al., 2014 b). The 0.6 MPa pressure may be insufficient to effectively infiltrate adhesive into the wood, leading to increased glue line thickness and shallow bonding compared to 1 MPa pressure. Consequently, this may have reduced shear strength and wood failure percentage (WFP). Previous studies have shown that stiffer adhesives such as MF/MUF or PRF enhance WFP (Hass, 2012; Kläusler et al., 2014 a; Knorz et al., 2016). This study discovered that ME, a structurally more rigid adhesive than 1C-PUR, had a higher WFP value. Moreover, the double shear test also minimised the impact of rolling shear and increased shear stress homogeneity, leading to minor variations in F_v and WFP.

Additionally, Table 14 compares the results obtained in this study and previously published data on bond shear strength. The data presented in the table indicates that the manufacturing pressure and lamella density are significant factors influencing the bond shear strength of the CLT panels. Additionally, it was observed that the bond shear strength in homogeneous aspen and poplar CLT is relatively higher in comparison to softwoods such as Irish Sitka Spruce CLT (Sikora et al., 2016 b), Southern Pine CLT (Satir et al., 2023), and hardwoods with comparable density such as yellow poplar CLT (Satir et al., 2023) and poplar CLT (Kramer et al., 2014). It has also been observed that the bond shear strength of hybrid maple-poplar CLT has higher bond shear strength compared to both homogeneous beech and hybrid beech-spruce CLT, as reported by Brunetti et al. (2020), as well as rubberwood CLT, as reported by Srivaro et al. (2022). From the obtained results from the comparative analysis, it is clear that a hybrid CLT panel with high-density outer layers with a low-density core layer reported better performance than the homogenous high-density CLT panels. Therefore, the study suggested that the low-density aspen could be used as both homogenous CLT and in hybrid combination with maple or other higher-strength hardwoods with a manufacturing pressure of 1 MPa.

Table 14: Comparative analysis of bond shear strength (F_v) of our study concerning some hardwoods and softwoods by other researchers

Specimens	**Adhesives**	***F_v* (N/mm²)**	**Comments**	**References**
Spruce	1C-PUR ME	3.3 - 3.6 3.6 - 4.3	Higher F_v with 1 Mpa	This study
Aspen	1C-PUR ME	2.8 - 4.6 3.1 - 5	Higher F_v with 1 Mpa	This study
Poplar	1C-PUR ME	4.1 - 5.2 4.3 - 5.6	Higher F_v with 1 Mpa	This study
Hybrid maple-poplar	1C-PUR ME	9.4 - 10.7 9.8 - 10.9	Higher F_v with 1 Mpa	This study
Irish Sitka Spruce	PUR PRF	2.8 - 3.2 2.5 - 2.8	Higher F_v with 1 Mpa	Sikora et al. (2016 b)
Poplar	PRF	3.06		Kramer et al. (2014)
Southern Pine Yellow poplar Hybrid pine-yellow poplar Hybrid yellow poplar-pine	1C-PUR	2.91 2.75 2.10 2.76		Satir et al. (2023)
Rubberwood Coconut Hybrid rubberwood-coconut Hybrid coconut-rubberwood	1C-PUR	9.7 5.8 8.6 8	Higher density with higher F_v	Srivaro et al. (2022)
Rubberwood Sesendok Hybrid rubberwood-sesendok	PRF	6.2 - 7.3 5.1 - 5.6 8.05	Higher F_v with 1 Mpa than 0.7 MPa	Adnan et al. (2021)
Beech Hybrid beech-spruce	MUF PUR+P PUR MUF PUR+P PUR	6.7 6.8 6.1 4.3 4.7 4	Primer in PUR improved the performance	Brunetti et al. (2020)

5.4.1. Shear failure

During the compression loading of the double shear test, it was observed that the initiation of shear stress occurs at the fixed (supporting) end of the CLT panel. Subsequently, this shear stress is transmitted to the core layer, leading to a greater likelihood of failure at the support points. Fu et al. (2020) and Gao et al. (2022) have observed comparable findings. As seen in Figure 29, the shear test revealed the presence of two distinct failure mechanisms: (a) failure occurring at the supporting end and (b) fracture occurring in the centre of the specimen accompanied by failure at the support. The failure in the weakest zone was a consequence of the ongoing loading. During the examination, it was noted that most of the samples, around 75%, failed at the supporting end. This trend was consistent across different wood species and adhesive types. The observed phenomenon may be attributed to the orthogonal configuration of the lamellas inside the CLT panels, leading to increased shear forces along the glue lines.

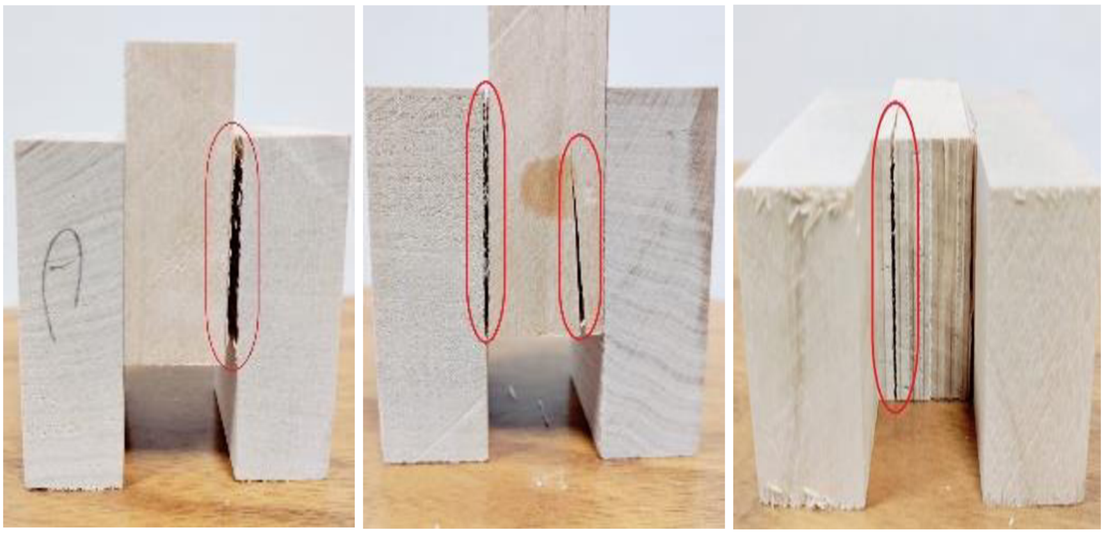


Figure 29: Shear failures in the CLT samples

5.5. Bending strength and stiffness

Figure 30 displays the load vs. displacement curves for homogeneous spruce, poplar, aspen, and hybrid maple-poplar CLT. The curves presented in the figure represent the low, high, and mean values. The load-displacement curves reported a notable level of resemblance, indicating consistent failure patterns among specimens with similar structural properties. The correlation between loads and displacements was nearly linear until reaching the maximum load (F_{max}). After exceeding F_{max}, a significant reduction in the applied force was seen, leading to brittle failure. According to Ettelaei et al. (2022 a), wood exhibits variations in its properties because of its inherent orthotropic nature. Specifically, the strength of the lamellas in the longitudinal direction is considerably lower compared to the parallel direction. Additionally, orthogonally arranged lamellas contributed to the reduced load-carrying capacity observed in homogeneous and hybrid CLT panels (Hematabadi et al., 2021). The poplar CLT panels bonded with 1C-PUR reported a range of maximum load (F_{max}) values between 27530 and 36190 N, with an average value of 32200 N. In contrast, the panels bonded with ME exhibited F_{max} ranging from 28100 to 35890 N, with a mean of 30890 N. Similarly, in aspen CLT, the F_{max} ranged from 26530 to 34190 N, with an average value of 32081 N with 1C-PUR adhesive, while the F_{max} ranged from 26230 to 33890 N, with an average value of 31408 N with ME adhesive. However, in spruce CLT bonded with ME adhesive, the F_{max} ranged from 28130 to 36890 N, with an average value of 32138 N, while with 1C-PUR, the mean F_{max} was 32148 N with a range from 28630 to 38993 N. However, the hybrid CLT bonded with 1C-PUR adhesive reported a mean F_{max} of 43290 N, with a range of 39930 - 47510 N. On the other hand, the mean F_{max} for the CLT bonded with ME was 42856 N, with a range of 39408 - 47176 N. Similarly, the maximum displacement (d_{max}) was reported to be 20 mm in both poplar and aspen CLT panels. Conversely, in spruce CLT, the d_{max} was recorded as 18 mm, while in hybrid maple-poplar CLT, it has been observed to be 15 mm. Additionally, the F_{max} in poplar and aspen CLT was like spruce CLT; however, it was around 36% lower than hybrid maple-poplar CLT. Comparably, the d_{max} observed in poplar CLT was approximately 11% higher than spruce CLT and a notable 33% higher compared to hybrid maple-poplar CLT due to its lower density and strength properties than spruce and maple wood. Spruce CLT had a load-bearing capacity like Sikora et al. (2016 a), while poplar and aspen CLT were like Hematabadi et al. (2020) and Rostampurhafatakhani and Hematabadi (2021).

Further, it can be observed that both poplar CLT and aspen CLT exhibited similar load vs. displacement curves as they were closely related to each other with equivalent density and mechanical properties. However, the hybrid maple-poplar CLT samples showed a gradual rise in load following an initial decline at the point of limit of proportionality. The residual bearing capacity seen in the lower layer can be ascribed to the high-density maple since its mechanical characteristics are notably superior to other types of wood (refer to Table 7). Li et al. (2023) also reported a similar load-displacement curve in a hybrid cross-laminated bamboo timber (CLBT) configuration.

The lamellas exhibit a relatively reduced strength in the longitudinal direction compared to the parallel direction (Ettelaei et al., 2022 b). Furthermore, Hematabadi et al. (2021) discovered the core lamellas arranged in an orthogonal manner across neighbouring CLT panel layers, significantly lowering the load-carrying capability observed in both homogeneous and hybrid CLT panels. Pangh et al. (2019) also reported a strong correlation between the stiffness of CLT panels and the bottom lamellas' modulus of elasticity (MOE). Furthermore, the authors suggested that using higher-grade boards in the bottom lamellas of CLT panels could potentially increase the flexural performance of the panels, mainly when utilised for floorings. Similarly, Ettelaei et al. (2022 a) conducted an analysis whereby they noticed that the use of lower-grade boards in the bottom lamellas of panel designs, as opposed to boards of higher quality, can have a noticeable impact on the tensile strength of the panel.

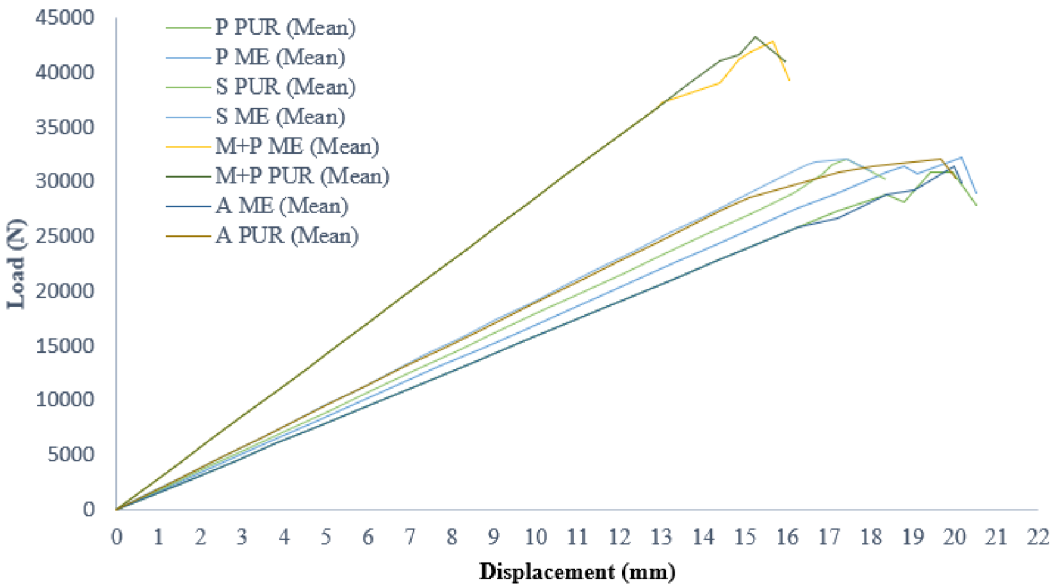


Figure 30: Load vs displacement curves from bending

During manufacturing, densification may have occurred in the hybrid maple-poplar CLT. The degree of densification observed in homogeneous CLT panels made of spruce, aspen, and poplar was minimal compared to hybrid maple-poplar CLT panels. This is due to the use of evenly dense and graded lumber in manufacturing the homogenous panels. Hariz et al. (2023) observed a similar result in the hybrid of *Acacia mangium* and Needle wood (*Schima wallichii*) CLT. This densification of the core lamellas between high-density outer lamellas increased the load-carrying capacity and the bending performance. Similar results were also reported by Feng and Chiang (2020) in their study of low-density plantation-grown species Batai (*Falcataria moluccana*) for

CLT manufacturing. Nevertheless, previous studies (Brandner et al., 2017; Zhou et al., 2017; Niederwestberg et al., 2018) have reported that the lack of edge-glueing and gaps negatively impact CLT panels' physical and mechanical characteristics. The absence of edge-glueing and the presence of gaps could be a barrier to the propagation of stress between adjacent lamellas, and concentrated stress at one point causes failure and may have caused slippage one lamella over another with the increasing load. As all the timbers were graded visually, permissible defects are allowed in CLT core lamellas, contributing to the CLT panels' load-carrying capacity. According to Ross (2010), maple's tensile and flexural strength is nearly double that of poplar, which potentially increases peak load due to the inherent resistance of the outer maple layer to tensile failure and the rolling shear resistance provided by the poplar core. However, homogenous CLT panels (spruce, poplar, and aspen), on the other hand, showed the least amount of variation in both load and stiffness because of their consistent composition and lower mechanical properties.

Two global bending stiffness was calculated for each CLT panel, one with the respective G ($EI_{mg,\ s}$) value and the second assumed as infinite ($EI_{mg,\ i}$) like Li et al. (2023) and the global bending modulus of elasticity (E_{mg}) was calculated only by considering the effect of shear. The resulting data is presented in Table 15. The bending stiffness of aspen CLT bonded with 1C-PUR adhesive was determined to be 4.27×10^{11} Nmm^2, whereas ME-bonded CLT was measured to be 4.02×10^{11} Nmm^2. The bending stiffness of poplar CLT panels bonded with 1C-PUR adhesive was determined to be 4.52×10^{11} Nmm^2, whereas CLT bonded with ME adhesive was measured to be 4.11×10^{11} Nmm^2. However, the bending stiffness of spruce CLT panels bonded with 1C-PUR adhesive was determined to be 4.62×10^{11} Nmm^2, whereas, for CLT bonded with ME adhesive, it was measured to be 4.38×10^{11} Nmm^2. The bending stiffness values for hybrid maple-poplar CLT were 7.88×10^{11} Nmm^2 and 7.60×10^{11} Nmm^2, respectively. Global bending stiffness (EI_{mg}) showed a slight variation of around 12% between these two shear modulus values. These results indicate that these variations were not statistically significant, which aligns with the findings reported by Li et al. (2020) and Navaratnam et al. (2020). Furthermore, it was noted that the difference in CLT panels' bending stiffness according to the adhesives was only 5%. The reduced variation within the adhesives was because the material's inherent properties mainly governed the bending performance (Stoeckel et al., 2013).

Table 15: The experimental bending test results of the CLT panels (P-Poplar, A-Aspen, S-Spruce, and M+P- Hybrid maple-poplar)

Specimen	***Global bending stiffness (EI_{mg}) × 10^{11} (Nmm²)*** ***EImg, s***	***EImg, i***	***Global bending modulus of elasticity (E_{mg}) (N/mm²)***	***Bending strength (f_m)(N/mm²)***
P ME	4.43 (4.73)	4.22 (4.79)	7944 (4.8)	31.06 (4.86)
P PUR	4.49 (5.79)	4.27 (5.83)	8359 (5.75)	32.81 (7.77)
A ME	4.22 (4.89)	4.01 (4.97)	7748 (4.91)	28.70 (6.67)
A PUR	4.31 (4.05)	4.09 (4.06)	8413 (4.08)	30.4 (5.95)
S ME	4.63 (4.73)	4.42 (4.79)	7881 (5.11)	29.51 (5.63)
S PUR	4.89 (5.79)	4.67 (5.83)	8336 (6.1)	30.92 (6.19)
M+P ME	7.11 (6.25)	6.88 (6.24)	14436 (6.17)	42.51 (6.67)
M+P PUR	7.38 (5.99)	7.15 (5.79)	15000 (5.78)	44.78 (5.95)

Note: *Parentheses value denotes the coefficient of variation (%)*

Table 16 shows the statistical analysis of how the wood species, adhesives and their interaction affect the bending properties, such as global bending modulus of elasticity and bending strength (E_{mg} and f_m) of the CLT panels. The statistical analysis revealed that the effect of wood species was found to be significant ($p=0.000$) on E_{mg}, f_m while the impact of adhesive was statistically insignificant ($p=0.381$), and the interaction effect ($p=0.637$) of wood species and adhesive was also found to be statistically insignificant.

Table 16: Statistical analysis of the effect of wood species and adhesive on E_{mg} and f_m of CLT panel

Effect	**F value**	**Degree of freedom (df)**	**error**	**p-value**
Intercept	17912.3	2	71	0.00000
Species	117.90	6	142	0.00000
Adhesive	2.06	2	71	0.3810
Species*Adhesive	0.72	6	142	0.63719

The effect of wood species and adhesive type on the global bending modulus of elasticity (E_{mg}) and bending strength (f_m) is shown in Figure 31. The results showed that the E_{mg} of poplar CLT bonded with 1C-PUR and ME was 8359 N/mm², 7944 N/mm², 15000 N/mm^2 and 14326 N/mm^2 for hybrid maple-poplar CLT, and 8336 N/mm^2 and 7881 N/mm^2 for spruce CLT and 8413 N/mm^2 and 7748 N/mm^2 with aspen CLT both 1C-PUR and ME adhesives. Further, spruce CLT's bending strength (f_m) bonded with ME adhesive was 29.5 N/mm^2 and 30.9 N/mm^2. Similarly, the f_m of aspen CLT were reported to be 28.7 N/mm^2 and 30.4 N/mm^{2,} while for poplar CLT were 31.06 N/mm^2 and 32.8 N/mm^2 for both ME and 1C-PUR adhesive respectively. However, the f_m of hybrid maple-poplar CLT was reported to be 42.5 N/mm^2 and 44.8 N/mm^2 for both ME and 1C-PUR adhesive, respectively. The study showed that E_{mg}, f_m of the CLT panels had a negligible fraction of variation (approx. 5%) for both adhesive types. Ma et al. (2021 a) reported similar results with a 5 % variation in hybrid maple-spruce CLT bonded with MF and PRF. However, when considering the lamella configuration, it was noted that incorporating outer maple layers in the hybrid structure resulted in a significant increase of 74% and 37% in the overall E_{mg} and f_m of the hybrid CLT panels, respectively. The resultant increase in the hybrid CLT could be due to the lamellas' anisotropy and inherent wood properties (Li et al., 2020; Ettelaei et al., 2022 b).

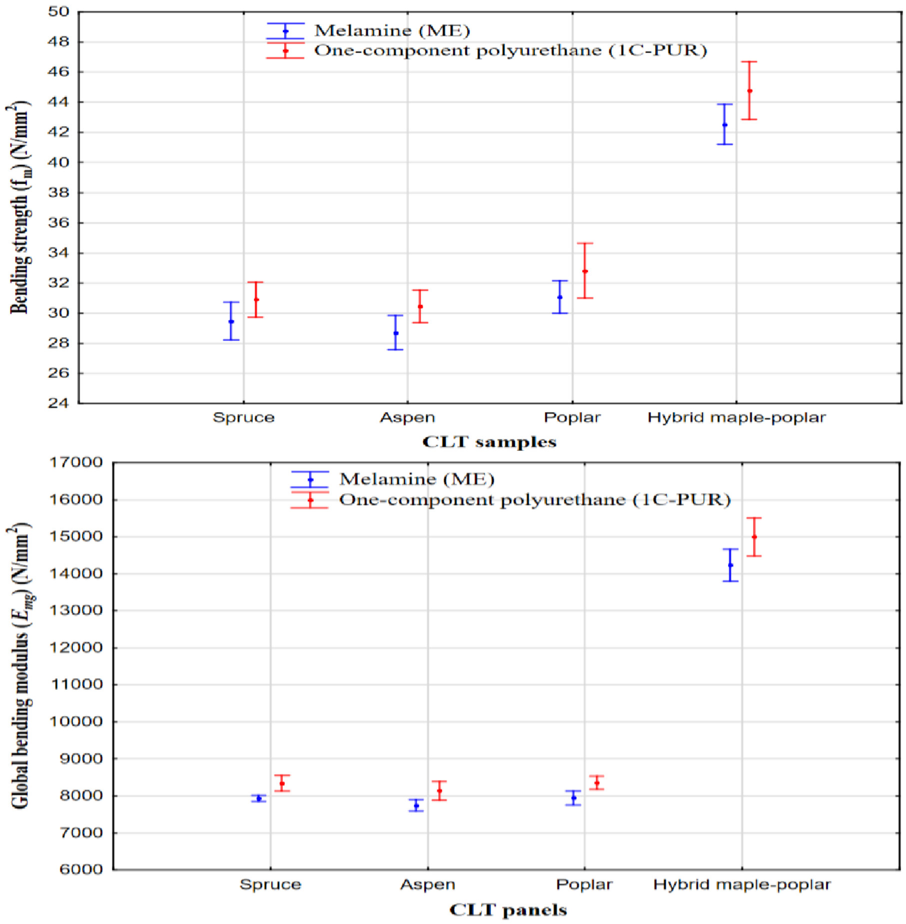


Figure 31: Effect of wood species and adhesive on global bending modulus of elasticity (E_{mg}) and bending strength (f_m) of the CLT panels

Table 17 also compares the results with previously published bending strength (f_m) and modulus of elasticity (E_{mg}) of different wood species. According to ANSI/APA PRG-320 (2019), the E_{mg} of aspen CLT is comparably lower than the E3 grade, but the f_m is higher than the E1 grade; however, in poplar, improved bending performance was observed with E_{mg} higher than the E3 grade and f_m than the E1 grade and higher than the reported results by Kramer et al. (2014). Further, the hybrid maple-poplar CLT showed similar f_m compared to hybrid maple-spruce CLT (Ma et al., 2021 a) and higher than the C24 grade spruce CLT (Franzoni et al., 2016).

Table 17: Comparison of bending strength (f_m) and modulus of elasticity (E_{mg}) of the CLT panels with some reported hardwood and softwood CLTs

Specimens	**E_{mg} (N/mm^2)**	**f_m (N/mm^2)**	**Comments**	**References**
Spruce	8342 - 8655	29.5 - 30.9	E_{mg} > Others	This study
Aspen	7907 - 8183	28.7 - 30.4	E_{mg} < E3, f_m > E1	This study
Poplar	8544 - 8659	31 - 32.8	E_{mg} > E3, f_m > E1	This study
Hybrid maple-poplar	14946 - 15000	42.5 - 44.8	Higher than C24 spruce	This study
Irish Sitka spruce	7584	36.8 - 37.6	Lower E_{mg} than our study	Sikora et al. (2016 a)
Norway spruce	8243	35.2	Lower E_{mg} than our study	Buck et al. (2016)
Beech	12306	43.8		Franke (2016)
Poplar	7356	26		Kramer et al. (2014)
Sugar maple Hybrid maple-spruce	17880 - 18620 22600 - 23900	77.1 - 86.9 43.9 - 46.2		Ma et al. (2021 a, b)
Corsican Pine Hybrid beech-pine	10010 15237	44.98 61.08		Sciomenta et al. (2021)
C24 spruce	10900	50		Franzoni et al. (2016)

5.6. Rolling shear strength

The rolling shear test exhibited similar behaviour to the load vs. displacement curves reported in bending. The impact of adhesive type and wood species on the rolling shear strength (f_r) of CLT panels is depicted in Figure 32. The statistical study revealed a highly significant ($p=0.00$) between the wood species and the adhesive type ($p=0.05$) in the CLT panels' rolling shear strength (f_r). Nevertheless, the interaction of the wood species and adhesive ($p=0.927$) was statistically insignificant. However, it was observed that the f_r of CLT panels bonded with 1C-PUR exhibited a higher value compared to ME-bonded CLT panels. A similar result was previously reported by Sciomenta et al. (2021), who observed a higher f_r in 1C-PUR bonded beech CLT panels compared to MUF-bonded beech CLT panels. The mean f_r in spruce CLT bonded with ME adhesive was reported to be 1.9 N/mm^2 and 2.01 N/mm^2 for 1C-PUR adhesive, while for aspen CLT, the f_r 1.87 N/mm^2 and 2.01 N/mm^2 respectively. However, in the case of hybrid maple-poplar CLT panels, the was recorded as 3.03 N/mm^2 and 3.09 N/mm^2, while for poplar CLT, the values were 2.13 N/mm^2 and 2.17 N/mm^2, respectively, for both adhesives. Ma et al. (2021 b) noted a difference in rolling shear strength between MF and RF-bonded panels. However, they claimed that the wood species primarily caused the variation.

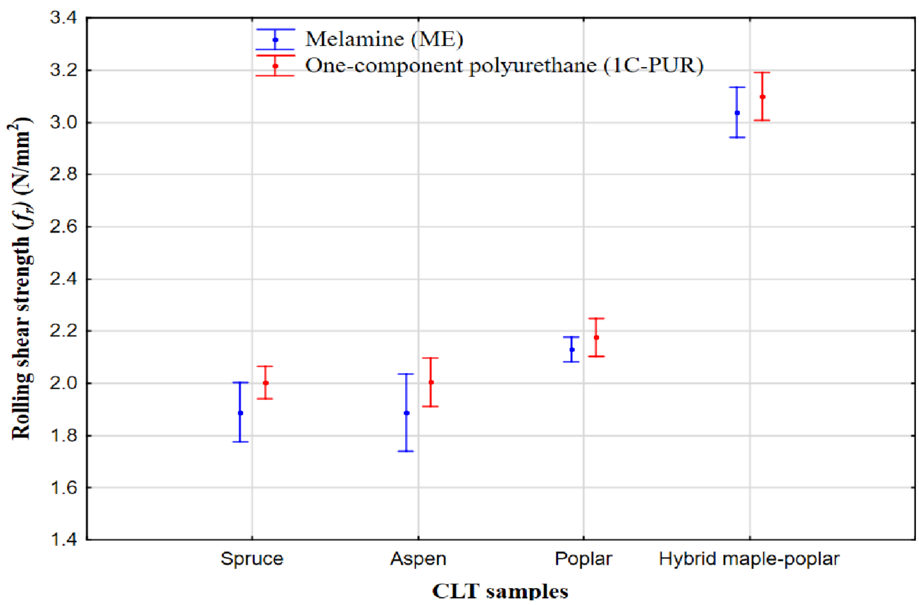


Figure 32: Effect of wood species and adhesive on the rolling shear strength (f_r) of the CLT panels

Previous studies (Gong et al., 2015; Wang et al., 2017) have reported that the softwood CLT panels are susceptible to rolling shear failure due to their comparatively low shear strength in the radial-tangential plane (*RT* plane). This vulnerability primarily arises from the reduced density observed in the earlywood regions of these panels (Niemz et al., 2023). Additionally, the longer wood fibres observed in softwoods have a higher tendency for sliding or shearing along their length than hardwoods (Aicher et al., 2016 b). These characteristics of softwoods primarily contributed to their rolling shear failure and lower rolling shear strength. Furthermore, it was also noted that the shear modulus in the radial-tangential (G_{RT}) plane of softwoods is approximately 10% of the G_{LT}, while around 40% of above G_{LT} in hardwoods (Niemz et al., 2023). Additionally, it has been observed that hardwoods exhibit a greater shear modulus, even when their densities are equivalent to that of softwoods (Ross, 2010). According to the data presented in Table 7, it can be observed that low-density woods such as poplar exhibit a shear modulus (G_{RT}) that is approximately 1.5 times higher than that of spruce. Conversely, high-density hardwoods like maple demonstrate a G_{RT} value nearly 2 times higher than spruce. Moreover, the current design practice in CLT reported a rolling shear modulus (G_{RT}) of 50 N/mm^2. However, Karakoç et al. (2013) observed that this value may decrease to as low as 25 N/mm^2 in the radial-tangential plane. They reported a positive correlation between density and shear modulus (G_{RT}). Because of all this, the reported f_r in spruce CLT was comparatively lower than the homogenous (aspen and poplar) and hybrid maple-poplar CLT. It was further reported that the rolling shear strength of CLT panels can be enhanced by using high-quality boards in the outer lamellae, while the shear modulus and bending strength can be improved by using them in the core (Balasso et al., 2021). Therefore, the current study revealed a significant improvement in the rolling shear strength of hybrid CLT panels by incorporating outer maple lamellas. Additionally, Nero et al. (2022) observed a positive relation between the rolling shear strength and the density of various wood species. Specifically, they observed that *Eucalyptus* CLT exhibited greater rolling shear strength due to its higher density, whereas radiata pine, with its lower density, reported comparatively lower rolling shear strength when compared to *Eucalyptus* CLT. However, Ettelaei et al. (2022 b) and Nero et al. (2022) reported that the core layer is more vulnerable to shear, causing the failures and suggested using wood species with higher shear modulus. Additionally, Gong et al. (2015) reported that adding aspen as a core layer in hybrid CLT panels yielded higher rolling shear strength when compared to birch despite notable differences in density. This outcome was attributed to the higher planar shear modulus or strength-to-density ratio shown by aspen. So, from the results, we can conclude that the increased rolling shear strength observed in the hybrid maple-poplar CLT may be ascribed to the synergistic influence of the high-density outer maple layer and the superior rolling shear capabilities exhibited by the poplar core layer.

The obtained results for both homogenous aspen and poplar and hybrid maple-poplar CLT in our study exceed the specified standard specified values for softwoods (Table 18). The f_r of homogenous aspen and poplar CLT was observed to be higher than that of softwood CLTs such as C24 graded Norway spruce CLT (Franzoni et al., 2016), SPF CLT (Davis et al., 2017), and poplar CLT (Kramer et al., 2014; Hematabadi et al., 2021) and hybrid maple-poplar CLT outperformed red maple CLT (Crovella et al., 2019), hybrid SPF-LSL CLT (Davis et al., 2017), and Australian radiata pine (Li et al., 2020).

Table 18: Comparison of rolling shear strength (f_r) of the CLT panels with some reported hardwood and softwood CLTs

CLT specimens	f_r (N/mm^2)	Comments	References
Spruce	1.9 - 2	Higher than others	This study
Aspen	1.9 - 2.1	Higher than spruce	This study
Poplar	2.13 - 2. 2	Higher than spruce and others	This study
Hybrid maple-poplar	3.05 - 3.12	Higher than spruce and others	This study
Irish Sitka spruce	2.14 - 2.22		O'Ceallaigh et al. (2018)
C24 Norway spruce	1.60		Franzoni et al. (2016)
Norway spruce	1.88		Ehrhart and Brandner (2018)
Poplar	1.80		Hematabadi et al. (2021)
Poplar	2		Kramer et al. (2014)
Australian radiata pine	2.33 - 2.83		Li et al. (2020)
Douglas fir	2.17		Wang et al. (2014)
Red maple	3.00		Crovella et al. (2019)
Hybrid maple-spruce	1.75		Ma et al. (2021b)
SPF Hybrid SPF-LSL	2.03 2.96		Davids et al. (2017)

5.7. Failure modes in bending and rolling shear

Figure 33 depicts the failures observed during the bending and rolling shear test. The observed failure modes of the CLT panels mainly consisted of rolling shear failures in the cross-layer and pure bending failures on the tension side of the panels, as seen in Figure 33 (a). Instances of adhesive bond failures were also discovered inside the CLT panels. Similar failures were also reported by Pangh et al. (2019).

a) RS failure with delamination in core

b) Tensile failure in the bottom lamella

c) RS failure along the width section

Figure 33: Failure modes observed during bending and rolling shear test

Tensile failures in the longitudinal direction may be attributed to defects in the wood fibres, such as knots and other growth faults. Wang et al. (2017) observed that the rolling shear failures in CLT panels occurred perpendicular to the grain and were primarily concentrated between the lamellas. Additionally, these failures were observed to originate in the top and bottom layers of the panels. The occurrence of this failure mode can be attributed to the lower tensile strength of earlywood in the radial direction compared to the tangential direction, as well as the presence of knots in the bottom lamination. These factors have led to failures in non-edge glueing and interface integrity between laminations, as depicted in Figure 33 (b). The failure first occurred near the midpoint of the beam and then propagated towards the supports as the applied load intensified. Nevertheless, it was shown that in hybrid CLT panels, including a poplar core layer, the primary failure mode was identified as rolling shear accompanied by delamination. As the applied load intensified, the prior site of tensile failure occurred in the central region of the lower lamella. The low-density species may not withstand the increasing load in the homogenous CLT panels (spruce, aspen, and poplar). Further, due to the orthogonal lamination in the CLT panels, the core strength of the core layer was lower, which was mainly attributed to the tensile failure at the bottom lamellas, like the findings of Sikora et al. (2016 a) and Hematabadi et al. (2021). Further, due to the non-edge glueing, the increased stress may not be able to get transferred to the nearest lamellas, which may also be attributed to the bottom lamellas' tensile failure. In the case of hybrid maple-poplar CLT, as the applied stress intensified, the inter-laminar adhesion between the maple and poplar layers exhibited signs of deterioration, causing tensile failure in the bottom lamellas. Additionally, it was observed that when the load in the middle of the CLT panels grew, the deflection did, too. As deflection increases, the stress can be transmitted to each supporting end. The increased stress may surpass the bonding strength shown by the CLT panels. The stress experienced in the width portion, as seen in Figure 33 (c), might fail in the supporting end.

5.8. Comparison between experimental data and theoretical data

Table 19 compares the experimental results of EI_{mg}, f_m, and f_r to the theoretically calculated values. The observed global bending stiffness (EI_{mg}) consistently exhibited greater values than all the theoretical bending stiffness values. Sikora et al. (2016 a) and He et al. (2018) reported similar results. The experimental EI_{mg} of homogeneous spruce, aspen, and poplar CLT were around 19% higher than the corresponding theoretical values. Similarly, the hybrid maple poplar CLT showed a 12% higher bending stiffness than its theoretical counterpart. In addition, it is observed that the infinite shear modulus values exhibit a lower degree of variations, precisely 15% and 10%, for both homogeneous and hybrid CLT panels. Li et al. (2020) and Navaratnam et al. (2020) also reported similar results. The infinite shear modulus signifies the extraordinary capacity of the material to resist shear deformation, which allows the material to endure significant shear stress without experiencing any deformation. The utilisation of the specimen's modulus of elasticity (MOE) in the measurement of the theoretical values for bending stiffness indicates that the influence of shear on the stiffness is negligible. However, the reduced variability observed in the hybrid CLT panels may be attributed to variations between the material parameters observed during testing and their corresponding theoretical values (Dong et al., 2021). It is worth noting that the observed

12% variation between the experimental bending stiffness and the theoretically calculated values in the hybrid maple-poplar CLT is consistent with the findings reported by Dong et al. (2021), who reported a variation of 7% in hybrid CLT-bamboo composite panels. Based on the results obtained, it can be shown that the effective bending stiffness $EI_{eff,\ gamma}$, is comparatively lower than $EI_{eff,\ shear}$ and $EI_{eff,timo}$. This finding suggests that including the connection efficiency factor (γ) in the analysis leads to more precise predictions of bending stiffness. Similar results were also obtained by Li et al. (2020) and Ettelaei et al. (2022 a). Nevertheless, both SA and TBM yielded similar bending stiffness values. The decrease in the accuracy of theoretical method analysis could be due to including the shear deformation effects by using the shear modulus (G) as an input parameter (Sikora et al., 2016 a). Moreover, the findings derived from our investigation exhibit superior outcomes compared to those documented by Crovella et al. (2019). The researchers observed that the SA technique yielded bending stiffness predictions around 25% higher than the experimental readings for untested hardwoods, including white ash and red maple when assuming values for the modulus of elasticity (MOE). However, this discrepancy decreased to 15% when using E_0/G_0 values specified in the wood handbook. According to their research, the input modulus of elasticity (MOE) used in the theoretical computation was solely accountable for the theoretical bending stiffness.

Table 19: Comparison of theoretical and experimental stiffness values in terms of percentage of variation

Specimen	**Experimental bending stiffness (EI_{mg}) × 10^{11} (Nmm^2)**		**Variation (%) in SA**		**Variation (%) in MG**		**Variation (%) in TBM**	
	G	$G=\infty$	G	$G=\infty$	G	$G=\infty$	G	$G=\infty$
S ME	4.63	4.42	18	14	20	15	18	14
S PUR	4.89	4.67	22	18	22	20	22	18
A ME	4.22	4.01	17	13	18	14	17	13
A PUR	4.31	4.09	18	14	20	16	18	14
P ME	4.43	4.22	22	17	22	18	22	17
P PUR	4.49	4.27	22	18	23	19	22	18
M+P ME	7.11	6.88	12	10	14	12	12	10
M+P PUR	7.38	7.15	15	13	17	15	15	13

Table 20 reported the bending and shear strengths obtained via experimental test and the equivalent values anticipated through theoretical analysis. The data presented in the study revealed that the bending strength predicted by the theoretical methods was around 4.5% higher compared to the experimental findings. From the table, the bending strength value calculated by SA is higher than both TBM and MG, while MG reported the lowest. These values are comparable with a variation of (<0.5% difference) for all CLT specimens. Similar results were reported by Sikora et al. (2016 a). Conversely, the rolling shear strength was approximately 6.5% lower than the experimental results. Li et al. (2020) reported a marginal variation of 7% between the theoretically predicted rolling shear strength values and the experimental findings. It was further observed that the SA approach showed superior accuracy in predicting bending and shear strength compared to the MG and TBM methods. The observed difference may be mainly attributed to the variations in the theoretically projected bending stiffness values used in the theoretical calculation approach and the impact of the structural characteristics (Li et al., 2020). The results suggest that the theoretical methods have the potential to predict the bending and shear strength correctly.

Table 20: Test results vs. theoretical results for both bending strength and rolling shear strength

Specimen	**f_m from test (N/mm²)**	**Theoretical bending strength (f_m)**			**(f_r) from test (N/mm²)**	**Theoretical rolling shear strength (τ_m)**		
		SA	**MG**	**TBM**		**SA**	**MG**	**TBM**
S ME	29.5	30.76	30.99	30.82	1.9	1.77	1.68	1.71
S PUR	31.2	32.53	32.78	32.60	2.01	1.87	1.77	1.81
A ME	28.7	30.76	30.99	30.82	1.87	1.74	1.63	1.67
A PUR	30.4	32.34	32.58	32.41	2.01	1.87	1.77	1.81
P ME	31.06	32.39	32.63	32.45	2.13	1.99	1.98	1.98
P PUR	32.81	34.25	34.54	34.31	2.17	2.03	2.02	2.02
M+P ME	44.33	46.23	46.63	46.32	3.03	2.83	2.82	2.82
M+P PUR	44.78	46.70	47.05	46.80	3.09	2.89	2.87	2.88

5.9. Results from the FEM analysis

In Figure 34, the contour plots of hybrid CLT and poplar CLT with bearing capacity are displayed with the deflection from the FEM analysis and the load vs displacement graph in Figure 34. Based on the finite element analysis (FEM), it was determined that applying a load of 31240 N resulted in a deflection of 17.263 mm along the y-axis for poplar CLT. In contrast, the experimental average deflection of the CLT panel bonded with 1C-PUR adhesive was 19.11 mm, whereas the deflection seen with ME adhesive was 19.17 mm, representing a 12% increase compared to the finite element method (FEM) prediction. In the case of hybrid maple-poplar CLT, it was seen that the maximum deflection reached 13.49 mm at a load of 43075 N. However, testing results yielded deflection values of 15.02 mm for 1C-PUR glue and 15.14 mm for ME adhesive, representing an approximate 11% increase compared to the values predicted by finite element analysis (FEM). Based on the obtained findings, it is evident that the finite element method (FEM) can accurately predict the breakdown load and displacement of cross-laminated timber (CLT) panels, as shown by a maximum deviation of 12%.

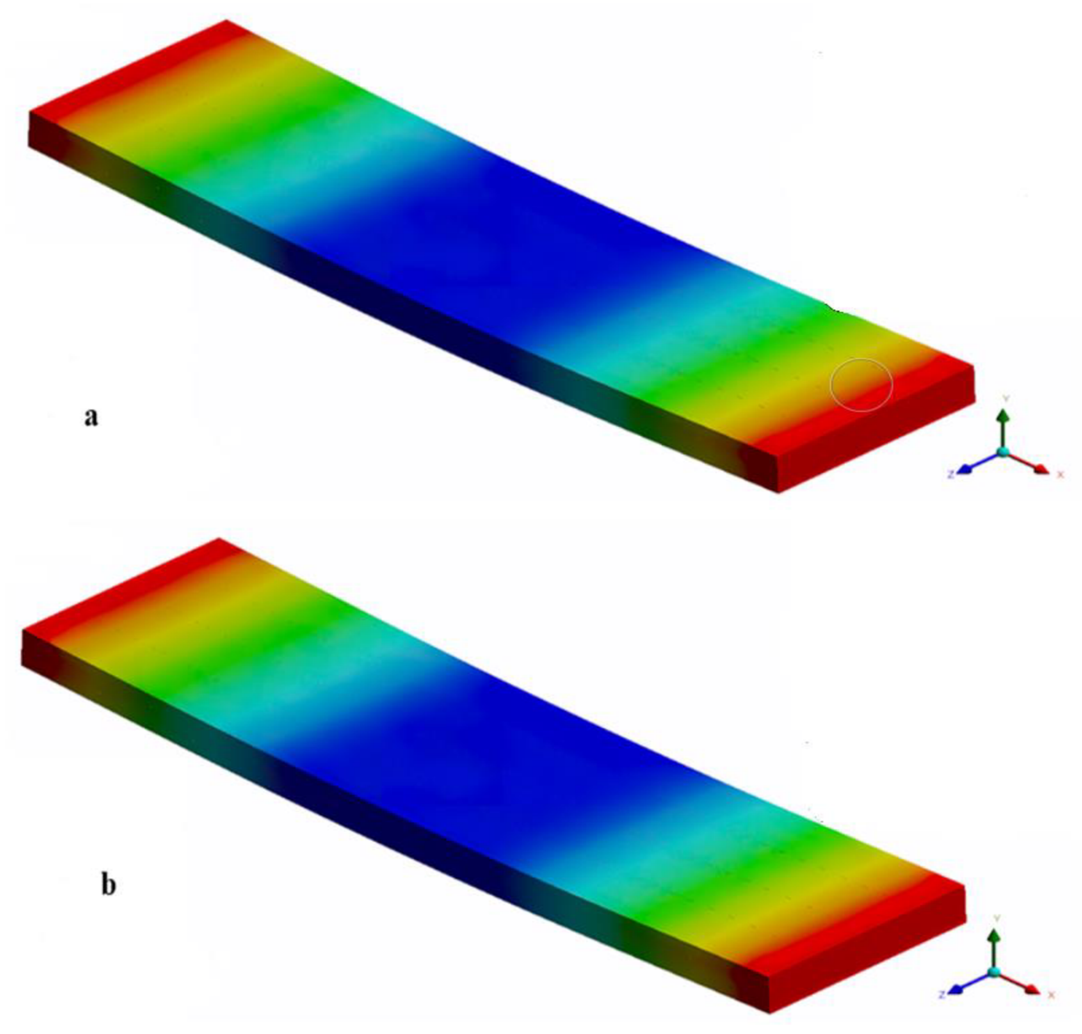


Figure 34: FEM contour plots with defections a) poplar CLT b) hybrid maple-poplar CLT

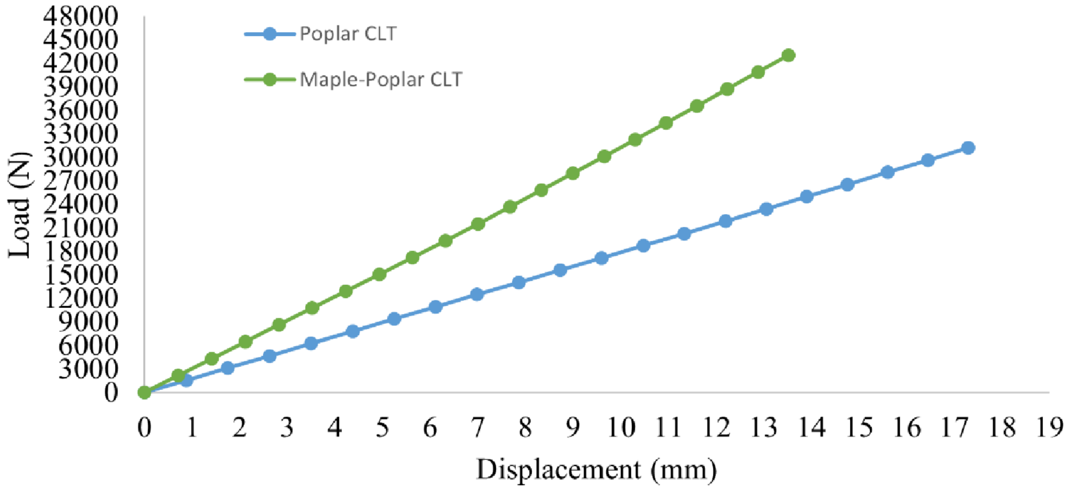


Figure 35: Load vs displacement curves of poplar hybrid maple-poplar CLT from FEM

Additionally, FEM was used to assess how well poplar and hybrid CLT performed in terms of the bending stress, as shown in Figure 36. The presented data illustrates that in both poplar and hybrid maple-poplar CLT, the maximum bending stress was seen in the upper layer experiencing compression, while the lower layer undergoing tension exhibited the highest stress. Conversely, the intermediate layers had the lowest stress levels, consistent with the results of Hematabadi et al. (2021). The bending stress shown by the hybrid cross-laminated timber (CLT) was measured to be 6.5 N/mm^2, whereas the poplar CLT had a bending stress of 3.6 N/mm^2. Furthermore, according to the FEM, all three layers of the CLT played a significant role in withstanding the applied load. Nevertheless, the discrepancy between the experiments' outcomes and the model's predictions may be attributed to the assumptions about the material qualities and the idealised bond assumptions.

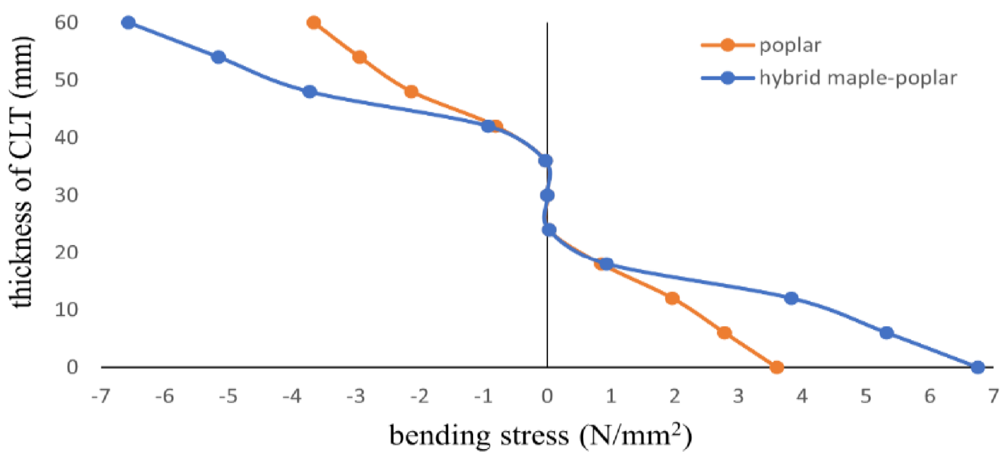


Figure 36: Distribution of bending stress in both poplar and hybrid maple-poplar CLT obtained from FEM

The bending stiffness was computed using the FEM data and confirmed with the appropriate test results. The global bending stiffness of Poplar CLT was determined to be 4.06×10^{11} Nmm^2, exhibiting a variation of about 9% from the experimental value. In contrast, hybrid maple-poplar CLT had a global bending stiffness of 6.07×10^{11} Nmm^2, indicating a deviation of roughly 18% from the experimental value. The lowest variation could result from the model with the assumption that the CLT panels were edge-glued. Similarly, Navaratnam et al. (2020) observed a discrepancy of 20% between the stiffness values given by the Finite Element Method (FEM) and the corresponding experimental findings.

6. Conclusion

This study provides a comprehensive overview of using lower-grade and underutilized plantation-grown hardwoods, such as aspen, poplar, and Norway maple, to produce CLT panels. The investigation evaluates these hardwoods' physical, bonding, and mechanical properties to determine their suitability for CLT panel preparation. Spruce CLT was also prepared to compare the findings of the hardwood CLT panels. The results were compared with those obtained from several scientific investigations conducted on softwood CLT panels of similar densities.

- The water absorption (WA) and thickness swelling (TS) are strongly affected by both the wood species and the manufacturing pressure. The WA and TS values observed in aspen, poplar, and hybrid maple-poplar CLT were relatively higher when compared to spruce CLT. This may be attributed to the higher coefficients of swelling and shrinkage and the increased porosity shown by these wood species. Increased manufacturing pressure (1 MPa) led to a decrease in wood absorption (WA) and tensile strength (TS) due to improved penetration of adhesives into the wood lumen.
- All the homogeneous CLT panels bonded using 1C-PUR adhesive prepared with 1 N/mm^2 pressure successfully passed the delamination test, indicating superior bonding performance. In the case of the hybrid maple-poplar CLT, the 1C-PUR bonding exhibited excellent performance. Nevertheless, it is essential to acknowledge that the hybrid maple-poplar CLT bonded with ME still met the $Delam_{max}$ criterion as recommended by the standard. All CLT panels prepared with 0.6 MPa pressure failed miserably due to inadequate adhesive penetration.
- All CLT panels (homogenous and hybrid) fulfilled the minimum glue line shear strength requirement. However, hybrid maple-poplar CLTs have much higher shear strength than homogeneous CLTs. The ME bonding performance showed a minor superiority over 1C-PUR bonding in all CLT panels, irrespective of the species and composition. Furthermore, the predominant factor leading to shear failure in shear testing was primarily wood failure, constituting over 80%.
- The adhesive type did not significantly affect the global bending stiffness (EI_{mg}), bending strength (f_m), and rolling shear strength (f_r) of CLT panels. However, the different wood species utilized in manufacturing significantly affect them. Both aspen and poplar CLT panels exhibited similar outcomes to spruce CLT

panels. Using maple as the CLT panels' outer layer in hybrid composition with lower grade poplar enhanced bending and shear capabilities.

- Theoretical methods with infinite shear modulus underestimated CLT panel bending stiffness by 19% for homogenous CLTs (spruce, poplar, and aspen) and 12% for hybrid CLT, while 15% and 10% with their shear modulus. The modified gamma (MG) hypothesis predicted the most accurate bending stiffness considering the effect of shear deformation, while shear analogy (SA) and Timoshenko beam theory (TBT) yielded similar bending stiffness values. Neglecting shear with an infinite shear modulus yields the most accurate bending stiffness result. In addition, SA predicted bending and shear strengths more accurately than other theoretical approaches. The variation between the two is around 4.5% in bending strength and 6.5% in rolling shear strength. The bending stiffness can be accurately predicted using the finite element technique, exhibiting a low variation of 9% for homogenous poplar CLT and 18% for hybrid maple-poplar CLT.
- Lower-grade hardwoods like aspen and poplar may be used for CLT manufacture because of their similar qualities to spruce CLT. Furthermore, underutilized Norway maple has the potential to be employed in hybrid form with poplar in the production of CLT. Using any of these three species instead of softwoods will help the economy and save costs.

7. Contributions towards science and practice

The findings of this research were presented at several conferences and published in several publications.

Due to the declining natural forest covers due to many factors such as biological, environmental, and human influences and growing demand for EWPs, it is imperative to explore alternative building materials that can serve as substitutes for conventional concrete and steel. The contributions of the study towards science and practice are as follows.

- This dissertation comprehensively analyses the performance characteristics exhibited by lower-grade poplar, aspen CLT, and hybrid hardwood maple-poplar CLT compared to softwood spruce CLT and CLTs derived from species with similar densities. The results of this study have provided evidence supporting the use of poplar as a viable substitute for spruce in manufacturing CLT panels.
- In addition, the improved performance of the hybrid CLT panels prepared from low-density poplar as the core layer and high-density maple as the outer layer, which are underutilised hardwood species, is another essential finding of this research. The study also suggested using locally grown plantation wood species like alder, walnut, lime tree, acacia, eucalyptus, etc., which can also be effectively utilised in load-bearing structures.
- Policymakers will be encouraged to consider hardwoods as a viable material for CLT production and to incorporate them into the standards because of the findings presented in this dissertation. Furthermore, this may inspire CLT manufacturers to investigate numerous underutilised hardwoods and propose hardwoods as a viable substitute for softwood CLT.
- Furthermore, the pricing of wood-based products like CLT is linked to individual timber species and determined by several market factors. Therefore, while looking for alternate materials, this study can lessen their dependency on softwoods by replacing them with lower-grade and underutilised hardwoods. Additionally, due to the relatively lower cost of lower-grade hardwoods compared to typical softwoods, their utilisation in CLT production is expected to result in a fall in the price of CLT panels. This price reduction would make CLT panels more affordable for customers.

8. Further study and recommendations

This dissertation provides a deeper understanding of underutilised hardwoods such as aspen, poplar, and maple in CLT production bonded with two different structural adhesives like 1C-PUR and ME designed explicitly for CLT, by analysing the physical properties like water absorption and thickness swelling, bonding performance, and bending and rolling shear performance compared to spruce CLT. From the results, the study suggested their practical uses to examine their performance in actual buildings and structures.

- Additional mechanical testing should assess the compression, shear, tension, and performance of metal fasteners such as nails and screws, which are believed to provide higher performance than spruce CLT. Further research on homogeneous aspen, poplar, and hybrid maple-poplar CLT fire performance will expand their border spectrum use.
- The study urges more research on moisture-induced stresses in both poplar and hybrid maple-poplar CLT in indoor conditions, particularly in the heated environment during winters, as the mix of materials can produce cracks and limit load-bearing capability and durability.
- One potential issue of utilising homogenous maple CLT is its weight, which can be attributed to the considerably higher density than softwood species. The study suggested more extensive research to use maple in combination with other softwoods or lower-grade hardwoods, or maple with core with poplar as outer layers, which will present a significant weight reduction compared to panels composed of a single species.

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List of published articles

1. **Das, S.**, Gašparík, M. G., Sethy, A. K., Niemz, P., Lagaňa, R., Kytka, T., Sviták, M., and Kamboj, G. (2023). Suitability of aspen *(Populus tremula* L.) for cross-laminated timber (CLT). *Wood Research*, *68*(3), 502–520.
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