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Feasibility of Using Trembling Aspen Lumber for Structural Wood Products

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EXECUTIVE SUMMARY

In Alberta, black spruce (*Picea mariana*) and lodgepole pine (*Pinus contorta*) dominate softwood lumber production. However, by 2050, reduced Annual Allowable Cuts (AAC) are expected to create a softwood fibre shortage, while hardwood fibres, especially from trembling aspen (*Populus tremuloides*), will be in surplus. Trembling aspen, comprising 81% of Alberta's hardwoods, offers significant untapped economic potential and environmental benefits. This project explored the feasibility of using trembling aspen for structural engineered wood products (EWPs) by analysing its physical and mechanical properties. Lumber from Northern Alberta was sampled to determine its specific gravity (SG), modulus of elasticity (MOE), and ultimate tensile strength (UTS). Based on these findings, prototypes of cross-laminated timber (CLT), glued-laminated timber (Glulam), and wood I-joists were produced. The CLT was tested for bending, shear, rolling shear, and bond performance, while the Glulam and wood I-joists were evaluated for bending performance. Additionally, the yield of the fabricated products was assessed.

Based on the results from this project, the following key findings are noted:

(1) Trembling aspen lumber exhibited 10% to 20% lower MOE and 5th percentile characteristic UTS than those of Spruce-Pine-Fir (S-P-F) lumber, at equivalent grade levels (Select Structural (SS) and No. 2).
(2) Under dry conditions, one-component polyurethane (1C-PUR) and emulsion polymer isocyanate (EPI) adhesives bonded aspen lumber effectively, with median block shear strengths (BBS) of 10.5 MPa (81.7% of wood failure percentage (WFP)) and 10.3 MPa (77.7% of WFP), respectively.
(3) About 40% of trembling aspen lumber met the requirement of 1450f-1.3E machine stress-rated (MSR) lumber grade, while 59% reached the 1200f-1.2E grade.
(4) The oven-dried SG of trembling aspen ranged from 0.40 to 0.46.
(5) Finger-jointing improved trembling aspen lumber mean MOE by 12.4% and the 5th percentile characteristic UTS by 14.0% for No. 2-grade trembling aspen lumber but has minimal effect on SS-grade lumber.
(6) The five-layer trembling aspen CLT surpassed grade E1 mean bending stiffness by 17.8% to 29.8%, with characteristic bending moment resistance showing a 4.3% decrease in major-strength and a 73.7% increase in minor-strength. The three-layer CLT nearly met grade E1 mean bending stiffness but fell 22.4% short of the characteristic bending moment resistance for grade E1.
(7) Trembling aspen CLT exhibited the mean rolling shear modulus of 106 MPa and characteristic strength of 0.76 MPa.
(8) Trembling aspen CLT could not meet the requirement of PRG-320 standards for bond performance, fallen 26.9% short of the required limit 80% WFP considering both dry and vacuum-pressure-soak conditions, further confirmed the challenge of achieving durable adhesives for trembling aspen.
(9) Trembling aspen glulam, with target grade of “20f-E Spruce-Pine”, met CSA O86 requirements, with the mean MOE exceeded the standard by 16.4% and the characteristic MOR by 1.2%.
(10) The mean bending stiffness of the wood I-joist exceeded the grade “PKI-35 PLUS-10” requirements by 25.4% and surpassed the characteristic Mr by 24.0%.
(11) Reasonable yields were achieved for selected EWPs evaluated in this study. However, it was noted that quality of trembling aspen logs varies significantly depending on harvest location, age of trees and other factors.

Overall, this study showed that even though trembling aspen lumber properties are in general inferior to those of S-P-F lumber of the same grade category, with the use of proper lumber sorting procedure, such as MSR machine and longitudinal stress wave device, trembling aspen EWPs with performance level similar to those fabricated with S-P-F can be achieved.

Further works are recommended in the following areas:
(1) Collaborating with adhesive manufacturers to identify structural adhesives suitable for bonding hardwoods, particularly trembling aspen.
(2) Expanding the current work to fabricate a broader range of glulam, CLT and wood I-joist grades and sizes, to further support the use of trembling aspen lumber in producing these products in Alberta.

(3) Developing a broader database of structural properties of trembling aspen lumber, including shear strength, compression perpendicular to grain strength and connection strength.

Keywords: Trembling aspen, lumber, physical properties, mechanical properties, bond performance, cross laminated timber, glulam, wood I-joists.

Acknowledgements

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1. INTRODUCTION

Wood, as a natural, sustainable, and renewable bio-composite material, has been integral to construction for centuries (Gong 2021). These factors have driven the demands for use of wood in construction. Technological advancements have led to the development of modern engineered wood products (EWPs), which are now widely utilized in construction, further boosting demand (Panshin & de Zeeuw 1981, Van Acker 2021). In North America, softwoods are favoured in construction due to their abundance, excellent mechanical properties and machining properties. In Alberta, black spruce (*Picea mariana*) and lodgepole pine (*Pinus contorta*) are the primary softwoods for lumber production. Alberta Innovates reports the current annual allowable cut (AAC) at 19 million m³ for softwoods and 13 million m³ for hardwoods, with actual harvests at 14.5 million m³ and 6.5 million m³, respectively. By 2050, AAC reductions to 13.6 million m³ for softwoods and 10.4 million m³ for hardwoods are expected due to natural forest disturbances and wildlife habitat management, potentially leading to a softwood fibre shortage. To meet the growing demand for forest products, fast-growing species are being considered as a viable solution for future supply needs (Balatinecz & Kretschmann 2001).

The term "Aspen/poplar" encompasses a group of hardwood species within the genus *Populus*, including Trembling Aspen (*Populus tremuloides*), Bigtooth Aspen (*P. grandidentata*), Balsam Poplar (*P. balsamifera*), Eastern Cottonwood (*P. deltoides*), and Black Cottonwood (*P. trichocarpa*) (Balatinecz and Kretschmann 2001). Widely distributed across the northern hemisphere, *Populus* species are notable for their rapid growth, with studies indicating that hybrid aspen achieves an average diameter growth rate of 10 to 14 mm per year between the ages of 10 and 20 (Heräjärvi and Junkkonen, 2006). They are also recognized for their ease of asexual reproduction and diversity, offering significant utility among temperate trees (Dickmann et al. 2001). However, these trees are also characterized by short fibres, susceptibility to moisture, rapid decay, and a relatively short lifespan of about 50 to 60 years (Perala et al. 1990). They typically range from 12 to 18 m in height, with occasional growth up to 30 m, and diameters generally between 20 to 25 cm, rarely exceeding 60 cm (Hosie 1979). Due to their rapid growth and decay susceptibility, *Populus* should be managed on a short rotation. Take trembling aspen as an example, by rotation age of 55 years, trembling aspen may show a gross merchantable volume of 300 m³ per hectare with a reject rate of 7.9%, whereas black spruce at a rotation age of 105 years shows a volume of 250 m³ per hectare with a reject rate less than half that of trembling aspen (Morley 1986). Historically, *Populus* species have been a primary resource for oriented strand board (OSB) and pulp production (Surmiński 1976, McKeever and Spelter 1998, Youngquist and Spelter 1990).

Despite their abundance, fast-growing *Populus* species are often considered weeds (Balatinecz and Kretschmann 2001). To ensure the planting of softwoods for scientific forestry management, the industry also harvests *Populus*. In this competitive market, the challenge lies in effectively utilizing these resources. Developing high-value EWPs from *Populus* is a necessary approach to improve the current forestry market structure and enhance its economic value. According to Alberta's forestry resource data from 2021, hardwoods constitute 40% of Alberta's total forest volume. Of this hardwood volume, approximately 81% is trembling aspen and 15% is balsam poplar, together comprising 96% of the hardwoods, with the remaining 4% consisting of other hardwood species (Alberta Forest Economy 2021). It is evident that Alberta has a rich reserve of *Populus* resources. If utilized effectively, these resources can significantly enhance the economic value of Alberta's forestry sector. The study and utilization of *Populus* continue today, driven by tradition and the development of new-generation EWPs. By capitalizing on their advantages and addressing their weaknesses, *Populus* species have proven to be suitable building materials. This report primarily focuses on testing and comparing trembling aspen lumber, which constitutes the largest proportion of Alberta's *Populus* resources.

The primary objective of this study is to assess the potential of using the under-utilized, fast-growing species, trembling aspen in the manufacturing of lumber-based EWPs for structural applications. The findings will aid the wood industry in Alberta in making informed business decisions regarding the potential production of these products within the province. The key project objectives are as follows:

(1) To evaluate the major physical, mechanical and bond properties, and grade yield (including visual grading and machine grading) of trembling aspen lumber.
(2) To sort trembling aspen lumber in sawmills and industries based on the developed sorting criteria, and fabricate prototypes of CLT, glulam, and wood I-joists.
(3) To evaluate the structural performance and the product yield of the aforementioned EWPs.

This project consisted of two (2) phases of research, as illustrated in Figure 1.

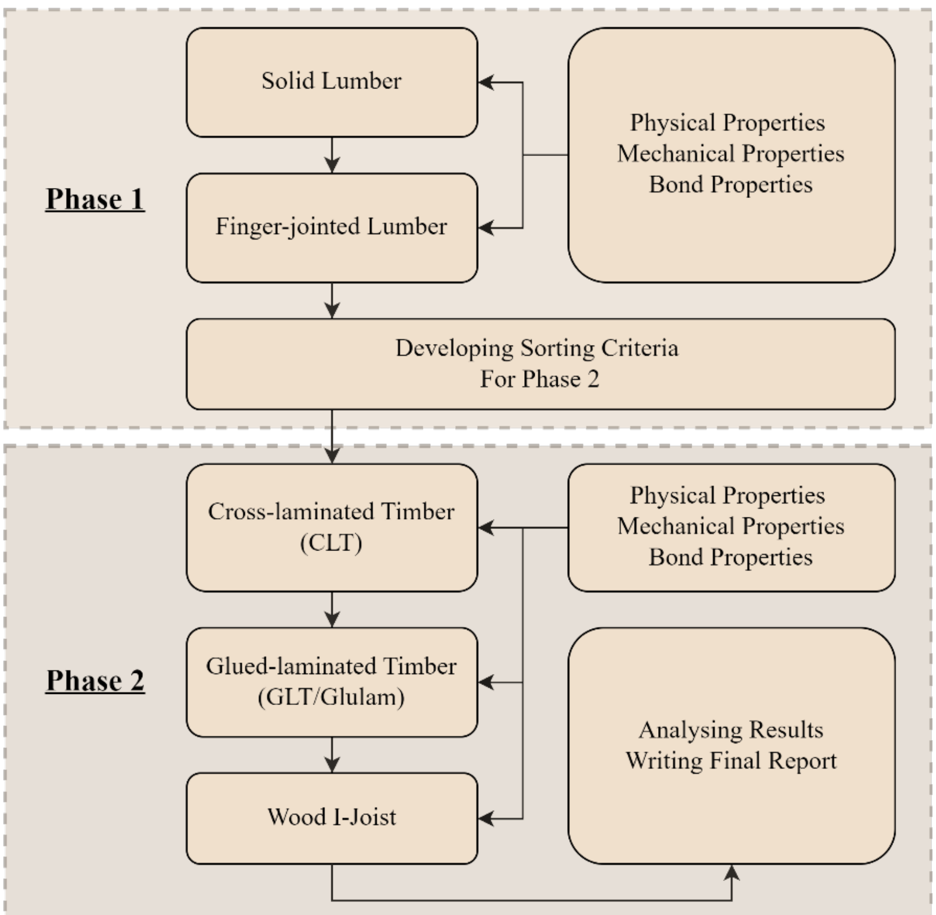


Figure 1 - Flowchart of Research Program.

2. EVALUATION OF TREMBLING ASPEN LUMBER PROPERTIES

2.1. Materials and Sampling

In this study, 38 mm × 89 mm trembling aspen lumber was used, which was supplied by a sawmill located in the Hines Creek, Alberta as shown in Figure 2a. A total of 368 pieces were sampled, which were divided into two bundles in terms of the visual grades, selected structural (SS) and No. 2, of three lengths (2,438 mm, 3,048 mm, and 3,658 mm), as shown in Table 1. These trembling aspen lumber pieces were sawn from the logs of an average diameter of 215.9 mm (8.5 inches) at the small end. All of the lumber was kiln-dried at a temperature of 95 °C for 96 hours until reaching the target moisture content (MC) of about 16%. The lumber was graded in accordance with "Standard Grading Rules for Canadian Lumber" (NLGA 2019) by an inspector from the Alberta Forest Products Association. All of the lumber specimens were wrapped and shipped to the Wood Science and Technology Centre, University of New Brunswick, Fredericton, Canada, for further conditioning (see Figure 2b), testing and analysis of their properties. It should be pointed out that the SS-grade 2,438 mm (8-foot-long) lumber was planned for making finger-jointed lumber, so the ultimate tensile strength (UTS) was not tested, but the modulus of elasticity (MOE)s of the lumber was tested in this study.

Figure 2 - (a) Trembling aspen lumber sampling in Hines Creek, AB; (b) Lumber conditioning in Fredericton, NB.

Table 1 - Dimensions and quantity of the trembling aspen lumber sampled at Hines Creek, Alberta.

Dimensions						Quantity (Pcs.)	
Length		Width		Thickness		SS-grade	No. 2-grade
foot	mm	inch	mm	inch	mm		
8	2,438	3.5	89	1.5	38	39	-
10	3,048	3.5	89	1.5	38	49	-
12	3,658	3.5	89	1.5	38	80	200

Note: "-" refers to no data.

2.2. Lumber Testing

2.2.1. Evaluation Procedures

The flowchart in Figure 3 shows how each piece of lumber was processed and tested in this test program.

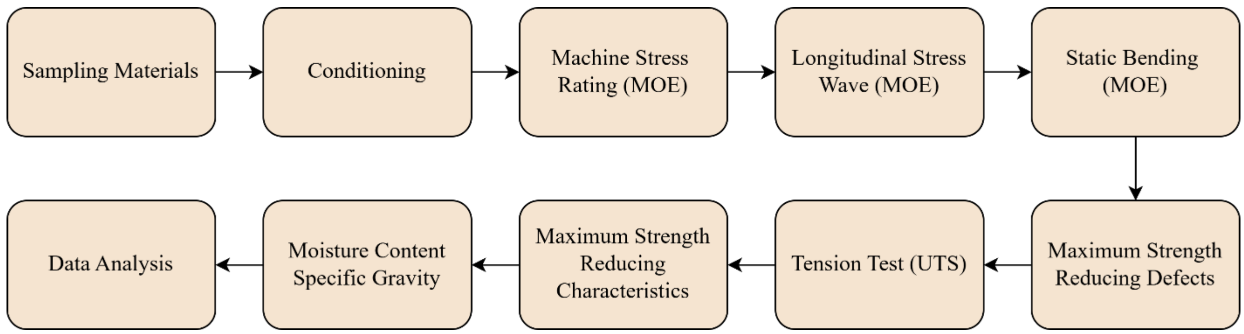


Figure 3 - Evaluation procedures.

2.2.2. Modulus of Elasticity (MOE)

Three non-destructive evaluation (NDE) methods were employed to measure the MOE of each lumber piece with different purposes for this research program, including the machine stress rating (MSR), longitudinal stress wave (LSW), and edgewise third-point bending (EWB) tests. The MSR testing was conducted using a "Cook-Bolinder" machine (model: Tecmach Limited Stress Grading Machine System SG-AF), Figure 4a. The MSR machine applies a point load on the flat face of the lumber to provide MOE along the pieces with the mean, maximum, and minimum values (Boström 1994). The MSR results were used to analyse the grade yield in this study. A commercial handheld stiffness grading device (model: MTG-820), developed by Brookhuis (Enschede,

The Netherlands) and TNO (Delft, The Netherlands), was used for testing the average MOE of each lumber piece (see Figure 4b). This device recorded the stress wave speed and attenuation in each piece to receive the signal in terms of the natural frequency of the lumber under longitudinal vibration (Ross and Pellerin 1994, Oscarsson et al. 2010, Biechele et al. 2011), which can be used to calculate the MOE as shown in Equation (1),

$$MOE_{LSW} = 4\rho \cdot \left(\frac{f_n l}{n}\right)^2 \tag{1}$$

where ρ = density (kg/m^3), n = mode number, l = length (mm), and f_n = n^{th} natural frequency under longitudinal vibration (Hz). This method was subsequently used for the on-site sorting of the lumber in this research program.

The EWB test (see Figure 5a), with two load points positioned at each of the one-third points along the span, was conducted on the lumber according to ASTM D198 (ASTM 2022) as the reference MOE for the lumber. The testing span-to-depth ratio was set at 17, with a test span of 1,513 mm. The loading speed was 3 mm/min. Each test was terminated when the load reached 2 kN. The mid-span deflection was measured by two 50 mm linear variable differential transformers (LVDTs) on each side. The Forintek In-Grade Lumber Testing Procedure (Barrett and Hejja 1984) was followed in this study (see Figure 5b). This procedure is designed to standardize the testing of in-grade lumber and provide a more accurate representation of the mechanical properties of full-size lumber in Canada. The maximum strength-reducing defect (MSRD) of each lumber piece was identified, and its position in the test span was randomly selected. The MC of each piece was measured and recorded using a moisture meter (model: Wagner Orion 950) prior to testing.

(a) (b)

Figure 4 - (a) MSR machine (model: Tecmach Limited Stress Grading Machine System SG-AF) grading test; (b) Longitudinal stress wave (model: MTG-820) test.

(a)

(b)

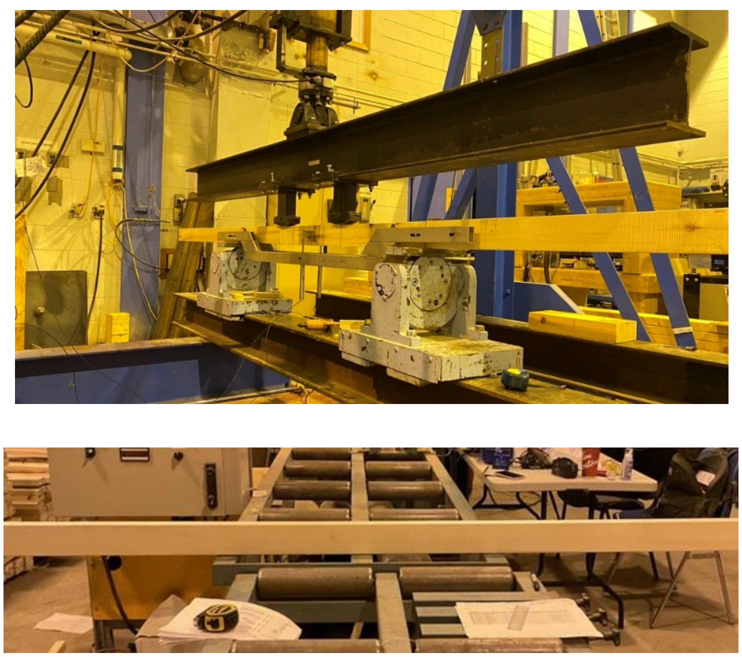
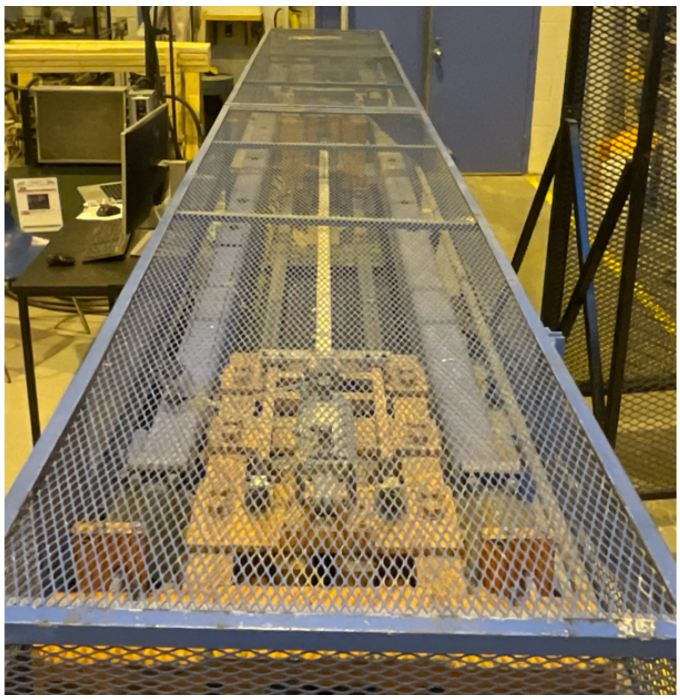


Figure 5 - (a) Static EWB test set-up (model: Instron Universal Testing Machine); (b) Maximum strength reducing defect (MSRD) recording.

2.2.3. Ultimate Tensile Strength (UTS)

The axial tension test was conducted on the lumber in accordance with ASTM D198 (ASTM 2022) using the Metriguard Testing Machine (model: Metriguard 401) (see Figure 6a). The testing span varied due to the different lengths of the specimens used, ranging from 1,829 mm to 2,438 mm (6 to 8 feet). Each grip was fixed at a length of 610 mm (2 feet). A loading rate of 10 kN/min was set, allowing for specimen failure at least in approximately 4 minutes. The visually captured MSRD was positioned within the span and as close to the centre as possible. The failure load and modes were recorded immediately after each test, while the failure load and maximum strength-reducing characteristics (MSRCs) were measured (see Figure 6b) following the "Forintek In-Grade Lumber Testing Procedure" (Barrett and Hejja 1984). The MSRC measurement aimed at documenting the failure location and modes, and to identify the correlations between the maximum defects based on the MSRDs and the strength.

(a)



(b)

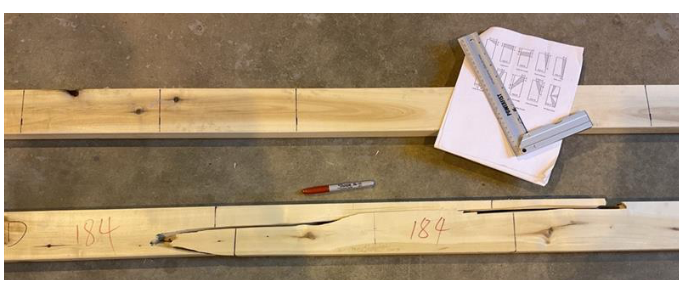


Figure 6 - (a) Axial tension test (model: Metriguard Testing Machine, Metriguard 401); (b) Maximum strength reducing characteristics (MSRC) recording.

2.2.4. Adhesive Bond Performance

The adhesive bond performance of trembling aspen lumber was evaluated based on the block shear strength (BSS) (Figure 7a), and the wood failure percentage (WFP) (Figure 7b, with dark areas representing adhesive). MATLAB software was used to grayscale the images, calculate the optimal binarization threshold, and determine black-and-white pixel proportions to measure the WFP accurately. Two adhesives were tested, a one-component polyurethane (1C-PUR) and emulsion polymer isocyanate (EPI) adhesive.

The block-shear test specimen dimensions were 50 mm (length) × 50 mm (width) × 38 mm (depth). The aspen lumber, from which the specimen blocks were cut, was conditioned at 23°C and 65% RH for one month until reaching a MC of 10-12%. The lumber was then planed to a thickness of 19 mm. For the 1C-PUR adhesive, a primer was applied at 1 to 3 g/ft² in a 9 wt% water solution, following the manufacturer's guidelines. After 15 minutes of drying, 1C-PUR was applied at 26 g/ft², and a pressure of 1.03 MPa (150 psi) was applied within a 45-minute open time, followed by a 24-hour curing period. For the EPI adhesive, a mixture of 16 parts crosslinker to 100 parts EPI resin was prepared in 3 minutes. The spread rate, pressure, and curing time were consistent with those for 1C-PUR, in accordance with CSA O112.9 (CSA 2021).

The variations in the wood block shear test involved specimen conditions and press times. Both dry and vacuum-pressure-soak conditions, as well as minimum and maximum press times, were applied for comparison, as detailed in Table 2, in accordance with CSA O112.9 (CSA 2021).

Figure 7 – (a) Block-shear test setup; (b) A wood failure percentage (WFP) analysis specimen.

Table 2 – Block shear test matrix for two types of adhesive.

Adhesive	Count	Press time	Condition	Specimen code
1C-PUR	15	115 min (Minimum)	Dry	PUR-115-Dry 1~15
	15		Vacuum-Pressure-Soak	PUR-115-VPS 1~15
	15	240 min (Maximum)	Dry	PUR-240-Dry 1~15
	15		Vacuum-Pressure-Soak	PUR-240-VPS 1~15
EPI	15	60 min (Minimum)	Dry	EPI-60-Dry 1~15
	15		Vacuum-Pressure-Soak	EPI-60-VPS 1~15
	15	120 min (Maximum)	Dry	EPI-120-Dry 1~15
	15		Vacuum-Pressure-Soak	EPI-120-VPS 1~15

2.2.5. Moisture Content (MC) and Specific Gravity (SG)

After the axial tension testing, a defect-free 25.4 mm thick (1 inch) wood block for each lumber piece was cut near the location of failure for the determination of the MC and the oven-dried specific gravity (SG), following ASTM D4442 (ASTM 2020).

2.3. Results and Discussion

2.3.1. Physical Properties of Trembling Aspen Solid Lumber

The statistics of the different grades, lengths, MCs, and SGs are summarized in Table 3. The average MC of the trembling aspen lumber at testing was about 7.0%, and the average SG across all groups was approximately 0.40. It can be noted that the average SG of the trembling aspen lumber in this study was about 3.5% larger than the value published in the Wood Handbook (the value from the Wood Handbook was adjusted from green to oven-dried for comparison) (Senalik and Farber 2021, Stamm 1964). The MC of each lumber piece at testing was used to convert the MOE and UTS values to those at an MC of 15% following the ASTM D1990 procedure (ASTM 2019) for further data analysis.

Table 3 – Physical properties (MC and SG) summary of the trembling aspen lumber tested.

Grade	Length (mm)	Index	MC (%)	SG
SS	2,438	Count	39	39
		Mean	8.3	0.43
		COV (%)	13.5	7.4
	3,048	Count	49	49
		Mean	7.5	0.41
		COV (%)	8.5	8.5
	3,658	Count	80	80
		Mean	7.4	0.41
		COV (%)	4.4	6.9
No. 2	3,658	Count	200	200
		Mean	7.0	0.42
		COV (%)	7.3	8.9

Note: "COV" stands for coefficient of variation.

2.3.2. Modulus of Elasticity

The mean MOE values of the trembling aspen lumber measured by the three methods are presented in Figure 8, ranging from 8,032 MPa to 10,673 MPa. The values of the SS-grade lumber are all higher than those of the No. 2-grade lumber, with the MSR showing the biggest difference and the LSW having the least difference. The F-test at the 95% confidence level revealed a significant difference in the MOE results obtained by these three NDE methods.

It should be pointed out that all of the MOE values measured in this study were in good agreement with those in other studies. Green and Evans (1987) conducted the North American In-Grade Testing Program on 38 mm × 89 mm aspen–

cottonwood lumber and found that the species had a mean MOE of 9,860 MPa for the SS-grade lumber and 8,818 MPa for

No.2-grade lumber at an MC of 15%. According to the American Forest & Paper Association (AF&PA) (American Forest & Paper Association 2018), the mean MOE of the aspen was measured at 7,584 MPa for the SS-grade lumber and 6,895 MPa for the No. 2-grade lumber at the MC of 12%. Kretschmann et al. (1999) found that the 38 mm × 89 mm SS-grade and No. 2-grade hybrid poplar had a mean MOE of 9,700 MPa and 8,700 MPa, respectively, at a MC of 11%. The Wood Handbook (Senalik and Farber 2021) presents a mean MOE value of 8,100 MPa at the MC of 12% for trembling aspen.

The statistical analysis revealed that the MOE measured by the MSR machine had a stronger linear correlation with those measured by the EWB method ($r = 0.82$) compared to the MOE measured by the LSW device ($r = 0.68$). This indicates that the MSR machine provided MOE measurements that were more closely aligned with the EWB method. The linear regression model was also conducted among the three methods. Figure 9 illustrates the relationship of the mean MOE values measured between the LSW/MSR and EWB methods. The blue line represents the 1:1 line. This analysis further demonstrated the comparative alignment of the MOE measurements obtained from the different testing methods. Although both R^2 values were high, the MOE values tested by the MSR showed a better fit with the EWB method ($R^2 = 0.67$) compared to the LSW ($R^2 = 0.46$), indicating that the MSR provided a more accurate MOE model than the LSW. The results of the LSW/MSR tests were consistently higher than those obtained from the EWB. The MSR machine measures the MOE of each piece of lumber at an interval of 100 mm. This produces an MOE profile along the length of a piece of lumber, from which the mean, maximum, and minimum MOE values can be extracted. The information on the minimum MOE generally corresponds to the location of strength-governing defects, such as knots. Therefore, it could be used as an indicator for the crosscutting of defects, most likely the MSRC, during the fabrication of finger-jointed lumber. The LSW technique was applied to lumber grading in this research program with the aim of pre-sorting the trembling aspen lumber based on the average MOE.

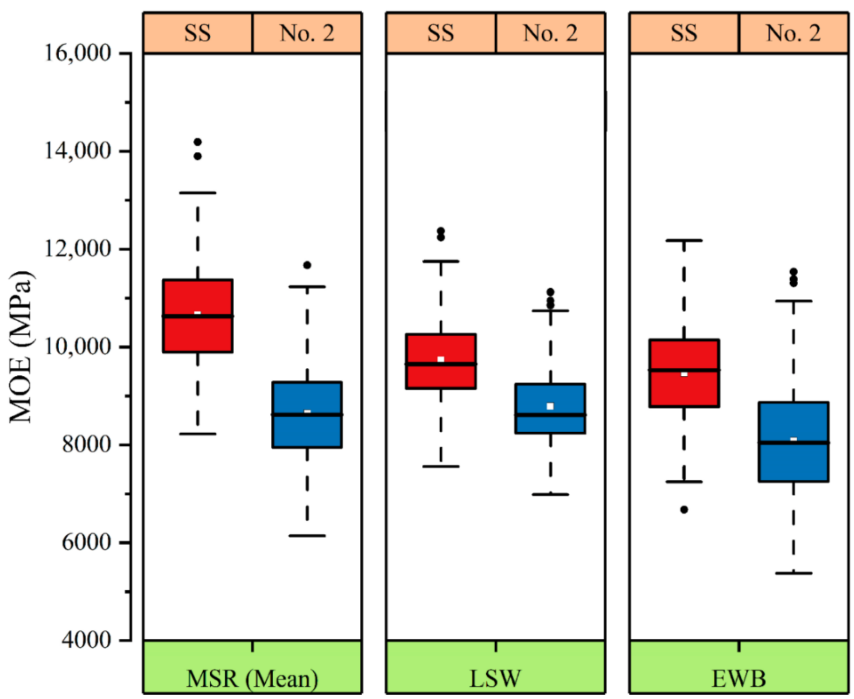


Figure 8 - Mean MOE values between the two grades (SS-red, No. 2-blue) of three NDE methods used in this study.

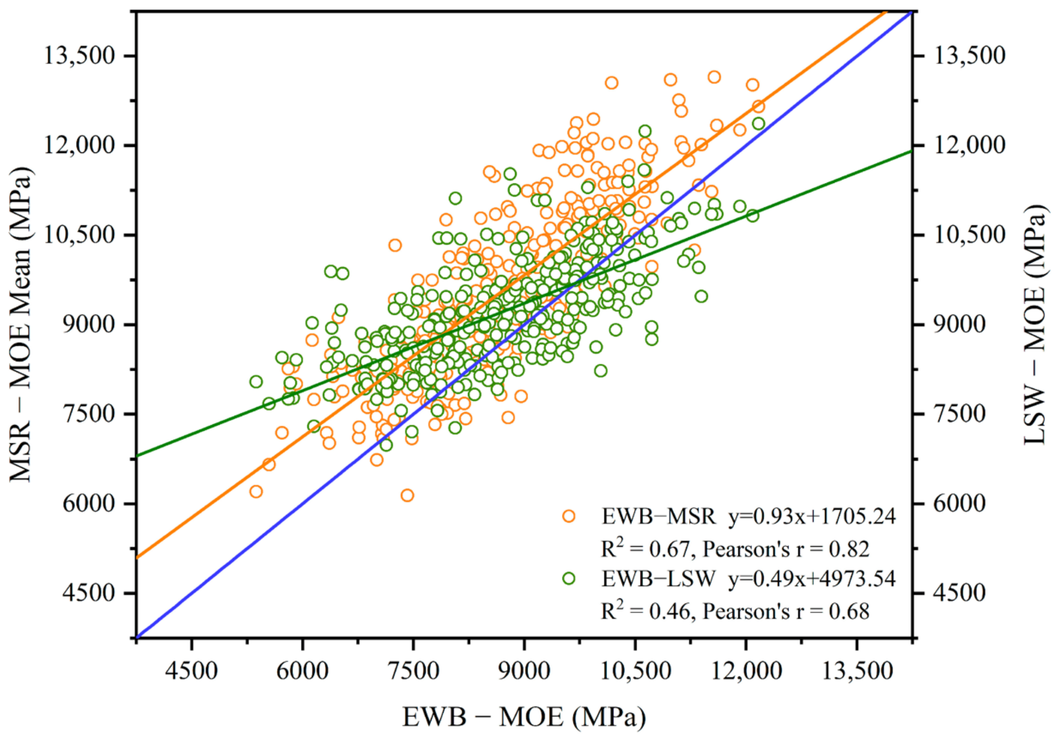


Figure 9 – Plot of EWB-MOE versus LSW-MOE (green) and EWB-MOE versus MSR-MOE (orange). (Blue is 45-degree line).

2.3.3. Ultimate Tensile Strength and Failure Modes

The tension test results are summarized in Table 4. It can be seen that the SS-grade lumber has a mean UTS of 25.40 MPa, which is approximately twice as high as the mean UTS of the No. 2-grade lumber at 13.12 MPa, with a relatively low coefficient of variation (COV).

It should be pointed out that those pieces, which were broken within the machine grips, were culled from the data analysis, resulting in a rejection rate of about 12% for each group. Figure 10 presents scatter plots of UTS versus LSW-MOE and UTS versus MSR-MOE_{min}. Since MSR-MOE_{min} is closely associated with strength-reducing characteristics, such as knots, while LSW represents the properties of the whole lumber piece, it is expected that MSR-MOE_{min} would have a stronger linear relationship with UTS, as depicted in Figure 10. The higher Pearson's r-value of 0.73 for MSR-MOE_{min} supports this assumption, compared to the Pearson's r-value of 0.58 for LSW-MOE. This also indicates a high R^2 value for both methods in relation to UTS, suggesting that both methods are reliable predictors of the UTS of trembling aspen lumber.

According to the MSRC, the same proportion of failure locations as predicted by the MSRD was 43.9% for the SS-grade lumber and 58.6% for the No. 2-grade lumber, respectively. The failure modes of both the SS-grade and No. 2-grade trembling aspen lumber were mainly observed at the knot location during the axial tension testing, suggesting that strength of the trembling aspen lumber could be reasonably predicted based on knot.

Table 4 - UTS test results.

	SS-Grade	No. 2-Grade
Count (Pcs.)	114	174
Failure at MSRD (Pcs.)	50	102
Reject (Pcs.)	15	26
Mean UTS (MPa)	25.40	13.12
COV (%)	38.42	42.32

Note: "MSRD" stands for maximum strength reducing defects.

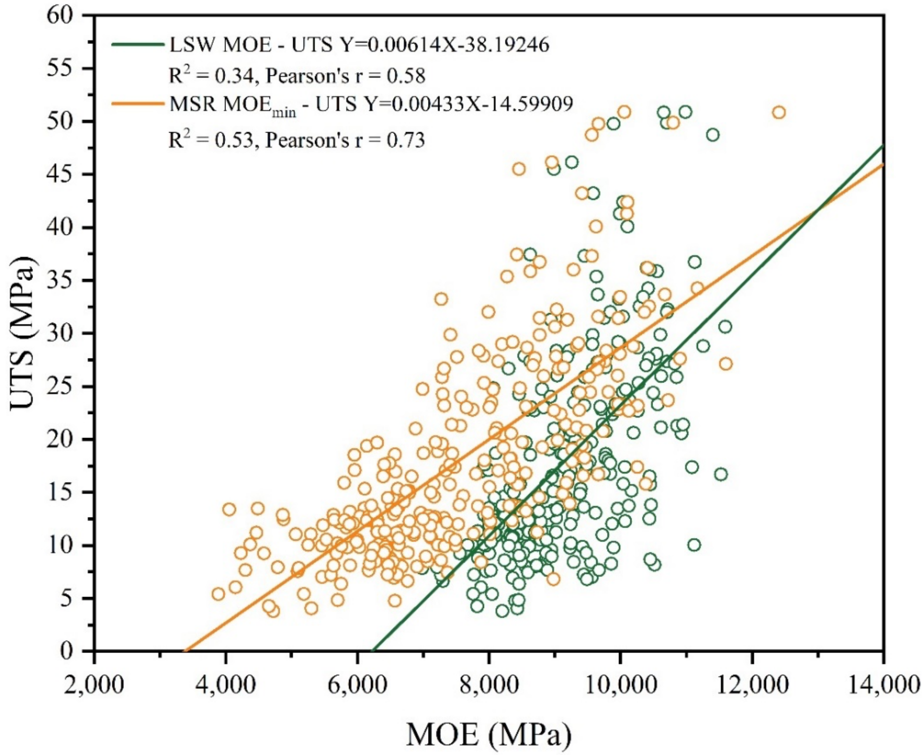


Figure 10 – Plot of UTS versus LSW-MOE (green) and UTS versus MSR-MOE$_{min}$ (orange).

2.3.4. Block Shear Strength (BSS) and Wood Failure Percentage (WFP)

Table 5 shows the mean and median BSS values from the block shear tests. The median values across all groups did not meet the CSA O112.9 standard for hardwoods. The maximum difference in mean BSS between the recommended curing times was 3.3% for PUR and 5.3% for EPI. The COV of mean BSS under VPS condition was higher than under dry condition for both adhesives. EPI had the lowest COV under dry conditions at 2.99%. Table 6 lists the minimum WFP required by CSA O112.9 for hardwoods, marked as a reference line in Figure 11 for comparison.

Table 5 – Block shear strengths of aspen lumber adhesive joints and corresponding CSA O112.9 requirements.

Condition		Press Time (minutes)	Mean BSS (MPa)	Median BSS (MPa)	CSA O112.9 Median BSS Requirement (MPa)
PUR	Dry	115	10.3 (8.22%)	10.0	≥19
		240	10.3 (9.35%)	10.5	
	Vacuum-Pressure-Soak	115	5.8 (16.74%)	5.9	≥11
		240	6.0 (12.75%)	5.6	
EPI	Dry	60	9.7 (3.60%)	9.7	≥19
		120	10.2 (2.99%)	10.3	
	Vacuum-Pressure-Soak	60	5.7 (10.77%)	5.9	≥11
		120	5.4 (24.18%)	5.8	

Note: The value in paratheses stands for the coefficient of variation.

Table 6 – Percent wood failure requirements (Data extracted from standard CSA O112.9).

Test Condition	Hardwood	
	Lower quartile* (%)	Median† (%)
Dry	15	60
Wet	55	80

* At least 75% of the specimens shall have a percent wood failure greater than or equal to the lower-quartile value specified in this table.
† At least 50% of the specimens shall have a percent wood failure greater than or equal to the median value specified in this table.

Figure 11 displays box plots representing the WFP for all groups, with the boxes indicating data between the 25th and 75th percentiles. According to the lower-quartile requirements outlined in Table 6, all groups met the criterion of having at least 75% of the sample data above or equal to the lower-quartile threshold, except for the PUR adhesive cured for 240 minutes under VPS condition, which did not meet the wet condition requirement. Regarding the median requirements, all samples tested under dry conditions met the standard, whereas PUR at 240 minutes and EPI at 60 minutes under VPS conditions did not. Overall, given that BSS did not meet the standard requirements, further research is recommended to develop adhesive formulations suitable for hardwoods, specifically trembling aspen.

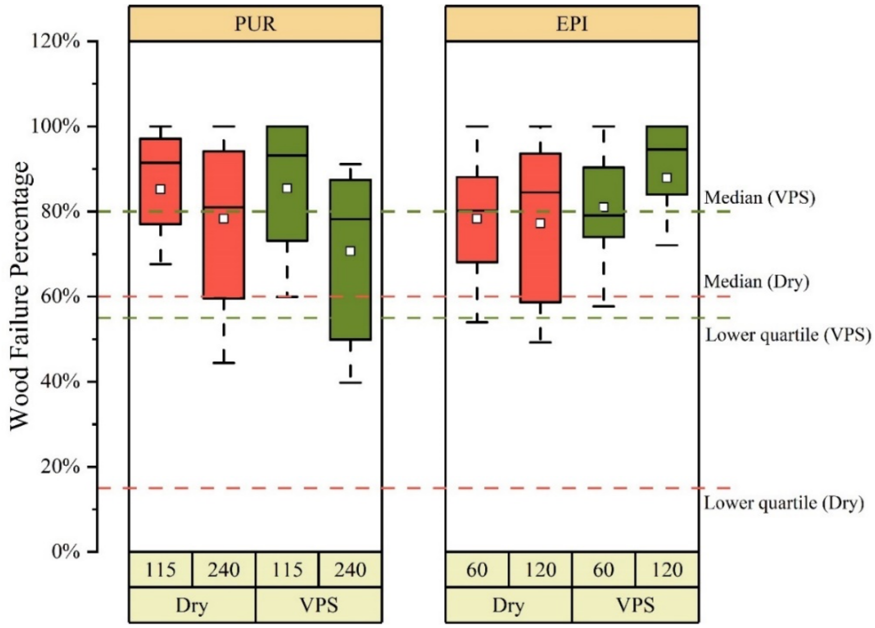


Figure 11 – Wood failure percentage (WFP) results and corresponding CSA O112.9 requirements (CSA 2021).

2.3.5. Effects of Lumber Length, Knot Size, and Species on Mechanical Properties

2.3.5.1. Lumber Length

Figure 12 presents the mean MOE values measured by the three NDE methods on the SS-grade trembling aspen lumber of three different lengths. The MOE values exhibited slight differences across the various length groups, under same testing method, ranging from 0.6% to 4.5%. Given the inherent variability due to the anisotropy of the wood material (Malaga-Toboła et al. 2019), the testing results in this study are considered reliable. It was concluded that, under the same testing method, the length effect does not significantly impact the outcomes.

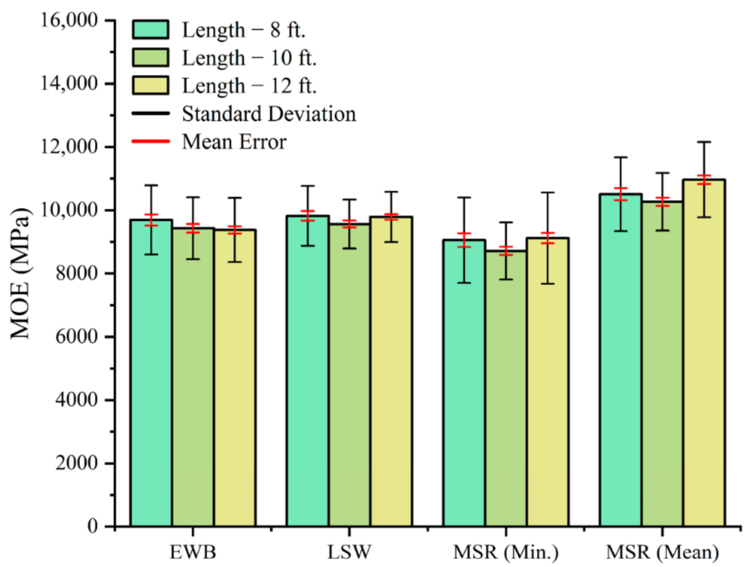


Figure 12 – SS-grade trembling aspen mean MOE values measured by three NDE methods under different lengths.

2.3.5.2. Knot Size

The strength of lumber is often determined by the sizes and locations of the knots (Fan et al. 2023), making knots a crucial indicator for lumber grading systems (NLGA 2019). Trembling aspen lumber is categorized as a "Northern Species" by the NLGA and included in the softwoods category along with red cedar (*Thuja plicata*), red pine (*Pinus resinosa*), and ponderosa pine (*Pinus ponderosa*) (NLGA 2019). However, these rules may not be applicable to trembling aspen lumber due to its hardwood nature, showing unique growth characteristics associated with physical and mechanical properties. Compared to softwoods, dead knots and early decay in trembling aspen are more easily identifiable (Hittenrauch 1976, Hiratsuka and Loman 1984), further affecting its properties. Therefore, a suitable grading rule for trembling aspen lumber should be developed by adapting the existing NLGA rules to accommodate its specific characteristics. To achieve this, re-classifying trembling aspen lumber only in terms of the maximum knot size (any-caused) were conducted in this study, based on the category as defined by the NLGA (NLGA 2019). Four tiers were produced for the trembling aspen lumber, which are associated with the mechanical properties listed in Table 7. A clear linear relationship was found to exist between the maximum knot size and a given mechanical property, such as the MOE or UTS. As the maximum knot size increased by 12.5 mm from 6.2 mm, the MOE_{min} for the MSR, as well as the mean and fifth-percentile UTS, decreased by 8.8%, 23.9% and 29.2%, respectively.

The linear regression between the MSR (MOE_{min}) and UTS was measured and is presented in Figure 13. The R^2 values for T1 are relatively low compared to the evident correlation observed for T2, T3, and T4, as might be expected due to the smaller sample sizes. The correlation between the maximum knot size and the four tiers, as shown in Figure 13, is evident, with R^2 values ranging from 0.14 to 0.51, suggesting that the sub-grade approach is validated.

Table 7 – Effect of the maximum knot size on the MSR-MOE_{min} and UTS

Index	Sub-Group			
	T1	T2	T3	T4
Max. Knot Size (any-caused)	< 1/4" (6.4 mm)	1/4" ~ 3/4" (19.1 mm)	3/4" ~ 5/4" (31.8 mm)	> 5/4
MSR-MOE_{min} (MPa)	9,026	8,286	7,867	6,842
Mean UTS (MPa)	31.94	21.99	19.18	13.89
Fifth-Percentile UTS (MPa)	16.09	9.53	7.68	5.58
Quantity (Pcs.)	19	45	89	135
Proportion (%)	6.6	15.6	30.9	46.9

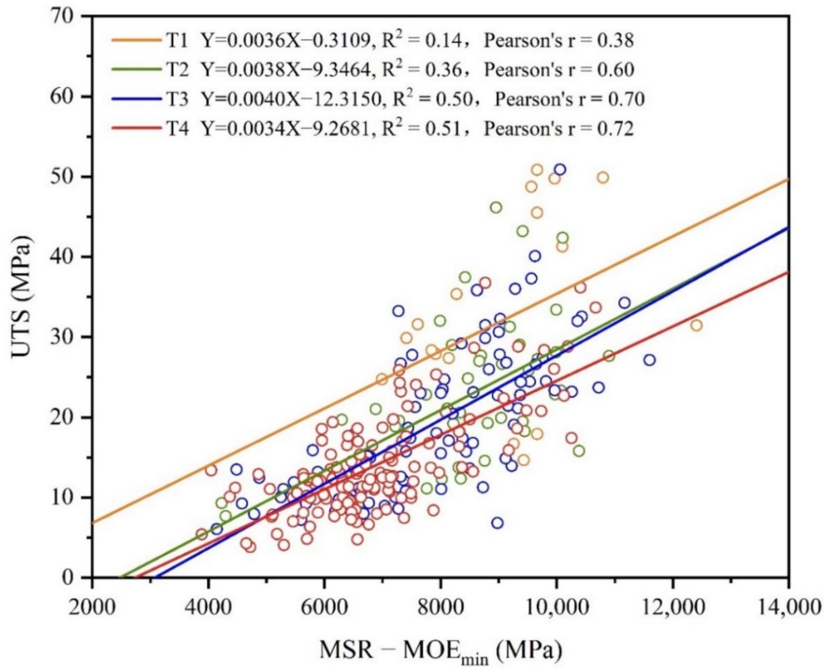


Figure 13 – Four tiers (T1-orange, T2-green, T3-blue, T4-red) of relationship between the maximum knot size, MSR-MOE_{min}, and UTS.

1.3.5.3. Comparison of MOE and UTS with Spruce–Pine–Fir (S-P-F) Lumber

As a comparison, the UTS and MOE values of the 38 mm × 89 mm S-P-F (CWC 1994) dimension lumber are listed together with the trembling aspen lumber in Table 8. The MOE values for the SS-grade trembling aspen lumber, tested via the EWB method, were considered for a mixed combination of three different lengths. For the 2,438 mm (8-foot-long) lumber, the values of the MOE were considered, but not the UTS in this comparison, since the axial tension was not tested. The ratio was defined as the value of the trembling aspen lumber to that of the S-P-F lumber. It can be found that the MOE and UTS of the trembling aspen lumber are overall lower, regardless of the grade, than those of the S-P-F lumber, in particular for the UTS of the No. 2-grade lumber.

Table 8 – MOE and UTS of trembling aspen and S-P-F lumbers.

Property	Grade	Sample Size (Pcs.)		Mean (MPa)			Fifth Percentile (MPa)		
		Aspen	S-P-F	Aspen	S-P-F	Ratio*	Aspen	S-P-F	Ratio*
MOE	SS	153	441	9,519	10,730	0.89	7,404	7,520	0.98
	No. 2	174	440	8,028	9,490	0.85	5,656	6,090	0.93
UTS	SS	114	440	25.40	30.86	0.82	10.57	14.88	0.71
	No. 2	174	444	13.12	23.27	0.56	5.67	9.11	0.62

Note: * Aspen/S-P-F.

2.3.6. MSR Grade Yields Analysis

The MSR technology is widely used in sawmill production lines for quickly and accurately sorting the lumber grades for manufacturing EWPs, which requires appropriate machine settings. Smith and Chui (1994) developed procedures for calculating the MSR machine settings and yield for each grade, represented by the percentage of lumber pieces falling into each grade. Despite NLGA SPS-2 (NLGA 2019) listing numerous MSR grades, only a few are commonly produced, namely, 1800f-1.6E, 1650f-1.5E, 1450f-1.3E, and 1350f-1.3E. Three combinations of MSR grades are considered in this analysis and are summarized in Table 9. Also shown in Table 9 are the MSR machine setting required for each MSR grade pulled from the population of trembling aspen lumber. The grade yields for combinations 1 and 2 are moderate, while the grade yields for combination 3 are generally good. A total of 59% of all of the produced trembling aspen lumber qualified as grade 1200f-1.2E and above, with 37% reaching the grade of 1450f-1.3E. This finding is similar to the conclusion reached by Kretschmann et al. (1999), who applied the MSR process to "No. 2 and better" hybrid poplar lumber and found that a yield of 60.5% was achieved for 1450f-1.3E MSR grade.

The use of trembling aspen lumber for manufacturing CLT panels is uncommon, so it would be valuable to evaluate the yield of trembling aspen lumber after sorting it for use in CLT panel production. The production of CLT using trembling aspen lumber as laminates was evaluated in accordance with the requirements of ANSI/APA PRG-320 (APA 2019). In ANSI/APA PRG320 (APA 2019), grade E1 CLT is fabricated using S-P-F lumber, while grade E3 is fabricated using "Northern Species" lumber, which includes trembling aspen lumber. Table 10 presents the yield results for laminates that meet the requirements of longitudinal and transverse layers for E1 and E3 grade CLT. It can be noted that the yields for grade E1 of the trembling aspen lumber is 57%, with 49% in the transverse layers and 8% in the longitudinal layers. Grade E3 of the trembling aspen lumber constitutes 1% of the reject material. It can be suggested that the trembling aspen lumber undergoes in-mill sorting in advance to reduce the rejection rate further and to allow for the sale of pieces that do not meet the CLT grade E1 as visually graded lumber.

Table 9 - MSR machine settings and grade yields based on MSR-MOE_{mean}.

Combination	High-Grade			Low-Grade			Reject (%)
	Grade	MSR Machine Setting (MPa)	Yield (%)	Grade	MSR Machine Setting (MPa)	Yield (%)	
1	1650f-1.5E	10,614	24	1450f-1.3E	9,880	13	63
2	1650f-1.5E	10,614	24	1350f-1.3E	9,715	16	60
3	1450f-1.3E	9,880	37	1200f-1.2E	8,949	22	41

Table 10 – Grade yield analysis of aspen lumber when used for fabricating E1 and E3 grade CLT in accordance with ANSI/APA PRG-320 standard (APA 2019).

CLT Grade	Longitudinal layer			Transverse layer			Reject (%)
	Standard (MPa)	MSR Machine Setting (MPa)	Yield (%)	Standard (MPa)	MSR Machine Setting (MPa)	Yield (%)	
E1	11,700	11,749	8	9,000	9,002	49	43
E3	8,300	8,301	76	6,500	6,659	23	1

3. TREMBLING ASPEN FINGER-JOINTED LUMBER TEST RESULTS

3.1. Materials

A total of 20 SS-grade and 81 No. 2-grade pieces of 38 mm × 89 mm trembling aspen finger-jointed lumber, each 3,658 mm (12 feet) in length, were fabricated by Boise Cascade All-Joints Ltd. in Saint-Jacques, New Brunswick. A commonly used structural finger profile with a finger length of 28.58 mm (1-1/8 inch) and horizontal joints was employed. End pressure was set at 45 psi (approximately 0.3 MPa), and a two-component polyurethane emulsion polymer (2C-PUR) adhesive was used. Lumber components ranged from 1,829 mm to 2,438 mm (6 to 8 feet) in length, contributing 2-3 joints per specimen. All specimens were fabricated at an average temperature above 19°C, with MC levels between 12% and 15%, measured using a moisture meter (model: Wagner Orion 950). Large knots exceeding 19.05 mm (3/4 inch) on the edge or 25.4 mm (1 inch) on the face were removed for quality controlling. After fabrication, specimens were wrapped and shipped to the Wood Science and Technology Centre at the University of New Brunswick, Fredericton, for further testing and analysis.

3.2. Testing

3.2.1. Modulus of Elasticity

In this research program, three NDE methods were utilized to measure the MOE of each finger-jointed piece: LSW, flatwise centre-point bending (FWB), and EWB. The LSW and EWB methods were performed using the same procedure as outlined in Section 1.

The FWB test involved manually loading a mass of 30 lbs (13.6 kg or 133.50 N) at the mid-span of each specimen. The span-to-depth ratio was set at 75, with an overhang of 410 mm on each end, and the testing span was 2,850 mm. Prior to applying the 30 lbs load, a preload of 5 lbs (2.3 kg or 22.24 N) was used to stabilize the test specimen, following NLGA SPS-2 (NLGA 2019) guidelines. A 50-mm LVDT was set up underneath the mid-span to monitor deflection immediately after the load was applied, shown in Figure 14. This procedure was conducted for quality control purposes.

Figure 14 - Centre-point loading long-span bending test set-up.

3.2.2. Ultimate Tensile Strength

The axial tension test was conducted with the purpose of obtaining strength on each finger-jointed lumber in accordance with ASTM D198 (ASTM 2022) using a Metriguard Testing Machine (model: Metriguard 401). The testing span was set to 2,438 mm (8 feet), with at least one joint within the span. The two grips were fixed at 610 mm (2 feet) each. A loading rate of 10 kN/min was applied, causing specimens to fail in approximately 4 minutes. Failure mode for each specimen was recorded and analysed according to ASTM D4688 (ASTM 2021).

3.2.3. Moisture Content and Specific Gravity

After the axial tension test, a defect-free 25.4 mm thick (1-inch) wood block was crosscut immediately from each lumber near the failure location to determine its MC and SG by oven-drying, following ASTM D4442 (ASTM 2020).

3.3. Results and Discussion

3.3.1. Moisture Content and Specific Gravity

The statistics of different grades of finger-jointed lumber MC and SG are summarized in Table 11. As MC and SG influence the mass and stiffness of a test specimen, both of which are input properties for dynamic modulus calculations, they have significant impacts on the measured results from the LSW tests (Sandoz 1993, Gray et al. 2008). It is noted that for both grades, the mean MC measured by the moisture meter was comparable to that determined by the oven-drying method, approximately 8.5%, but the COV was higher. The mean SG across the two groups was approximately 0.40, slightly higher than the value reported in the Wood Handbook (Senalik and Farber 2021). The MC of each specimen at the test was used to convert the MOE and UTS values to those at an MC of 15%, following the ASTM D1990 procedures for further data analysis (ASTM 2019).

Table 11 - Descriptive data values of the MC and SG of the samples investigated

Index	SS-Grade	No. 2-Grade
Mean MC (Moisture meter) (%)	8.5 (9.52%)	9.0 (12.27%)
Mean MC (Oven dried) (%)	8.0 (7.68%)	8.4 (6.83%)
Mean SG (Oven dried)	0.40 (6.12%)	0.41 (7.33%)
Quantity (pcs.)	20	81

Note: The value in paratheses stands for the coefficient of variation.

3.3.2. **Modulus of Elasticity**

The MOE values of specimens of both grades were measured using three NDE methods, as shown in Table 12, with mean values ranging from 8,125 to 9,508 MPa. The SS grade finger-jointed lumber exhibited mean MOE values comparable to those of No. 2 grade lumber, accounting for the grade effect. It can be inferred that finger-jointing may influence MOE values of lower grade lumber, likely due to the removal of strength-reducing defects. Thus, the finger-jointing technique can potentially enhance the yield of lower visual grade trembling aspen lumber. However, the increased number of joints also imposes a limitation on the upper bounds of the MOE, consistent with findings by Biechele et al. (2011), Muthumala et al. (2022), and Timbolmas et al. (2022).

Table 12 - Descriptive statistics for MOE of the samples investigated.

Method	Index	Mean Data for Groups	
		SS-Grade	No. 2-Grade
Longitudinal Stress Wave	MOE (MPa)	8,610	8,648
	COV (%)	9.34	10.63
Flatwise Centre-point Bending	MOE (MPa)	8,250	8,288
	COV (%)	14.47	13.60
Edgewise Third-point Bending	MOE (MPa)	9,508	9,168
	COV (%)	10.92	15.54

3.3.3. Ultimate Tensile Strength and Failure Modes

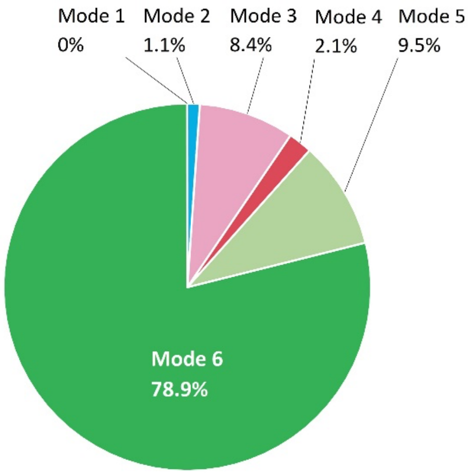
The tension testing results for finger-jointed lumber, summarized in Table 13, show that SS-grade lumber has a mean UTS of 17.24 MPa, which is approximately 18.7% higher than the 14.01 MPa recorded for No. 2-grade lumber. Additionally, SS-grade exhibited a lower COV at 33.66%. Specimens were rejected if they broke within the fixed grip or if the testing time was less than 4 minutes, with a rejection rate of 7.6% for both grades, as listed in Table 13.

Table 13 - Descriptive data values for UTS measurement.

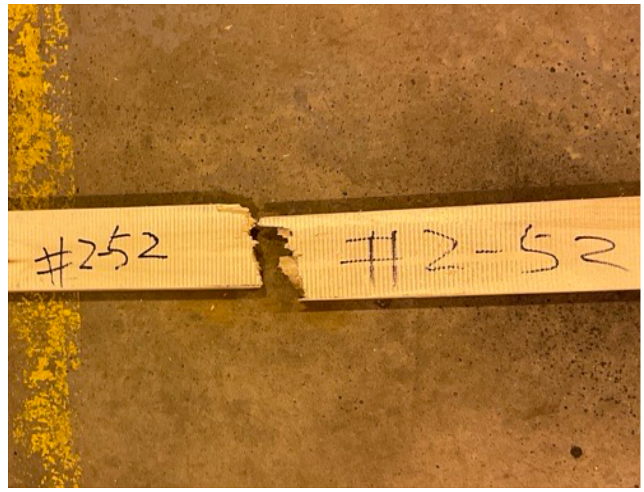
Index	Statistic Data for Groups		
	SS-Grade	No. 2-Grade	SS + No. 2 Grade
Mean (MPa)	17.24	14.01	14.62
COV (%)	33.66	38.94	38.54
Reject (%)	15.0	9.5	7.6
Failure by Mode 6 (%)	77.8	79.2	78.9

ASTM D4688 categorizes the failure modes of structural finger-joints into six modes, with Mode 1 indicating complete joint failure and Mode 6 indicating complete fibre failure, the tested results as depicted in Figure 15. Modes 2 through 5 fall in between these extremes. Mode 5 describes failure initiating at the joint (potentially due to a stress riser) and extending outward, resulting in nearly 100% wood failure. Mode 4 represents primarily tensile wood failure at finger-joint roots or scarf tips, with high overall wood failure and minimal failure along the joint profile. Mode 3 indicates failure predominantly along the joint profile, with some failure at the finger roots or scarf tips and good overall wood shear failure along the joint surfaces. Mode 2 involves failure mainly along the bond line of the joint profile, with wood shear failure exceeding 70%.

No. 2 grade finger-jointed lumber showed a higher incidence of Mode 6 failure at 79.2%, compared to 77.8% for SS-grade, suggesting that the joints were stronger than the fibres. This outcome supports the suitability of 2C-PUR for producing high-quality finger-joints in trembling aspen lumber across both grades of specimens.



(a)



(b)

Figure 15 – (a) The proportion of failure modes of finger-jointed lumber (SS and No. 2 included); (b) Mode 6 defined by ASTM D4688.

3.3.4. Comparison of MOE and UTS with Un-jointed Trembling Aspen Lumber

For comparison, Table 14 presents UTS and MOE values of 38 mm × 89 mm trembling aspen un-jointed lumber alongside those of finger-jointed lumber. The MOE values were determined using the EWB method. Rejected pieces from the tension test were excluded from the UTS data analysis. The analysis employed a normal distribution for the MOE data and a three-parameter Weibull distribution for the UTS data.

Table 14 - MOE and UTS comparisons between trembling aspen finger-jointed and un-jointed lumber.

Grade		Sample Size (Pcs.)		Mean (MPa)			Fifth percentile (MPa)		
		Jointed	Un-jointed	Jointed	Un-jointed	Ratio*	Jointed	Un-jointed	Ratio*
MOE	SS	20	153	9,508	9,519	1.00	7,811	7,404	1.06
	No. 2	81	174	9,168	8,028	1.14	6,829	5,656	1.21
UTS	SS	18	114	16.04	25.40	0.63	8.95	10.57	0.85
	No. 2	77	174	13.84	13.12	1.06	6.59	5.67	1.16

Note: *Jointed/Un-jointed.

According to Table 14, despite the significant differences in sample sizes, the data trends remain clearly observable. The mean MOE of jointed lumber shows minimal variation in the SS grade but exhibits a significant increase in the No. 2-grade, likely due to the removal of larger knots during the finger jointing process. The fifth percentile UTS value for SS-grade jointed lumber is lower than that of un-jointed lumber, whereas in the No. 2-grade, the jointed lumber has a higher UTS

than its un-jointed counterpart. In conclusion, a comparison of results before and after finger jointing, using the same testing methods, indicates that finger jointing can lead to a moderate improvement in the MOE of trembling aspen, while having no discernible impact on the UTS trend.

3.3.5. Grade Yields

Table 15 presents the yield values of trembling aspen finger-jointed lumber from the industrial production line. The No. 2 grade achieved a yield value of 50.6% during the finger-jointing process. Due to technical issues in the production line, SS-grade specimens were excluded from yield calculations and analysis in this report, as their yield value was only 13.3%. This exclusion was necessary because trembling aspen's dimensional stability is highly sensitive to MC changes, particularly in the tangential direction, due to the species' rapid growth rate (Haygreen and Bowyer 1996). The tight tolerance of the jointing machine's in-feed cross-section tunnel led to the rejection of most SS grade specimens. It is recommended that future production processes address the dimensional stability of trembling aspen and adjust machine settings accordingly.

Table 15 - Yield of No. 2 grade finger-jointed lumber.

Grade	Volume (board feet)		Yield (%)
	Lumber components	Finger-jointed Lumber	
No. 2	1,280	648	50.6

4. DEVELOPMENT OF SORTING CRITERIA FOR EWPS GRADE TARGET

The purpose of establishing the sorting criteria was to fabricate the EWPs with target bending stiffness, using "No. 2 and Better" grade trembling aspen lumber. Once the sorting criteria have been established for each laminate type in CLT and glulam or flange stock in wood I-joists, they could be used to sort "No. 2 and Better" grade trembling aspen lumber to select lumber pieces that meet the criteria for specific laminate or flange stock grade. Given that the LSW machine is portable, and results discussed above have shown that it is at least as efficient as MSR machine for grading or sorting purposes, LSW-MOE is adopted as the sorting parameter in this study. The development of the sorting criteria for the component lumber grades involves the following steps:

(1) Combine the EWB-MOE and LSW-MOE data for SS- and No. 2-grade obtained from Phase 1, to establish the "No. 2 and Better" grade database for trembling aspen lumber.
(2) For each piece of lumber tested, there are EWB-MOE and LSW-MOE values associated with it, rank all the EWB-MOE and LSW-MOE data pair in ascending order according to LSW-MOE.
(3) If the target mean MOE (same as EWB-MOE) for the higher grade is E_H, through a manual trial-and-error process, identify the minimum LSW-MOE (called machine setting) that would allow all pieces with LSW-MOE greater than this minimum EWB-MOE to have an average MOE equal to or greater than E_H.
(4) If another lumber grade with a lower MOE, E_L, is required for the product, e.g. transverse laminate for CLT or inner laminate for glulam, the same trial-and-error manual process is repeated on the remaining data (since the higher-grade material has already been selected from the same sample), until a lower LSW-MOE machine setting is identified.

As shown in Table 16, each product along with its target and laminate requirements is listed. For CLT and wood I-joists, the requirement of each laminate grade was based on the mean MOE, while glulam targeted the minimum MOE of each laminate grade.

Table 16 - EWP target grade and requirements.

Product	Target Grade	Laminate Requirements
CLT	E1 (APA 2019)	Longitudinal Layer (MOE_{mean} = 11,700 MPa)
		Transverse Layer (Visual Grade "No. 3")
Glulam	20f-E S-P (CSA 2016)	Outer 1/8 Layers ($MOE_{min.}$ = 11,000 MPa)
		Outer 1/4 Layers ($MOE_{min.}$ = 9,700 MPa)
		Inner Layers ($MOE_{min.}$ = No Minimum)
Wood I-joist	PKI-35 PLUS-10 (Manufacturer Standard)	Flange (MOE_{mean} = 9,377 MPa)

The 38 mm × 89 mm trembling aspen lumber was sorted at La Crete, AB, a location renowned for providing high-quality trembling aspen from Northern Alberta. Table 17 presents the sorting criteria and yield values for the target laminate of each product. The yield value is calculated based on the proportion of visually graded "No. 2 and Better" trembling aspen lumber that meets the MOE range determined by the LSW method. Consequently, even for different products, the sorting yield remains the same if the lumber falls within the same grade range.

Table 17 - Laminate sorting criteria and yield value.

Product	Target Grade	Sorting Criteria	Yield (%)
CLT	E1	Longitudinal Layer ($MOE_{min.}$ > 10,500 MPa)	43.2
		Transverse Layer (Visual Grade "No. 2 & Btr.")	100
Glulam	20f-E S-P	Outer 1/8 Layer ($MOE_{min.}$ > 11,000 MPa)	28.1
		Outer 1/4 Layer ($MOE_{min.}$ > 10,500 MPa)	43.2
		Inner Layer (Visual Grade "No. 2 & Btr.")	100
Wood I-joist	PKI-35 PLUS-10	Flange ($MOE_{min.}$ > 11,000 MPa)	28.1

After sorting, the graded lumber was carefully packed and shipped to different locations for EWP fabrication: CLT at Wood Science and Technology Centre, Fredericton, NB; Glulam at Western Archrib, Edmonton, AB; and wood I-joist at Pinkwood Ltd., Calgary, AB.

5. PROPOSED TREMBLING ASPEN CROSS-LAMINATED TIMBER (CLT) AND TEST RESULTS

5.1. Materials

Kiln-dried trembling aspen lumber, with a grade of "No. 2 and better" and nominal dimensions of 38 mm × 89 mm, was sourced from a sawmill at La Crete, Alberta. The LSW method was employed for on-site sorting lumber in terms of the MOE using a commercial handheld stiffness grading device (model: MTG-820) developed by Brookhuis (Enschede, The Netherlands) and TNO (Delft, The Netherlands). The trembling aspen lumber, with a minimum MOE of 10,500 MPa, was selected to fabricate grade E1 CLT panels according to the ANSI/APA PRG-320 standard (APA 2019). The lumber used for the major-strength direction laminations was 2,667 mm (8.75 feet) in length, while the lumber for the minor-strength direction laminations, cut from the longitudinal pieces, was 1,220 mm (4 feet) in length.

The 1C-PUR adhesive was supplied by Bostik Canada Ltd. Table 18 summarizes the basic characteristics and recommended application parameters for the adhesive. A water-based primer, solids content 58%, was used in manufacturing, with a recommended dilution range in water of 2 ~ 10 wt% and a spray rate of 10.8 ~ 32.3 g/m^2 (1 ~ 3 g/ft^2). A minimum primer dry time of 15 minutes was recommended by the adhesive supplier.

Table 18 - Basic characteristics and recommended application parameters of 1C-PUR used.

	Metric System	Imperial System
Solids Content	100 %	100 %
Density	1.17 ~ 1.23 g/cm^3	9.8 ~ 10.3 lbs/gal
Cured Adhesive Colour	Light Wood Tone	Light Wood Tone
Wood MC	8 ~ 18 %	8 ~ 18 %
Preferred Environment	18°C, 65% Relative Humidity	68°F, 65% Relative Humidity
Target Application Rate	194 ~ 269 g/m^2	18 ~ 25 g/ft^2
Applied Pressure	0.83 ~ 1.72 MPa	120 ~ 250 psi
Pressing Time	> 5 hours	> 5 hours
Assembly Time	45 ~ 60 minutes	45 ~ 60 minutes

5.2. Manufacturing

Three-layer and five-layer CLT panels were made with reference to ANSI/APA PRG-320 standard (APA 2019) at the Wood Science and Technology Centre, UNB. The lumber was planed to a thickness of 35 mm within 24 hours prior to making CLT, with all lumber free of end joints. The primer was applied following manufacturer's instruction. The adhesive was then applied with an average spread rate of 24.6 g/ft^2 (264.8 g/m^2), within the manufacturer's recommended range of 18 ~ 25 g/ft^2 (194 ~ 269 g/m^2). The spreading of adhesive was completed within 30 minutes. Each three-layer or five-layer CLT panel was composed of orthogonally crossed layers without edge gluing, with a thickness being 105 mm or 175 mm, respectively. The panels were assembled using a hydraulic press (model: 1000-T). The pressure applied during making a

CLT panel was 220 psi (1.52 MPa) for 8 hours, with curing continuing until the adhesive was fully cured at an ambient temperature of 20°C. The average MC of the lumber was measured as 10 ~ 12% using a moisture meter (model: Wagner Orion 950), within the recommended range of 9 ~ 15% as specified in ANSI/APA PRG-320 standard (APA 2019). All the CLT panels were then cut into specimens with the required dimensions for further testing.

5.3. Testing

5.3.1. Test Procedures

The fabricated CLT panels were cut into test specimens for a series of subsequent tests aimed at a comprehensive evaluation of its mechanical performance. These tests including bending and shear tests in the major- and minor-strength directions and rolling shear. In addition, the adhesive bond quality was assessed using block shear and delamination tests. Table 19 provides the test matrix for CLT specimens.

5.3.2. Bending Properties (Long-span Third-point Bending)

The long-span bending test was conducted to measure the bending stiffness of the full-size CLT panels in both major- and minor-strength direction, using an INSTRON Universal Testing Machine. Initially, each CLT panel underwent a third-point bending test to measure the effective bending stiffness $(EI)_{eff}$, following ASTM D198 (ASTM 2021), as shown in Figure 16. The test span-to-depth ratios were 23.7 for three-layer CLT and 14.2 for five-layer CLT respectively, with a span of 2,489 mm (98 inches) and a loading speed of 1 mm/min. Testing was terminated at 5 kN for three-layer minor-strength CLT and 10 kN for the remaining panels. Mid-span deflection was measured using two 50 mm LVDTs.

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

Figure 16 - Third-point bending test setups for CLT panels (a, b) and specimens (c, d).

Subsequently, all panels were cut into narrow strip specimens for destructive bending test to measure the effective bending stiffness $(EI)_{eff}$ and bending moment resistance $(F_bS)_{eff}$, with an extended span of 2,520 mm (99 inches) and span-to-depth ratios of 24.0 for three-layer CLT and 14.4 for five-layer CLT, in accordance with ANSI/APA PRG-320 (APA 2019) and ASTM D198 (ASTM 2021). The loading rate was set at 5 mm/min, and displacement was measured at the neutral axis using two 50 mm LVDTs.

The MC of each CLT panel and specimen was measured and recorded using a moisture meter (model: Wagner Orion 950) prior to testing.

Table 19 - The dimensions and quantity of CLT panels and specimens for bending test.

Type	No. of layers	Dimensions						Quantity (Pcs.)	
		Length		Width		Depth		Major-strength	Minor-strength
		mm	in.	mm	in.	mm	in.		
Panel	3	2,667	105.0	1,220	48.0	105	4.1	4	3
	5					175	6.9	3	3
Specimen	3			200	7.9	105	4.1	16	12
	5					175	6.9	12	12

5.3.3. Shear Properties (Short-span Centre-point Bending & Rolling Shear)

Two shear tests were performed to measure the longitudinal shear and rolling shear strengths of the CLT. Short-span centre-point bending tests and rolling shear tests were conducted using an INSTRON Universal Testing Machine, as shown in Figure 17a, b. The dimensions and quantities of the specimens are detailed in Table 20. The short-span centre-point bending tests were carried out on three-layer and five-layer CLT specimens, oriented in both the major and minor strength directions, in accordance with ASTM D198 (ASTM 2021) and ANSI/APA PRG-320 (APA 2019) standards. A span-to-depth ratio of 6 was used, with spans of 635 mm (25 inches) for the three-layer specimens and 1,050 mm (41.3 inches) for the five-layer specimens. The loading speed was set at 5 mm/min, and the load was applied until the specimens failed. The short-span bending test provided the shear strength of the specimen. Failure modes were observed and recorded. Prior to testing, the MC of each CLT specimen was measured using a moisture meter (model: Wagner Orion 950).

Figure 17 - (a, b) Short-span centre-point bending test setups for three- and five-layer CLT specimens; (c) Rolling shear test setup for three-layer CLT specimens.

In the rolling shear test, three-layer CLT specimens aligned in the major-strength direction were assessed (see Figure 17c). The dimensions of the specimens are provided in Table 20 including aspen (23 pieces) and S-P-F (10 pieces) CLT for comparison. The inclination angle (α) adopted for the rolling shear tests was 15.2°. A data-logging frequency of 4 Hz was used, with a loading rate of 0.5 mm/min. Displacement on both sides of the specimens was measured using two 50 mm LVDTs. For the preliminary test, one specimen from each group was randomly selected to estimate the peak load level. Each specimen was initially loaded to 50% of the estimated peak load, with the load-displacement curve recorded to determine the apparent rolling shear modulus (G). Subsequently, each specimen was loaded to failure to measure the rolling shear strength (τ_r). Prior to testing, the MC of each CLT specimen was measured and recorded using a moisture meter (model: Wagner Orion 950).

Table 20 - The dimensions and quantity of CLT specimens for centre-point bending and rolling shear test.

Type	No. of layers	Dimensions						Quantity (Pcs.)	
		Length		Width		Depth		Major-strength	Minor-strength
		mm	in.	mm	in.	mm	in.		
Centre-point Bending	3	635	25.0	200	7.9	105	4.1	16	12
	5	1,050	41.3	200	7.9	175	6.9	12	12
Rolling Shear	3	267	10.5	89	3.5	105	4.1	33*	/

Note: *The quantity included 23 pieces of trembling aspen and 10 pieces of S-P-F.

5.3.4. Bond Properties

Block shear and delamination test were conducted in accordance with ANSI/APA PRG-320 (APA 2019), as illustrated in Figure 18a. The dimensions and quantities of each type of specimen are listed in Table 21.

For the block shear test, specimens were randomly selected from both the edge and middle of each type of CLT panel and then specifically machined for testing. In accordance with ANSI/APA PRG-320, CLT specimens were tested under two conditions: dry and vacuum-pressure-soak treated (with an autoclave used for the vacuum-pressure-soak cycle) (APA 2019). The block shear test was conducted using an INSTRON Universal Testing Machine, with a loading speed of 5 mm/min and a logging frequency of 4 Hz. Data were recorded to determine the bond shear strength (f_v), and failure modes were documented to calculate the wood failure percentage.

The delamination test was conducted in strict accordance with ANSI/APA PRG-320 for both specimen preparation and testing (APA 2019). Vacuum-pressure-soak cycle treatment and drying were performed using an autoclave as shown in Figure 18b. The open lengths of the adhesive layer along with the total length were recorded to calculate the rate of delamination (RD).

Figure 18 - (a) Block-shear test setup for CLT specimens; (b) Autoclave for delamination cycle test of CLT specimens.

Table 21 - The dimensions and quantity of CLT specimens for block shear and delamination test.

Test	Dimensions						Quantity (Pcs.)
	Length		Width		Depth		
	mm	in.	mm	in.	mm	in.	
Block Shear	38	1.5	51	2.0	70	2.8	48
Delamination	80	3.2	80	3.2	105	4.1	24
					175	6.9	24

5.3.5. Specific Gravity

A total of 30 defect-free, 25.4 mm thick × 305mm long wood blocks were cut from the same batch of raw materials used for the CLT to determine the oven-dried SG, following ASTM D4442 (ASTM 2020).

5.4. Results and Discussion

5.4.1. Moisture Content and Specific Gravity

The mean MC of each type of CLT specimen and the overall mean SG are presented in Table 22. The mean MC across the groups ranges from 7.1% to 9.8%, with a mean SG of 0.42 and COV between 2.68% and 10.10%. The mean oven-dried SG of trembling aspen wood tested is 8.3% higher than the value published in the Wood Handbook (Note: SG was adjusted from green to oven-dried condition for comparison purposes) (Stamm 1964, Senalik and Farber 2021).

Table 22 - The MC and SG of CLT products under different tests.

Property	**Test**	**Three-layer CLT**		**Five-layer CLT**	
		Major-Strength	Minor-Strength	Major-Strength	Minor-Strength
Mean MC (%)	Third-point Bending	9.3 (4.83%)	9.0 (3.19%)	9.8 (3.84%)	9.7 (6.69%)
	Centre-point Bending	9.4 (3.99%)	9.0 (2.68%)	9.5 (10.10%)	9.6 (5.82%)
	Rolling Shear	7.1 (9.07%)	-	-	-
Mean Oven-dried SG (%)		0.42 (5.85%)			

Note: The values in the parentheses are the coefficient of variations; "-" stands for no data.

5.4.2. Bending Properties

5.4.2.1. Stiffness of Full-Size Panels

In this study, the effective flatwise bending stiffness of the CLT specimens is denoted as $(EI)_{eff,f,0}$ and $(EI)_{eff,f,90}$ in the major- and minor-strength directions, respectively, while the bending moment resistance is denoted as $(F_bS)_{eff,f,0}$ and $(F_bS)_{eff,f,90}$. The global load-deflection curves in both strength directions for three- and five-layer CLT panels are plotted in Figure 19. It can be found that under a load of 10 kN, the average deformation of the three-layer major-strength CLT panels is approximately four times greater than that of the five-layer panels. Additionally, under a load of 5 kN, the average deformation of the three-layer minor-strength CLT panels is nearly nine times greater than that of the five-layer panels.

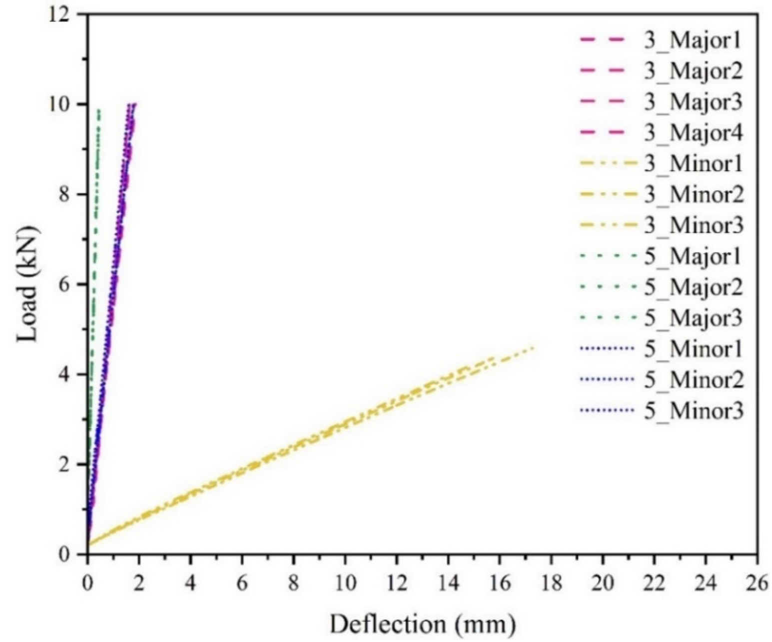


Figure 19 - Load-deflection curves of the full-size CLT panels.

Table 23 - Comparison of $(EI)_{eff}$ ($\times 10^9$ N·mm^2/m of width) of CLT panels based on test, shear analogy model, and published values in ANSI/APA PRG320 for grade E1 and E3 CLT.

		Three-layer Panel		Five-layer Panel	
		Major-Strength	Minor-Strength	Major-Strength	Minor-Strength
Experimental	Panel #1	1,682	58	7,094	1,426
	Panel #2	1,435	55	7,820	1,552
	Panel #3	1,644	58	7,722	1,416
	Panel #4	1,376	-	-	-
	Average	1,534 (9.87%)	57 (3.04%)	7,545 (5.22%)	1,465 (5.18%)
ANSI/APA PRG-320	Grade E1	1,088	32	4,166	837
	Grade E3	772	23	2,956	605

Note: The values in the parentheses are coefficient of variations, "-" stands for no data.

Table 23 compares the tested values and published $(EI)_{eff}$ for stress grades E1 and E3. Note that the test values are normalized to a width of 1 metre. Table 23 shows that all trembling aspen CLT panels exhibited significantly higher $(EI)_{eff}$ values, specifically, the mean $(EI)_{eff,f,0}$ of the three-layer panels was approximately 29.1% higher and $(EI)_{eff,f,90}$ was 43.9% higher than those of grade E1 (represented by the S-P-F combination). Similarly, the mean $(EI)_{eff,f,0}$ of the five-layer panels was 44.8% higher and $(EI)_{eff,f,90}$ was 42.9% higher.

5.4.2.2. Mechanical Response and Failure Modes of Bending Specimens

After the full-size panel bending stiffness tests, all CLT panels were cut to make narrow strip specimens for destructive tests, according to ANSI/APA PRG-320. The global load-deflection curves of all the bending specimens are illustrated in Figure 20. The $(EI)_{eff,f,90}$ of three-layer CLT specimens was tested exclusively, as no edge-glue bond in this study meant only the core layer contributed to bending strength capacity, precluding $(F_bS)_{eff,f,90}$ measurements. The ultimate load reached (P_{max}) for the three-layer major-strength CLT specimens ranged from 15.18 to 32.38 kN, with an average of 24.97 kN. For the five-layer major-strength and minor-strength CLT specimens, P_{max} ranged from 41.71 to 76.15 kN and 22.75 to 41.69 kN, respectively, with average values of 61.44 kN and 31.27 kN. Notably, the mean P_{max} of the five-layer major-strength specimens was 49.1% higher than that of the minor-strength ones and 59.4% higher than that of the three-layer major-strength ones.

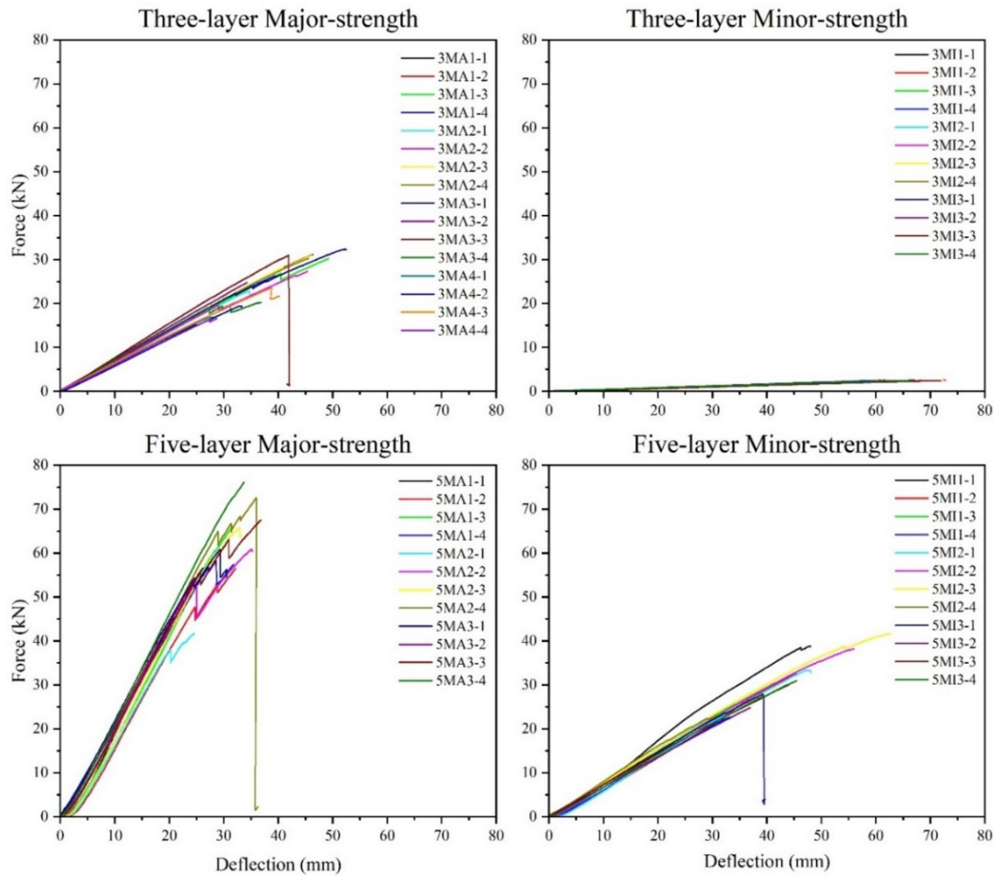


Figure 20 - Load-deflection curves of three-layer and five-layer CLT bending specimens.

The proportion results of failure modes were calculated for each group of CLT are shown in Table 24. For the three-layer and five-layer major-strength groups, rolling shear was the dominant failure mode, observed in 50% of tested CLT specimens, followed by tension failure at 37.5% and 33.3% and longitudinal shear failure at 12.5% and 16.7%, respectively. In the five-layer minor-strength group, tension failure was predominant at 50%, with rolling shear and longitudinal shear failures each accounting for 25%. Three types of failure modes are listed in Figure 21. For those specimens' failure by tension was further separated out for characteristic bending moment resistance calculation as listed the results in Table 26. It should be noted that due to the limitation of the press that fabricated the CLT panels, the required span-to-depth ratios specified in ANSI/APA PRG-320 cannot be achieved (i.e. 25 for major-strength and 18 for minor-strength direction). The reduced spans used were the main reason why a substantial number of test specimens failed in shear. In addition, the reduced span also led to an estimation of the effective bending stiffness due to the influence of shear deformation captured in the deflection measurement.

Table 24 – The proportion of failure mode(s) for each type of CLT specimens.

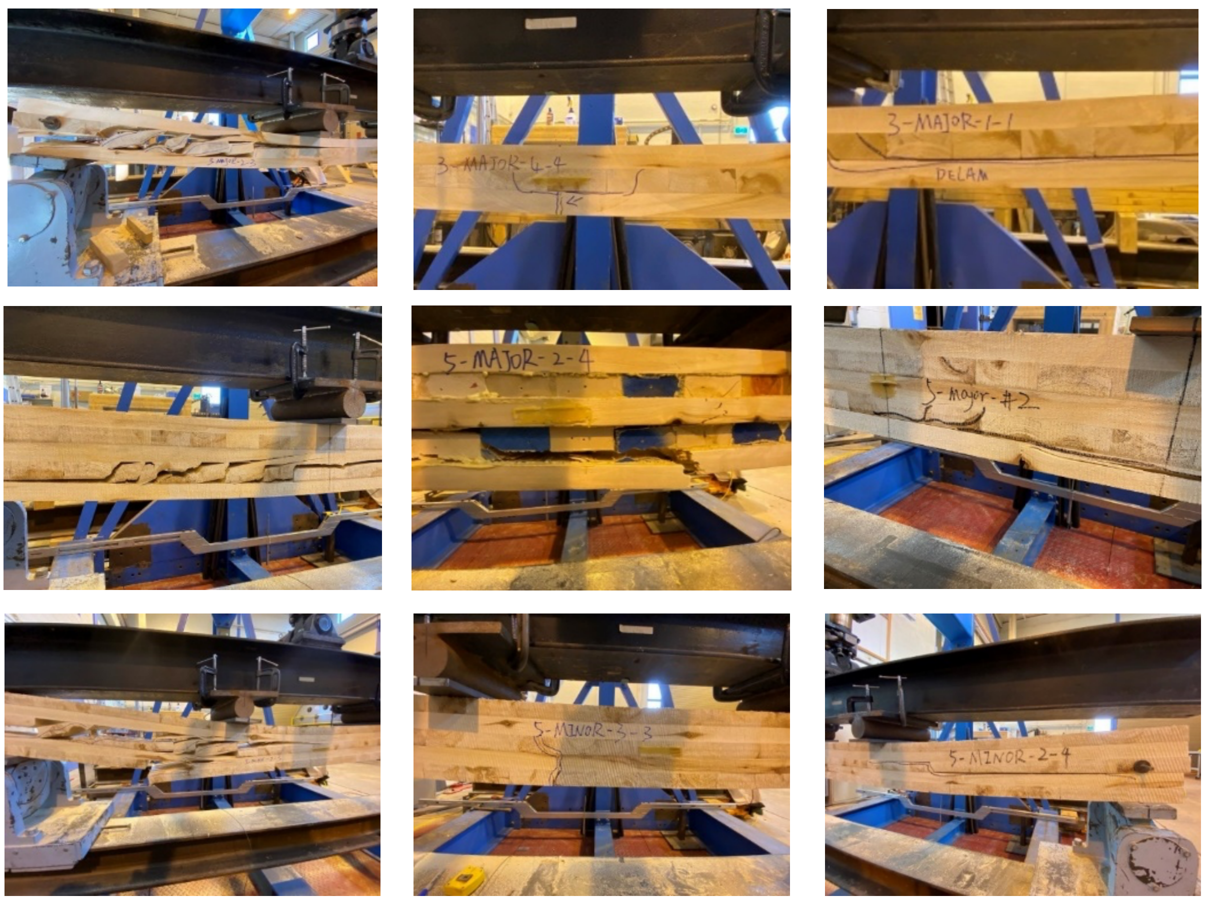
Failure Mode	Three-layer	Five-layer	
	Major-strength	Major-strength	Minor-strength
Rolling Shear Failure	50.0%	50.0%	25%
Longitudinal Shear Failure	12.5%	16.7%	25%
Tension Failure[1]	37.5%	33.3%	50%
Total Proportion	100.0%	100.0%	100.0%

Note: [1]Specimens broken in tension failure were selected for the characteristic $(F_bS)_{eff}$ calculation.

Three-layer Major

Five-layer Major

Five-layer Minor



Rolling shear failure | Tension failure | Longitudinal shear failure

Figure 21 - Failure mode(s) observed in CLT bending specimens.

5.4.2.3. Bending Test Results

Table 25 and Table 26 present the test results of mean $(EI)_{eff}$ and characteristic $(F_bS)_{eff}$ values for all the groups, respectively, along with the reference values published in ANSI/APA PRG-320 standard (APA 2019). The test results indicated that, except for the mean $(EI)_{eff,f,0}$ of three-layer CLT did not exceed the values for grade E1, the other groups all exceeded the requirements of grade E1 in the ANSI/APA PRG-320 standard. The mean $(EI)_{eff,f,0}$ of five-layer trembling aspen CLT was 17.8% higher and $(EI)_{eff,f,90}$ was 29.8% higher than those of grade E1, while for the three-layer CLT, the mean $(EI)_{eff,f,0}$ was

1.1% lower and $(EI)_{eff,f,90}$ was 40.7% higher.

Table 25 - The bending stiffness of CLT specimens.

Group		Mean Value $(EI)_{eff}$ $\times 10^9$ (N·mm²/m)		
		Reference (PRG-320)		Experimental Result
		Grade E1	Grade E3	
Three-layer	Major-1	1,088	772	1,086 (7.70%)
	Major-2			1,109 (3.44%)
	Major-3			1,152 (6.56%)
	Major-4			956 (3.71%)
	Average			1,076 (8.72%)
	Minor-1	32	23	58 (6.35%)
	Minor-2			47 (3.74%)
	Minor-3			57 (11.56%)
	Average			54 (12.32%)
Five-layer	Major-1	4,166	2,956	4,954 (12.41%)
	Major-2			5,158 (2.27%)
	Major-3			5,095 (5.39%)
	Average			5,069 (7.26%)
	Minor-1	837	605	1,205 (4.02%)
	Minor-2			1,258 (2.63%)
	Minor-3			1,117 (5.46%)
	Average			1,193 (6.28%)

Note: The value in paratheses stands for the coefficient of variation.

The characteristic values of $(F_bS)_{eff}$ were categorized based on failure modes. Based on Table 24, the characteristic value of $(F_bS)_{eff}$ was derived from specimens that failed in tension, providing a realistic $(F_bS)_{eff}$ for comparison with the published characteristic values in the ANSI/APA PRG-320 standard. Note that ANSI/APA PRG-320 requires that the experimental characteristic $(F_bS)_{eff}$ be no less than the specified $(F_bS)_{eff}$ divided by 0.96. The characteristic values were expected to be the 5th percentile with 75% confidence for each group. However, due to the limited specimens, a normal distribution model was applied for characteristic value estimation. The test results showed that the three-layer $(F_bS)_{eff,f,0}$ group was 22.4% below the published E1 values in ANSI/APA PRG-320, the five-layer $(F_bS)_{eff,f,0}$ was 4.3% below, and the five-layer $(F_bS)_{eff,f,90}$ exceeded by 73.7%.

Table 26 - The bending moment resistance of CLT specimens.

Group		Characteristic Value $(F_bS)_{eff}$ ×10^6 (N·mm/m)		
		Reference (PRG-320)		Experimental Result
		Grade E1	Grade E3	
Three-layer	$(F_bS)_{eff,f,0}$	43.75	27.08	33.95
Five-layer	$(F_bS)_{eff,f,0}$	102.08	62.50	97.65
	$(F_bS)_{eff,f,90}$	12.50	8.33	47.55

In summary, the five-layer CLT specimens in the minor-strength direction showed mean $(EI)_{eff}$ and characteristic $(F_bS)_{eff}$ values exceeding the target grade E1, while the five-layer and three-layer major-strength specimens did not meet this grade.

5.4.3. Shear Properties

5.4.3.1. Rolling Shear Property

Table 27 presents the rolling shear test results of the tested trembling aspen and S-P-F CLT. Previous studies have shown that trembling aspen exhibits higher rolling shear properties compared to softwoods. In this study, the mean rolling shear modulus (G) was 106 MPa, and the rolling shear strength (τ_r) was 1.20 MPa for trembling aspen CLT, both comparable to earlier studies for trembling aspen (Gong et al. 2015, Wang et al. 2018). The S-P-F CLT exhibited lower values of 76 MPa and 0.90 MPa, respectively. The characteristic value of rolling shear strength, τ_r, was calculated using a normal distribution model due to the limited specimen quantity. The results showed with trembling aspen being 13.2% higher than S-P-F.

Table 27 - The rolling shear properties of aspen and S-P-F CLT specimens.

		Count	Rolling Shear Test Results (MPa)	
			Mean Value	Characteristic Value
Aspen	Rolling Shear Modulus G	23	106 (32.44%)	-
	Rolling Shear Strength τ_r		1.20 (22.24%)	0.76
S-P-F	Rolling Shear Modulus G	10	76 (29.37%)	-
	Rolling Shear Strength τ_r		0.90 (16.53%)	0.66

Note: The value in paratheses stands for the coefficient of variation, and "-" stands for no data.

5.4.3.2. Short-span Centre-point Bending Property

The characteristic experimental V_s results, calculated as the lower 5^{th} percentile based on a normal distribution and presented in Table 28, consistently exceed the reference values across all groups. The characteristic experimental results for the three-layer $V_{s,0}$ were 73.7% higher and $V_{s,90}$ were 77.3% higher than the E1 grade value. For the five-layer specimens, $V_{s,0}$ exceeded by 68.4% and $V_{s,90}$ by 58.6% compared to the E1 grade value.

Table 28 - The shear resistance of CLT specimens.

Group		Characteristic Value Shear Resistance V_s (kN/m)		
		Reference (PRG-320)		Experimental Result
		Grade E1	Grade E3	
Three-layer	$V_{s,0}$	36.46	31.25	138.35
	$V_{s,90}$	12.50	10.42	55.15
Five-layer	$V_{s,0}$	60.42	52.08	190.90
	$V_{s,90}$	36.46	31.25	88.05

5.4.4. Adhesive Bond Properties

Adhesive bond quality is essential for maintaining structural design capacities of CLT. According to ANSI/APA PRG-320 adhesive bond performance is evaluated using block shear strength (BSS) and delamination tests. Sampling of test specimens from CLT panels for shear and delamination tests was conducted randomly, ensuring that both the edges and the central sections of the CLT panels were included. For the block shear test, six specimens were obtained from each CLT type. Specimens treated under dry and vacuum-pressure-soak conditions were tested for their BSS and corresponding wood failure percentage (WFP). The test results are shown in Tables 29 and 30.

Table 29 shows that the average BSS under dry conditions is 2.99 MPa, with a WFP of 58.5%. The corresponding COV values are 22.40% and 53.68%, respectively. Comparing the results across CLT types, the three-layer specimens exhibit 17.3% higher BSS and 24.4% higher WFP than the five-layer specimens. However, according to ANSI/APA PRG-320 standard for CLT bond line qualification, a WFP of 80% or higher is required for acceptance. The WFP test results fall short by 26.9%, suggesting that the adhesive, although proven effective for softwoods, is not suitable for hardwoods. As shown in Table 30, under vacuum-pressure-soak conditions, the average BSS is 1.89 MPa, with an average WFP of 39.8%. The COV for BSS is 41.94%, and for WFP, it reaches 76.30%. The differences between three-layer and five-layer CLT specimens are minor, with BSS differing by 18.5% and WFP by 2.5%. Like the dry condition, the vacuum-pressure-soak specimens failed to meet the CLT bond line qualification, with WFP falling short by 50.3%.

Table 29 - The mean value of dry condition block shear test results of all CLT prototypes.

CLT Panel Type		Dry Condition		
		Mean BSS (MPa)	Mean WFP (%)	Min. requirement for WFP (PRG-320)
Three-layer	Major	3.06 (20.18%)	61.6 (47.55%)	≥ 80%
	Minor	3.49 (16.15%)	81.6 (23.37%)	
Five-layer	Major	2.93 (12.89%)	63.0 (66.89%)	
	Minor	2.49 (31.63%)	45.2 (73.45%)	
Average		2.99 (22.40%)	58.5 (53.68%)	-

Note: The value in paratheses stands for the coefficient of variation, and “-” stands for no data.

Table 30 - The mean value of vacuum-pressure-soak condition block shear test results of all CLT prototypes.

CLT Panel Type		Vacuum-Pressure-Soak Condition		
		Mean BSS (MPa)	Mean WFP (%)	Min. requirement for WFP (PRG-320)
Three-layer	Major	1.60 (17.26%)	52.2 (71.96%)	≥ 80%
	Minor	2.56 (52.56%)	36.9 (46.75%)	
Five-layer	Major	1.64 (20.98%)	39.8 (104.33%)	
	Minor	1.75 (20.30%)	47.1 (73.59%)	
Average		1.89 (41.94%)	39.8 (76.30%)	-

Note: The value in paratheses stands for the coefficient of variation, and "-" stands for no data.

The adhesive's unsuitability for hardwoods was further confirmed by the delamination test, which evaluated adhesive durability through the rate of delamination (RD) value. Randomly selected specimens from each CLT type, with a minimum of 12 specimens per type, were tested in strict accordance with PRG-320 procedures. The results, shown in Table 31, indicate that three-layer CLT had a lower average RD (11.2%) compared to five-layer CLT (23.1%), a difference of 51.5%. The overall average RD across all CLT groups was 16.7%, exceeding the ANSI/APA PRG-320 qualification threshold of 5%. Even under the ANSI A190.1 (2022) standard, which sets an RD limit of 8% for hardwoods and 5% for softwoods, the results did not meet qualification criteria, likely due to the adhesive's incompatibility with hardwoods.

Table 31 - The delamination test results of all CLT products.

CLT Panel Type		Rate of Delamination (%)			
		Mean	Maximum	Minimum	Max. requirement for RD (PRG-320)
Three-layer	Major	11.8 (86.58%)	30.9	0	≤ 5%
	Minor	10.4 (71.77%)	21.1	0	
Five-layer	Major	25.4 (47.93%)	44.0	7.4	
	Minor	20.9 (44.60%)	33.8	4.1	
Average		16.7 (68.79%)	44.0	0	-

Note: The value in paratheses stands for the coefficient of variation, and "-" stands for no data.

A Scanning Electron Microscope (SEM) (Model: JEOL 6400), operated at an accelerating voltage of 15kV, was also employed to examine the bond line of CLT. Figure 22 presents SEM images of the bond line at a magnification of "×50" (on the left) and "×100" (on the right). After post-processing, including colour enhancement and scaling, the bond line and adhesive penetration, highlighted in red, are clearly visible. Kurt (2006) studied the effect of glue-line thickness on the shear strength of wood-to-wood joints and reported that glue-line thicknesses exceeding 0.25 mm result in weaker bonds. In this case, the bond line thickness is estimated to range from approximately 0.06 to 0.11 mm, with penetration reaching depths of up to 0.4 mm, supporting the suitability of the bond line thickness. SEM images reveal that trembling aspen is a diffuse-porous wood with fine fibres and no visible wood rays. The upper portion of the CLT shows a cross-section where the adhesive visibly penetrates fibres and vessels. In contrast, the lower portion, consisting of radial or tangential sections, contains pits inside the vessels that block adhesive flow, limiting further penetration.

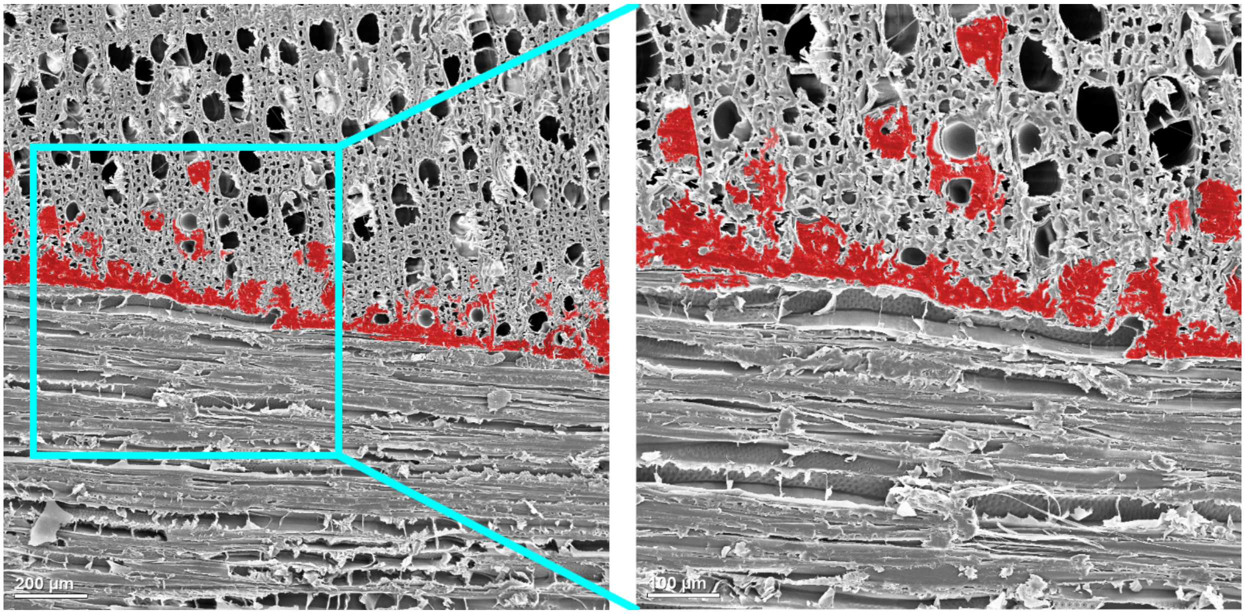


Figure 22 – The scanning electron microscope (SEM) image of the CLT bond line.

5.4.5. Product Yield

The yield flowchart for the CLT product is illustrated in Figure 23. La Crete Sawmill Ltd. reported a yield of approximately 51.2% from logs to kiln-dried, visually graded “No. 2 and better” lumber. Targeting grade E1, lumber selection adhered to the sorting criteria outlined in Section 3, using the longitudinal stress wave (LSW) method. About 43.2% of the lumber qualified for the longitudinal layer, while the rest materials met the visual grade No. 3 requirement for the transverse layer according to ANSI/APA PRG-320, resulting in a yield of 56.8%. All selected lumber can be used in CLT fabrication.

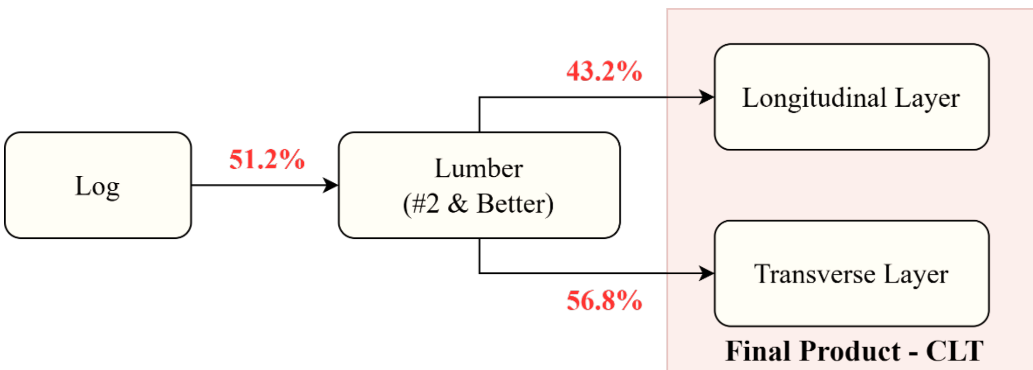


Figure 23 – Yield values for trembling aspen CLT laminates.

6. PROPOSED TREMBLING ASPEN GLULAM AND TEST RESULTS

6.1. Materials and Manufacturing

No. 2 and better grade trembling aspen lumber with dimensions of 38 mm × 89 mm was sorted for glulam production, using the longitudinal stress wave method as detailed in Section 3. After careful packaging, the lumber was shipped to Western Archrib, Edmonton, Alberta for glulam manufacturing. The selected lay-up is shown in Table 32. The lumber was conditioned to an average MC of 10% and subjected to industry-standard visual grading to ensure compliance with specifications for the glulam assembly's inner and outer layers, resulting in a 43% yield for outer layer applications and a 9% rejection rate. Due to significant "skip and miss" observed on the width of lumber, it was planed to a thickness of 35 mm to achieve a uniform surface before finger-jointing for the final gluing process. These beams, with a target grade equivalent to the 20f-E for Spruce-Pine (S-P), were bonded using a modified melamine formaldehyde (MF) adhesive in accordance with CSA O122 standards (CSA 2016). Quality control was conducted by the manufacturer prior to gluing. A total of 10 full-size glulam beams were fabricated, each consisting of 13 layers and measuring 9,100 mm in length, 80 mm in width, and 455 mm in depth. The beams were packed and shipped to the I. F. Morrison Structures Lab, University of Alberta for testing.

Table 32 – The trembling aspen lumber requirements for glulam lay-up.

80 × 455 mm trembling aspen glulam refer to 20f-E S-P requirements		
Layer #	Minimum MOE (MPa)	Visual Grade
1	11,000	C
2	11,000	C
3	10,500	D
4	No. 2 & Better	D
5	No. 2 & Better	D
6	No. 2 & Better	D
7	No. 2 & Better	D
8	No. 2 & Better	D
9	No. 2 & Better	D
10	No. 2 & Better	D
11	10,500	C
12	11,000	B
13	11,000	B-F

6.2. Testing

6.2.1. Full-size Third-point Bending

The third-point bending tests were conducted following ASTM D198 (ASTM 2022), with the span-to-depth ratio set at 18, shown in Figure 24. The purpose of this test is to evaluate the bending properties of the trembling aspen glulam beams by measuring the MOE and Modulus of Rupture (MOR). A total of 4 LVDTs were installed at the neutral layer of a beam

specimen on both sides and supports with a precision of 0.01 mm. The loading rate was set at 10 mm/min, with a data logging frequency of 5 Hz, resulting in the time to failure of a specimen to be 4 to 20 minutes. Lateral supports were installed to prevent buckling. Failure modes were recorded after specimen breakage.

Figure 24 - Third-point bending test setup for a full-scale glulam beam.

6.2.2. Moisture Content and Specific Gravity

The oven-dried MC and SG of each specimen were measured by cutting three 25-mm-thick (1 inch) blocks from each side of the beam, as close as possible to the failure location, following ASTM D4442 (2020).

6.3. Results and Discussion

6.3.1. Moisture Content and Specific Gravity

A total of 60 pieces of wood blocks were cut from the failure location as close as possible for examining oven-dried MC and SG. The test results are listed in Table 33. The average MC of testing was 11.4% with the COV of 8.61%. The SG was 0.43, which is 10.2% higher than the value reported in Wood Handbook (the value from the Wood Handbook was adjusted from green to oven-dried for comparison) (Senalik and Farber 2021, Stamm 1964).

Table 33 – Physical properties (MC and SG) of glulam specimens.

Count	MC (%)	SG
60	11.4 (8.61%)	0.43 (7.65%)

Note: The value in paratheses stands for the coefficient of variation.

6.3.2. Full-size Third-point Bending Test and Failure Modes

The load-displacement curves are illustrated in Figure 25. Based on Figure 25, the peak loads of all tested trembling aspen glulam specimens range from 55.9 to 85.1 kN, with deflection at failure ranging from 60.4 to 131.3 mm.

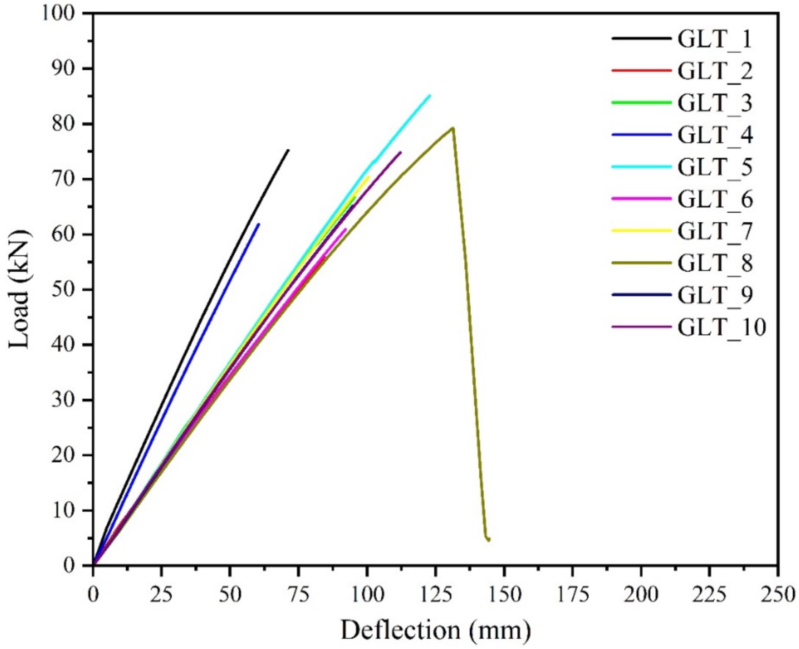


Figure 25 – The load-displacement curves of tested glulam beams.

Table 34 presents the test results for the glulam specimens. The apparent MOE (MOE_{app}) and MOR were calculated in accordance with ASTM D198 (ASTM 2022). The published MOE and specified bending strength (MOR) of 20f-E S-P grade glulam are 10,300 MPa and 25.6 MPa respectively according to CSA O86 (CSA 2024). Without more reliable information and following similar approach in ANSI/APA PRG-320 for CLT, it can be assumed that the required 5th percentile of MOR is estimated to be: specified bending strength / 0.96 = 25.6/0.96 = 26.67 MPa. Based on test results the mean MOE_{app} is 12,315 MPa with the COV of 19.87%. If the MOR data is fitted to a normal distribution model, the lower 5th percentile is obtained as 27.00 MPa. Comparison of grade requirements with test results indicates that the mean MOE_{app} and characteristic MOR of the trembling aspen glulam met the target 20f-E S-P glulam criteria. The mean MOE_{app} was 16.4% above the requirement, and the characteristic MOR exceeded the target by 1.2%. As will be discussed below, the failure was related to natural defects or finger joints. It seems that this issue of low MOR could be addressed in the future by applying a more stringent knot restriction and better-quality finger joint fabrication. Similar to the CLT glue issue, another contributing factor to this could be due to the fact that the formulation of the MF glue may not be optimized for hardwoods.

Table 34 - Static Data of trembling aspen glulam.

Group	Mean MOE_{app} (MPa)		Characteristic MOR (MPa)	
	20f-E S-P Target	Experimental	20f-E S-P Target	Experimental
10 Glulam beams	10,300	12,315 (19.87%)	26.67	27.00

Note: The value in paratheses stands for the coefficient of variation.

The failure modes were documented, as shown in Figure 26, with two observed failure modes recorded, and representative specimens were selected accordingly. Approximately 50% of the specimens experienced material fracture around natural defects such as knots. The remaining 50% of failures were primarily attributed to fractures near the finger-joints. According to ASTM D4688 (ASTM 2021), all finger-joint failures were classified as Mode 4, characterized by predominantly tensile wood failure at the finger-joint roots or scarf tips, minimal joint profile failure, and a high overall wood failure rate.

Specimen #2 *Specimen #4*

Failure by tension **Failure at finger-joints**

Figure 26 - The failure modes of glulam beam specimens.

6.3.3. Product Yield

The production flowchart is shown in Figure 27. The yield from logs to “No. 2 & Better” grade lumber is approximately 51.2%, same as the CLT. Using the longitudinal stress wave (LSW) method, 28.1% of the lumber met the requirements for the outer 1/8 layer, 43.2% for the outer 1/4 layer, and 28.7% for the inner layer. During GLT manufacturing, 9% of the lumber was rejected during visual and MSR grading, with an additional 3% lost during finger-jointing. Ultimately, all products passed quality control and were successfully manufactured into glulam.

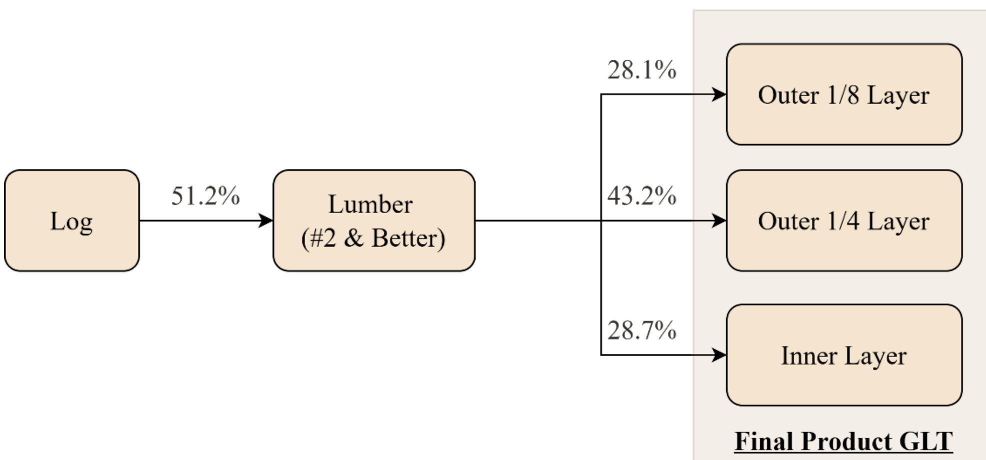


Figure 27 – Yields for aspen glulam laminates.

7. PROPOSED TREMBLING ASPEN WOOD I-JOIST AND TEST RESULTS

7.1. Materials and Manufacturing

No. 2 and better grade trembling aspen lumber with dimensions of 38 mm × 89 mm was sorted for Wood I-joist production using the LSW method described in Section 3. The lumber was then shipped to Pinkwood Ltd., Calgary, Alberta, for I-Joist manufacturing. Prior to fabrication, the flanges were conditioned to achieve a consistent MC, averaging 9.5%. Additional visual grading and finger-jointing were performed, with quality control conducted according to Pinkwood's in-house procedures. These I-joists comprised two finger-jointed trembling aspen flanges connected by an OSB web using 1C-PUR adhesive. A total of 18 Wood I-joists, each measuring 4,877 mm in length, 89 mm in width, and 241 mm in depth, were produced and tested at Pinkwood Ltd.

7.2. Testing

7.2.1. Long-span Third-point Bending

The long-span third-point bending tests were conducted as shown in Figure 28, following ASTM D198 standard, with a span-to-depth ratio of 19.6. The mid-span deflection was measured at the bottom flange with a LVDT. Due to the non-linear nature of machine loading, five load levels were applied at increments of 0.50, 0.75, 1.00, 1.25, and 1.50 times the design value of the target grade. After recording the deflections under each load level for calculating the effective bending stiffness ($(EI)_{eff}$), the I-joist specimens were loaded to failure for the moment capacity (Mr), with each specimen failing within 4 to 20 minutes. The load-deflection slope within the linear region was employed to determine the $(EI)_{eff}$, and the peak load was recorded for calculating Mr. Failure modes were documented right after the breakage of a specimen in accordance with ASTM D5055 standard (ASTM 2019).

Figure 28 – The wood I-joist specimen setup for bending test.

7.2.2. Moisture Content and Specific Gravity

The oven-dried MC and SG of lumber flanges in each specimen were determined by cutting two 25 mm thick blocks from each side of the bottom flange, as close as possible to the failure location, in accordance with ASTM D4442 (2020).

7.3. Results and Discussion

7.3.1. Moisture Content and Specific Gravity

A total of 72 wood blocks were cut as close as possible to the failure location to examine oven-dried MC and SG. The test results are presented in Table 35. The average MC was 9.1%, with a COV of 7.85%. The mean SG was 0.46, which is 16.1% higher than the value reported in the Wood Handbook (adjusted from green to oven-dried for comparison) (Senalik and Farber 2021, Stamm 1964).

Table 35 - Mean MC and SG of aspen flanges in wood I-joist specimens.

Count	Mean MC (%)	Mean SG
72	9.1 (7.85%)	0.46 (9.61%)

Note: The value in paratheses stands for the coefficient of variation.

7.3.2. Long-span Third-point Bending

The effective bending stiffness test results for the I-joist specimens are displayed in Table 36. Specimen #1, with a stiffness value of 1,773×10⁶ kN·mm², the highest among the specimens, was removed as an outlier. This elevated stiffness is likely attributed to the SG of its bottom flange, recorded as 0.53 in Section 6.3.1, the highest SG value within the group. A total of 17 pieces of I-joist specimens were further analysed, with the mean $(EI)_{eff}$ across all specimens measured at 899×10^6 kN·mm², and the characteristic Mr measured at 9,730 kN·mm.

Based on the sorting criteria outlined in Section 3, the “PKI-35 PLUS-10” product of Pinkwood Ltd. was confirmed as the manufacturing target. From Pinkwood Ltd literature (CCMC 2020), the effective bending stiffness for PKI-35 PLUS-10 is 671×10^6 kN·mm^2 and factored moment resistance is 7,565 kN·mm. According to CSA O86 Clauses 15.3.2.1 and 16.2.4.1, the required lower 5th percentile with a 75% confidential level, M_{cv}, for moment capacity is estimated to be $M_r/(\phi K_r)$, where M_r is the factored moment capacity, ϕ is the resistance factor of 0.9 and K_r is the reliability normalization factor which is assumed to be 0.88. Therefore, the required lower 5th percentile for moment capacity is 7,397 kN·mm.

Table 36 - Static data of trembling aspen I-joist.

Group	Mean $(EI)_{eff}$ (kN·mm^2)		Characteristic Mr (kN·mm)	
	PKI-35 PLUS-10	Experimental	PKI-35 PLUS-10	Experimental
17 Pcs. I-Joists	671×10^6	899×10^6	7,397	9,730

Note: The value in paratheses stands for the coefficient of variation.

The mean test value for $(EI)_{eff}$ is 899×10^6 kN·mm^2 which exceeds the PKI-35 PLUS-10 design value by 25.4%. According to ASTM D5055 (ASTM 2019), the lower 5% tolerance limit of the test moment capacity at 75% confidence was calculated as 9,730 kN·mm, which is also 24.0% higher than the required moment capacity of 7,397 kN·mm.

As shown in the pie chart on the left side of Figure 29, the failure modes of the test specimens in accordance with ASTM D5055 (ASTM 2019) are summarized. Approximately 77.8% of the specimens experienced failure at the finger-joint of the bottom flange, while 22.2% of the specimens broken in the solid wood of the bottom flange. The right side of Figure 29 provides examples of fractures occurring at the finger-joint.

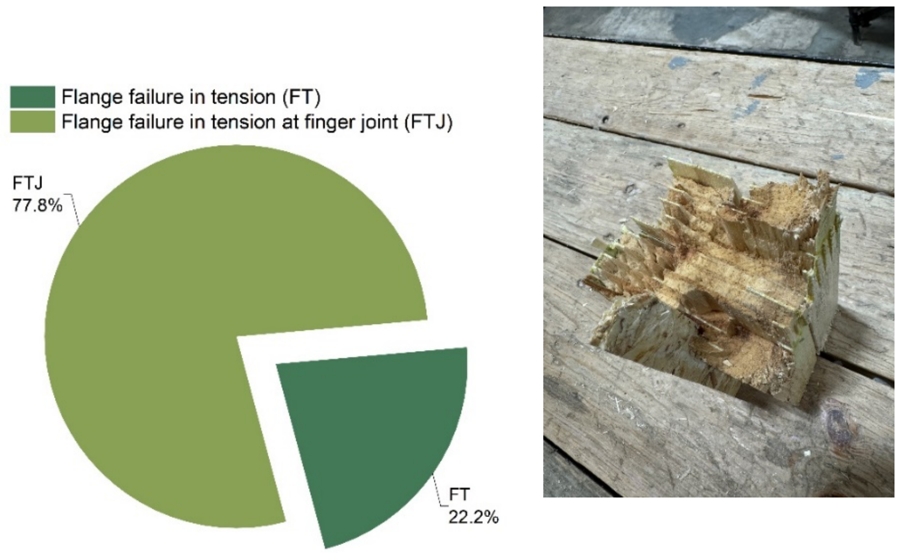


Figure 29 – The failure modes proportion of bending test.

7.3.3. Product Yield

Figure 30 illustrates the production process for wood I-joists made from trembling aspen lumber. According to a report from La Crete Sawmill, 51.2% of the logs yield lumber visual graded as “No. 2 and Better”. Of this, 28.1% was selected for flange production based on stiffness requirements using the LSW method referred to in Section 3. Production losses, including further visual grading and finger-jointing, account for 67.8%. Ultimately, all quality-approved products were fully processed into final wood I-joist products for the testing.

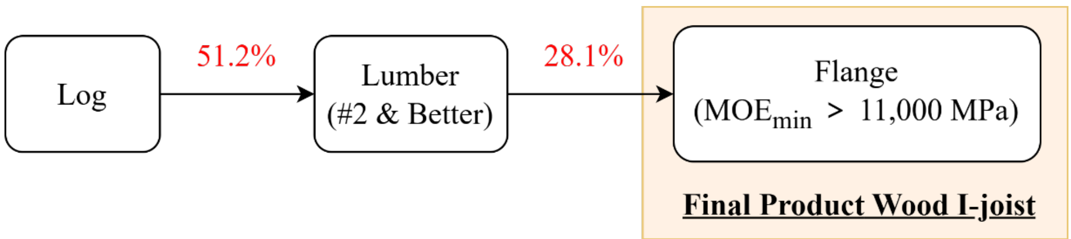


Figure 30 - Yield values for flange stock of PKI-35 PLUS-10 wood I-joist production.

8. GENERAL CONCLUSIONS

Based on the test results and above discussion, the following conclusions could be drawn:

► For trembling aspen lumber:

1) Based on mean or characteristic values, S-P-F lumber consistently exhibits approximately 10% to 20% higher MOE and UTS than trembling aspen lumber sampled from Northern Alberta at equivalent grade levels (SS and No. 2). It could be observed that as the knot size increased by half-inch, the MOE_{min} measured using MSR, as well as the UTS_{mean} and UTS_{5th}, decreased by about 8.8%, 23.9%, and 29.2%, respectively. Given the dominant influence of knots on trembling aspen lumber strength, there may be a need to impose additional restrictions on knot size for specific EWPs fabrication in order for the product to be competitive.

2) PUR and EPI adhesives provided effective bond under dry conditions in trembling aspen, achieving median BSS of 10.5 MPa with a mean WFP of 81.7%, and 10.3 MPa with a WFP of 77.7%, respectively. Both bond performance under vacuum-pressure-soak conditions was sub-optimal.

3) Approximately 37% of trembling aspen lumber can achieve the 1450f-1.3E grade for MSR lumber, while 59% can qualify for the 1200f-1.2E grade. Theoretically, 57% of trembling aspen lumber was suitable for producing E1 grade CLT.

4) The oven-dried SG of trembling aspen wood sampled from Northern Alberta was within the range of 0.40 - 0.46, approximately 5% to 16.1% higher than the value reported in the Wood Handbook.

► For trembling aspen finger-jointed lumber:

5) The finger-jointed trembling aspen lumber improved the mean MOE by 12.4% and the 5^{th} percentile UTS by 14.0% in No. 2 grade trembling aspen lumber by removing large knots. However, for SS-grade lumber, the finger-jointed aspen had no improvement in mean MOE, and the 5^{th} percentile UTS was 15.3% lower than that of solid lumber.

► For trembling aspen CLT:

6) The five-layer trembling aspen CLT specimens exhibited mean $(EI)_{eff,f,0}$ and $(EI)_{eff,f,90}$ values of 5,069×10^9 N·mm²/m and 1,193×10^9 N·mm²/m, exceeding grade E1 standards by 17.8% and 29.8%, respectively, as per ANSI/APA PRG-320. The three-layer specimens showed $(EI)_{eff,f,0}$ and $(EI)_{eff,f,90}$ values of 1,076×10^9 N·mm²/m and 54×10^9 N·mm²/m, with a 1.1% decrease and 40.7% increase, respectively. Only the five-layer minor-strength CLT met the characteristic $(F_bS)_{eff,f,90}$ for grade E1, exceeding the reference by 73.7%. The three-layer and five-layer major-strength characteristic $(F_bS)_{eff,f,0}$ fell short of the reference by 22.4% and 4.3%, respectively.

7) The test results indicated that trembling aspen CLT achieved a mean rolling shear modulus of 106 MPa and a characteristic rolling shear strength of 0.76 MPa. In short-span centre-point bending, both five- and three-layer trembling aspen CLT samples exceeded the shear resistance requirements for grade E1. The five-layer specimens showed $V_{s,0}$ and $V_{s,90}$ values exceeding requirements by 68.4% and 58.6%, respectively, while the three-layer surpassed $V_{s,0}$ by 73.7% and $V_{s,90}$ by 77.3%.

8) The WFP and RD results for all types of CLT samples were substantially lower and higher than the corresponding requirements in ANSI/APA PRG-320. The results highlighted the need to develop commercial-use structural adhesives that are suitable for hardwoods. Consequently, a significant challenge in using hardwoods for manufacturing EWPs is the development of adhesives capable of providing strong and durable bonds.

► For trembling aspen Glulam:

9) The materials were selected to meet the target grade of “20f-E S-P” in accordance with CSA O86. The test results exhibited the mean MOE_{app} was 12,315 MPa, exceeded the standard by 16.4%. Additionally, the characteristic MOR of the tested specimens was 27.00 MPa, surpassed the CSA O86 specifications for the grade by 1.2%.

► For trembling aspen Wood I-joist:

10) The wood I-joists were selected to meet the target grade of PKI-35 PLUS-10 (as specified by Pinkwood Ltd.). The mean $(EI)_{eff}$ of the wood I-joists reached 899×10^6 kN·mm^2, exceeding the target grade by 25.4%. Additionally, the characteristic Mr of the test specimens was 9,730 kN·mm, surpassing the grade requirement by 24.0%.

9. FUTURE WORK AND RECOMMENDATIONS

This study provides reliable test data and calculations supporting the feasibility and potential of using trembling aspen from Alberta to produce high-value EWPs. Further research is recommended to establish a more comprehensive technical foundation, enabling the formal market recognition and application of EWPs made from trembling aspen in construction, thereby creating significant economic value. The recommended additional work includes the following:

(1) Collaborate with adhesive manufacturers to conduct further research with the goal of identifying optimum industrial adhesives suitable for hardwoods, specifically trembling aspen.
(2) Expand the current work to fabricate a broader range of glulam, CLT and wood I-joist grades and sizes, to further support the use of trembling aspen lumber in producing these products in Alberta.
(3) Develop a broader database of structural properties of trembling aspen lumber, including shear strength, compression perpendicular to grain strength and connection strength.
(4) Test for additional lumber material properties, including compressive strength parallel to grain and perpendicular to the grain, and shear parallel to grain.
(5) Promote aspen-based EWP as a highly engineered, green product that is suitable for low-rise and mid-rise residential and non-residential building applications.

REFERENCES

Alberta's Forest Economy (2021). A Handbook of Public Economic and Socioeconomic Accounts. Alberta Agriculture and Forestry. ISBN 978-1-4601-5172-3.

American Forest & Paper Association (AF&PA). (2018). National Design Specification (NDS) Supplement: Design Values for Wood Construction 2018 Edition. American Wood Council. Leesburg, VA, USA.

American Society for Testing Materials. (2020). Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Based Materials (ASTM D4442-07). ASTM, Philadelphia, PA, USA.

American Society for Testing Materials. (2022). Standard Test Methods of Static Tests of Lumber in Structural Sizes (ASTM D198-22a). ASTM, Philadelphia, PA, USA.

American Society of Testing and Materials (ASTM). (2019). Standard Practice for Establishing Allowable Properties for Visually Graded Dimension Lumber from In-Grade Tests of Full-Size Specimens. (ASTM D1990-19). ASTM, Philadelphia, PA, USA.

American Society of Testing and Materials (ASTM). (2019). Standard Specification for Establishing and Monitoring Structural Capacities of Prefabricated Wood I-Joists. (ASTM D5055-2019). ASTM, Philadelphia, PA, USA.

American Society of Testing and Materials (ASTM). (2021). Standard Test Method for Evaluating Structural Adhesives for Finger Jointing Lumber. (ASTM D4688-21). ASTM, Philadelphia, PA, USA.

APA - The Engineered Wood Association. (2017). American National Standard for Structural Glued Laminated Timber. ANSI A190.1-17. APA - The Engineered Wood Association, Tacoma, WA, USA.

APA - The Engineered Wood Association. (2019). Standard for performance-rated cross-laminated timber. ANSI/APA PRG 320-19. APA - The Engineered Wood Association, Tacoma, WA, USA.

APA - The Engineered Wood Association. (2021). Performance rated I-joists. APA PRI-400-21. APA - The Engineered Wood Association, Tacoma, WA, USA.

Balatinecz, J. J., & Kretschmann, D. E. (2001). Properties and utilization of poplar wood. Poplar Culture in North America, (Part A), 277-291.

Barrett, J. D., & Hejja A. (1984). Compression strength of Canadian softwood lumber. Forintek Canada Corp. Western Laboratory 6620 N.W. Marine Drive Vancouver, BC, Canada.

Biechele, T., Chui, Y. H., & Gong, M. (2011). Comparison of NDE techniques for assessing mechanical properties of unjointed and finger-joined lumber. Holzforschung, 65, 397-401.

Boström L. (1994). Machine strength grading. Comparison of four different systems. Swedish National Testing and Research Institute, Building Technology, SP Report 1994: 49.

Canadian Standards Association (CSA). (2021). Evaluation of adhesives for structural wood products (exterior exposure). CAN/CSA-O112.9-21, Canadian Standards Association, Ottawa, Ontario, Canada.

Canadian Standards Association (CSA). (2016). Structural glued-laminated timber. CAN/CSA-O122-16, Canadian Standards Association, Ottawa, Ontario, Canada.

Canadian Standards Association (CSA). (2024). Engineering design in Wood. CAN/CSA-O86-24, Canadian Standard Association. Ottawa, Ontario, Canada.

Canadian Wood Council (CWC). (1994). Canadian Lumber Properties. Canadian Wood Council, Ottawa, ON, Canada.

CCMC. (2020). Pinkwood PKI 10, PKI 20, PKI 23, PKI 35 Plus, PKI 40 and PKI 50 Series I-Joists and WEBshield®. Evaluation Report CCMC 14001-R. Canadian Construction Materials Centre, NRC, Ottawa, ON.

Dickmann, D. I., Isebrands, J. G., Eckenwalder, J. E., & Richardson, J. (Eds.). (2001). Poplar Culture in North America. NRC Research Press, Ottawa, ON, Canada.

Fan, S., Wong, S. W., & Zidek, J. V. (2023). Knots and their effect on the tensile strength of lumber: A case study. Journal of Quality Technology, 1-13.

Gong, M. (2021). Wood and Engineered Wood Products: Stress and Deformation. In Engineered Wood Products for Construction. IntechOpen. https://doi.org/10.5772/intechopen.101199. (accessed August 15, 2024).

Gong, M., Tu, D., Li, L., & Chui, Y. H. (2015). Planar shear properties of hardwood cross layer in hybrid cross laminated timber. ISCHP 2015, 85-90.

Gray, J. D., Grushecky, S. T., & Armstrong, J. P. (2008) Stress wave velocity and dynamic modulus of elasticity of yellow poplar ranging from 100 to 10 percent moisture content. In: Proceedings of the 16th Central Hardwoods Forest Conference. GTRNRS- P-24. Eds.

Green, D. W., & Evans, J. W. (1987). Mechanical properties of visually graded lumber. US Department of Agriculture, Forest Service, Forest Products Laboratory.

Haygreen, J. G., & Bowyer, J. L. (1996) Forest Products and Wood Science. 3rd Edition, Iowa State University Press, Iowa City, 243-247.

Heräjärvi, H., & Junkkonen, R. (2006). Wood density and growth rate of European and hybrid aspen in Southern Finland. Baltic Forestry, 12, 2-8.

Hiratsuka, Y. & Loman, A. A. (1984). Decay of Aspen and Balsam Poplar in Alberta; Information Report, NOR-X-262; Northern Forest Research Centre: Edmonton, AB, Canada.

Hittenrauch, H. R. (1976). Response of aspen to various harvest techniques. Utilization and marketing as tools for aspen management in the Rocky Mountains. USDA For. Serv. Gen. Tech. Rep. RM-29, 41-44.

Hosie, R. C. (1979). Native trees of Canada. Fitzhenry & Whiteside. Don Mills, Ontario, Canada.

Kretschmann, D. E. (1999). Structural lumber properties of hybrid poplar (Vol. 573). US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, USA.

Kreuzinger, H. (1999). Platten, Scheiben und Schalen–ein Berechnungsmodell für gängige statikprogramme. Bauen mit holz, 1(99), 34-39.

Kurt, R. (2006). Effect of glue line thickness on shear strength of wood-to-wood joints. Wood Research. 51, 59-66.

Malaga-Tobola, U., Lapka, M., Tabor, S., Nieslony, A., & Findura, P. (2019). Influence of wood anisotropy on its mechanical properties in relation to the scale effect. International Agrophysics, 33(3), 337-345.

McKeever, T., & Spelter, H. (1998). Wood-based panel plant locations and timber availability in selected U.S. states. Gen. Tech. Rep. FPL–GTR–103. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, USA.

Morley, P. M. (1986). Management and use of aspen poplar in North America. The Forestry Chronicle, 62(2), 104-107.

Muthumala, C. K., Arunakumara, K., De Silva, S., & Alwis, P. (2022). Evaluation of the Flexural Strength and Failure Modes of Seven Types of Finger Jointed Wood Species. Journal of Failure Analysis and Prevention, 22(2), 680-689.

National Lumber Grades Authority (NLGA). (2019). Grading rules for Canadian lumber National Lumber Grades Authority, New Westminster, BC, Canada.

National Lumber Grades Authority (NLGA). (2019). SPS-2. Special Products Standard for Machine Graded Lumber. National Lumber Grades Authority, New Westminster, BC, Canada.

Oscarsson, J., Olsson, A., Johansson, M., Enquist, B., & Serrano, E. (2010). Strength grading of wet Norway spruce side boards for use as laminations in wet-glued laminated beams. In The final conference of COST action E53, 4-7 May 2010, Edinburgh, Scotland, UK.

Panshin, A. J., & de Zeeuw, C. (1981). Textbook of wood technology. 4th Ed. New York: McGraw Hill.

Perala, D. A., Burns, R. M., & Honkala, B. (1990). *Populus tremuloicies Michx*.- Quaking Aspen. Silvics of North America: Hardwoods; Burns, RM, Honkala, BH, Eds, 555-569.

Ross, R. J., & Pellerin, R. F. (1994). Non-destructive testing for assessing wood members in structures. Forest Products Laboratory, Madison, WI, USA.

Sandoz, J. L. (1993) Moisture content and temperature effect on ultrasound timber grading. Wood Sci. Technol. 23:95–108.

Senalik, C. A., & Farber, B. (2021). Chapter 5: Mechanical properties of wood. In: Wood handbook wood as an engineering material. General Technical Report FPL-GTR-282. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. pp-46.

Smith, I., & Chui, Y. H. (1994). Derivation of machine settings in machine-controlled stress grading of lumber: some statistical considerations. Journal of Institute of Wood Science 13(4): 449-454.

Stamm, A. J. (1964). Wood and cellulose science. New York, NY: Ronald Press. pp. 549.

Surmiński, J. (1976). Technical properties and uses of poplar wood. The Poplars (*Populus* L.), 12, 385.

Timbolmas, C., Rescalvo, F. J., Portela, M., & Bravo, R. (2022). Analysis of poplar timber finger joints by means of Digital Image Correlation (DIC) and finite element simulation subjected to tension loading. European Journal of Wood and Wood Products, 80(3), 555-567.

Van Acker, J. (2021). Opportunities and challenges for hardwood based engineered wood products. Proceedings of the 9th Hardwood Proceedings Part II, 5.

Wang, Z., Zhou, J., Dong, W., Yao, Y., & Gong, M. (2018). Influence of technical characteristics on the rolling shear properties of cross laminated timber by modified planar shear tests. Maderas. Ciencia y tecnología, 20(3), 469-478.

Youngquist, J. A., & Spelter, H. (1990). Aspen wood products utilization: impact of the Lake States composites industry. NC–GTR–140. Aspen symposium 89. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 91-102.

APPENDIX I – **Tables and Diagrams Illustrating the Differences in SG, MOE and UTS of Trembling Aspen Lumber Sampled from Alberta and Saskatchewan**

Table I.1 – Comparison of physical properties (MC & SG) between Alberta and Saskatchewan provinces.

Note: The value in parathesis stands for the coefficient of variation.

Lumber	Lumber from Alberta			Lumber from Saskatchewan		
	Count	MC (%)	SG	Count	MC (%)	SG
SS-Grade	168	7.6 (9.27%)	0.42 (7.63%)	98	10.1 (4.78%)	0.45 (9.62%)
No. 2-Grade	200	7.0 (7.28%)	0.42 (8.90%)	107	10.7 (3.91%)	0.45 (8.07%)
Sum	368	7.3 (9.42%)	0.42 (8.34%)	205	10.4 (4.99%)	0.45 (8.82%)

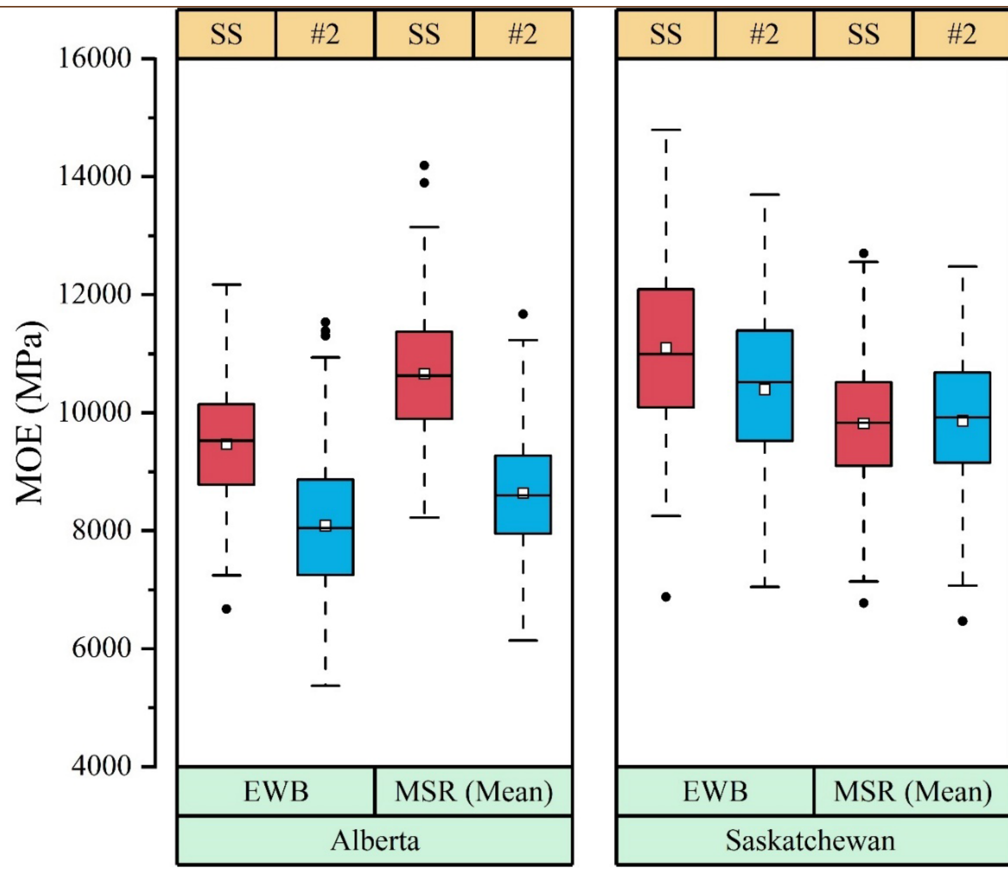


Figure I.1 – Comparison of the mean MOE between two grades (SS-red, No. 2-blue) of EWB and MSR methods across two provinces.

Table I-2 - Saskatchewan lumber MOE tested results.

Method	Index	Static Data for Groups	
		SS-Grade	No. 2-Grade
EWB	Mean MOE (MPa)	11,096 (13.45%)	10,393 (13.21%)
	Fifth Percentile MOE (MPa)	8,641	8,135
MSR	Mean MOE (MPa)	9,782 (11.81%)	9,864 (12.19%)
	Fifth Percentile MOE (MPa)	7,882	7,887

Note: The value in parathesis stands for the coefficient of variation.

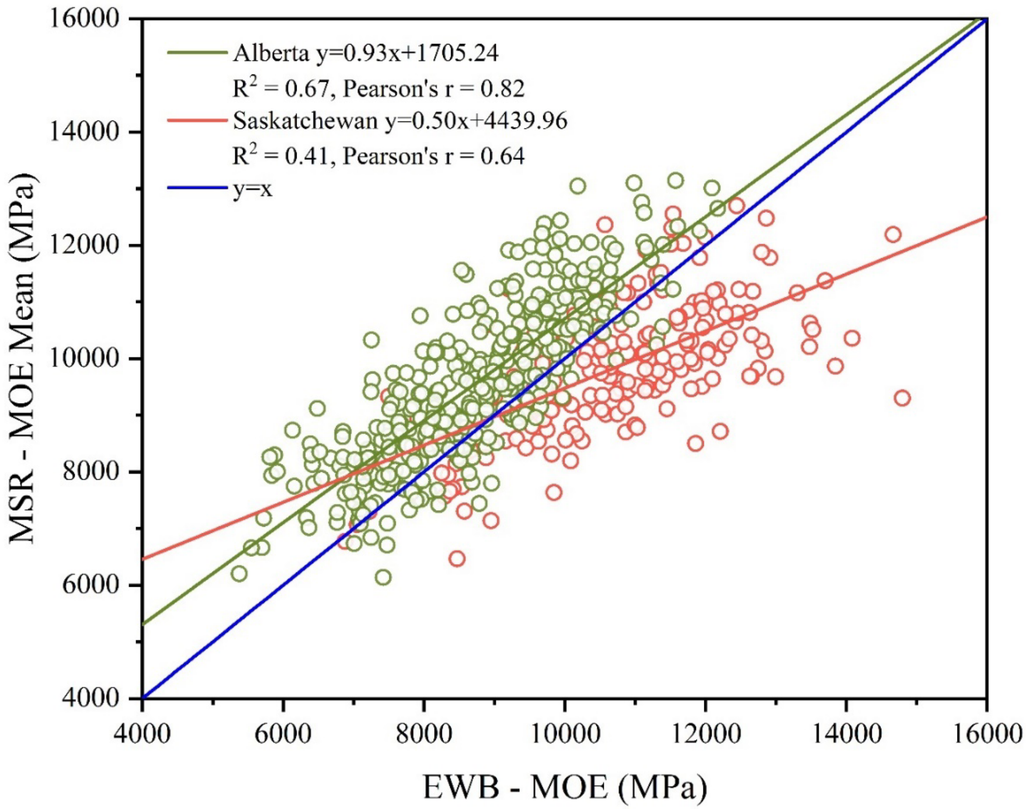


Figure I.2 - Relationships of the mean MOE values between the EWB and MSR methods based on two provinces.

Table I-3 – Saskatchewan lumber UTS tested results.

Index	SS-Grade	No. 2-Grade
Mean UTS (MPa)	37.01 (39.36%)	29.65 (42.06%)
Fifth Percentile UTS (MPa)	14.72	14.88
Count (Pcs.)	98	107

Note: The value in parathesis stands for the coefficient of variation.

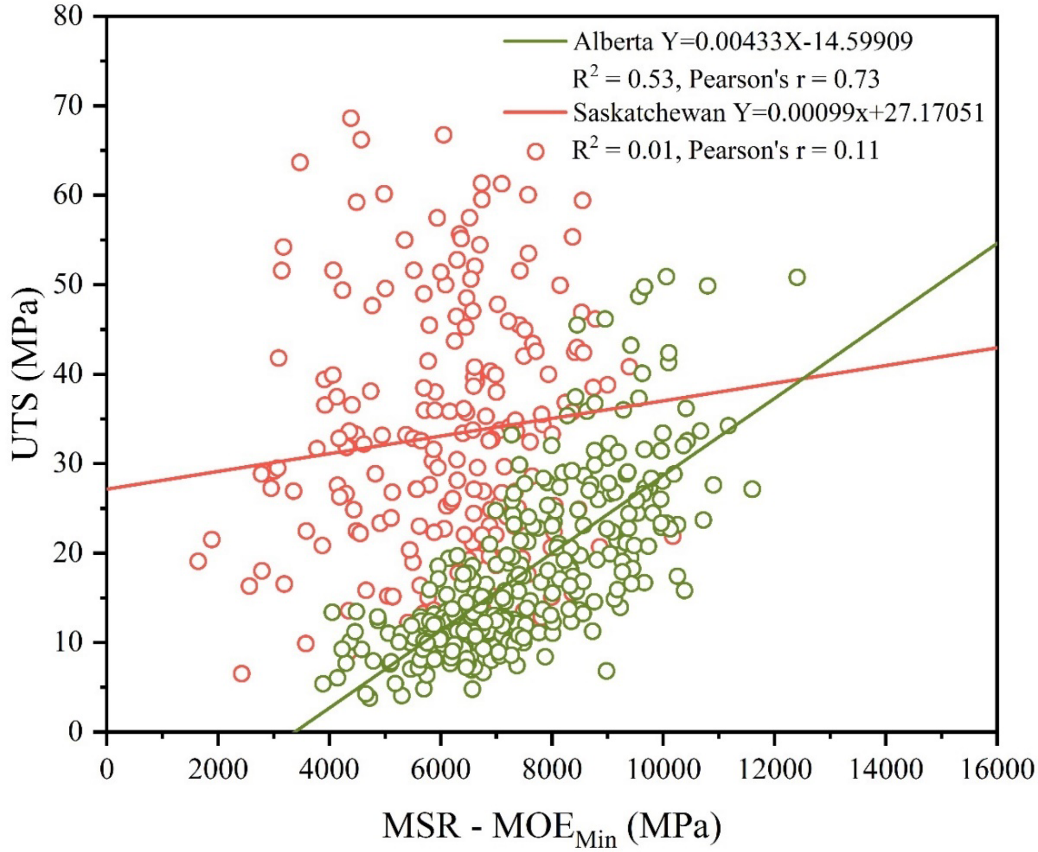
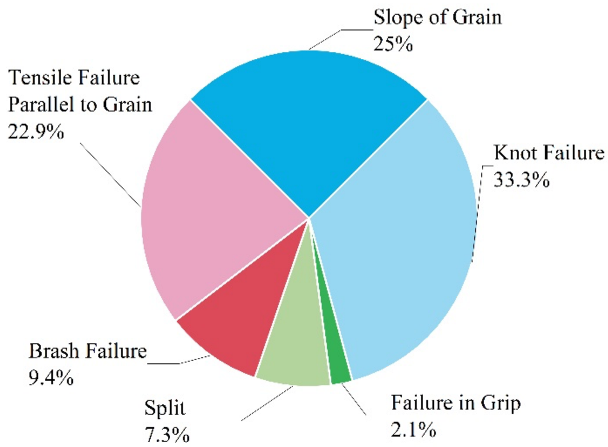


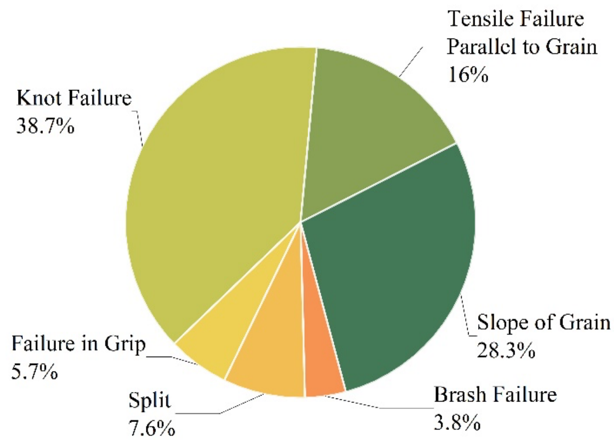
Figure I.3 - The relationship between UTS and MSR MOE_{min} based on two provinces test results.

Table I.4 - Comparison of the MOE (EWB method) and UTS between Saskatchewan aspen lumber and the in-grade results of S-P-F lumber.

Property	Grade	Sample Size (Pcs.)		Mean (MPa)			Fifth Percentile (MPa)		
		Aspen	S-P-F	Aspen	S-P-F	Ratio	Aspen	S-P-F	Ratio
MOE	SS	98	441	11,096	10,730	1.03	8,641	7,520	1.15
	No. 2	107	440	10,393	9,490	1.10	8,135	6,090	1.34
UTS	SS	98	440	37.01	30.86	1.20	14.72	14.88	0.99
	No. 2	107	444	29.65	23.27	1.27	13.05	9.11	1.43



(a)



(b)

Figure I.4 – (a) Failure modes and proportion of ss-grade aspen lumber tested from Saskatchewan; (b) Failure modes and proportion of No. 2 grade aspen lumber tested from Saskatchewan.

(a)

(b)

Figure I.5 – (a) Knot Failure; (b) Slope of Grain Failure.

Table I.5 - MSR settings and grade yields of Saskatchewan lumber based on MSR-MOE_{mean}.

Combination	High-Grade			Low-Grade			Reject (%)
	Grade	Setting (MPa)	Yield (%)	Grade	Setting (MPa)	Yield (%)	
1	1650f-1.5E	10,352	32	1450f-1.3E	9,005	48	20
2	1650f-1.5E	10,352	32	1350f-1.3E	9,005	48	20
3	1450f-1.3E	9,005	80	1200f-1.2E	8,318	12	8

Table I.6 - Grade yield analysis of Saskatchewan lumber for CLT manufacturing in accordance with PRG-320 standards, utilizing MSR-MOE_{mean}.

Grade	Major-Strength Direction			Minor-Strength Direction			Reject (%)
	Standard (MPa)	Setting (MPa)	Yield (%)	Standard (MPa)	Setting (MPa)	Yield (%)	
E1	11,700	11,785	6	9,000	9,005	80	14
E3	8,300	8,318	92	6,500	6,775	8	0

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