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USE OF TREMBLING ASPEN LUMBER TO PRODUCE GLUED-LAMINATED TIMBER BEAMS: BENDING PERFORMANCE

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ABSTRACT: Trembling aspen (*Populus tremuloides*) is recognized for its rapid growth and broad distribution across North America. Given its substantial standing volume in Alberta, Canada, this study investigated the feasibility of utilizing trembling aspen lumber for fabricating glued-laminated timber (glulam). A total of 10 full-scale, 13-layer glulam beams were fabricated using trembling aspen lumber sourced from northern Alberta, which was selected in terms of the modulus of elasticity with a longitudinal stress wave device. The moisture content, specific gravity, apparent modulus of elasticity (MOE_{app}), and modulus of rupture (MOR) of the beams were tested, and lumber yield was analysed. Static third-point bending tests were performed with reference to ASTM D198 standards, with failure modes being recorded. The results showed that 1) the mean MOE_{app} was 12,315 MPa, and the characteristic MOR was 27.00 MPa, meeting the "20f-E S-P" grade as specified in the CSA O86 standard; 2) two distinct failure modes were observed, 'failure by tension' and 'failure at finger joints', with the latter being dominant and 3) the overall estimated material yield of "No. 2 and Better" trembling aspen lumber into glulam beams was approximately 45.2%, accounting for all manufacturing-related factors.

KEYWORDS: Trembling aspen, glued-laminated timber, apparent modulus of elasticity, modulus of rupture, grade yield.

1 INTRODUCTION

Trembling aspen (*Populus tremuloides*), a hardwood species native to North America, grows alongside related species such as bigtooth aspen (*Populus grandidentata*), balsam poplar (*Populus balsamifera*), eastern cottonwood (*Populus deltoides*), and black cottonwood (*Populus trichocarpa*). It is primarily used in the production of oriented strand board (OSB) and pulp or paper [1-3]. The National Lumber Grades Authority (NLGA) classifies trembling aspen as a "Northern species", alongside western red cedar (*Thuja plicata*) and red pine (*Pinus resinosa*). Despite its rapid growth, ease of reproduction, and wide distribution, trembling aspen has limited structural applications due to inherent characteristics such as short fibres, high moisture content (MC), susceptibility to decay, and low durability [4]. These traits result in shorter rotation cycles, with trembling aspen reaching maturity in 55 years compared to black spruce (*Picea mariana*), which requires 105 years [5]. This faster growth enables greater raw material production over a shorter period. Trembling aspen yields 300 m³/ha with a 7.9% rejection rate over 55 years, while black spruce produces 250 m³/ha over 105 years with a rejection rate below 3.5% [5], indicating potential for structural use with appropriate engineering.

Despite these advantages, trembling aspen remains underutilized in production of engineered wood products (EWPs). Glued-laminated timber (glulam or GLT), a high-performance EWP commonly used in beams and columns [6-7], presents an opportunity for its utilization. Glulam is a timber product composed of dimension lumber laminations bonded with a structural adhesive

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under controlled conditions [8]. Glulam offers superior strength and flexibility compared to solid sawn timber and was first developed in Europe in the 1890s, with modern production commencing after a Swiss patent in 1901 [7]. It consists of sawn lumber laminations (lamstock) commonly bonded with one-component polyurethane (1C-PUR) [9-10], melamine formaldehyde (MF) [11], or phenol formaldehyde (PF) [12], with the grain oriented parallel to the beam length. Lamstock is visually graded and mechanically tested, and finger-jointing is frequently employed to achieve desired lengths. Higher-grade lumber is placed in tension and compression zones, while lower-grade lumber is positioned near the neutral axis [3,7], enhancing structural performance and material efficiency. In North America, glulam production predominantly utilizes softwoods like Douglas fir (*Pseudotsuga menziesii*) [13], lodgepole pine (*Pinus contorta*) [14], and eastern hemlock (*Tsuga canadensis*) [15-16], valued for their decay resistance, strong adhesion, nail-holding capacity, and ease of finishing [8]. Glulam maintains a significant market share in North America due to consistent construction demand [17]. Incorporating affordable hardwoods into glulam production could expand material options, improve hardwood utilization, and support local forest resources.

Canada possesses 347.7 million hectares of forest, primarily composed of spruces (53.2%), poplars (11.6%), and pines (9.3%) [18], offering a substantial *Populus* reserve. In 2020, the hardwood supply and harvest, mainly *Populus* species, reached 56.4 million m^3 and 25.5 million m^3, respectively, which were 64.3% and 77.9% lower than corresponding softwood figures [19], highlighting underutilization. The Canadian government plans to adjust sustainable supply strategies to enhance forest management and meet the rising demand for hardwoods [20-21]. In Alberta, hardwoods account for 40% of forest resources, with trembling aspen comprising 80% of this volume [22], emphasizing the need for efficient harvesting and utilization.

Research on trembling aspen glulam remains limited. Legrais et al. [23] evaluated its bending properties following ASTM D198 [24] and CSA O122 [25] standards, reporting a mean modulus of rupture (MOR) of 30.3 MPa and a mean apparent modulus of elasticity (MOE_{app}) of 9,013 MPa, both below the stipulated value in CSA O122 [25]. Silva et al. [26] investigated bonding performance using 1C-PUR, polyvinyl acetate (PVAc), and emulsion polymer isocyanate (EPI), with tests conducted under ASTM D905 [27] and CSA O122 [25]. Although micro-CT scans were used to assess glue lines, contrast issues limited their effectiveness. Trembling aspen bonded with 1C-PUR and EPI exhibited the delamination being less than 6% and shear strength exceeding 8.5 MPa. Monteiro et al. [28] studied hybrid poplar (*Populus × canadensis*, *Populus nigra*, *Populus alba*) glulam, testing 21 beams under four-point bending. The results showed a mean MOR of 55.3 MPa and an MOE_{app} of 10,533 MPa, with over 70% of specimens displaying ductile behavior. A 3D numerical model accurately predicted beam performance, supporting the use of hybrid poplar in glulam applications. Additional studies on hardwood glulam, including red maple (*Acer rubrum*) [29], red oak (*Quercus rubra*) [30], and yellow poplar (*Liriodendron tulipifera*) [31], were focused on bending strength capacity, a critical factor for structural applications.

This study was aimed at expanding the use of trembling aspen in glulam production, contributing to a more balanced hardwood supply and demand in Alberta, Canada, and enhancing the economic value of the wood industry. The bending performance of full-scale, 13-layer trembling aspen glulam was fabricated in an industry production line and evaluated, with particular focus on the mean MOE_{app} and characteristic MOR.

2 MATERIALS AND METHODS

2.1 MATERIALS

Kiln-dried "No. 2 and Better" trembling aspen lumber, visually graded according to NLGA rules [32], with dimensions of 38 mm × 89 mm (nominal 2 in. × 4 in.) and a length of 2,667 mm (8.75 ft.), was sourced from a sawmill in La Crete, Alberta, Canada, for glulam beam production. The longitudinal stress wave (LSW) method, a non-destructive technique, was employed on-site to sort the lumber based on the dynamic modulus of elasticity (MOE_d) readings, using a commercial handheld stiffness grading device (Model: MTG-820) made by Brookhuis. Due to the portability of the LSW device and previous studies demonstrating its efficiency [33], which is comparable to machine stress rated (MSR) grading and static bending tests, MOE_d was selected as the sorting parameter in this study.

A total of 630 trembling aspen lumber pieces were selected for fabricating a total of 10 full-scale glulam beams. The lumber was assigned to specific layers, identified as the "outer 1/8 layer," "outer 1/4 layer," and "inner layer," based on visual appearance and MOE_d readings, following the guidelines outlined in the CSA

O122 [25]. The MOE_d requirements, sorting criteria, and lumber quantities for manufacturing glulam beams are presented in Table 1. MOE_{min} represents the minimum MOE of lumber laminate required by CSA O122 [25].

Table 1: The laminate and quantity requirements of trembling aspen lumber for making glulam beams.

		Requirement by CSA O122	In-mill Sorting Criteria	Quantity (Pcs.)
Glulam	Outer 1/8-Layers	$MOE_{min.}$ = 11,000 MPa	$MOE_{d,min.} \geq$ 11,000 MPa	140
	Outer 1/4-Layers	$MOE_{min.}$ = 9,700 MPa	$MOE_{d,min.} \geq$ 10,500 MPa	230
	Inner Layers	No requirement for MOE_{min}	Visual Grade "No. 2 & Better."	260
Total				630

An industrially modified MF adhesive was used for making glulam beams in a production line. The selected trembling aspen lumber was processed at Western Archrib in Edmonton, Alberta, following the CSA O122 [25].

2.2 MANUFACTURING

A total of 10 full-scale 13-layer glulam beams were manufactured, which were targeted to a grade equivalent to "20f-E Spruce-Pine (S-P)" in accordance with CSA O122 [25]. Table 2 gives the grade requirement for each layer. Table 3 provides the dimensions and quantity of the glulam beams.

For production, the lumber was conditioned to an average MC of 10% and visually re-graded by the manufacturer to ensure compliance with specifications for the inner and outer layers, maintaining consistency with the target grade. This process resulted in a total rejection rate of 9%. During re-grading of lumber, "skip and miss" defects were identified on the wide face. The lumber was planed to a thickness of 35 mm, ensuring a uniform surface before finger-jointing and the final gluing process. Quality control was performed by the manufacturer.

After fabrication, the beams were securely packed and shipped to the I. F. Morrison Structures Lab at the University of Alberta, Canada, for static third-point bending tests.

Table 2: Grades of layers for manufacturing glulam beams.

Layer #	Layup Requirement	Visual Grade
1	$MOE_{d,min} \geq$ 11,000 MPa	B
2	$MOE_{d,min} \geq$ 11,000 MPa	B
3	$MOE_{d,min} \geq$ 10,500 MPa	C
4	Visual No. 2 & Btr.	D
5	Visual No. 2 & Btr.	D
6	Visual No. 2 & Btr.	D
7	Visual No. 2 & Btr.	D
8	Visual No. 2 & Btr.	D
9	Visual No. 2 & Btr.	D
10	Visual No. 2 & Btr.	D
11	$MOE_{d,min} \geq$ 10,500 MPa	C
12	$MOE_{d,min} \geq$ 11,000 MPa	B
13	$MOE_{d,min} \geq$ 11,000 MPa	B-F

Table 3: Dimensions and quantity of glulam beam manufactured.

	Dimension						Quantity (Pcs.)
	Length		Width		Depth		
	mm	ft.	mm	in.	mm	in.	
Glulam	9,100	29.9	80	3.2	455	17.9	10

2.3 METHODS

2.3.1 Static third-point bending test

The destructive static third-point bending test was conducted on each glulam specimen in accordance with ASTM D198 [24], using a span-to-depth ratio of 18. The test schematic and practical setup are presented in Fig. 1 and Fig. 2. The primary objective was to evaluate the MOE_{app} and MOR of the trembling aspen glulam beams.

Four linear variable differential transformers (LVDTs) were installed along the neutral axis of each beam, with two positioned on either side of the geometric centre and one at each reaction point on one side. These LVDTs

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recorded displacement with a precision of 0.01 mm. The loading rate was set at 10 mm/min, resulting in a time to failure of each specimen ranging from 4 to 20 minutes. The data were logged at a frequency of 5 Hz, including load, cross-head movement, elapsed time, and four LVDTs' readings. To prevent lateral buckling, five lateral supports were installed along the compression edge of each beam. Failure modes were documented immediately after each specimen fractured.

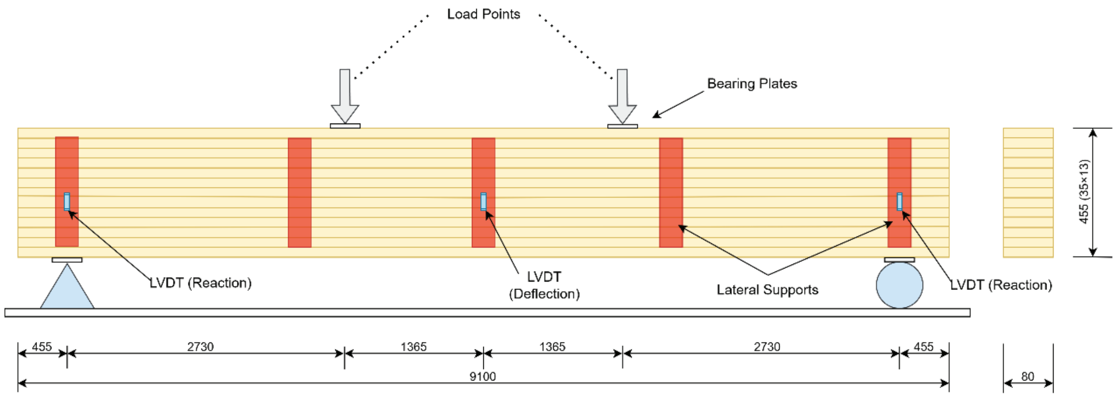

Figure 1: Schematic of testing a glulam beam under bending.

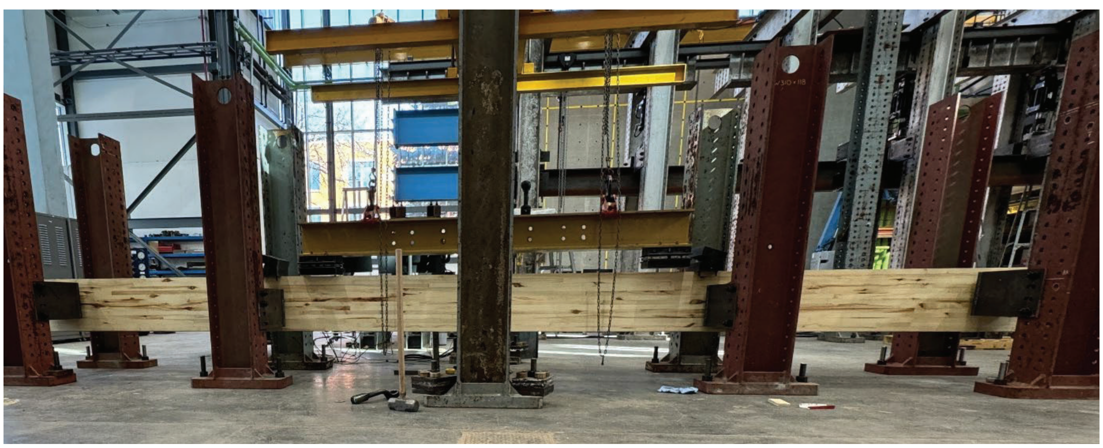

Figure 2: Setup for testing a glulam beam under bending.

2.3.2 Moisture content and specific gravity

Three (3) blocks were cut from each end as close as possible to the fractured area of a broken glulam beam directly after testing, generating a total of 60 blocks for testing MC and specific gravity (SG), which were immediately weighed using a high-precision balance. All the blocks were then well wrapped using plastic films and sent to the Wood Science and Technology Centre, the University of New Brunswick, Fredericton, Canada for analyzing. Upon arrival, each specimen was oven-dried and tested for MC and SG following ASTM D4442 [34] and ASTM D2395 [35], respectively. A total of 60 wood blocks were tested from the glulam beams to determine MC and SG.

2.4 CALCULATIONS

The experimental MOE_{app} and MOR values can be calculated using Equations (1) and (2):

$$MOE_{app} = \frac{23L^3}{108bt^3}\frac{P}{\Delta} \tag{1}$$

$$MOR = \frac{P_{max}L}{bt^2} \tag{2}$$

Where, L is the test span (mm), P is the applied load (N) corresponding to the linear portion of the load-deflection diagram, up to the ultimate load-resisting capacity (P_{max}), and Δ is the displacement (mm) measurement corresponding to P, b is the width of the specimen (mm), and t is the depth of the specimen (mm).

A glulam beam is composed of multiple layers with varying MOE layups. The composite beam theory can be employed to predict MOE ($E_{predict}$), as outlined in Equation (3) below:

$$E_{Predict} = \frac{\sum_{i=1}^{n}\left(E_i \cdot \frac{b_i \cdot t_i^3}{12}\right) + \sum_{i=1}^{n}(E_i \cdot b_i \cdot t_i \cdot z_i^2)}{I_{total}} \quad (3)$$

Where, E_i is the modulus of elasticity of the i-th lamina, bi is the width of the i-th lamina, and t_i is the thickness of the i-th lamina, Z_i is the distance between the centre-point of the i-th lamina and the overall neutral axis. I_{total} is the total sectional moment of inertia of a beam specimen [36]. The prediction of the MOR is complex due to the influence of multiple factors, such as top surface compression, bottom tension, knot characteristics on the beam's interior or surface, inter-laminate shear, and the quality of finger joints. Given these complexities, this study did not include calculation and/or discussion related to the prediction of the MOR of a glulam beam.

The mean absolute percentage error (MAPE) was introduced to evaluate the accuracy between the predicted value and test data, following Equation (4):

$$MAPE\ (\%) = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right| \times 100 \quad (4)$$

Where, A_t is the test value, F_t is the forecast value, and n is the total number of data. The MAPE measures the average magnitude of error produced by Equation (4), or how far off from the predicted value on average. The lower the MAPE values, the smaller the difference between tested and forecast values [37].

3 RESULTS AND DISCUSSION

3.1 MOISTURE CONTENT AND SPECIFIC GRAVITY

The MC and SG values tested are summarized in Table 4. The average MC was 11.4%, with a coefficient of variation (COV) of 8.61%. The average SG was 0.43, with a COV of 7.65%, which is 10.2% higher than the value reported in the Wood Handbook [38], adjusted from green to oven-dried conditions for comparison [38-39].

Table 4: Summary of MC and SG of glulam beams.

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

Note: The values in parentheses are the COV.

3.2 MECHANICAL RESPONSE AND FAILURE MODES

As shown in Fig. 3, the load-deflection curves illustrate the mechanical performance of the 10 glulam beams tested. The load at failure ranged from 55.9 to 85.1 kN, with an average of 69.5 kN and a COV of 13.07%. This variability is likely due to differences in material properties, manufacturing processes, and adhesive bonding or curing conditions. Deflection values ranged from 60.4 to 131.3 mm under loads between 61.9 kN and 79.3 kN, indicating further variation in deformation behaviour. These measures assist to better understand the mechanical performance of trembling aspen glulam beams.

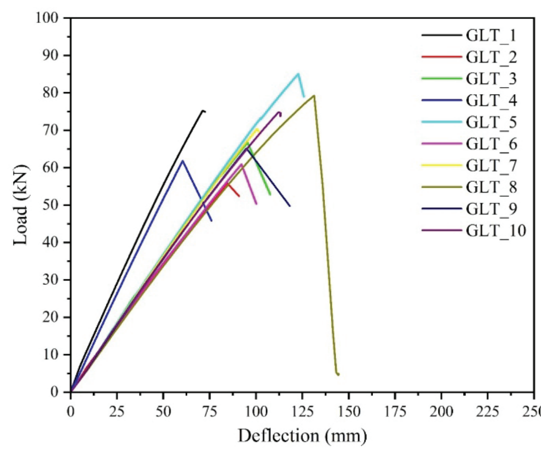

Figure 3: The load-deflection curves of glulam beams tested.

Failure modes were documented immediately after each beam failed, as shown in Fig. 4. Two distinct failure modes were observed: "failure by tension" and "failure at finger joints," with representative beams selected for each. It was found that 50% of the beams experienced wood fractures around natural defects, such as knots located either on the surface or within a beam. The remaining 50% of failure was primarily due to fracture near the finger joint(s). According to CSA O122 [25], the reference failure modes are detailed in Fig. 5. All finger-joint failure in this study was classified as Mode 4, characterized by predominantly tensile wood failure occurring at finger-joint roots or tips, with high percentage of wood failure.

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(a)

(b)

Figure 4: The typical failure modes of glulam beams: (a) Failure by tension (Specimen #2); and (b) Failure at finger-joints (Specimen #4).

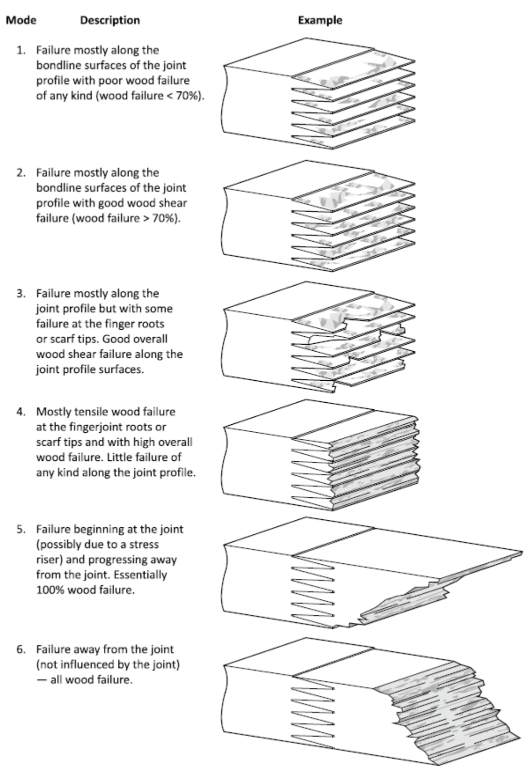

Figure 5: Classification of failure modes of finger-joint specimens referred from [25].

3.3 BENDING PROPERTIES

Table 5 summarizes the MOE_{app} and MOR of the glulam beams tested, which were calculated using Equations (1) and (2), respectively. According to CSA O86 [40], the specified values for "20f-E S-P" grade glulam are 10,300 MPa for MOE_{app} and 25.6 MPa for MOR. Similar to the "Qualification for Structural Performance" section on the cross-laminated timber from APA PRG-320 standard [41], where the specified bending moment resistance is divided by 0.96 to obtain the characteristic value, the characteristic MOR for glulam was calculated similarly, yielding 26.67 MPa (25.6 MPa / 0.96) in this study. This derived value can be directly compared with the characteristic value calculated from the testing. Based on the test results, the mean MOE_{app} was 12,315 MPa with a COV of 19.87%. Due to the limited number of glulam beams, a normal distribution model was applied to fit both MOE_{app} and MOR data with an aim to estimate the 5^{th} percentile value at a 75% confidence level using Minitab 21 software [42]. The lower 5^{th} percentile of MOR was determined to be 27.00 MPa, which can be considered the characteristic value.

A comparison between the grade requirements and test results shows that both the mean MOE_{app} and characteristic MOR of the glulam beams met the value of the glulam of "20f-E S-P" grade. Specifically, the mean MOE_{app} exceeded the required value by 16.4%, while the characteristic MOR just surpassed the target value by 1.2%. As discussed below, the observed failure modes were primarily associated with natural defects such as knots or weaknesses at the finger joint roots or tips. These findings align with those values reported in other relevant studies [29,43].

Table 5: Statistics summary of the glulam beams examined.

Mean MOE_{app} (MPa)		**Characteristic MOR (MPa)**	
Target value of '20f-E S-P' grade glulam	This study	Target value of '20f-E S-P' grade glulam	This study
10,300	12,315 (19.87%)	26.67	27.00

Note: The values in parentheses are the COV.

Table 6 presents a comparative analysis of glulam beams manufactured with various hardwood species, including trembling aspen, yellow poplar (*Liriodendron tulipifera*), red maple (*Acer rubrum*), and red oak (*Quercus rubra L.*), from the previous studies [29-31]. The outer 1/8 layers and outer 1/4 layers of these glulam beams were composed of E-rated lumber with MOE values exceeding

13,800 MPa and 12,400 MPa, respectively, in accordance with the grade requirements for glulam specified by ANSI A190.1 [44]. All cited studies used 2 × 4 hardwood lumber to fabricate the glulam beams, targeting an 8-layer configuration as outlined by ANSI A190.1 [44]. The MC during testing was controlled between 8% and 12%, ensuring minimal variation across groups. Bending tests were conducted following ANSI A190.1 [44] using a four-point bending method, with a span-to-depth ratio of at least 18 maintained in all tests to ensure the shear-free conditions. The glulam beams incorporated finger-jointed lumber, and width effects were disregarded in data comparisons. The results revealed that trembling aspen exhibited MOE_{app} that was comparable to those of other hardwood species listed in Table 6, despite its lower average SG (0.43). The difference in MOE_{app} ranged from 0.9% to 5.5%, suggesting that trembling aspen might offer an elasticity advantage relative to its density. The characteristic MOR of trembling aspen glulam beams in this study was 27.0% lower than that of yellow poplar and 34.8% lower than red maple, but 27.8% higher than red oak.

Table 6: Comparison of mean MOE_{app} and characteristic MOR values of hardwood glulam beams.

Source	Wood Species	Target Grade	Glulam Cross-Sectional dimension (mm)	No. of Layers	Span-to-depth Ratio	Moisture Content (%)	Mean MOE_{app} (MPa)	Characteristic MOR (MPa)
This Study	Trembling Aspen	20f-E S-P [25]	80 × 455	13	18	11.4	12,315	27.0
Moody et al. [31]	Yellow Poplar	24f-1.8E [44]	76 × 305	8	28	8.2	13,031	37.0
Janowiak et al. [29]	Red Maple				19	12.6	12,204	41.4
Shedlauskas et al. [30]	Red Oak				18	12.8	12,962	19.5

3.4 COMPARISON OF MOE_{app} BETWEEN EXPERIMENTAL RESULTS, AND THEORETICALLY PREDICTED AND STANDARD-STIPULATED VALUES

Fig. 6 presents the MOE_{app} values of the glulam beams studied. Using the fixed minimum lay-up requirements from Table 2 and the defined glulam cross-section, the $E_{predict}$ was calculated based on the $MOE_{d,min}$ of each lamina, as outlined in Equation (3). The $E_{predict}$ was 10,078 MPa, which is slightly below 10,300 MPa, the target value of “20f-E S-P” grade glulam. However, the experimental results of glulam beams exceeded both the predicted value and the “20f-E S-P” grade stipulated value. The lowest MOE_{app} tested just surpassed the value of “20f-E S-P” grade glulam by 2.2%, while the highest exceeded by 40.1%. To evaluate the accuracy of Equation (3), the mean absolute percentage error (MAPE) was introduced and calculated using Equation (4), considering the uncertainty of applying Equation (3) to trembling aspen glulam beams. According to the criteria established by Gustriansyah et al. [45], a MAPE below 10% indicates high accuracy, while values between 10% and 20% are considered good. The calculated MAPE in this study is 15.80%, confirming that Equation (3) provides a good model for forecasting the $E_{predict}$ of trembling aspen glulam beams when the $MOE_{d,min}$ value of each lamina is accurately specified.

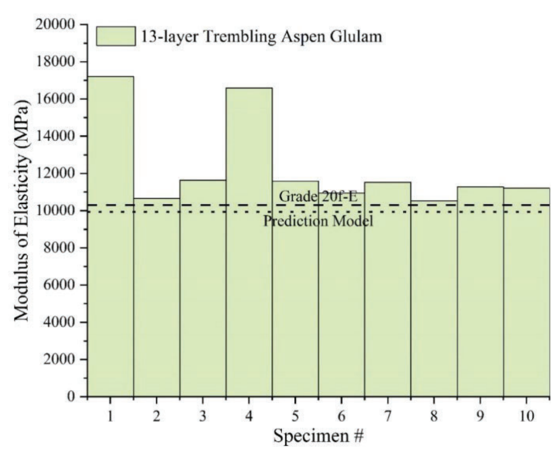

Figure 6: MOE_{app} values of trembling aspen glulam beams studied.

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3.5 LUMBER YIELD

The production flowchart is presented in Fig. 7. The sawmill reported a yield of 51.2% from log to lumber. Using the LSW method combined with visual inspection, 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. The manufacturer reported that approximately 9% of the lumber was rejected during lamination re-grading, with an additional 3% lost during the finger-jointing process. Taking these material losses into account, the yield from logs to different layers varied: 12.7% for the outer 1/8 layer, 19.5% for the outer 1/4 layer, and 13.0% for the inner layer, resulting in a total material yield of approximately 45.2%.

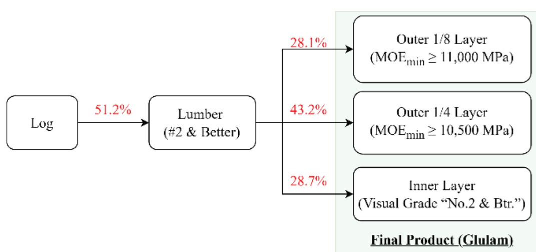

Figure 7: Estimation of the lumber yields for producing trembling aspen glulam beams.

4 CONCLUSIONS

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

1. The mean MOE_{app} and characteristic MOR of trembling aspen glulam beams were 12,315 MPa and 27.0 MPa, respectively, meeting the target value of "20f-E S-P" glulam specified in CSA O86. The MOE_{app} and MOR exceeded CSA O86 required values by 16.4% and 1.2%, respectively.
2. The mean MOE_{app} of trembling aspen glulam beams was 18.2% higher than the theoretically predicted value (10,078 MPa).
3. The material yields of trembling aspen lumber for glulam production were estimated at 12.7% for the outer 1/8 layer, 19.5% for the outer 1/4 layer, and 13.0% for the inner layer, with a total material yield of approximately 45.2% after accounting for all manufacturing-related factors.
4. The MAPE value of trembling aspen glulam beams examined in this study was 15.80% in terms of the composite beam theory, suggesting a good prediction of $E_{predict}$.

In conclusion, trembling aspen could be used to manufacture glulam beams that met the value of "20f-E S-P" glulam by properly selecting lumber based on MOE_d. Future research should explore alternative layer configurations and sizes to further optimize the structural performance of the glulam made with trembling aspen lumber.

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