Effect of Lumber Quality Grade on the Mechanical Properties and Product Costs of Cross-Laminated Timber Panels

Mahmut M. Bayramoglu ,[a,b] Aydin Demir ,[c] Abdullah Ugur Birinci ,[c] Hasan Ozturk ,[b,d] Okan Ilhan ,[c] Zeki Candan ,[e,f,*] and Cenk Demirkir ,[b,c]

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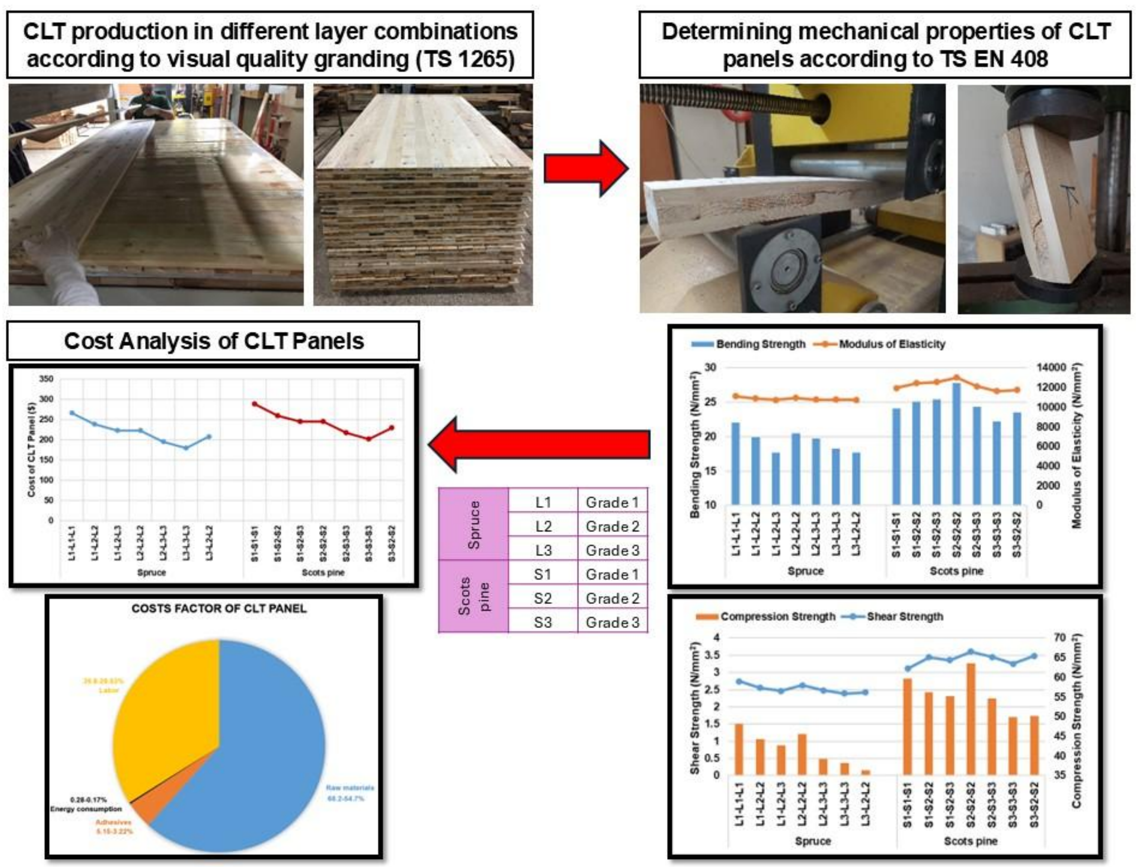
GRAPHICAL ABSTRACT



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This study aimed to investigate the effects of wood species and lumber quality grades on the mechanical properties and costs of cross-laminated timber (CLT) panels. Various combinations of lumber with different quality grades were utilized in the layers to identify the optimal configurations for producing CLT panels with high mechanical performance and low costs. In the study, spruce and Scots pine lumber of three different quality grades (Grades 1, 2, and 3), classified according to TS 1265 standards, were used. Some mechanical properties of the CLT panels produced from lumber of varying quality grades were determined following the TS EN 408 standard. Additionally, cost analyses of the CLT panels were conducted based on the calculation of raw material costs. The results show that while higher-grade lumber improves mechanical performance, lower-grade combinations still can meet structural needs at lower costs. Mixed-grade configurations offer a balance between strength and affordability. These findings can help CLT producers optimize material selection and reduce costs while maintaining structural integrity. Using lower-grade lumber can address shortages and reduce reliance on expensive timber. Policymakers can promote sustainable forestry and lower production costs, making mass timber construction more viable and environmentally sustainable.

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Keywords: Cross-laminated timber (CLT) panels; Engineered wood composites; Lumber quality grade; Mechanical properties; Cost analysis; Scots pine; Spruce; Sustainability

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INTRODUCTION

In recent years, the use of engineered wood composite products (EWP) has significantly increased worldwide, with many countries introducing regulatory incentives to promote lumber construction. The use of wood in construction has reached levels of approximately 45 to 70% in some regions of Europe, 45% in Japan, and up to 90% in North America (Nunes *et al.* 2020). Among the most preferred EWP are Cross-Laminated Timber (CLT), Glued Laminated Timber (Glulam), Dowel-Laminated Timber (DLT), Nail-

Laminated Timber (NLT), Laminated Veneer Lumber (LVL), and Mass Plywood Panel (MPP) (Ayanleye *et al.* 2022). Despite numerous advantages, such as low carbon emissions, short construction times, high structural performance, good seismic behavior, and sustainability, concerns over high raw material costs remain a barrier to the further growth of the mass timber industry. Ahmed and Arocho (2021) noted that the construction cost of a mass timber building is 6.43% higher compared to a modeled concrete alternative, with processed wood costs being the primary factor for this increase. A global CLT industry survey by Larasatie *et al.* (2020) indicated that participants from Central Europe, Asia-Pacific, and North America agreed that high material costs are a significant obstacle to industry growth. One of the most critical factors affecting material costs is the quality of the wood. Softwood species are generally used in mass timber production. Two standards are used to determine lumber quality: TS 1265 (2012) provides visual grading for construction purposes, while TS EN 338 (2016) assigns strength classes for structural lumber. In Turkey, timber procurement commonly relies on the visual grading method outlined in TS 1265 (2012), which classifies timber based on surface characteristics such as knots, grain deviation, cracks, and discoloration. This method is widely used due to its cost-effectiveness, rapid assessment process, and applicability in various settings without requiring specialized equipment. However, its subjectivity and reliance on external defects rather than direct mechanical property measurements present certain limitations. Despite these drawbacks, visual grading remains the preferred approach in the industry, significantly influencing lumber pricing. Although lumber prices are set according to visual grading (Grades 1, 2, and 3), the strength class defined by TS EN 338 (2016) is the primary factor for selecting wood in mass timber production. These classifications not only determine the quality of the wood but also significantly affect its market price.

The cost of wood is the main component in CLT production, sometimes estimated to account for nearly half of the total production expenses (Anderson 2016). Studies have shown that material costs contribute between 50% and 77% of the total CLT panel cost (Toosi 2011; Beck Group 2015). Another study indicated that fluctuations in lumber prices have the most significant impact on the final price of CLT panels (Brandt *et al.* 2019). Many studies have focused on optimizing CLT production costs, with findings consistently highlighting that raw material expenses account for the largest share of production expenditures (Toosi 2011; Brandt *et al.* 2019). In terms of mechanical properties, prior research has established that CLT panels made from higher-density or higher-grade lumber exhibit superior performance (Park *et al*. 2016, Kumar *et al*. 2022). Additionally, several studies have explored the feasibility of using lower-grade or underutilized wood species in CLT production to reduce costs while maintaining structural performance (Liao *et al.* 2017; Espinoza and Buehlmann 2018).

However, these studies primarily have relied on grading classifications used in Europe and North America, with limited research conducted under TS 1265 (2012) the standard applicable in Turkey. The primary contribution of this study is the provision of region-specific mechanical performance and cost data for spruce and Scots pine, two widely used softwood species in Turkey. While previous research has generally confirmed that higher-grade lumber leads to superior mechanical performance and lower-grade lumber reduces costs, this study goes further by examining how specific layer combinations of different quality grades can optimize both factors simultaneously. Notably, some layer configurations were found to meet structural requirements while significantly reducing costs, offering a strategic advantage for cost-effective CLT production.

While previous studies have extensively examined the relationship between lumber quality and CLT performance, this study introduces a novel approach by exploring cost-performance optimization through strategic layer configurations using visual grading classifications specific to Turkish standards (TS 1265). Unlike earlier research conducted predominantly under European and North American standards, this study addresses a notable gap by providing region-specific insights into the mechanical performance and cost efficiency of CLT panels manufactured with spruce and Scots pine—two widely used softwood species in Turkey. By evaluating the performance of different quality combinations in CLT layers, the study highlights potential configurations that meet structural requirements while significantly reducing costs. This innovative approach offers a practical solution to mitigate the high material costs that have been identified as a key barrier to the broader adoption of mass timber construction. The findings provide actionable insights for the Turkish timber industry and are expected to inspire similar strategies in other regions where visual grading methods like TS 1265 are widely employed.

Based on these considerations, this study examined the effects of wood species and visual quality grading (TS 1265, 2012) on the mechanical properties and production costs of CLT panels, specifically for spruce and Scots pine, under Turkish grading standards. Unlike previous studies that focused on generalized quality-performance relationships, this research provides region-specific insights by identifying optimal grade combinations that balance structural performance and cost efficiency. The findings contribute to the development of cost-effective CLT production strategies while supporting the sustainable utilization of lower-grade lumber in mass timber construction.

EXPERIMENTAL

Materials

Currently, spruce (*Picea orientalis* L.) and Scots pine (*Pinus sylvestris* L.) are among the primary softwood species used as raw materials for the commercial production of CLT panels (Srivaro *et al.* 2020).

In this study, these two species were selected. For each species, lumber with three different visual quality grades (Grade 1, 2, and 3) were sourced according to the TS 1265 (2012) standard. Each piece of lumber was planned on all four sides and dried to a moisture content of 12% ± 3%. Before CLT production, the lumber was dimensioned to sizes of 120 x 10 x 2.5 cm and 240 x 10 x 2.5 cm.

The lumber was organized into layer combinations based on visual quality grades to create three-layer CLT prototypes. The information regarding the test groups formed in the study is presented in Table 1.

A single-component polyurethane adhesive was used for bonding the draft panels, and 160 g/m² of adhesive solution was applied to the surfaces of the lumber. The pressing of the draft panels was carried out in industrial conditions using a hydraulic cold press capable of vertical and lateral pressing. The vertical pressing pressure was set at 0.8 N/mm², and to minimize gaps between lumber pieces, lateral pressing was applied with pressures ranging from 0.276 to 0.550 N/mm². For each test group formed based on the visual quality characteristics of spruce and Scots pine lumber, two CLT panels with dimensions of 240 x 120 x 7.5 cm were produced.

Table 1. Test Groups Formed According to Wood Species and Visual Quality Grades

Group No.	Wood Species	Lumber Quality Grade	Layer Combination (outer layer-core layer outer layer)
1	Spruce	Grade 1 - Grade 1 - Grade 1	L1-L1-L1
2		Grade 1 - Grade 2 - Grade 2	L1-L2-L2
3		Grade 1 - Grade 2 - Grade 3	L1-L2-L3
4		Grade 2 - Grade 2 - Grade 2	L2-L2-L2
5		Grade 2 - Grade 3 - Grade 3	L2-L3-L3
6		Grade 3 - Grade 3 - Grade 3	L3-L3-L3
7		Grade 3 - Grade 2 - Grade 2	L3-L2-L2
8	Scots pine	Grade 1 - Grade 1 - Grade 1	S1-S1-S1
9		Grade 1 - Grade 2 - Grade 2	S1-S2-S2
10		Grade 1 - Grade 2 - Grade 3	S1-S2-S3
11		Grade 2 - Grade 2 - Grade 2	S2-S2-S2
12		Grade 2 - Grade 3 - Grade 3	S2-S3-S3
13		Grade 3 - Grade 3 - Grade 3	S3-S3-S3
14		Grade 3 - Grade 2 - Grade 2	S3-S2-S2

Method

To determine the mechanical properties of the CLT panels produced from different wood species and quality grade combinations, tests for bending strength, modulus of elasticity in bending, shear strength parallel to the grain, and compressive strength parallel to the grain were conducted according to TS EN 408 (2016) standards. Six specimens were used for mechanical strength tests, and 20 specimens were used for density tests. The dimensions of the bending strength and modulus of elasticity samples were 1080 mm × 108 mm × 54 mm. The dimensions of shear strength parallel to the grain samples were 300 mm × 32 mm × 54 mm. The dimensions of compressive strength parallel to the grain samples were 324 mm × 108 mm × 54 mm. Prior to testing, the specimens were conditioned at 20 °C and 65% relative humidity.

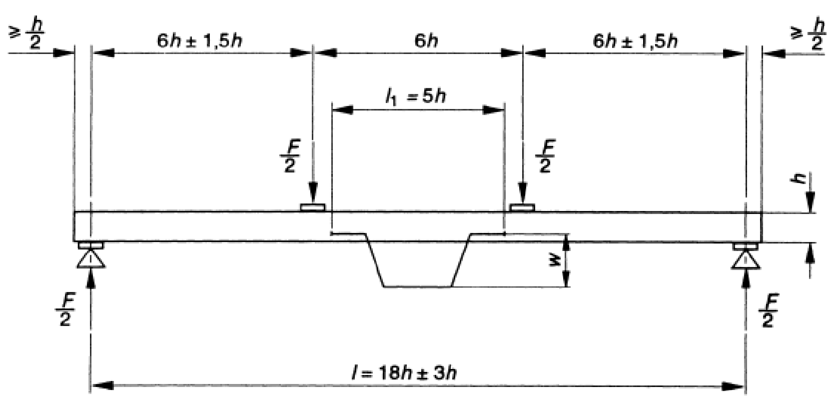

Fig. 1. Bending strength and modulus of elasticity test setup of CLT panels (TS EN 408, 2016)

Bending strength and modulus of elasticity are given by the equations,

$$Bending\ strength\ (N/mm^2) = \frac{FL}{bd^2} \tag{1}$$

$$\text{modulus of elasticity } (N/mm^2) : \frac{al_1^2(F_2-F_1)}{16I(w_2-w_1)} \quad (2)$$

where F is the load at a given point on the load deflection curve, in N, L is the support span, in mm, b is the width of test specimens, in mm, and d is the depth of test specimens, in mm.

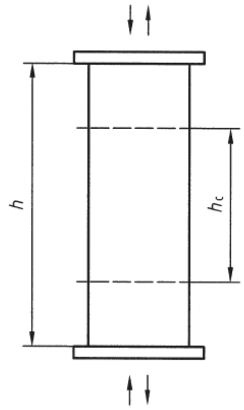

Fig. 2. Compressive strength parallel to the grain test setup of CLT panels (TS EN 408, 2016)

Compressive strength parallel to the grain is given by the equation,

$$\text{Compression strength (N/mm2)} = \frac{F_{max}}{A} \quad (3)$$

where F_{max} is the maximum load, in N, and A is the cross-sectional area, in mm^2.

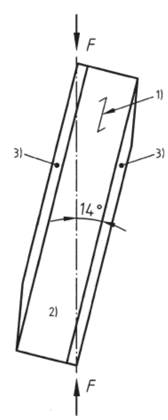

Fig. 3. Shear strength parallel to the grain test setup of CLT panels (TS EN 408, 2016)

Shear strength parallel to the grain f_v is given by the equation,

$$f_v = \frac{F_{max} cos14°}{\ell b} \quad (4)$$

where F_{max} = maximum load, in N, ℓ is the length of a test piece between the testing machine grips in compression and tension, in mm, b is the smaller dimension of the cross section, in mm.

The cost analysis of the CLT panels produced in this study was conducted based on the calculation of raw material costs. Labor and general production costs were assumed to be constant across all panel groups, ensuring that the specific effects of wood species and quality grade on costs could be accurately assessed.

In the calculation of the production costs of CLTs, raw material (glue and timber) amount, energy consumption, labor cost, and depreciation were used. Grades 1, 2, and 3 lumber were used in the cost calculation. The cost of the timber used in each layer was calculated by multiplying the amount of timber used according to the quality classes by the purchase price of the lumber. In each layer, 1.2 kg of adhesive was consumed. The cost of adhesive used in a layer was determined by multiplying the amount of consumption by the purchase price of adhesive. The hourly energy consumption of the pressing machine is 5.3 kWh. The pressing time of one sheet in the project was 40 min. The amount of energy consumed in pressing was calculated as 3.53 KW. In the production of CLT, two days of labor cost is included in the calculations. In this context, the cost of one worker was obtained by dividing the current minimum wage and social security premium by 30. After that, 10% depreciation was added to the obtained cost. Transportation and assembly costs are not included in the cost calculations.

RESULTS AND DISCUSSION

Mechanical Properties of Lumber Quality Grade

The density, bending strength and elastic modulus values of visually graded timber were determined according to the TS EN 408 (2016) standard and the average values are given in Table 2.

Table 2. Density, Bending Strength and Elastic Modulus Values of Lumber Quality Grade

Wood Species	Lumber Quality Grade	Density (g/cm³)	Bending Strength (N/mm²)	Modulus of Elasticity (N/mm²)
Spruce	Grade 1	0.309±0.06	25.4±0.97	11287±846
	Grade 2	0.305±0.08	22.99±1.23	11039±653
	Grade 3	0.297±0.05	20.82±1.76	10606±720
Scots pine	Grade 1	0.470±0.09	26.85±2.04	11635±780
	Grade 2	0.484±0.08	32.32±1.98	13450±460
	Grade 3	0.466±0.07	30.38±2.56	12767±840

Table 2 provides the density, bending strength, and modulus of elasticity (MOE) of visually graded spruce and Scots pine lumber. Scots pine exhibited superior mechanical properties compared to spruce across all grades. While higher-grade lumber generally demonstrates better properties, some variations are observed, particularly in Scots pine, where Grade 2 showed the highest MOE and bending strength. These findings highlight the significance of visual grading in timber classification and its relevance to structural applications.

Mechanical Properties of CLT Panels

The mean, standard deviation (Std) and coefficient of variation (CoV) values of the density and some mechanical properties of CLT panels produced from different timber quality class combinations are given in Table 3.

Table 3. Findings for Density and Some Mechanical Properties of CLT Panels

Wood Species	Group	Density (g/cm³)			Bending Strength (N/mm²)			Modulus of Elasticity (N/mm²)			Shear Strength (N/mm²)			Compression Strength (N/mm²)		
		Mean	Std.	CoV	Mean	Std.	CoV	Mean	Std.	CoV	Mean	Std.	CoV	Mean	Std.	CoV
Spruce	L1-L1-L1	0.471	0.017	3.61	22.03	1.26	5.72	11123	557	5.01	2.74	0.15	5.44	48.21	4.15	8.61
	L1-L2-L2	0.457	0.021	4.60	19.88	1.54	7.75	10883	653	6.00	2.55	0.14	5.69	44.33	3.25	7.33
	L1-L2-L3	0.461	0.008	1.74	17.65	1.34	7.59	10751	462	4.30	2.46	0.25	10.24	42.66	2.86	6.70
	L2-L2-L2	0.454	0.012	2.64	20.52	1.42	6.92	10963	498	4.54	2.63	0.34	13.12	45.56	4.56	10.01
	L2-L3-L3	0.463	0.005	1.08	19.74	1.05	5.32	10792	512	4.74	2.48	0.18	7.50	39.26	2.96	7.54
	L3-L3-L3	0.453	0.014	3.09	18.23	1.16	6.36	10780	617	5.72	2.39	0.21	9.00	38.18	2.45	6.42
	L3-L2-L2	0.455	0.011	2.42	17.66	1.28	7.25	10752	350	3.26	2.42	0.31	13.02	36.41	3.12	8.57
Scots pine	S1-S1-S1	0.542	0.013	2.40	24.08	1.46	6.06	11955	354	2.96	3.11	0.21	6.95	59.63	3.46	5.80
	S1-S2-S2	0.554	0.011	1.99	25.06	1.04	4.15	12458	654	5.25	3.44	0.11	3.43	56.24	3.76	6.69
	S1-S2-S3	0.547	0.008	1.46	25.44	1.25	4.91	12559	524	4.17	3.36	0.16	4.79	55.21	2.98	5.40
	S2-S2-S2	0.563	0.005	0.89	27.81	1.47	5.29	13026	469	3.60	3.61	0.29	8.20	63.53	3.15	4.96
	S2-S3-S3	0.551	0.009	1.63	24.33	1.36	5.59	12126	405	3.34	3.45	0.46	13.48	54.61	4.02	7.36
	S3-S3-S3	0.559	0.007	1.25	22.25	1.25	5.62	11653	425	3.65	3.25	0.32	10.03	49.88	4.15	8.32
	S3-S2-S2	0.549	0.018	3.28	23.55	1.14	4.84	11747	512	4.36	3.48	0.38	11.06	50.22	5.13	10.22

The mean values of the data varied according to the groups, and it was found that the standard deviations and CoV values were low. These low values showed that the findings obtained from the groups were consistent and homogeneous. The density, bending strength, and elastic modulus values obtained from CLT panels were similar to the values of visually graded timber used in their production (Table 2).

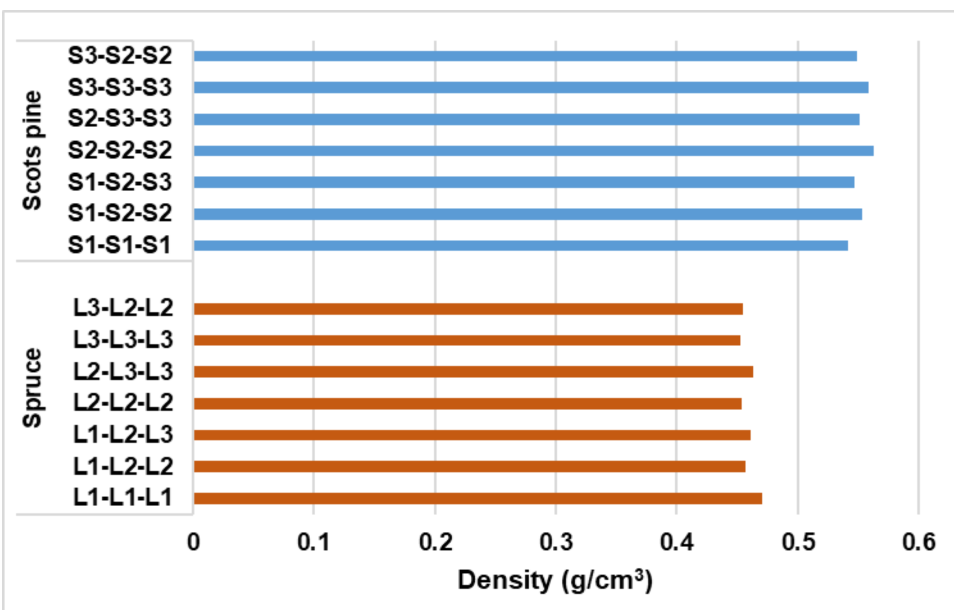

Fig. 4. Differences in the density values of CLT panels

The differences in the density values of CLT panels produced with different layer combinations of lumber classified by quality grades are shown in Fig. 4.

Upon examining the density values of the produced CLT panels, the highest values were found in the L1-L1-L1 group for spruce panels and the S2-S2-S2 group for Scots pine panels. Literature indicates that the density of CLT panels is determined by the density of the lumber used to form the panels (Callegari *et al.* 2010). Similar results were observed in this study for CLT panels produced from Scots pine lumber. Panels made from Grade 1 spruce and Grade 2 Scots pine lumber, both having higher densities, also showed higher panel densities.

According to ANSI/APA PRG-320 (2019), any softwood species with a density greater than 0.350 g/cm³ is suitable for CLT production. In this study, all produced CLT panels exceeded this threshold. The density of CLT panels is influenced by factors such as wood species, layer thickness, type and amount of adhesive, moisture content of the lumber, strength classes of the lumber, pressing parameters (pressure, temperature, duration), grain orientation, panel dimensions, and surface coatings used (TS EN 16351 2014; Sharifnia and Hindman 2017). Additionally, Paridah *et al.* (2019) found a strong correlation between the density of wood materials and their anatomical properties.

The differences in the bending strength and modulus of elasticity values of CLT panels produced with different layer combinations are shown in Fig. 5.

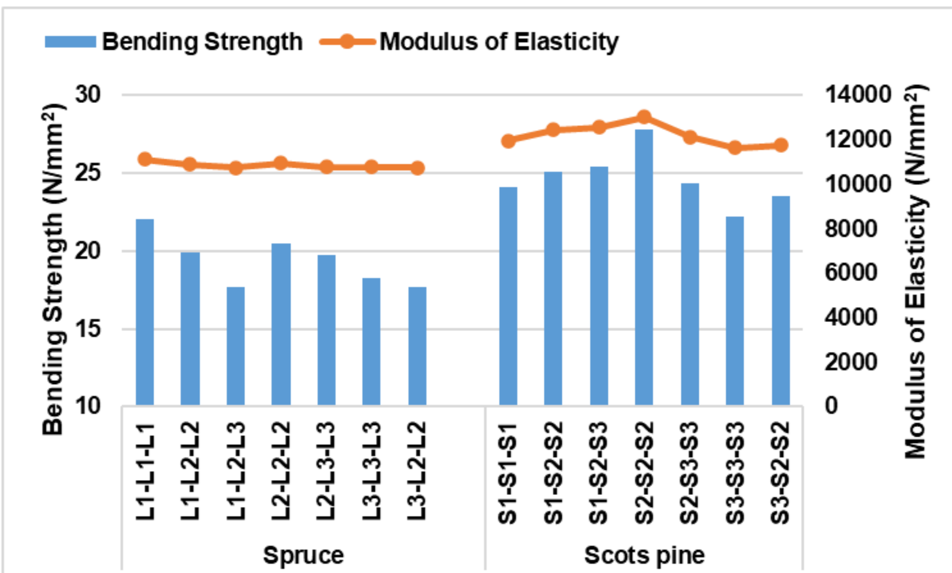

Fig. 5. Differences in bending strength and modulus of elasticity of CLT panels

In the comparison conducted with reference to the L1-L1-L1 combination, which demonstrated the highest performance among spruce groups, the L2-L2-L2 combination's bending strength was found to be only 6.8% lower and its modulus of elasticity 3% lower. This result indicates that the L2-L2-L2 combination offers a strong alternative in terms of performance while providing a cost advantage. On the other hand, the L2-L3-L3 combination showed 10.4% lower bending strength, and the L1-L2-L2 combination performed 9.8% lower than the baseline; both combinations demonstrate potential for meeting structural requirements. The weakest performance was observed in the L3-L3-L3 and L3-L2-L2 combinations, with reductions in bending strength of 17.3% and 19.9%, respectively. These combinations are better suited for low-cost, non-load-bearing applications. In the comparison conducted with reference to the S1-S1-S1 combination, which demonstrated the highest performance among Scots pine groups, the S2-S2-S2 combination exhibited 15.5% higher bending strength and 8.9% stronger modulus of elasticity. This result highlights that the S2-S2-S2 combination is the most durable option for applications requiring high structural load capacity. The S1-S2-S3 and S1-S2-S2 combinations performed 5.6% and 4.0% higher in bending strength, respectively, marking them as strong alternatives. In terms of modulus of elasticity, these groups achieved 5.1% and 4.2% higher values, respectively. On the other hand, among the lower-performing groups, the S2-S3-S3 combination showed only 1% lower bending strength, making it a close alternative to the S1-S1-S1 combination while offering cost advantages. The weakest performance was observed in the S3-S3-S3 and S3-S2-S2 combinations, with reductions in bending strength of 7.6% and 2.2%, respectively, and modulus of elasticity reductions of 2.5% and 1.7%, respectively. These combinations are more suitable for low-cost applications with minimal load-bearing requirements. Park *et al.* (2016) conducted a study on CLT panels produced from six different wood species (softwood and hardwood) and found that as the density of the wood increased, both the bending strength and modulus of elasticity values also increased. Furthermore, it was noted that there was little difference between the calculated modulus of elasticity values of the lumber and the values obtained from CLT panel tests.

In this study, similar results were found for Scots pine CLT panels, with the L1-L1-L1 and S2-S2-S2 groups showing higher bending strength and modulus of elasticity due to the higher density of Grade 1 spruce and Grade 2 Scots pine lumber, respectively. While using high-resistance lumber in all layers of a CLT panel increases overall strength and stiffness, it may also increase the likelihood of shear failure before bending failure, thus limiting classification thresholds (Ettelaei *et al.* 2022).

Natural defects, such as knots, grain deviations, and pith presence, in low-structural-grade lumber can cause localized variations in the mechanical properties of CLT panels. If these variations are concentrated in specific parts of the panel, it may reduce the homogeneity and, consequently, the elastic properties of the panels (Gsell *et al.* 2007; Steiger *et al.* 2012). Similarly, in this study, CLT panels produced from lower-grade lumber generally showed lower bending strength and modulus of elasticity values. The bending strength and elastic modulus values of the spruce and Scots pine CLT panels produced in the study met the limit value of the E1 quality class specified in ANSI/APA PRG 320 (2019). The E1 quality class is the highest of all classes given in the relevant standard.

The differences in shear strength parallel to the grain and compressive strength parallel to the grain for CLT panels produced with different layer combinations are shown in Fig. 6. The results showed that among the Spruce groups, the L1-L1-L1 combination demonstrated the highest performance. Compared to this reference, the L2-L2-L2 combination exhibited only 2.2% lower shear strength and 5.5% lower compression strength, making it a strong alternative with potential cost advantages. The L1-L2-L2 and L1-L2-L3 combinations showed 6.9% and 10.2% reductions in shear strength, and 8.1% and 11.5% reductions in compression strength, respectively, suggesting these combinations remain viable for structural use where cost optimization is a priority. Meanwhile, the L2-L3-L3 combination recorded 9.5% lower shear strength and 18.5% lower compression strength. The weakest performance was observed in the L3-L3-L3 and L3-L2-L2 combinations, where shear strength reductions of 12.8% and 11.7%, along with compression strength reductions of 20.8% and 24.4%, respectively, were recorded. These combinations are better suited for non-structural or low-load applications.

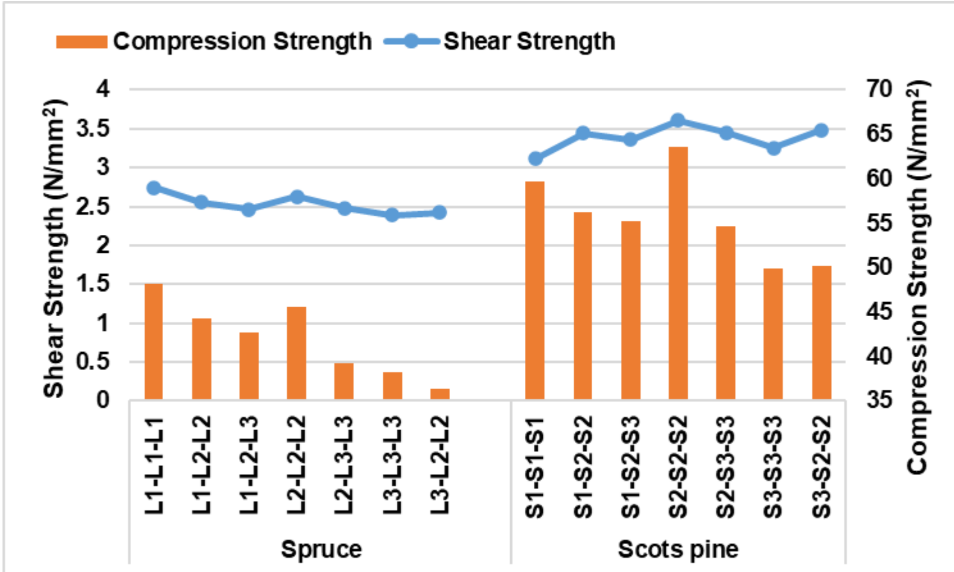

Fig. 6. Differences in shear and compressive strength parallel to the grain of CLT panels

For the Scots pine groups, the S1-S1-S1 combination served as the reference. The S2-S2-S2 combination exhibited the highest performance, with 16.1% higher shear strength and 6.5% higher compression strength, making it the optimal choice for high-load structural applications. The S1-S2-S3 and S1-S2-S2 groups showed reductions in shear strength by 8.1% and 10.4%, and in compression strength by 7.4% and 5.7%, respectively. Despite these reductions, they still present strong alternatives with better cost efficiency. The S2-S3-S3 group closely followed, showing 4.5% lower shear strength and 8.4% lower compression strength. The weakest performance was observed in the S3-S3-S3 and S3-S2-S2 combinations, where shear strength reductions of 13.1% and 11.5%, along with compression strength reductions of 16.4% and 15.8%, were recorded. These combinations are recommended for non-structural applications where cost efficiency is crucial. Various studies in the literature have reported that wood species, density, orientation of annual rings, aspect ratio of lumber, and the presence of knots significantly affect the shear strength of CLT panels parallel to the grain (Kumar *et al.* 2022). Density, moisture content, anatomical structure, porosity, buffering capacity of the wood surface, surface quality, and process parameters, such as compression pressure, adhesive types, spreading speed and curing temperature, are among the various factors affecting the adhesion properties of wood (Yusoh *et al.* 2021). It has been confirmed in many studies that the shear strength values parallel to the fibers of most CLT panels produced from wood species commonly used in CLT production are in the range of 1.0 to 2.0 N/mm^2 with tests (Zhou *et al.* 2014; Fink *et al.* 2018; Cao *et al.* 2019; Navaratnam *et al.* 2020; Huang *et al.* 2022). In this study, the shear strength values of CLT panels parallel to the fibers are in agreement with this information given in the literature. The results of the compressive strength values parallel to the fibers obtained in the study were similar to the shear strength. It was observed that the densities of the groups with high strength values were also high. It has been stated in the literature that there is a linear relationship between density and mechanical resistance properties (Bal and Bektaş 2018).

Failure Modes of CLT Panels

In order to determine the mechanical properties of CLT panels produced from different wood species and quality class combinations, the general damage modes occurring in CLT panels as a result of the bending strength, bending elasticity modulus, fiber parallel shear strength, and fiber parallel compressive strength tests performed according to TS EN 408 (2016) standards are given in Fig. 7.

Fig. 7. Some failure modes of CLT panels

The images illustrate failure modes observed in timber specimens under mechanical loading. Rolling shear failure, seen in the first and last images, occurs due to shear stress-induced separation along the grain, commonly in CLT or laminated wood products. The second image shows glue-line failure, indicating insufficient adhesive strength or bonding defects. These failure patterns highlight the critical role of material properties and bonding quality in the structural performance of timber elements.

Cost Analysis of CLT Panels

The strength classes based on bending properties and the costs of CLT panels produced from different visual quality combinations of spruce and Scots pine are presented in Table 4.

Table 4. Costs and Strength Classes of CLT Panel Test Groups

Group No	Wood Species	Layer Combination*	Strength Class	Cost ($)
1	Spruce	L1-L1-L1	C22	266.10
2		L1-L2-L2	C20	238.12
3		L1-L2-L3	C18	222.85
4		L2-L2-L2	C21	222.85
5		L2-L3-L3	C20	194.87
6		L3-L3-L3	C18	179.61
7		L3-L2-L2	C18	207.59
8	Scots pine	S1-S1-S1	C24	287.72
9		S1-S2-S2	C24	259.74
10		S1-S2-S3	C24	244.48
11		S2-S2-S2	C24	244.48
12		S2-S3-S3	C24	216.49
13		S3-S3-S3	C22	201.23
14		S3-S2-S2	C24	229.21

* 1: Grade 1 Lumber; 2: Grade 2 Lumber; 3: Grade 3 Lumber

Analysis of cost and strength class relationships

When analyzed in terms of wood species, CLT panels produced from Scots pine exhibited higher strength class values compared to those made from spruce. However, it was determined that spruce CLT panels met the minimum C18 strength class required for structural applications. This indicates that using spruce instead of the more expensive Scots pine in CLT production could be an economically viable choice.

Among all groups, CLT panels made from Grade 1 Scots pine lumber had the highest production costs, while panels produced from Grade 3 spruce lumber had the lowest. Analysis of the data regarding raw material quality suggests that CLT panels manufactured from low-grade raw materials for both species meet the necessary strength classes for structural purposes. Consequently, depending on the intended application in buildings, CLT panels can be manufactured using lower-quality, more affordable raw materials.

Table 5. Costs Factor of CLT Panel Test Groups

Cost Factor	(%)
Raw materials	68.2 to 54.7
Adhesives	5.15 to 3.22
Energy consumption	0.28 to 0.17
Labor	39.8 to 28.3

The distribution of production costs among various components exhibits notable variations depending on process conditions and production parameters. Raw materials constituted the largest proportion, ranging from 54.7% to 68.2% of the total cost. Adhesives represented a smaller share, ranging between 3.22% and 5.15%. Energy consumption remained minimal, accounting for only 0.17% to 0.28% of the overall expenditure. Labor cost, however, is a significant cost factor, comprising between 28.3% and 39.8% of total production expenses. These cost variations highlight the influence of material selection, manufacturing efficiency, and energy utilization on overall production economics.

CONCLUSIONS

1. The density values of cross-laminated timber (CLT) panels produced from Scots pine lumber were found to be higher than those produced from spruce lumber. The L1-L1-L1 group, using Grade 1 spruce in all layers, and the S2-S2-S2 group, using Grade 2 Scots pine in all layers, showed the highest density values.
2. Bending strength and modulus of elasticity values of CLT panels produced from Scots pine lumber were higher compared to those from spruce lumber. The L1-L1-L1 group (Grade 1 spruce) and the S2-S2-S2 group (Grade 2 Scots pine) demonstrated the highest values in these properties.
3. Shear strength and compressive strength parallel to the grain were also higher in Scots pine CLT panels than in spruce panels. The highest values were observed in the L1-L1-L1 group for spruce and the S2-S2-S2 group for Scots pine.
4. The production costs of CLT panels made from Scots pine lumber were higher than those made from spruce. This was primarily due to increased lumber prices during the COVID-19 pandemic and the limited availability of Grade 1 Scots pine logs in Turkey.

5. The L3-L3-L3 group (Grade 3 spruce) and the S3-S3-S3 group (Grade 3 Scots pine) exhibited the lowest cost values. This is attributed to the lower cost of Grade 3 spruce lumber compared to Scots pine.
6. In groups where different quality grades were used in the layers, the L2-L3-L3 group for spruce and the S2-S3-S3 group for Scots pine showed lower costs.

This study highlights the potential of lower-grade spruce as a cost-effective alternative to higher-quality Scots pine in CLT production while maintaining structural integrity. The findings suggest that utilizing lower-grade materials and mixed-grade combinations can reduce raw material costs by approximately 15 to 25%, particularly in applications such as prefabricated structures, temporary buildings, and interior elements covered with surface materials. To enhance adoption, policymakers could implement financial incentives and revise industry standards to support the use of lower-grade lumber. Additionally, further research on sustainable production methods could optimize resource utilization and strengthen the forestry and wood processing sectors. These strategies would contribute to a more economical, sustainable, and resilient CLT industry.

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