Mechanical Properties of Laminated and Aramid Fiber-Reinforced Laminated Wood Elements

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The mechanical performance of laminated panels manufactured from beech (*Fagus orientalis*) wood was enhanced by reinforcement with aramid fibers. Specimens were organized into three primary groups: (i) a solid (control) group, (ii) laminated groups composed of two and three layers without aramid reinforcement, and (iii) laminated groups incorporating one or two layers of aramid fiber reinforcement. Results of compressive strength tests revealed that both laminated and aramid-reinforced laminated specimens exhibited improved performance compared to the control group. Static bending strength was improved by lamination alone, and inclusion of aramid reinforcement in the lamination interface gave further enhancement. Lamination by itself did not yield a statistically significant improvement in the modulus of elasticity in static bending. A significant increase in the modulus of elasticity was observed only when aramid fibers were embedded in the lamination interface. Moreover, dynamic bending strength was substantially improved by the incorporation of aramid reinforcement into the laminated structure. The enhancement ratios were 63.4% for two-layer laminates with one aramid layer and 123.5% for three-layer laminates with two aramid layers. These findings indicate that aramid fiber reinforcement is an effective strategy for improving the mechanical performance of laminated wood composites.

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Keywords: Beech wood; Lamination; Aramid reinforcement; Mechanical properties; Material

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INTRODUCTION

Wood is a natural and organic polymer. For centuries, it has been directly preferred to meet basic needs (Usta 2016). However, when left to its natural durability, especially in exterior applications, wood deteriorates and loses its economic value over time. To prevent this loss and extend the service life of wood materials, they need to be made resistant to biological, physical, and chemical factors through various chemical treatments (Şimşek 2013). The anatomical structure, physical and mechanical properties, and chemical composition of wood are utilized for different purposes (Arriaga *et al.* 2023). Steel elements are commonly used for strengthening and joining wood materials. Because joints in wooden structures are exposed to high loads, the use of metal is generally recommended. However, fiber-reinforced polymers (FRPs) offer several advantages over metals, including being lightweight, corrosion-resistant, and high strength. Reinforcement using steel elements requires maintenance over time, contributes to environmental pollution, and adds extra weight to the structure. The use of fiber-reinforced polymers has been suggested as a more sustainable and renewable approach to construction (Kılınçarslan and Şimşek Türer 2020). Engineered wood products are reinforced using various techniques and materials, including high-strength steel, wire, and fiber-reinforced polymers. Compared to traditional wood products, FRP-reinforced wood materials offer numerous advantages such as improved mechanical behavior, being more esthetic and durable (Morales-Conde *et al.* 2015).

Wood and aramid (a kind of FRPs) materials have different structural properties and are widely used across various industries. Aramid fibers, which were first commercially used in the 1970s, are one of the advanced synthetic materials known for their high tensile strength, elevated modulus of elasticity, outstanding strength-to-weight ratio, toughness, and excellent impact resistance (Song 2015; Ertekin 2017). Due to these superior mechanical properties, aramid fibers are widely utilized in a range of high-performance applications, including ballistic protection systems, sports equipment, high-strength ropes, and structural engineering, particularly for retrofitting and strengthening purposes (Callister and Rethwisch 2015). Wood, on the other hand, is a naturally sourced, sustainable material with a significant role as a construction material, backed by thousands of years of history. Its durability, workability, aesthetic appeal, and renewability make it a preferred choice in numerous fields, including construction, furniture manufacturing, packaging, and interior decoration. When aramid and wood materials are combined, innovative composite structures can be formed that exploit the advantages of both materials. For instance, using aramid fibers to reinforce wooden structures can significantly enhance mechanical properties (Salman *et al.* 2015; Karaman *et al.* 2021). Additionally, composite materials reinforced with aramid fibers can be integrated with wood to create lighter yet more durable structures. Research studies on aramid and wood materials aim to better understand their physical and mechanical properties, improve processing techniques, and explore new application areas. Such research contributes to the development of more sustainable and high-performance solutions, particularly in the fields of materials science, engineering, and design. In this context, interdisciplinary collaboration plays a crucial role in advancing innovative material technologies and optimizing industrial applications.

A review of the existing literature reveals a growing number of recent studies focusing on the combined use of FRPs and wood. Zhang *et al.* (2018) stated that aramid fiber-reinforced polymer (AFRP) is effective to enhance the mechanical properties of parallel bamboo strip lumber beams. Wang *et al.* (2023) showed that hybrid fiber-reinforced polymer (HFRP) sheets can be widely used for wooden columns in the construction sector. Karaman *et al.* (2021) conducted four-point bending strength and modulus of elasticity in bending tests for aramid fiber-reinforced laminated Scots pine materials and obtained the highest static bending strength and modulus of elasticity in laminated wood samples prepared using an intermediate layer of AFRP. The highest modulus of elasticity in bending was found in samples prepared with an intermediate layer of epoxy and AFRP. They concluded that aramid fiber-reinforced laminated Scots pine materials can be used as structural materials in the construction industry. Novosel *et al.* (2021) noted that increasing the number of layers of carbon fiber-reinforced polymer (CFRP) in laminated oak-wood specimens resulted in increased ductility. The reinforcement of laminated veneer lumber (LVL) beams with aramid fiber-reinforced polymer (AFRP) and glass fiber-reinforced polymer (GFRP) sheets was investigated by Bakalarz and Kossakowski (2019). They found that aramid fiber-reinforced and glass fiber-reinforced beams performed better in terms of bending resistance than LVL beams. Perçin

(2023) produced and tested carbon fiber-reinforced five-layer wood veneer test samples. As a result of the tests, multilayer composite structures showed better compression resistance compared to traditional laminated wood panels. Ulaşan and Söğütlü (2024) reinforced Scots pine and Eastern beech wood using carbon fiber fabric, steel wire mesh, and bamboo veneer. The highest dynamic bending strength was obtained in five-layer carbon fiber fabric reinforced and polyurethane adhesive-coated Eastern beech samples. As shown in the summarized studies above, fiber-reinforced polymers have great potential in enhancing the properties of wood. Figure 1 illustrates the potential applications FRPs in engineered wood materials.

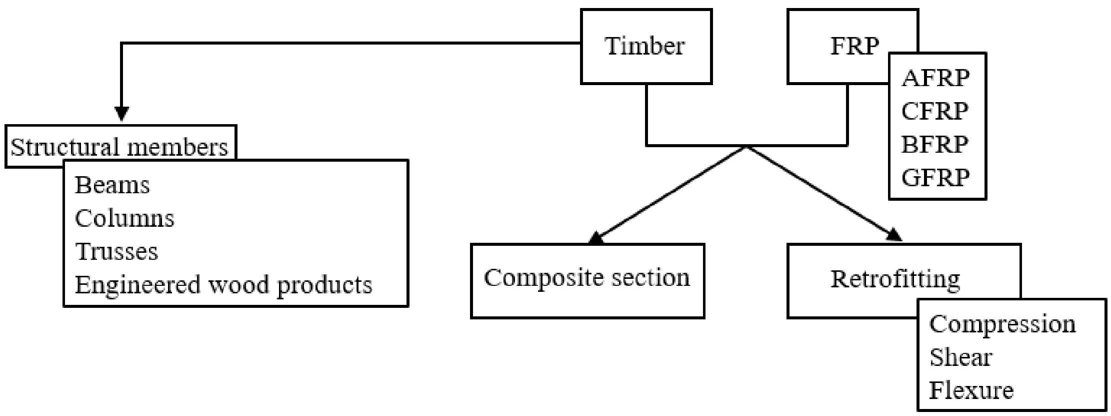

Fig. 1. General usage areas of FRPs in timber engineering (AFRP: Aramid Fibre-Reinforced Polymer, CFRP: Carbon Fibre-Reinforced Polymer, BFRP: Basalt Fibre-Reinforced Polymer, GFRP: Glass Fibre-Reinforced Polymer) (modified from Steiger (2004))

The main aim of this study was to highlight the contribution of aramid reinforcement to the mechanical properties of wood materials, evaluate the potential applications of aramid-wood composites in engineering, and provide a scientific foundation for developing sustainable, high-performance material solutions. The combination of aramid fibers with wood materials provides significant advantages, especially in the construction sector. While preserving the natural elasticity and aesthetic properties of wood, aramid reinforcement can significantly enhance impact resistance, compressive strength, and bending resistance. It should be noted that there has been a lack of studies to investigate the effect of aramid fibers on the mechanical performance of wood materials.

EXPERIMENTAL

Materials

Select grade Eastern beech (*Fagus orientalis* Lipsky) was used as wood material, considering its widespread use in the woodworking industry. The timber was randomly sourced from businesses in the Ankara Siteler furniture industry market. The selection of the timber took into account factors such as being dry, sound, naturally colored, flawless, free from fiber curvature, and unaffected by insect or fungal damage.

The density (ρ) of the wood was obtained in accordance with TS ISO 13061-2 (2021) and calculated using Eq. 1, where m is mass (g) and v is volume (cm^3). Accordingly, the air-dry density of the beech wood at the moisture level of 12.1% was found to be 0.706 g/cm³ by averaging the test results of 10 specimens (standard deviation was 0.021 g/cm³). On the other hand, the oven-dry density of the wood was found to be 0.620 g/cm³.

$$\rho = \frac{m}{v} \tag{1}$$

Moisture content (m) was calculated as per TS ISO 13061-1 (2017) based on the ratio of the weight of the wood material at its current moisture level (W_m) to its oven-dry weight (W_0) (Eq. 2). The average moisture content of 10 specimens was determined to be 12.1% with the standard deviation of 0.57%:

$$m = \frac{W_m - W_0}{W_0} \times 100 \tag{2}$$

Unidirectional aramid fiber fabric with a nominal yarn linear density of 1500 D and an areal weight of 280 g/m² was used as aramid reinforcement. Tensile strength and ultimate tensile strain of the aramid reinforcement were determined through direct tensile tests. Accordingly, average tensile strength and average ultimate tensile strain of five specimens was determined to be 1815 MPa (standard deviation was 157.7 MPa) and 0.025 (standard deviation was 0.007), respectively.

Kleiberit 506.0 polyurethane-based humidity curing single component adhesive was used to glue laminated wood layers with or without AFRP reinforcement. Specific gravity and viscosity of the glue are 1.14 ± 0.02 g/cm³ and 1600 ± 400 mPas, as given by the manufacturer. Since the adhesive does not contain any evaporating water or solvent, the solid content can be accepted as 100%.

Method

Preparation of specimens

Cross-sectional sizes of test specimens were 20 × 20 (mm × mm). The lengths of the samples for compression, dynamic bending, and static bending were 30 mm, 300 mm, and 340 mm, respectively. A total of 90 specimens for five different groups were tested. These groups comprised solid wood (control) specimens, two-layer and three-layer laminated specimens, as well as aramid-reinforced two-layer and three-layer laminated specimens. Apart from most available studies, aramid fibers were glued within the lamination interface rather than gluing on the outer surface, which prevents aramid fibers from outer environmental effects. Moreover, the integration of aramid fibers within the lamination interface can be carried out without compromising the natural aesthetic of the wood in the outer surface of the element.

The layer thickness for two-layered laminated specimens was 10 mm, and it was 6.7 mm for three-layered laminated specimens. It should be noted that the final board thickness was the same (20 mm) for all configurations. During the lamination process, adhesive was applied to the wood surface at an average rate of 120 g/m² between successive layers and uniformly distributed using a spatula and hand roller. For the laminated and aramid-reinforced groups, an aramid layer followed by a wood layer was placed, while only wood layers were used in the laminated groups without reinforcement. This procedure was repeated until the required number of layers was obtained. For specimens measuring 600 mm × 600 mm, the application time was approximately 10 minutes for two-layer configurations and 15 minutes for three-layer configurations. The lamination process was conducted under air-dry conditions at a moisture content of 12.1%. A pressure of 16 kg/cm² was applied for 120 minutes to both laminated and aramid-reinforced laminated specimens to ensure adequate interlayer bonding. Some photos for the fabrication of the test specimens are provided in Fig. 2, while the sectional configurations of the different specimen groups are presented in Fig. 3.

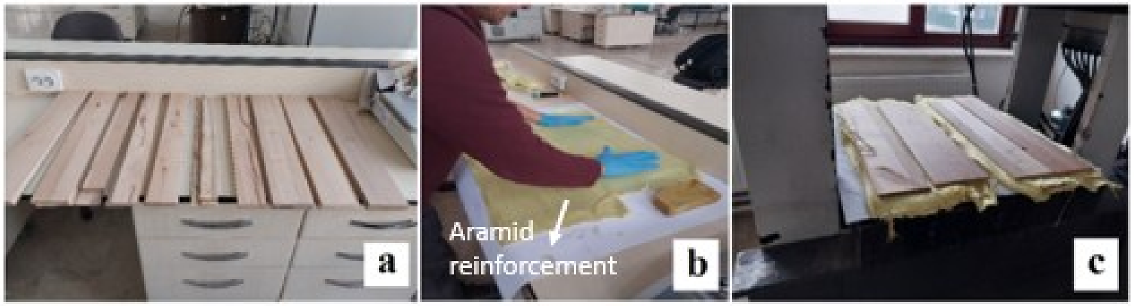

Fig. 2. (a) Cutting the wood, (b) Placement of the aramid reinforcement between layers (only for aramid-reinforced specimens), and (c) Placement of the upper layer

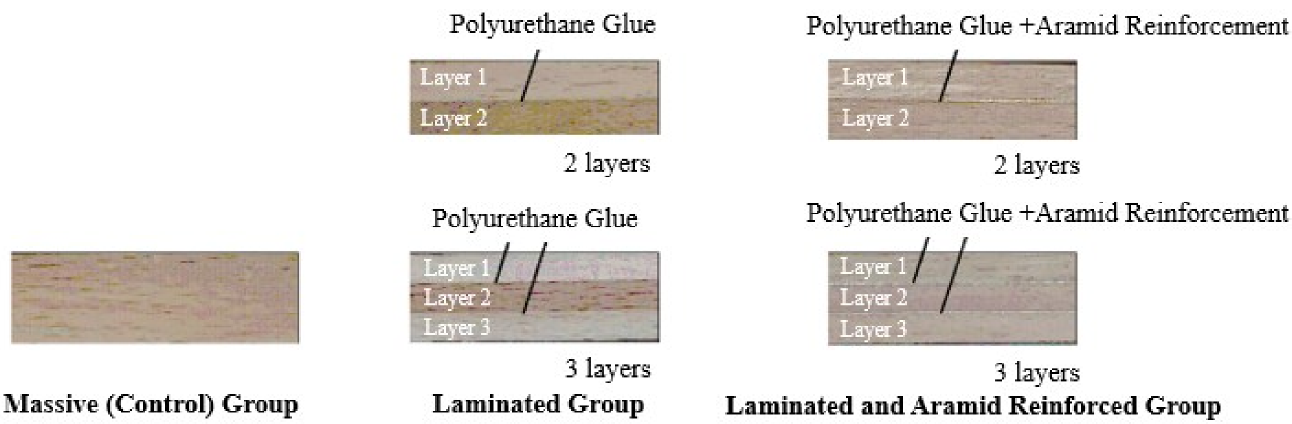

Fig. 3. Sectional details of the tested specimens groups

Tests

Compressive strength and static bending strength tests were conducted using an Instron 5969 universal testing machine. Dynamic bending strength tests were performed utilizing Shenzhen Wance testing machine at Gazi University Wood Products Industrial Engineering Laboratory.

Compressive strength test

Compressive strength tests parallel to fiber orientation were conducted on the specimens conditioned with the climate conditions specified in TS ISO 13061-17 (2014). The loading rate was set to 3 mm/min. The maximum force was recorded in Newtons. The compressive strength parallel to wood fibers was calculated using Eq. 3 where σ_c represents the compressive strength, F_{max} is maximum force, and A denotes the cross-section area. Six specimens were tested for each configuration; thus, the total number of compressive strength tests was 30 for five configurations.

$$\sigma_c = \frac{F_{max}}{A} \tag{3}$$

Static bending strength test

According to the principles of TS ISO 13061-3 (2014) and TS ISO 13061-4 (2014), a three-point bending test was conducted on each test specimen (Fig. 4). The load capacity of the testing device was 5 tons, and the static loading rate was set to 2 mm/min. The maximum force at the failure was recorded in Newtons (N), and the bending strength was calculated using Eq. 4. In Eq. 4, σ_f is bending strength (MPa), F_{max} is maximum force (N), L is span (mm), and b and h are the cross-section dimensions (both 20 mm). A total of 30 static bending tests (six specimens for each configuration) were conducted.

$$\sigma_f = \frac{3F_{max}L}{2bh^2} \tag{4}$$

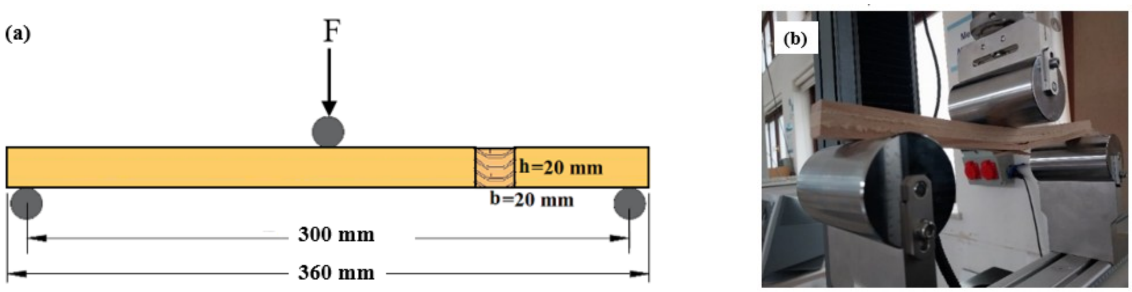

Fig. 4. (a) and (b) Static bending test

Dynamic bending strength test

Wood-based materials utilized in applications, such as aircraft, buses, fitness equipment, ladders, tool handles, and various structural components in construction, are primarily exposed to dynamic rather than static loads. Shock resistance is defined as a form of mechanical resistance that occurs within an extremely brief time interval—typically on the order of one-thousandth of a second. High shock resistance is an indicative of material elasticity and toughness, whereas low shock resistance is associated with brittleness (Bozkurt 1987). A total of 30 specimens were subjected to dynamic bending testing as per TS ISO 13061-10 (2014), using a Shenzhen Wance testing machine to calculate the dynamic bending strength of each configuration (Fig. 5).

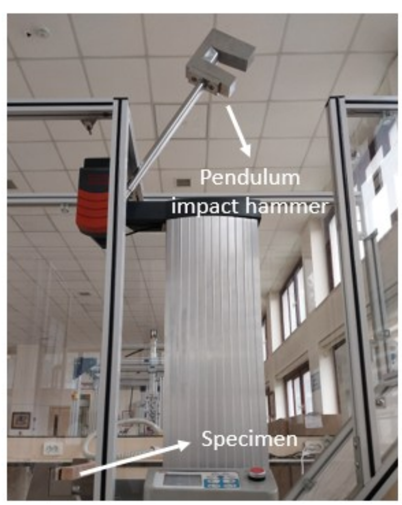

Fig. 5. Dynamic bending test

Specimens were dynamically loaded in the midspan using a pendulum hammer and dynamic bending strength was calculated according to Eq. 5, where A_W is dynamic bending strength (kj/m^2), Q is the total work at failure, and b and h are the cross-sectional dimensions.

$$A_W = \frac{Q}{b \times h} \tag{5}$$

Statistical analysis

The statistical analyses of the test results were conducted with MSTAT-C statistical analysis software. The effects of laminated layer and aramid material and the dual interactions of these factors on the compressive strength, static and dynamic bending strength, and modulus of elasticity in static bending were determined with multiple analysis of variance (ANOVA). The least significant difference test was applied for the differences in the analysis for the level of significance among the groups that emerged as statistically significant according to a level of reliability of p 0.05.

RESULTS AND DISCUSSION

Compressive Strength

The results of the compressive strength tests, along with the corresponding statistical data, are presented in Table 1. The results of analysis of variance are given in Table 2.

Table 1. Results of Compressive Strength Tests and Related Statistical Values

Group	Type	HG	$\bar{X}^a$ (MPa)	Min. (MPa)	Max. (MPa)	SD (MPa)	CoV (%)
Control	Solid	D	69.2	67.1	70.3	1.3	1.8
Laminated	2L*	B	81.4	77.9	88.8	4.4	5.5
	3L*	C	73.7	72.7	74.6	0.8	1.0
Laminated and Aramid Reinforced	2L+1A*	C	77.3	75.2	79.0	1.8	2.3
	3L+2A*	A	91.3	89.8	92.8	1.5	1.6

Notes: *2L: two layers laminated, 3L: three layers laminated, 2L+1A: two layers laminated+one layer aramid reinforced, 3L+2A: three layers laminated+two layers aramid reinforced, HG: Homogeneity group, LSD:±4.36, $\bar{X}$: Average, Min: Minimum value; Max: Maximum value, SD: Standard deviation, CoV: Coefficient of variation, [a]Average results of six specimens (n=6)

Table 2. Results of Analysis of Variance for Compressive Strength Tests

Source of Variance	Degrees of Freedom	Sum of Square	Mean Square	F Value	p < 0.05
Factor A	4	1149.6	287.4	44.8	0.000
Error	20	128.3	6.4		
Total	29	131901.3			

Multiple comparison of means analysis revealed statistically significant differences among the tested groups. Both lamination techniques, with and without aramid reinforcement, resulted in increased compressive strength compared to the control group. Notably, the highest compressive strength was observed in the group with three layers of lamination combined with two layers of aramid reinforcement (3L+2A), exhibiting an approximately 32% increase relative to the control group. However, because the three-layer laminated specimens (3L) and the specimens with two layers of lamination+one layer of aramid reinforcement (2L+1A) belonged to the same homogeneity group, it can be inferred that three-layer lamination alone provided a similar improvement in compressive strength as the combination of two-layer lamination and one layer of aramid reinforcement. Considering the substantially higher cost of aramid compared to wood, three-layer lamination may be a more cost-effective alternative to two-layer lamination with aramid reinforcement. Consistent with the findings regarding compressive strength, Perçin (2023) observed an enhancement in the compressive performance of black pine specimens through lamination and CFRP reinforcement. Ulaşan and Söğütlü (2024) also reported increased compressive strength for laminated and CFRP reinforced Scots pine and Eastern beech specimens.

Static Bending Strength and Modulus of Elasticity

Static bending test results and the corresponding statistical data are presented in Table 3. The results of analysis of variance are provided in Table 4.

Table 3. Static Bending Strength Test Results and Related Statistical Values

Group	Type	HG	$\bar{X}^a$ (MPa)	Min. (MPa)	Max. (MPa)	SD (MPa)	CoV (%)
Control	Solid	C	66.0	58.0	81.3	8.4	12.8
Laminated	2L*	B	113.0	94.3	129.3	14.4	12.8
	3L*	B	128.8	89.5	151.8	21.5	16.7
Laminated and Aramid Reinforced	2L+1A*	A	155.2	149.2	160.9	4.7	3.0
	3L+2A*	A	160.0	145.6	166.5	7.7	4.8

Notes: *2L: two layers laminated, 3L: three layers laminated, 2L+1A: two layers laminated+one layer aramid reinforced, 3L+2A: three layers laminated+two layers aramid reinforced, HG: Homogeneity group, LSD: ± 15.86, $\bar{X}$: Average, Min: Minimum value; Max: Maximum value, SD: Standard deviation, CoV: Coefficient of variation, [a]Average results of six specimens (n=6)

Table 4. Results of Analysis of Variance for Static Bending Strength Tests

Source of Variance	Degrees of Freedom	Sum of Square	Mean Square	F Value	p < 0.05
Factor A	4	10970490.4	2742622.6	0.6	0.0000
Error	20	1140651.5	57032.6	48.1	
Total	29	12269771.4			

As shown in Table 3, static bending strength increased with lamination and aramid-reinforced lamination. The increase ratios with respect to solid (control) group were respectively 71.2% and 93.9% for two (2L) and three layer (3L) laminated specimens. Enhancement in static bending strength further increased with the placement of aramid reinforcement between the layers. Aforementioned enhancement ratios dramatically rose up to 135.2% and 142.4% when aramid reinforcement was placed between two and three layers. Other studies also reported increases in static bending strength after reinforcing with FRP composites or with hardwood species (Zhou *et al.* 2020; Perçin and Uzun 2023; Bal

2024; Kaya 2024; Zdravković *et al.* 2025). It should be stated that the high coefficient of variation values of static bending strength of solid and laminated specimens (Table 3) due to the anisotropic and non-homogeneous nature of wood can be dramatically reduced after placement of aramid reinforcement between the layers. This can be attributed to more stabile mechanical properties of aramid than the wood.

Modulus of elasticity in static bending with statistical data are presented in Table 5. Furthermore, analysis of variance results for modulus of elasticity are given in Table 6. When the modulus of elasticity values are examined, because the homogeneity groups are the same for laminated and control groups, it can be said that lamination had no significant effect on the modulus of elasticity. However, when the aramid reinforcement was placed between layers, the modulus of elasticity value significantly increased. However, unlike the trend observed in the other tests, the slightly higher modulus of elasticity of the 2L+1A board compared to the 3L+2A board may be attributed to the local distribution of stiffness and interactions between the wood layers and aramid reinforcement, which may not always scale linearly with the number of layers. Minor variations in adhesive application, layer alignment, or local defects could also have influenced the modulus of elasticity measurements.

Table 5. Modulus of Elasticity Values with Statistical Data

Group	Type	HG	$\bar{X}^a$ (MPa)	Min. (MPa)	Max. (MPa)	SD (MPa)	CoV (%)
Control	Solid	B	10956.4	10244.4	13205.7	1267.3	11.6
Laminated	2 L*	B	10791.1	10560.8	11254.1	248.5	2.3
	3 L*	B	11733.6	9615.5	12883.1	1181.1	10.1
Laminated and Aramid Reinforced	2L+1A*	A	17772.6	14622.9	23808.3	4381.0	24.7
	3L+2A*	A	16047.9	14463.8	16836.7	917.4	5.7

Notes: *2L: two layers laminated, 3L: three layers laminated, 2L+1A: two layers laminated+one layer aramid reinforced, 3L+2A: three layers laminated+two layers aramid reinforced, HG: Homogeneity group, LSD:± 2454, $\bar{X}$: Average, Min: Minimum value; Max: Maximum value, SD: Standard deviation, CoV: Coefficient of variation, [a]Average results of six specimens (n=6)

Table 6. Results of Analysis of Variance for Modulus of Elasticity

Source of Variance	Degrees of Freedom	Sum of Square	Mean Square	F Value	p < 0.05
Factor A	4	249961280.2	62490320.1	14.5	0.0000
Error	20	86351720.2	4317586.0		
Total	29	363011395.9			

Dynamic Bending Strength Test

Dynamic bending test results are presented in Table 7 along with the related statistical data. When the dynamic bending strength test results were evaluated, significant difference was observed between aramid reinforced and other groups. To determine the factors that affect the dynamic bending strength, analysis of variance was performed (Table 8). Table 7 clearly shows the aramid reinforced groups had the highest dynamic bending strength. When the number of lamination and aramid layers increased, dynamic bending strength further increased. As expected, the highest dynamic bending strength was obtained for three layers laminated+2 layers aramid reinforced group (3L+2A). The enhancement ratios were 63.4% for two-layer laminates containing one aramid layer (2L+1A) and 123.5% for three-layer laminates containing two aramid layers (3L+2A). By contrast, lamination without aramid reinforcement produced only a marginal improvement in dynamic bending strength.

Table 7. Results of Dynamic Bending Strength Tests with Statistical Data

Group	Type	HG	$\bar{X}^a$ (kJ/m²)	Min. ((kJ/m²)	Max. (kJ/m²)	SD (kJ/m²)	CoV (%)
Control	Solid	C	42.9	24.4	65.0	18.5	43.1
Laminated	2 L*	C	45.4	39.7	52.9	52.0	11.5
	3 L*	C	48.0	37.8	63.8	10.5	21.9
Laminated and Aramid Reinforced	2L+1A*	B	70.1	50.0	86.5	12.4	17.7
	3L+2A*	A	95.9	89.2	110.8	9.1	9.4

Notes: *2L: two layers laminated, 3L: three layers laminated, 2L+1A: two layers laminated+one layer aramid reinforced, 3L+2A: three layers laminated+two layers aramid reinforced, HG: Homogeneity group, LSD:± 13.18, $\bar{X}$: Average, Min: Minimum value; Max: Maximum value, SD: Standard deviation, CoV: Coefficient of variation, [a]Average results of six specimens (n=6)

Table 8. Results of Analysis of Variance for Dynamic Bending Strength Test

Source of Variance	Degrees of Freedom	Sum of Square	Mean Square	F Value	p < 0.05
Factor A	4	12233.4	3058.4	24.5	0.0000
Error	20	2493.1	124.7		
Total	29	15242.4			

CONCLUSIONS

This study demonstrated that aramid reinforcement and the number of lamination layers had a significant influence on mechanical properties of beech wood materials. According to findings in the study, the following conclusions can be drawn.

1. Experimental results revealed that the three layers laminated+two layers aramid reinforced specimens (3L+2A) exhibited the highest compressive strength (91.3 MPa). Enhancement ratio was 31.9% when compared to solid (reference) group. Enhancement ratios for the compressive strength were recorded as 11.7%, 6.5% and 17% for three layers laminated+two layers aramid reinforced (2L+1A), three layers laminated (3L) and two layers laminated (2L) specimens.
2. Static bending strength increased with lamination and was further enhanced by the addition of aramid textile reinforcement. Compared to the control group, the enhancement ratios for laminated specimens were 71.2% for two-layer (2L) and 93.9% for three-layer (3L) laminated samples. For aramid-reinforced laminates, the enhancement ratios were 135.2% for two-layer laminates with one aramid layer (2L+1A) and 142.4% for three-layer laminates with two aramid layers (3L+2A).

3. While the control group exhibited the lowest modulus of elasticity in static bending, the laminated and aramid reinforced groups showed a notably higher modulus of elasticity compared to the control.
4. Similar to static bending, aramid-reinforced specimens exhibited significantly higher dynamic bending resistance compared to the control group. The enhancement ratios were 63.4% for two-layer laminates with one aramid layer (2L+1A) and 123.5% for three-layer laminates with two aramid layers (3L+2A). In contrast, lamination without aramid reinforcement had only a minor effect on dynamic bending strength.

Future research should focus on the investigation of different aramid fiber types, alternative wood species, and varied manufacturing techniques to further examine the mechanical behavior of composite materials. Additionally, the impact of environmental conditions—such as temperature and humidity—on mechanical performance warrants detailed analysis.

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