Compressive Strength and Dynamic Bending Behavior of Fiber-Reinforced Structural Timbers: Experimental Study

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The compressive strength and dynamic bending resistance were tested for solid wood reinforced with glass and carbon fiber fabrics perpendicular to the fibers. The obtained data were used to predict the structural suitability of fiber-reinforced systems, especially for strengthening vertical load-bearing elements of historical buildings. Scotch pine (*Pinus sylvestris* L.*)* and Turkish beech (*Fagus orientalis* Lipsky), which are widely used in the construction and furniture industries in Türkiye, were coated with 200, 300, and 400 g/m² glass fiber fabric, carbon fiber fabric, and glass chip using epoxy resin. Compression tests conducted in the direction perpendicular to the fibers were applied according to the TS ISO 13061-5 (2021) standard. The highest compressive strength was obtained in the KK group (84.6 N/mm²), while the lowest value was obtained in group ÇCW1 (48.6 N/mm²). Dynamic (shock) bending strength tests were conducted in accordance with the TS ISO 13061-10 (2021) standard, and the highest dynamic bending strength was measured in the KCW2 group (70.2 kJ/mm²), while the lowest value was measured in the Scotch pine control group (35.6 kJ/mm²). Fiber-reinforced systems, with their mechanically weak properties, offer a viable solution for improving the compressive and dynamic bending strength of wood materials.

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INTRODUCTION

Wood is a recyclable, environmentally compatible, highly durable, and sustainable material. When properly used, it performs compatibly with other construction materials. Wood is one of the oldest building materials and holds a significant place in Turkish architecture. In historical structures, it has demonstrated long-term durability, even without preservative treatment. For example, the wooden burial chamber in the Midas Tumulus in the Ancient City of Gordion dates back to 740 BC and is the oldest surviving wooden structure worldwide. This exceptional preservation contributed to the inscription of the Ancient City of Gordion on the UNESCO World Heritage List in 2023.

Wood has been a preferred material in the construction industry for centuries due to its sustainability, aesthetic value, and structural properties. However, over time, factors such as environmental exposure, biological deterioration, and structural fatigue can reduce the durability of wooden elements, especially in historical structures. Therefore, the combination of modern material technologies with traditional construction techniques has become essential for the preservation and strengthening of existing structures (Jardim *et al*. 2025).

Fiber-reinforced polymer (FRP) materials, particularly carbon fiber (CFRP) and glass fiber (GFRP) systems, are modern materials that have proven effective in enhancing the mechanical performance of timber structural elements. Such reinforcements can significantly improve the load-carrying capacity of structural elements by increasing the compressive strength and stiffness of wood (Fiore *et al.* 2015; Lengyel and Saad 2022).

Recent studies have revealed that timber structural elements reinforced with CFRP and GFRP materials exhibit significant improvements, particularly in flexural and compressive strength (Chen *et al*. 2025). These reinforcements offer an effective method for overcoming wood's inherent mechanical limitations and are also applicable to the rehabilitation of historic structures (Raftery and Harte 2011; Fiore *et al*. 2015; Bal and Büyüksarı 2019).

The use of FRP materials in historic buildings is less invasive than traditional reinforcement methods and offers advantages with respect to preserving the authenticity of the structure (Atilgan and Kocaer 2025). In this context, CFRP and GFRP materials stand out as effective methods for increasing the strength of the load-bearing elements of historic wooden structures (Triantafillou 2001).

Wood is a preferred construction material among architects and engineers because its benefits far outweigh its disadvantages. Its advantages include easy accessibility, sufficient strength while being lightweight, low transportation costs, practical assembly, simple interlocking mechanism, resistance to chemical effects, and ease of shaping it to the desired form on site (Çalışkan *et al.* 2019).

Furniture has been produced in various forms for centuries (Eckelman 1966). (Eckelman 1966). Wood, with its natural structure, environmental friendliness, and historical significance, has been a building material used in the construction industry for centuries. In traditional Turkish architecture, wood has been widely preferred both as a load-bearing material and as an aesthetic element (Aydınoğlu 2018).

In the research conducted by Çiğdem and Perçin (2022), the physical and mechanical properties of laminated composite samples produced from beech wood reinforced with glass fiber and carbon by phenol-formaldehyde (PF) adhesive and heat application were investigated. Accordingly, the wood materials were heat-treated for 3 h at temperatures of 150, 175, and 200 °C, and then test samples were prepared. The test results showed that the flexural strength and modulus of elasticity in bending of the samples reinforced with glass fiber and carbon increased. Furthermore, significant changes were observed in the compressive strength values parallel to the fibers, depending on the type of reinforcing material and the heat treatment temperature, and reductions in the adhesion value parallel to the fibers was observed. The test samples reinforced with carbon fiber exhibited higher bending strength and modulus of elasticity in bending than the glass fiber-reinforced samples, while the compressive strength values parallel to the fibers and the adhesion strength values parallel to the fibers were lower.

Wood has been used as a primary material in the construction industry throughout history. Laminated timber products are preferred in modern construction due to their high strength and aesthetic appeal (Keskin 2001). Laminated timber consists of layers with parallel fibers bonded together, a configuration that enhances the material's mechanical properties (TS EN 386 1999).

The mechanical properties of wood, particularly compressive and flexural strength, are critical to the performance of structural elements. These properties vary as a function of grain orientation, moisture content, and the type of adhesive used (Usta 2018; Meriç 2019). Pressure applied parallel to the grain determines wood's load-bearing capacity, while pressure applied perpendicular to the grain affects the material's crushing resistance (Erkoç 2004).

The demand for sustainable and environmentally friendly building materials is increasing. Wood stands out in this area due to its low carbon footprint and its renewable resource status (Somer 2010). In addition, wooden structures are highly energy efficient and have the potential to reduce greenhouse gas emissions (İMO 2011).

Several studies have investigated reinforced wood materials. In a study conducted by Bollmus *et al*. (2020) the effects of different chemical modification agents (melamine-formaldehyde, phenol-formaldehyde, *etc.*) and various concentrations (0.5%, 5%, and 20%) on dynamic bending (impact bending strength) and tensile strength were investigated. Consequently, the modification generally reduced the strength under bending impacts; significant decreases were observed even at particularly low concentrations.

A study by Gaff *et al.* (2016) examined the effects of board thickness, adhesive type (PVAc and PUR), densification, and cyclic loading on European beech (*Fagus sylvatica*) and birch (*Populus tremula*). The results demonstrated that wood type and structural configuration (laminated *vs.* monolithic) affect impact bending strength (IBS) values (Gaff *et al*. 2016). Susainathan *et al.*'s 2025 study investigated changes in impact energy absorption, impact bending stiffness, and peak force of structures with a plywood core and a flax/epoxy coating change under increasing impact energy level. An increase in impact resistance due to the composite was reported (Susainathan *et al*. 2025).

Doğan's 2020 study compared impact energy absorption, bending, and compression strength of carbon/epoxy-coated sandwich structures with different core materials (*e.g*., wood). Both impact and static (*flexural and compression*) tests were performed (Doğan 2020). In the cited study, the compressive strengths of wood samples reinforced with glass fiber and carbon fiber fabrics were investigated, and the resulting data were used to evaluate the applicability of these methods for strengthening of vertical load-bearing elements in historical buildings.

Wei *et al.* (2013) investigated the mechanical properties of CFRP laminated veneer lumber (LVL), a fast-growing poplar tree species in China. Two experimental configurations were examined: LVL-SR reinforced with a single-sided CFRP layer and LVL-DR reinforced with a double-sided CFRP layer. The CFRP-reinforced LVL exhibited a greater flexural elasticity and modulus of rupture than the control LVL, with the flexural modulus values comparable to those of conventional LVL.

Glulam presents limitations in some applications with height restrictions (Johnsson *et al.* 2007). One proposed solution involves strengthening the LVL by applying FRP between the LVL plies and to the beams. This study investigated the reinforcement of laminated timber with pultruded rectangular carbon fiber rods, and the required anchorage length was evaluated. A total of 10 specimens were tested, along with a reference series, across three series. Four-point bending tests were conducted. The anchorage length of the reinforcement bar was determined to prevent premature failure. An analytical model was subsequently developed to describe anchorage behavior. A 49 to 63% increase in flexural load-carrying capacity was recommended.

EXPERIMENTAL

Wood Material

Sandwich panels were produced by coating the upper and lower tangential surfaces of the wood with strength-enhancing fibers. For sandwich panel production, one type of wood from each of the coniferous and broadleaf species was selected as the core material to represent different specific gravities. Scotch pine (*Pinus sylvestris* L.) and Turkish beech (*Fagus orientalis* Lipsky), which are frequently used in horizontal and vertical load-bearing as well as decorative applications in the Turkish construction industry, were selected. The wood materials were obtained by random selection from Akın Timber Transportation Industry Trade Limited Company (Afyonkarahisar, Turkey). The timber was selected to be free from defects, reaction wood, sapwood, and fungal or insect damage.

Covering Material

Layered composite structures generally contain a core material, which should be lightweight, rigid, and durable. Three types of reinforcement materials 0 to 90° bi-directional woven fiberglass fabric, carbon fiber fabric, and 6 cm strand length fiberglass scraps were used to reinforce the selected solid wood core material. These reinforcements were applied to enhance mechanical performance. These were supplied in roll form by Fiber Composite Industry and Trade Co. Ltd. (Istanbul, Türkiye) in three areal weights: 200, 300, and 400 g/m².

Adhesive Material

During production, MGS L285 thermosetting epoxy resin and MGS H285 hardener were mixed to form the adhesive. The mixing ratio of resin adhesive to hardener was determined according to the manufacturer's instructions (Dost Chemical Industrial Raw Materials Industry and Trade Ltd., Istanbul, Türkiye). A 100 to 40 ratio is recommended.

Preparation of Test Samples

Test specimens were first cut as drafts of 2 × 5 × 75 cm^3 in accordance with the principles of TS ISO 3129 (2021).

Fig. 1. Preparation stages of test samples

The wood specimens were then kept in a climate chamber at 20 ± 2 °C and 65 ± 5% relative humidity according to the principles of TS ISO 13061-1 (2021) until they reached 12% humidity to determine the moisture content. A total of 280 test specimens (2 × 2 × 10x + 5 control) were prepared, including 2 wood material types (Turkish beech and Scotch pine), 2 test types (compressive strength and dynamic shock), 5 replications, 9 fiber types + 1 control group. The final size of the double surface-coated test specimens for compressive strength was 20 × 20 × 30 mm^3, and the final size of the test specimens used for dynamic bending strength was 20 × 20 × 300 mm^3 (Figs. 1 and 2).

Fig. 2. Double surface-coated solid wood material test samples

Coating of Test Samples

Because of the limited number of veneer samples, the "hand-laying" method, which is commonly used for low-volume production, was chosen. In this process, liquid resin mixed with a hardener was applied to the surface of both the reinforcing material (fabric threads and remaining fibers) and the wood base using a roller. After the reinforcement material was coated onto the wood, it was rolled until the resin hardens. Rolling removed any air bubbles trapped between the sandwich panels. This rolling process was repeated intermittently after each layer of reinforcement was applied. The sandwich panels were then left to cure for 24 h at room temperature (23 °C). Chemical reactions in the resin hardened the material, allowing for high-strength, lightweight products.

Compressive Strength Parallel to Fibers

To determine the compressive strength of the fibers in the vertical direction, experiments were conducted in a multipurpose testing machine with a capacity of 15,000 kp in accordance with the TS ISO 13061-5 (2021) standard. For this purpose, the prepared 20 × 20 × 30 mm^3 samples were conditioned at 20 °C and 65% relative humidity until the equilibrium humidity was reached and subsequently reduced to 12% moisture content. A load was applied to the cross-sectional center of the samples; this process was performed at a specific speed to cause the samples to fracture within 1.5 and 2 min. Loading was continued until complete fracture, and the maximum force recorded at the moment of fracture was recorded. The obtained maximum force (F_{max}) value was evaluated using Eq. 1 in calculating the compressive strength (σ) in the direction parallel to the fibers (Fig. 3).

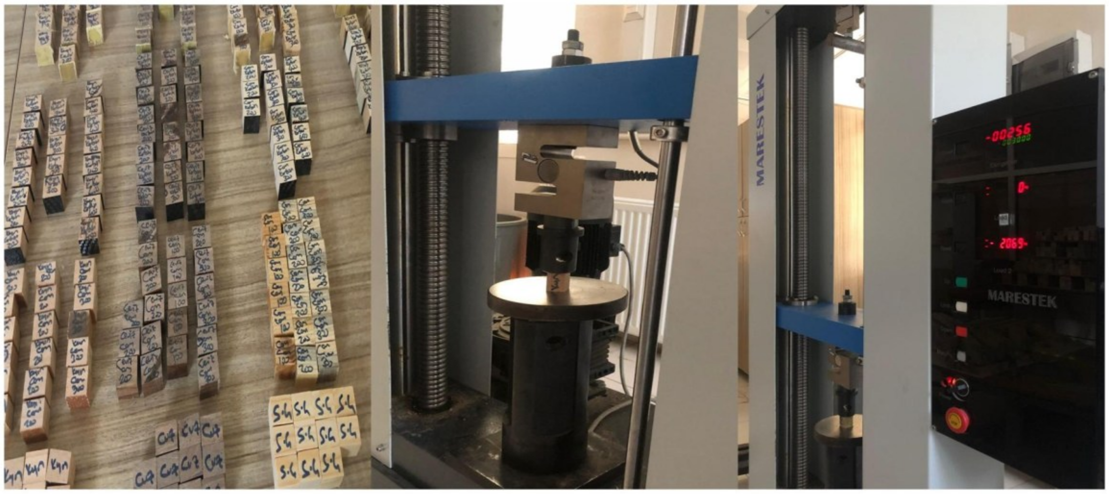

Fig. 3. Compression test collage for solid wood material

In the experiments, the force at the moment of crushing (F_{max}) and the compressive strength (σ) for the sample cross-sectional area ($A=a \times b$) were calculated as follows,

$$\sigma = F_{max.} / A \text{ (N/mm}^2\text{)} \quad (1)$$

where σ// is the compressive strength parallel to the fibers, F_{max} is the force at fracture (N), a is the Sample cross-sectional edge length (mm), and b is the sample cross-sectional edge length (mm).

Dynamic Bending Strength Parallel to Fibers

The dynamic (shock) bending strength test was performed in accordance with the principles of TS ISO 13061-10 (2021). Accordingly, the distance between supports was set at 260 mm, and test samples were prepared with dimensions of 20 mm × 20 mm × 300 mm. Dynamic bending strength values were determined by an unmodified Charpy brand device (Fig. 4).

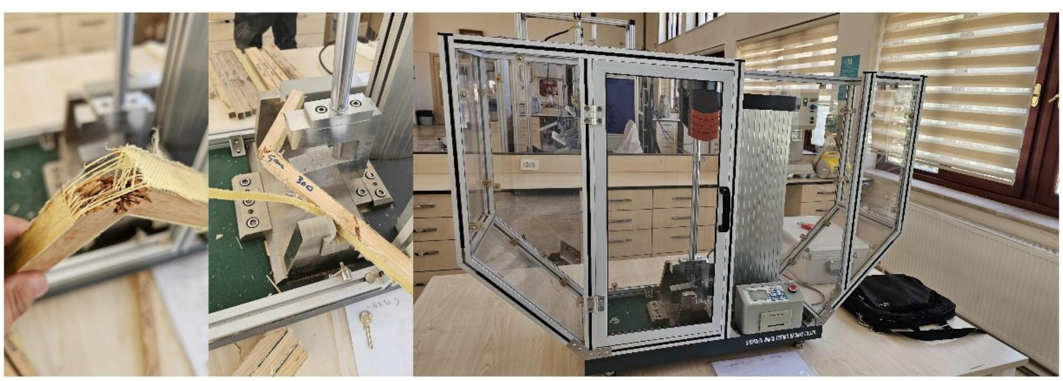

Fig. 4. Dynamic bending resistance collage for solid wood material

Evaluation of Data

The experimental data were statistically analyzed using MSTAT-C software. One-way analysis of variance (ANOVA) was applied, and Duncan's multiple comparison test was used to determine significant differences between groups at a confidence level of $p < 0.05$.

RESULTS AND DISCUSSION

Compressive strength data obtained from compression tests on solid wood samples reinforced with different fiber systems were statistically evaluated, and the effects of reinforcement types on mechanical performance were presented comparatively (Table 1).

One-way analysis of variance (ANOVA) was applied to determine whether significant differences existed among the experimental groups. All statistical analyses were conducted at a 95% confidence level ($\alpha = 0.05$). In addition, effect size values were calculated using eta-squared (η^2) to evaluate the magnitude of group differences.

Table 1. Independent Variables and Codes for Compressive and Dynamic Bending Strength

Argument Name		Code	Number of Samples
Beech Control		Control B	10+10
Pine Control		Control P	10+10
Carbon Fiber Weaving (200 g)	Pine Carbon Fiber Coating	PC200	10+10
	Beech Carbon Fiber Veneer	BC200	10+10
Fiberglass Weaving	Pine Fiberglass (200 g) Coating	PF200	10+10
	Pine Fiberglass (300 g) Coating	PF300	10+10
	Pine Fiberglass (400 g) Coating	PF400	10+10
	Beech Fiberglass (200 g) Coating	BF200	10+10
	Beech Fiberglass (300 g) Coating	BF300	10+10
	Beech Fiberglass (400 g) Coating	BF400	10+10
Chopped Fiberglass (Whiskers)	Pine Fiberglass 1 Layer Coating	PFW1	10+10
	Pine Fiberglass 2 Layer Coating	PFW2	10+10
	Beech Fiberglass 1 Layer Coating	BFW1	10+10
	Beech Fiberglass 2-Layer Coating	BFW2	10+10

Table 2. Compressive Strength

Group Code	Compressive Strength (N/mm^2)	Standard Deviation	Coefficient of Variation (COV)	Similarity Class
Control B	55.540	1.155	2.080	E
Control P	68.671	3.702	5.391	C
PC200	57.153	1.391	2.434	E
BC200	84.597	1.839	2.173	A
PF200	49.857	1.546	3.101	G
PF300	49.980	2.184	4.371	G
PF400	59.262	0.881	1.487	D
BF200	65.450	2.310	3.530	C
BF300	80.282	2.836	3.533	B
BF400	80.179	2.168	2.704	B
PFW1	48.548	1.160	2.389	G
PFW2	52.368	0.577	1.102	F
BFW1	80.321	1.694	2.109	B
BFW2	80.763	1.186	1.469	B

Table 2a. One-Way ANOVA Results for Compressive Strength

Source	SS	df	MS	F	p
Between Groups	4684.55	6	780.76	**41.57**	**<0.001**
Within Groups	1183.37	63	18.79	—	—
Total	5867.92	69	—	—	—

Effect size (η^2) = 0.80

When the 14 experimental groups were compared in terms of compressive strength, the values ranged from 48.6 to 84.6 N/mm². This range indicates that the reinforcement type and ratio had a significant effect on mechanical performance. The results of one-way ANOVA demonstrated that compressive strength differed significantly among the investigated groups ($F(6,63) = 41.57$, $p < 0.001$). The calculated eta-squared value (η^2 = 0.80) indicated a strong practical effect of reinforcement configuration on mechanical performance. Subsequent Duncan's test classified the experimental groups into distinct similarity classes at the 95% confidence level observed between the groups when $p < 0.05$. Duncan's multiple comparison test classified the groups into similarity classes ranging from A to G. This indicates that the groups are statistically different from each other at the 95% confidence level. In particular, the BC200 group performed significantly better than all other groups, placing it in the highest class (A) (Table 2).

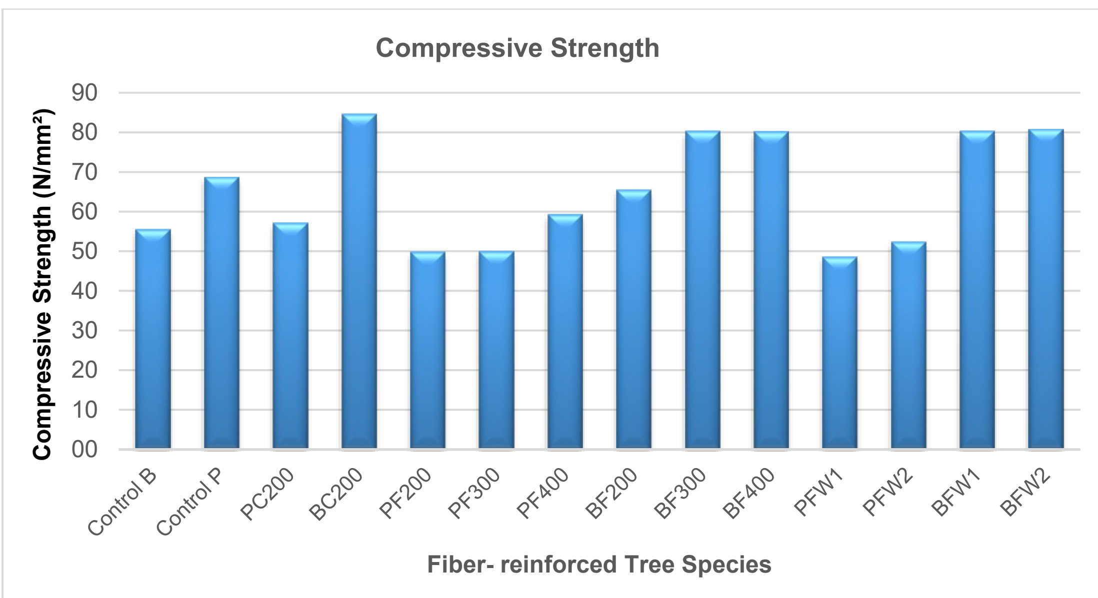

Fig. 5. Compressive strength by groups

As shown in Fig. 5, groups BC200, BFW1, and BFW2 exhibited the highest compressive strengths. Groups PFW1, PF200, and PF300 had comparatively lower values. Group BC (84.6 N/mm²) exhibited the highest compressive strength among all groups.

Previous studies have reported that glass fiber additives enable a 25% increase in compressive strength in composite materials (Smith *et al.* 2018). Similarly, Yılmaz *et al.* (2021) reported that strength increases considerably when the additive ratio exceeds 10% in polymer matrix systems.

Consistent with these findings, statistically significant increases in compressive strength were observed in the present study for groups incorporating reinforcement materials such as BC200, BFW1, and BFW2.

The results demonstrate that fiber-reinforced cladding considerably increased the compressive strength of wood perpendicular to the grain. The use of fiberglass fabric and carbon fiber provided an effective approach for overcoming wood's inherent mechanical limitations. Similarly, Raftery and Harte (2011) reported that carbon fiber reinforcement of wood beams had positive effects on flexural strength. Borri and Speranzini (2005) further emphasized that fiberglass-based strengthening of historic timber elements both improved structural integrity while minimizing intervention.

One of the primary concerns in reinforcing of load-bearing elements in historic structures is ensuring reversibility and compatibility with original materials. Epoxy-based fiber reinforcement systems used in this context provide additional strength without damaging the structure and offer ease of on-site application (Görün *et al*. 2020). However, further investigation is required on the long-term performance, environmental durability, and aesthetic compatibility of synthetic reinforcements, such as carbon fiber, in historic contexts.

Reinforcing timber structural elements with fiber-reinforced polymer (FRP) materials represents an effective solution, particularly in the restoration of historical buildings. This approach improves the durability of load-bearing elements by improving the mechanical properties of wood.

Recent studies have demonstrated that carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) materials can drastically increase the compressive strength and stiffness of timber columns. Chen *et al.* (2025) reported substantial improvements in the ultimate load-bearing capacity and stiffness of square-section timber columns strengthened with CFRP and BFRP.

The use of FRP materials in historic structures is less invasive than traditional strengthening methods, offering advantages in preserving the structure's authenticity. Triantafillou (2001) stated that FRP materials are effective in increasing the strength, stiffness, and ductility of historic structures.

Nevertheless, the long-term behavior of FRP materials and their resistance to environmental influences remains a critical consideration. Chen *et al.* (2025) evaluated the performance of FRP-reinforced timber structures under various environmental conditions and obtained positive results.

Overall, the findings indicate that fiber-reinforced cladding is an effective technique for strengthening existing columnar (*vertical*) timber load-bearing elements and are consistent with previously reported results. However, when assessing practical implementation, the cultural value of the structure, material authenticity, and intervention principles and limitations should be considered.

In the study, various fabric reinforcements were applied to Scotch pine and beech wood species, and dynamic bending strength (kJ/mm²) was measured. The measured values, along with standard deviation, coefficient of variation, and Duncan's similarity classes, are presented in Table 3.

The control groups (Control B and Control P) exhibited the lowest dynamic flexural strength values. Control P (35,569 kJ/mm^2) exhibited particularly poor performance. The highest performing groups were PF400, PFW2, and BFW2 groups and were classified as Class A. These groups were characterized by high mean values and low coefficients of variation.

Table 3. Dynamic (Shock) Bending Resistance

Group Code	Dynamic Bending Strength (kJ/mm^2)	Standard Deviation	Coefficient of Variation (COV)	Similarity Class
Control B	48.970	3.500	7.148	E
Control P	35.569	3.863	10.862	F
PC200	65.092	2.345	3.603	B
BC200	59.609	0.627	1.052	C
PF200	60.045	6.188	10.305	C
PF300	62.512	0.773	1.237	C
PF400	68.304	0.558	0.817	A
BF200	56.206	5.286	9.404	D
BF300	59.034	0.837	1.417	C
BF400	64.368	0.323	0.503	B
PFW1	55.092	0.749	1.360	E
PFW2	69.473	1.390	2.000	A
BFW1	58.741	0.421	0.716	D
BFW2	70.172	0.359	0.511	A

Table 3a. One-Way ANOVA Results for Dynamic Bending Strength

Source	SS	df	MS	F	p
Between Groups	4129.21	6	688.20	38.94	<0.001
Within Groups	1113.55	63	17.68	—	—
Total	5242.76	69	—	—	—

Effect size (η^2) = 0.79

Glass fiber and carbon fiber reinforcements increased impact resistance depending on the number of plies and density. Similarly, significant differences were observed in dynamic bending strength values ($F(6,63) = 38.94$, $p < 0.001$). The corresponding effect size was also high ($\eta^2 = 0.79$), suggesting that both fiber type and ply number played an important role in impact resistance. Two-ply glass fiber configurations, such as PFW2 and BFW2, produced statistically significant differences with the highest dynamic flexural strength ($p < 0.05$). A low coefficient of variation (≤ 2%) indicates high measurement reliability for these groups, reflecting both increased strength and consistency in these reinforcement types. Although beech exhibited higher mechanical performance, the results show that pine performance can reach levels comparable to beech with appropriate reinforcements. Overall, the data indicate that fabric type, areal density, and number of plies in wood reinforcements are critical for optimizing mechanical strength (Table 3).

The Scotch pine control (Control P) and beech control (Control B) showed the lowest dynamic flexural strength values (35.6 and 49.0 kJ/mm^2, respectively). Glass fiber and carbon fiber reinforcements provided substantial increases in all wood species. In particular, PF400 and BFW2 achieved the highest values and were classified as Class A. Increasing the reinforcement type and number of plies drastically increases dynamic flexural strength. For example, while PFW1 was 55.09 kJ/mm², the two-ply application reached 69.47 kJ/mm² in PFW2. Therefore, two-ply glass fiber and carbon fiber reinforcements represent effective and reliable strategies for improving mechanical performance. These results can guide the determination of reinforcement strategies in engineering applications of wood materials.

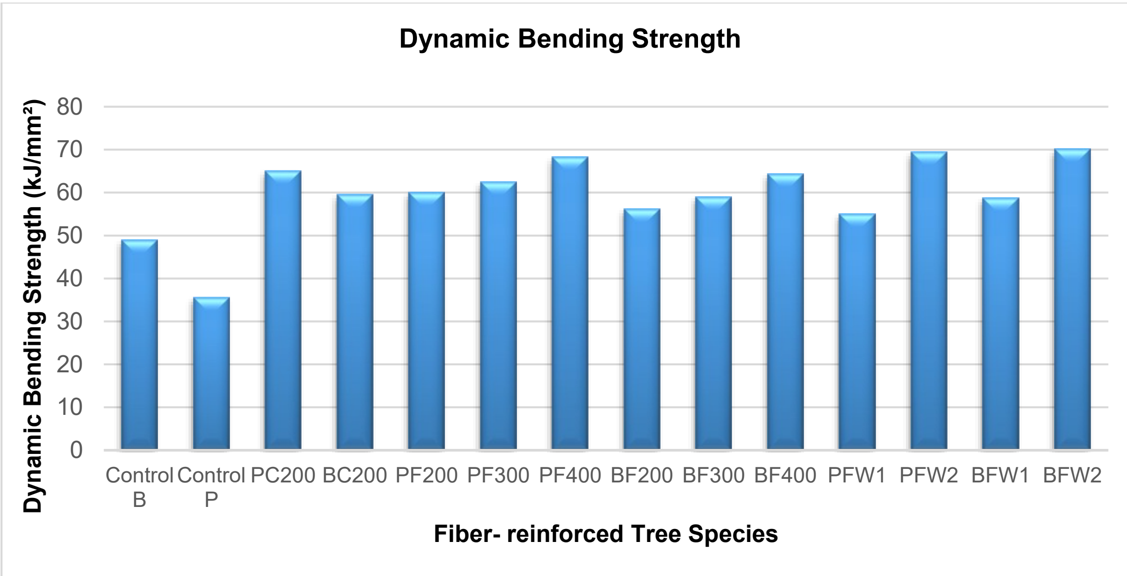

Fig. 6. Dynamic bending strength by groups

CONCLUSIONS

The effects of reinforcing Scots pine and Turkish beech solid wood samples with glass fiber and carbon fiber fabrics were experimentally evaluated relative to the compressive strength perpendicular to the fibers and dynamic bending strength. Solid wood samples were coated with glass fiber fabric, carbon fiber fabric, and glass chips using epoxy resin.

1. As a result of the application, the highest compressive strength was obtained in the BC group (84.6 N/mm²), and the lowest value was obtained in the PFW1 group (48.6 N/mm²). In the dynamic bending strength test, the highest value was obtained in the BFW2 group (70.2 kJ/mm²), and the lowest value was obtained in the CP group (35.6 kJ/mm²).
2. Lower-performance groups such as PCW1, PC200, and PC300 remained between 49 and 50 N/mm². These results indicate that the type and quantity of fiber used is a determining parameter, especially for strength perpendicular to the fiber direction.
3. Such reinforced systems offer significant potential for preserving the structural integrity of historical buildings in restoration and structural engineering.

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