Effect of Glass Fiber Reinforcement on Mechanical Properties of Wood Material

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Increasing the mechanical strength of wooden materials with glass fiber fabric reinforcement and composite elements can be a very suitable method for restoration and strengthening techniques in historical wooden structures. In this study, the effects of fiber-reinforced laminated wood composites were examined with respect to bending strength and modulus of elasticity in bending. Experimentally, 0°/90° woven glass fiber fabrics with areal weights of 200, 300, and 400 g/m² were bonded using epoxy resin to the longitudinal surfaces of two different wood species (Scots pine and Turkish beech). An evaluation of the bending properties of these wooden sandwich structures revealed that the incorporation of glass fiber fabric reinforcement led to a significant enhancement in their bending strength. In addition, a significant improvement was achieved in the modulus of elasticity. It was observed that glass fiber fabric, especially the 400 g/m² weight options, increased the durability of wood materials more. As a result, the bending strength of wood materials can be significantly increased with glass fiber fabric reinforcement. This method can be considered a promising reinforcement technique, particularly in the fields of engineering and construction. However, in the context of historical restoration, the use of external reinforcement must be approached with caution due to conservation principles such as material authenticity, reversibility, and minimal intervention.

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INTRODUCTION

Wood is a recyclable, nature-friendly, sustainable, and harmonious product when used correctly and combined with other materials. Wood has a very old history compared to other building materials and has an important place in Turkish architecture. Wood was more commonly used in the past, and it has surv.ived to the present day in historical buildings without any significant processing, maintaining its structural integrity over time.

The use of wood as a structural material in buildings decreased after the Industrial Revolution in the 19th century and was replaced by stone and brick materials. Despite this, it was preferred more as a bearing skeleton frame with the development of building systems in the early 20th century. The correct way of using wood as building material is to ensure it has suitable moisture conditions and for using it as bearing unit with sufficient cross-sectional area. One can examine wood in two groups in terms of its physical and mechanical properties. In the use of wood in historical buildings, priority should be given to its natural durability rather than solely its physical properties. For effective integration into load-bearing systems, both the natural resistance of the wood to biological and environmental factors and its mechanical performance must be evaluated holistically. The main physical properties of the material are the moisture content, specific gravity, and heat properties. Important mechanical properties are compressive strength, bending strength, shear strength, splitting strength, and elasticity, which are examined.

Wood is a building material widely preferred by architects and engineers due to its numerous advantages over its disadvantages. Its ease of procurement, high strength-to-weight ratio, low transportation costs, ease of assembly, interlocking capability, resistance to chemical effects, and the flexibility to be shaped directly on-site make it a favorable option in construction (Çalışkan *et al.* 2019). Wooden structures generally provide adequate performance under vertical loads including the self-weight of structural elements, permanent loads such as walls, floors, and roofs, and live loads such as furniture, occupants, and equipment. They are particularly vulnerable to lateral forces. During earthquakes, structures are exposed to intense horizontal loads, which can significantly affect their stability and integrity (Çalışkan *et al.* 2019). Therefore, understanding and improving the seismic behavior of wood as a structural material is crucial, especially in earthquake-prone regions.

In historical buildings where wooden materials are used, a total of four methods are preferred for protection and maintenance, namely Impregnation and protection, Rehabilitation, Restoration, and Reconstruction. The common feature of these materials is to preserve the architectural characteristics of the original structure. For this reason, it is important to have a good design in wooden structures based on the durability, quality, and economy of the materials. In order to keep the service life of the wooden material used in the structure, it is necessary to take precautions against moisture and insect problems. This situation also brings about significant load bearing problems in the structure. In historical buildings where wooden materials are used, reinforcement of damaged load bearing elements with fiberglass fabric can help increase the resistance, durability, and long service life of the material (Çelik and Şakar 2022).

Today the wooden material used in historical structures is preferred as a load-bearing structural element in the carcass wall and roof constructions while using traditional construction methods. Tree species such as chestnut, beech, oak, pine, spruce, and fir are preferably for use in carcass systems in different sizes such as pillars, buttresses, main beams, floor beams, fathers, drip purlins, ridge purlins, and rafters. Nails, glue, bolts, or dovetails are being used in applications. Studies on the balanced use of the material to maximize its efficiency, sustainability, conservation, and increasing the ability to be reused when necessary are continuing (Özder *et al*. 2024).

Extending the service life of wooden materials is important in terms of using the resources efficiently in environmental sustainability. It is known that various chemicals are widely used in impregnation applications, which is one of the main methods for protecting wooden materials (Teaca *et al*. 2019; Hülagü 2021; Perker and Öztürk 2024). Experimental studies are being conducted on the impregnation effectiveness of plant substances such as tree barks and fruits, leaves of trees and other plants, tannins, plant-based oils, *etc*. (Peker and Ulusoy 2021). The effect of the impregnation process applied with plant-based substances on the mechanical properties of wood material such as bending resistance/elasticity, pressure and dynamic bending resistance have been studied. In addition, the effects of the impregnation process on the physical properties of wood material such as moisture, density, and retention value have been determined with various studies (Özkan *et al*. 2020).

Çiğdem and Perçin (2022) examined the mechanical and physical properties of laminated composite samples obtained from beech wood reinforced with glass fiber and carbon using phenol formaldehyde (PF) glue with heat treatment application and determined that the bending strength and elastic modulus of the samples reinforced with glass and carbon fibers have been increased.

Bal (2021) produced laminated veneer lumber using glass fiber mesh and poplar rotary-cut veneers, bonded with polyvinyl acetate (PVAc) adhesive. Experimental groups (3) and control group (1) were formed, glass fiber mesh was placed in 2, 4, and 6 glue layers. It was reported that there was a significant increase in the splitting and bending resistances of the boards using 6 glass fiber compared to the control group.

The reinforcement of timber materials with fiber-based composites has gained increasing attention in recent decades, particularly in the context of structural retrofitting and conservation of historical buildings. Numerous studies have demonstrated that the integration of high-performance fibers such as glass and carbon into wood-based composites can significantly enhance their mechanical behavior, especially in terms of bending strength and elastic modulus.

Fiore *et al.* (2015) highlighted that natural and synthetic fiber-reinforced polymers can significantly improve the flexural properties of wood composites, making them suitable for structural applications. Similarly, Bal and Ozyurt (2015) showed that the incorporation of woven glass fiber fabric into poplar veneer-based laminated wood panels substantially improved their bending resistance and stiffness. Osmannezhad *et al.* (2014) also confirmed the positive influence of glass fiber reinforcement on the modulus of elasticity and overall durability of wood-based materials, suggesting its potential in load-bearing applications.

In restoration contexts, Chuang and Quang (2018) argued that composite-reinforced timber elements not only offer mechanical advantages but also meet conservation principles by preserving the original material with minimal intervention. The use of glass fiber fabrics bonded with epoxy resin provides a chemically stable and mechanically resilient solution, especially in heritage buildings subjected to aging, seismic risk, or environmental stressors.

It is understood that glass fiber reinforcement particularly when applied as woven fabric in combination with appropriate adhesive systems is recognized as a reliable and effective method for enhancing the structural integrity of wooden elements. These advancements are of great significance for fields such as civil engineering, architecture, and cultural heritage conservation, where the demand for sustainable and long-lasting reinforcement techniques continues to grow.

This study was conducted with the aim of expanding the scale and application areas of wooden materials and enhancing their technological performance beyond optimal levels through the use of glass fiber and carbon fiber fabrics. The targeted applications include improving resilience in cases of earthquakes, fires, and other natural disasters, as well as enhancing the durability of wooden elements in interior and exterior furniture, wooden bridges, historical restoration projects, and moisture- or water-exposed environments such as wetlands.

EXPERIMENTAL

Wood Material

A multilayer composite sheet was produced by covering the upper and lower (tangential) surfaces of the wood substrate with strength-enhancing fiber fabrics. In order to produce sandwich panel sheets, one tree species each from coniferous and deciduous tree species was chosen as the core material to represent different specific gravities. Scots pine (*Pinus sylvestris* L.) and Turkish beech (*Fagus orientalis* Lipsky), which are frequently preferred in horizontal/vertical carrier and decoration applications in the construction industry, were chosen as experimental materials. These materials were procured from timber enterprises located in Afyonkarahisar province, Turkey, using a purposive sampling method. The selection process was conducted meticulously to ensure that the timber specimens were defect-free, exhibited straight and uniform fibers, contained no knots or reaction wood, consisted of sapwood, and showed no signs of fungal or insect damage.

Covering Material

Layered composite structures typically incorporate a core material, which is generally required to be lightweight, stiff, and durable. In this study, solid wood was selected as the core material, and to enhance its mechanical strength, bidirectional (0°–90°) woven glass fiber fabrics were applied as reinforcement elements in three different areal weights: 200, 300, and 400 g/m².

The material properties provided for the glass fiber fabric such as tensile strength, modulus of elasticity, elongation at rupture, fabric thickness, and areal weight were primarily obtained from the technical data sheets provided by the manufacturer. These values reflect standard properties of E-glass fiber fabrics commonly used in composite reinforcement applications and are consistent with those reported in the literature (*e.g.*, Osmannezhad *et al.* 2014; Fiore *et al*. 2015).

However, the final composite performance indicators such as the bending strength and modulus of elasticity of the reinforced wood specimens were determined experimentally by the authors through laboratory testing. The influence of fabric areal weight (200, 300, and 400 g/m²) on the mechanical behavior of laminated wood panels was analyzed based on a standardized bending test procedure.

Thus, while the intrinsic material properties of the reinforcement fabric were sourced externally from the manufacturer, the mechanical performance of the composite systems incorporating these fabrics was evaluated through the authors' original experimental work.

Adhesive Material

During production, MGS L285 (Dost Chemistry Industrial Raw Materials Industry and Trade Co. Ltd. Istanbul, Türkiye) thermosetting epoxy resin material and MGS H285 hardener were mixed and applied as adhesive. During application, the mixing ratios of resin glue and hardener were applied according to the manufacturer's instructions. This ratio to use is recommended as 100/40.

The test samples were first cut as 2 × 5 × 75 cm drafts according to TS ISO 3129 standard and then kept in the air conditioning chamber at 20±2 °C and 65±5% relative humidity following TS ISO 13061-1 until they reached 12% moisture content. A total of 70 test samples ((2 × 2 × 3 × 5) + 10 = 70) piece controls were prepared, including 2 wood material types (Turkish beech and Scots pine), 2 test samples (bending strength) + 1 control and 5 repetitions, and 3 glass fiber fabric types. The final size of the test samples coated on both surfaces for bending and elastic modulus is 360 × 20 × 20 mm.

METHODS

Coating of Test Samples

The "hand lay-up method," which is widely used in low production levels, was selected for coating of wood material. In this process, the liquid resin was mixed with the hardener as an adhesive. When it was ready, it was applied to both the reinforcement (fiberglass fabric) materials and to the surface of the wood material used as the core with a roller. Following the application of the reinforcement material onto the wood surface, a rolling procedure was performed to ensure proper adhesion and uniform distribution, continuing until the resin fully cured. Air bubbles trapped within the sandwich panel during the rolling process were eliminated. The compaction procedure was repeated periodically after the application of each layer of reinforcement material. Afterwards, the sandwich panels were allowed to cure for 24 h at room temperature. This hardening of the material *via* chemical reactions occurring in the resin provided a way to achieve high-strength and lightweight products (Fig. 1).

Fig. 1. Coating of wood material with fiber

Flexural Strength and Modulus of Elasticity

The determination of the bending strength of the wood material was determined based on the TS ISO 13061-3 (2021) standard, and the elasticity modulus was determined according to the principles of TS ISO 13061-4 (2021). The experiments were carried out on a computer-controlled 1000 kp capacity universal testing machine. For this purpose, the 20x20x300 mm samples prepared were climatized at 20 °C and 65% relative humidity until they reached equilibrium humidity and brought to 12% moisture content. A load was applied from above to the center of the sample length; this application was carried out with a constant loading rate (15 mm/min) that would ensure that the samples broke in 1.5 to 2 minutes. The loading was continued until the sample broke completely, and the maximum force obtained at the moment of breakage was read from the device and recorded. The following formula was used in the calculation of the bending resistance (Fig. 2),

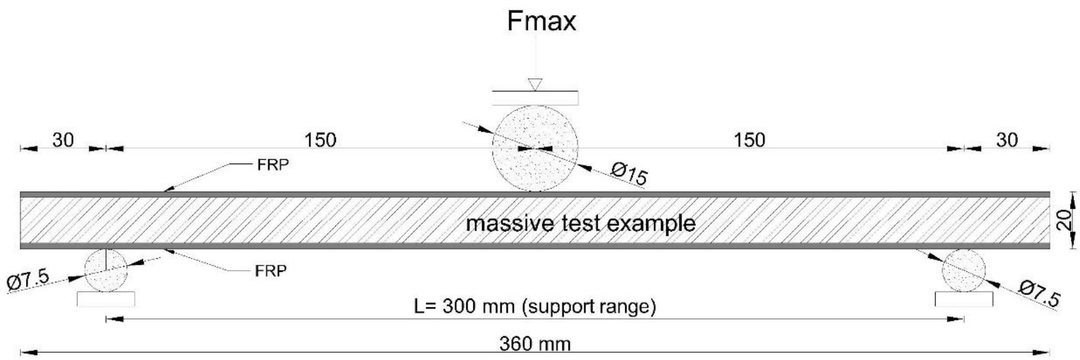

Fig. 2. Bending strength test experimental setup diagram

$$\sigma_e = \frac{3.F_{max}.L}{2.b.\ h^2} \quad N/mm^2 \tag{1}$$

where L is the distance between the support points (mm); b is the width of the sample (mm); and H is the thickness of the sample (mm). Test samples used in bending resistance were used to determine the elasticity modulus. For the force difference (ΔF) applied in the elastic deformation zone, the elasticity modulus (E) was calculated with the help of the bending amount difference (Δf) in the sample.

$$E = \frac{\Delta F.\ L^3 \text{-} b \pm \sqrt{b^2 \text{-} 4ac}}{4.b.H^3.\Delta f} \quad N/mm^2 \tag{2}$$

The bending strength of the wood material was determined based on the TS ISO 13061-4 (2021) standard, and the elasticity modulus was determined according to the principles of TS ISO 13061-4 (2021). The experiments were carried out on a computer-controlled 9806.65 N capacity universal testing machine. For this purpose, the 20x20x300 mm samples prepared were acclimatized at 20 °C and 65% relative humidity until they reached equilibrium humidity and had been brought to 12% moisture content. A load was applied from above to the center of the sample length; this application was carried out with a constant loading rate (15 mm/min) that would ensure that the samples broke in 1.5 to 2 minutes. The loading was continued until the sample broke completely, and the maximum force obtained at the moment of breakage was read from the device and recorded. The following formula was used in the calculation of the bending resistance.

Here, ΔF is the force equal to the difference between the arithmetic averages of the lower and upper limits of loading in the elastic deformation region (N); L is the span between the support points (mm); Δf is the deflection in the net bending area, the difference between the arithmetic averages of the results of the deflections measured at the lower and upper limits of loading (mm); b is the cross-sectional width of the test piece (mm); and h is the cross-sectional thickness of the test piece (mm) (Fig. 3).

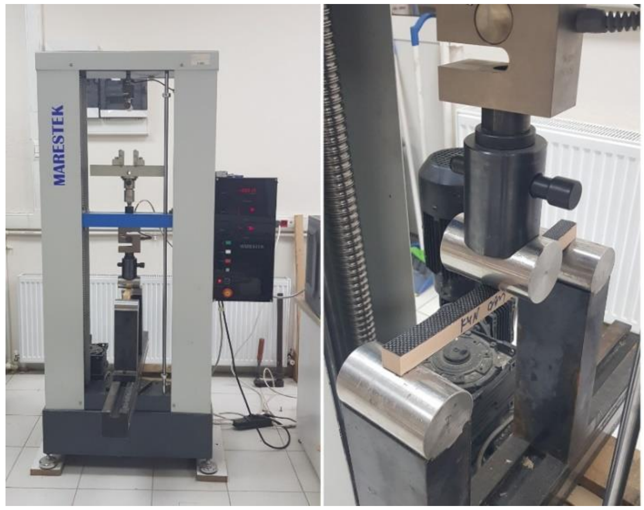

Fig. 3. Universal testing machine/three point bending test application

Evaluation of Data

The AT-C program was used for statistical analysis of the obtained data. Data were analyzed using Duncan test ($p < 0.05$) and variance analysis (one-way ANOVA).

RESULTS AND DISCUSSION

Bending Strength (N/mm^2)

Bending strength values were obtained based on wood type, and the results are given in Table 1.

Table 1. Bending Strength Values by Wood Type (N/mm^2)

Wood Type	$\bar{X}$	HG
Scots Pine (SP)	87.39	B
Turkish Beech (TB)	112.9	A
LSD: 5.953 (HG: Homogeneity Group)		

When evaluated based on wood species, beech wood exhibited a higher bending strength (112.9 N/mm^2), whereas Scots pine demonstrated a comparatively lower value (75.3 N/mm^2).

The bending strength values obtained according to fabric type are given in Table 2.

Table 2. Bending Strength Values According to Fabric Type (N/mm^2)

Fabric Type (B)	$\bar{X}$	HG
Control (Cont.)	80.56	C
Woven glass fiber fabric 200 g/m^2 (WGFF200)	100.9	B
Woven glass fiber fabric 300 g/m^2 (WGFF300)	103.7	B
Woven glass fiber fabric 400 g/m^2 (WGFF400)	115.3	A
LSD: 8.419 (HG: Homogeneity Group)		

According to the fabric types used, the highest bending strength value was determined for specimens with woven glass fiber fabric with 400 g/m^2 (WGFF400) (115.3

N/mm^2), whereas the lowest bending strength was determined in woven glass fiber fabric with 200 g/m^2 (WGFF200) (100.9 N/mm^2). Fabric types showed a significant increase in strength compared to the control sample.

The Duncan test results obtained for bending strength values according to wood type and to fabric type are given in Table 3.

Table 3. Bending Strength Duncan Test Results

Wood Type × Fabric Type	$\bar{X}$ (N/mm^2)	$\bar{X}$ (%)		HG
SP Cont. (Scots Pine)	75.39	0		D
SP * WGFF200	86.16	14.28		CD
SP * WGFF300	89.36	18.53		C
SP * WGFF400	98.64	31.00		C
TB Cont. (Turkish Beech)	85.74	0		CD
TB * WGFF200	115.7	35		B
TB * WGFF300	118.1	38		B
TB * WGFF400	132.0	54		A
LSD: 11.91 (HG: Homogeneity Group)				

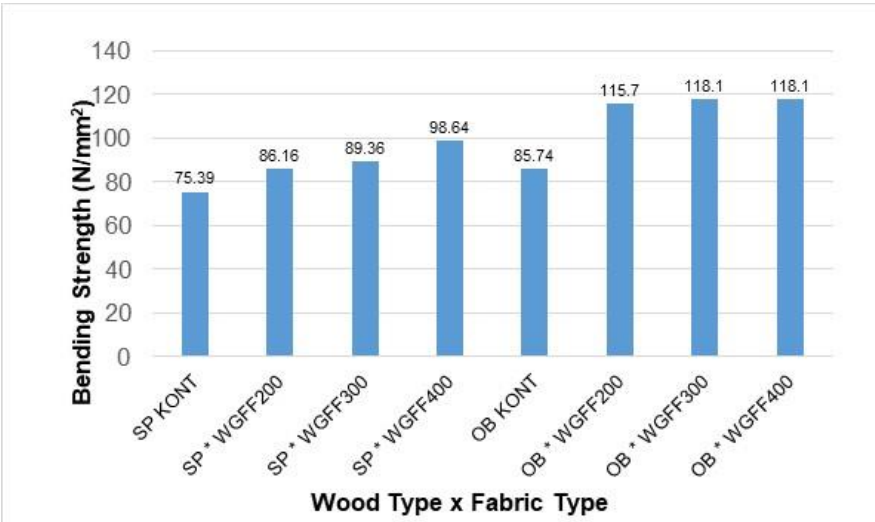

Fig. 4. Change in bending strength depending on wood and fabric types

The results of the Two-Way ANOVA regarding the effects of wood type and fabric type on the bending strength values are presented in Table 4.

Table 4. Bending Strength Duncan Test Results

Variance Source	Degree of Freedom	Sum of Squares	Average Squares	F Account	P < 0.05
Wood Type (A)	1	6496.635	6496.635	75.0062	0.0000****
Fabric Type(B)	3	6273.704	2091.235	24.1441	0.0000****
AB	3	794.912	264.971	3.0592	0.0422
Eror	32	2771.667	264.971		
Total	39	2771.667			

****:0.005 importance level

When the tables and figures were examined, the highest bending resistance value was determined in Turkish beech wood, followed by Scots pine wood. The glass fiber fabric reinforcement of both wood types provided significant increases in bending resistance values compared to the control sample; especially when the fabric type was considered. It was determined that the main factor structure provided significant increases over the 400 g/m^2 (WGFF400) bending strength of both wood types treated with woven glass fiber fabric. The highest value of 132.0 N/mm^2 was determined in Turkish beech wood (TB * WGFF400).

The external application of reinforcement—such as using fiber-reinforced polymer (FRP) fabrics bonded onto the surface of wooden elements—can be a highly effective method for improving the structural performance of deteriorated or weakened historical timber. It offers several advantages, including minimal invasiveness, increased flexural and tensile strength, enhanced resistance to environmental stressors, and compatibility with various adhesive systems such as epoxy resins. However, whether it is the best option depends on multiple factors, particularly when viewed through the lens of heritage conservation ethics and reversibility, as emphasized in documents such as the Venice Charter (1964) and the ICOMOS Principles.

Advantages:

- Mechanical Efficiency: External reinforcement significantly improves bending strength and stiffness without requiring major modifications to the original structure (Fiore *et al*. 2015; Bal 2015).
- Ease of Application: The technique is relatively fast, clean, and does not require extensive dismantling of historical elements.
- Material Compatibility: Modern adhesives and woven fabrics (*e.g*., glass or carbon fiber) can be selected to ensure compatibility with wood's mechanical behavior.

Limitations and Considerations:

- Aesthetic Impact: External applications can alter the visual integrity of heritage materials, which is critical in preservation contexts.
- Reversibility: According to conservation principles, any intervention should ideally be reversible. Epoxy-bonded reinforcements are generally not reversible, which may conflict with preservation ethics.
- Moisture Trapping Risk: Improper application or material incompatibility can result in moisture entrapment, leading to decay or fungal attack over time.
- Material Aging: Long-term performance of synthetic reinforcements (*e.g*., under UV or humidity) remains a concern in heritage structures.

While external reinforcement using FRP fabrics is technically effective and often structurally beneficial, it may not always align with the conservation goals of authenticity, minimal intervention, and reversibility. Therefore, it should be considered as one of several possible methods, to be selected after a thorough assessment of the object’s cultural value, material condition, and intended use. In some cases, internal reinforcement, traditional repair methods, or hybrid solutions (combining new materials with traditional techniques) may offer a better balance between preservation and performance.

Bal and Ozyurt (2015) produced laminated veneer lumber using glass fiber fabric and poplar veneer. The technological properties of the manufactured material were evaluated by forming one control group and three experimental groups reinforced with different types of glass fiber fabric. The study specifically examined bending strength and modulus of elasticity. Test results indicated that the incorporation of glass fiber fabric significantly enhanced the material's density, bending strength, and modulus of elasticity in flexural loading.

Yıldırım *et al.* (2021) conducted a study to determine the four-point bending strength of wood-based laminated composites reinforced with glass fiber fabric. Test specimens were prepared using chestnut (*Castanea sativa*) wood and bonded with two types of adhesives: polyvinyl acetate (PVAc-D4) and polyurethane (PU-D4). To improve the mechanical performance of the laminated elements, two types of plain-woven glass fiber fabrics were used: Type 1 (100 g/m², loose weave) and Type 2 (200 g/m², tight weave). According to the results, the highest static bending strength parallel to the glue line was recorded in the laminated samples reinforced with Type 2 glass fiber fabric (200 g/m², tight weave) and bonded with polyurethane (PU-D4) adhesive, reaching 85.2 N/mm². The lowest value, 75.1 N/mm², was observed in the control group samples without interlayer reinforcement and bonded with polyvinyl acetate (PVAc-D4) adhesive.

The experimental results in this study were also consistent with findings in the literature. Glass fiber fabric, composed of numerous fine fibers, enables a more uniform distribution of stress, pressure, and other loads across the surface of the material to which it is applied. This is believed to enhance the structural performance and mechanical stability of the wood material. Glue also plays a major role in increasing the bending resistance. Epoxy resin is a rigid and durable adhesive that chemically interacts with the surface of the wood material while bonding the fibers of the glass fiber fabric. This interaction contributes to a significant enhancement in the overall strength of the composite structure.

Modulus of Elasticity (N/mm^2)

The values of modulus of elasticity in bending obtained according to wood type are given in Table 5.

Table 5. Values of Modulus of Elasticity in Bending Obtained According to Wood Type (N/mm^2

Wood Type	$\bar{X}$	HG
Scots Pine (SP)	8795.531	B
Turkish Beech (TB)	11422.761	A
LSD: 518.3 (HG: Homogeneity Group)		

According to the wood type, the highest elastic modulus value was determined in Turkish beech wood (11400 N/mm^2), and the lowest in Scots pine (8800 N/mm^2). The elastic modulus in bending obtained according to the fabric type is given in Table 6.

Table 6. Elasticity Modulus Values Obtained in Bending According to Fabric Type (N/mm^2)

Wood Type	$\bar{X}$	HG
Control (Cont.)	7920	C
Woven Glass Fiber Fabric 200 g/m^2 (WGFF200)	10400	B
Woven Glass Fiber Fabric 300 g/m^2 (WGFF300)	10600	B
Woven Glass Fiber Fabric 400 g/m^2 (WGFF400)	11480	A
LSD: 733 (HG: Homogeneity Group)		

When evaluated according to the fabric type; a significant increase was determined compared to the control sample. The highest elastic modulus value was determined as 400 g/m^2 (WGFF400) (11500 N/mm^2) in woven glass fiber fabric.

The elastic modulus values obtained according to wood type and fabric type are given in Table 7.

Table 7. Duncan Test Results on Elasticity Modulus Values in Bending

Wood Type × Fabric Type	$\bar{X}$ (N/mm²)	$\bar{X}$ (%)	HG
SP Cont.	7538.084	0	E
SP * WGFF200	8987.307	20	CD
SP * WGFF300	9090.389	21	CD
SP * WGFF400	9566.344	27	C
TB Cont.	8294.114	0	DE
TB * WGFF200	11686.618	41	B
TB * WGFF300	12308.668	49	B
TB * WGFF400	13401.643	62	A
LSD: 1037 (HG: Homogeneity Group)			

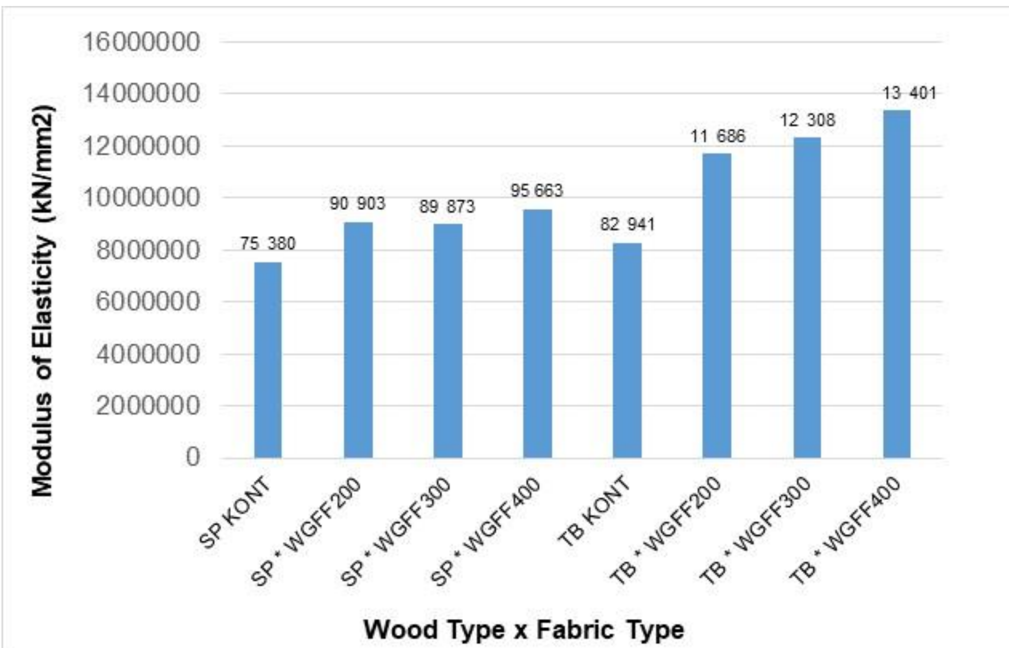

Fig. 5. Change in modulus of elasticity in bending according to wood and fabric types

The results of multiple variance analysis regarding the effects of elastic modulus on bending according to wood type and fabric type given in Fig. 5 are given in Table 8.

Table 8. Multiple Variance Analysis on the Effects of Elastic Modulus Value in Bending According to Wood Species and Fabric Type

Variance Source	Degree of Freedom	Sum of Squares	Average Squares	F-Account	P < 0.0
Wood Type (A)	1	69023367.289	69023367.289	105.1068	0.0000****
Fabric Type (B)	3	70680508.833	23560169.611	35.8768	0.0000****
AB	3	13608999.087	4536333.029	6.9078	0.0010***
Eror	32	21014311.614	656697.238		
Total	39	174327186.823			

The highest elastic modulus value was determined for TB * WGFF400 (13400 N/mm^2) in Turkish beech wood, and the lowest value was determined as SP * WGFF300 (8990 N/mm^2) in Scots pine. Both wood types provided a significant increase compared to the control sample. A 0.005 error probability was determined with the Duncan test that the main factor here was the fabric fiber structure, which had a significant effect on the elastic modulus.

Keskin *et al.* (2003) determined that the modulus of elasticity in bending of laminated Scots pine (*Pinus sylvestris*) wood increased by 2.74% compared to solid wood. Furthermore, it has been reported that the incorporation of woven glass fiber reinforcement significantly enhances the modulus of elasticity in wooden materials (Osmannezhad *et al.* 2014; Bal *et al.* 2015). In another study, Güler and Subası (2012) examined the mechanical properties of laminated Scots pine materials reinforced with varying proportions of glass and carbon fibers. The results demonstrated that the incorporation of both fiber types contributed to notable improvements in the mechanical performance of the laminated composites.

The influence of adhesive type and loading direction on the bending strength of oak (*Quercus* spp.) laminated with polyvinyl acetate (PVAc) and polyurethane (PU) adhesives was investigated by Güray *et al.* (2003). The study revealed that samples bonded with polyurethane adhesive exhibited the highest bending resistance, while those bonded with PVAc adhesive displayed the lowest.

The experimental findings of the present study are consistent with the existing literature. The choice of adhesive was found to play a critical role in enhancing the modulus of elasticity in bending. Epoxy resin, in particular, offered a dual advantage by contributing both rigidity and flexibility to the composite system. While the fibers in the glass fiber fabric provide flexibility and tensile strength, the epoxy matrix contributes stiffness and dimensional stability. This synergistic interaction is believed to enhance the material’s resistance to deformation under load. Moreover, glass fiber fabric serves as a barrier against the propagation of micro-cracks or surface damage in the wood substrate, thereby increasing the structural durability and service life of the composite, especially under mechanical stress.

The experimental results in this study are also parallel to the literature. The role of the glue in increasing the elasticity value in bending is substantial. Epoxy resin provides both hardness and flexibility. While the fibers of the glass fiber fabric provide flexibility to the structure, the epoxy resin adds hardness. This balance is thought to help the material resist deformation. Glass fiber fabric has a structure that prevents micro cracks or damage from spreading on the surface of the wood material. This can help the material deform less and last longer, especially under load.

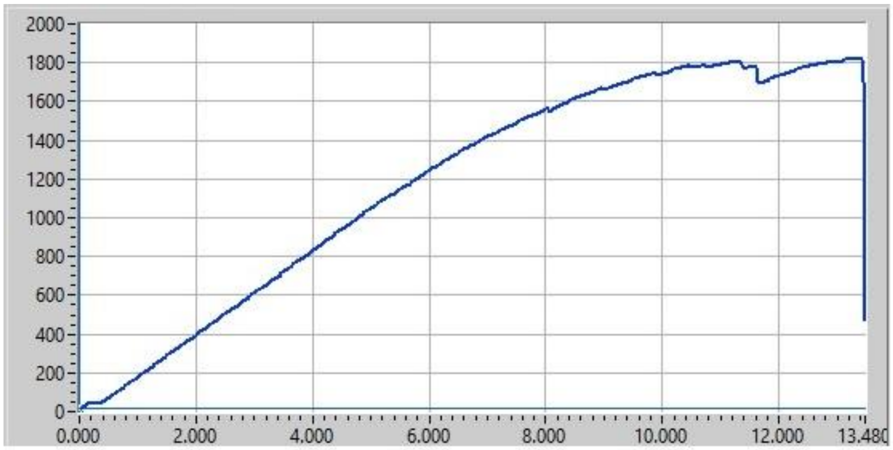

Fig. 6. Load-deflection curve graph

Figure 6 presents the load-deflection curve of a wood specimen strengthened with Fiber Reinforced Polymer (FRP) under flexural loading. The curve illustrates the structural behavior of the composite system throughout the loading process, with particular emphasis on the flexural stiffness and ultimate load-carrying capacity.

At the initial stage of the curve, a linear relationship between load and deflection was observed. This region corresponds to the elastic behavior of the material, where Hooke's Law is valid. The slope of this linear portion represents the flexural stiffness (modulus of elasticity) of the strengthened member. Compared to unreinforced control specimens, the increased slope indicates that FRP reinforcement enhanced the elastic modulus of the wood, indicating an improvement in stiffness.

As the load increased, the curve gradually deviated from linearity, indicating the onset of non-linear behavior and yielding. This transition reflects the material's progression from elastic to plastic deformation, during which the structural element begins to absorb more energy with reduced stiffness.

The peak point of the curve denotes the maximum load-bearing capacity of the specimen. Following this point, a noticeable drop in the load was observed, suggesting the occurrence of localized failures such as fiber rupture, interfacial delamination, or debonding of the FRP layer. These sudden reductions in load indicate a loss of structural integrity and the end of ductile behavior.

Overall, the load-deflection behavior demonstrated that FRP reinforcement significantly improved both the flexural strength and stiffness of the wood member. Additionally, the enhanced deformation capacity in the post-elastic region indicates a more ductile failure mode compared to unreinforced wood, supporting the potential use of FRP-strengthened timber elements in structural applications where increased performance and safety are desired.

CONCLUSIONS

1. The bending strength and modulus of elasticity in bending of wood material supported with glass fiber fabric were investigated, and it was determined that there were significant increases compared to the control sample in both wood types. Glass fiber fabric reinforcement significantly increased the bending strength of wood materials. An increase of 54% was achieved in Turkish beech samples and 31% in Scotch pine samples.
2. Glass fiber fabric reinforcement increased the modulus of elasticity of wooden materials, contributing to the material being more flexible and durable. Glass fiber fabric with a weight of 400 g/m² increased the durability of wooden materials even more, which showed that the effectiveness of the reinforcement method may vary depending on the weight and number of layers.
3. This situation can be interpreted as glass fiber fabrics increasing elasticity in wood materials depending on their structures. The reason for this is that the high flexibility and rupture properties of the glass fiber fabric construction material and the high rupture resistance of the MGS L285 thermoset-based epoxy resin material and MGS H285 hardener glue can be said to have a positive effect on the bending resistance of laminated elements.

REFERENCES CITED

Bal, B. C. (2021). "A study on some mechanical properties of laminated veneer lumber (TKK) reinforced with glass fiber mesh," *Journal of Furniture and Wood Materials Research* 4(2), 174-182. DOI: 10.33725/mamad.1014198

Bal, B., and Ozyurt, H. (2015). "Some technological properties of laminated veneer timber reinforced with glass fiber fabric," *Kahramanmaras Sutcu Imam University Journal of Engineering Sciences* 18(1), 9-16. DOI: 10.17780/ksujes.28535

Chuang, W., and Quang, T. H. (2018). "Strengthening of traditional wooden structures using fiber-reinforced polymers: Principles and case studies," *Journal of Cultural Heritage* 31, 117-125. DOI: 10.1016/j.culher.2017.11.006

Çalışkan, Ö., Meriç, E., and Yüncüler, M. (2019). "Yesterday, today and tomorrow of timber and timber structures," *Bilecik Şeyh Edebali University Journal of Science* 6(1), 109-118. DOI: 10.35193/bseufbd.531012

Çelik, H. K., and Şakar, G. (2022). "Wood as a building material of the past and the future: A study in the framework of structural engineering," *European Journal of Science and Technology* 36, 298-304.

Çiğdem, E., and Perçin, O. (2022). "Some physical and mechanical properties of heat-treated laminated veneer lumber (lvl) reinforced with carbon fiber and glass fiber," *Journal of the Faculty of Engineering and Architecture of Gazi University* 38(2), 653-664. DOI: 10.17341/gazimmfd.984248

Fiore, V., Scalici, T., Nicoletti, F., Vitale, G., Prestipino, M., and Valenza, A. (2015). "A new eco-friendly chemical treatment of natural fibers: Effect of sodium bicarbonate on properties of sisal fiber and its epoxy composites," *Composites Part B: Engineering* 85, 150-160. DOI: 10.1016/j.compositesb.2015.09.001

Güler, C., and Subası, S. (2012). *Karbon ve Cam Lifi ile Güçlendirilmiş Lamine Sarıçam (Pinus sylvestris* L.*) [Laminated Scots Pine Reinforced with Carbon and Glass*

Fiber], *Kahramanmaraş Sütçü İmam University Journal of Engineering Sciences*, Special Issue, 78-82.

Güray, A., Kılıç, M., Dogru, G., and Özer, M. (2003). "Meşe (*Quercus robur* L.) Odunun'dan Üretilen Lamine Ağaç Malzemede Kuvvet Yönü ve Tutkal Türünün Eğilme Direncine Etkileri [Effects of force direction and glue type on bending strength in laminated wood material produced from oak (*Quercus robur* L.) wood]," *Technology Journal* 6(1-2), 1-9.

Hülagü, B. (2021). *Environmental Approach to the Protection of Wooden Building Materials: Usability of Vegetable Oils*, Master's Thesis, Mimar Sinan Fine Arts University, Institute of Science, Department of Architecture, Istanbul.

Keskin, H., Atar, M., and Kurt, R. (2003). "Some physical and mechanical properties of laminated Scots pine wood," *Kahramanmaraş Sütçü İmam University Journal of Science and Engineering* 6(1), 75-84.

Osmannezhad, S., Faezipour, M., and Ebrahimi, G. (2014). "Effects of GFRP on bending strength of glulam made of poplar (*Populus deltoids*) and beech *(Fagus orientalis)*," *Construction and Building Materials*, 51, 34-39.

Özder, C., Atar, M., and Atilgan, A. (2024). "Determination of the antimicrobial effect of varnishes modified with nano particles on the surface of wood materials," *BioResources* 19(4), 8935-8946. DOI: 10.15376/biores.19.4.8935-8946

Özkan, E., Arpaci, S. S., Dizman Tomak, E., and Yildirim, N. (2020). "Effect of impregnation with waste oil on physical properties of wood material," *Tree and Forest* 1(1), 36-41.

Peker, H., and Ulusoy, H. (2021). "Impregnation effect of medical aromatic plant extract on the anatomic structure of wood," *Bartin Forestry Faculty Journal* 23(2), 520-527. DOI: 10.24011/barofd.892209

Perker, Z. S., and Öztürk, H. (2024). "A research on plant impregnation solutions in wood materials for environmentally friendly architecture," *Journal of Sustainable Engineering Practices and Technological Developments*, 7(1), 60-69

Teaca, C. A., Roşu, D., Mustaţă, F., Rusu, T., Roşu, L., Roşca, I., and Varganici, C. D. (2019). "Natural bio-based products for wood coating and protection against degradation: A Review," *BioResources* 14(2), 4873-4901. DOI: 10.15376/biores.14.2.Teaca

TS ISO 3129 (2021). "Wood-sampling methods and general requirements for physical and mechanical testing of small clear wood specimens," Turkish Standardization Institute, Ankara, Turkey.

TS ISO 13061-3 (2021). "Physical and mechanical properties of wood – Test methods of small defect-free wood samples – Part 1: Determination of moisture content for physical and mechanical tests," Turkish Standardization Institute, Ankara, Turkey.

TS ISO 13061-4 (2021). "Physical and mechanical properties of wood — Test methods for small clear wood specimens," Turkish Standardization Institute, Ankara, Turkey.

Yıldırım, M. N., Karaman, A., and Zor, M. (2021). "Bending characteristics of laminated wood composites made of poplar wood and GFRP," *Zagreb Univ, Fac Forestry. Drvna Industrija* 72(1), 3-11. DOI: 10.5552/drvind.2021.1913

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