

Effect of Different Types of FRP Placed Between Layers on Flexural Properties of Laminated Timber

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Keywords

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Between layers,
Composite

Abstract: Wood is widely used in the construction sector as a natural, renewable, and sustainable material. It stands out with its features such as requiring little processing, low waste production and being environmentally friendly. Its use, especially for structural purposes, is increasing with developing technology. Laminated laminated timber is an industrial product consisting of wood layers combined parallel to the grain direction. Wooden structures need repair and reinforcement over time. Traditional methods include applications such as steel or aluminum plates and wood patches, but these methods are both costly and ineffective in all cases. At this point, fiber-reinforced polymer (FRP) composites offer an alternative solution. FRPs have the advantages of high strength and stiffness-to-weight ratios, low maintenance costs, and easy installation. Studies on strengthening wooden structures with FRP have generally focused on the bending strength of beams. In this project, laminated timber beams produced from spruce wood were strengthened with carbon, glass, and aramid fiber reinforcements, and their bending behaviors were examined. The results show that carbon fiber-reinforced polymers provide the highest performance. Glass and aramid fibers show certain improvements but have not been found to be as effective as carbon fiber-reinforced polymers in improving flexural properties. This suggests that the reinforcement material to be used in structural elements should be carefully selected according to the targeted performance characteristics.

Tabakalar Arasına Yerleştirilen Farklı FRP Türlerinin Lamine Kerestelerin Eğilme Özellikleri Üzerine Etkisi

Anahtar Kelimeler

Ahşap,
FRP,
Güçlendirme,
Tabakalar arası,
Kompozit

Öz: Ahşap, doğal, yenilenebilir ve sürdürülebilir bir malzeme olarak yapı sektöründe yaygın biçimde kullanılmaktadır. Az işlem gerektirmesi, düşük atık üretimi ve çevre dostu oluşu gibi özellikleriyle ön plana çıkmaktadır. Gelişen teknolojiyle birlikte özellikle yapısal amaçlı kullanımı artmaktadır. Tabakalı lamine kereste, lif yönüne paralel olarak birleştirilmiş ahşap katmanlardan oluşan endüstriyel bir üründür. Ahşap yapılar zamanla onarım ve güçlendirmeye ihtiyaç duymaktadır. Geleneksel yöntemler çelik veya alüminyum plakalar, ahşap yamalar gibi uygulamalar içermektedir ancak bu yöntemler hem maliyetli hem de her durumda etkili değildir. Bu noktada fiber takviyeli polimer (FRP) kompozitler alternatif bir çözüm sunmaktadır. FRP'ler yüksek mukavemet ve sertlik-ağırlık oranları, düşük bakım maliyeti ve kolay kurulum avantajlarına sahiptir. Ahşap yapıların FRP ile güçlendirilmesine yönelik çalışmalar genellikle kirişlerin eğilme dayanımı üzerinde yoğunlaşmıştır. Bu projede, ladin odunundan üretilmiş tabakalı lamine kereste kirişler, karbon, cam ve aramid fiber takviyeleri ile güçlendirilmiş ve eğilme davranışları incelenmiştir. Sonuçlar, karbon fiber takviyeli polimerlerin en yüksek performansı sağladığını göstermektedir. Cam ve aramid fiberler belirli iyileştirmeler göstermektedir ancak eğilme özelliklerinin geliştirilmesinde karbon fiber takviyeli polimerler kadar etkili olmadığı belirlenmiştir. Bu da, yapı elemanlarında kullanılacak takviye malzemesinin, hedeflenen performans özelliklerine göre dikkatle seçilmesi gerektiğini ortaya koymaktadır.

1.Introduction

Wood is a natural and renewable resource that is one of the oldest construction and production materials in human history and still maintains its importance today [1-3]. Thanks to its natural fiber structure, aesthetic appearance, workability, and environmental friendliness, it offers a wide range of uses from the construction sector to furniture production, packaging to interior decoration. In addition, its low carbon footprint and the fact that it requires less energy in production processes make wood preferred in terms of sustainability [4-9]. However, natural wood materials have some limiting features such as sensitivity to environmental factors, dimensional instability, differences in mechanical strength, and deformation that may occur over time. This situation has created a need for more controlled and performance-enhanced wood materials in engineering applications. Developed in line with this need, laminated timbers (laminated timbers) are engineering products with homogeneous properties, formed by combining wooden lamellae arranged in different directions using adhesives [10,11]. Laminated timbers minimize the disadvantages of natural wood, while increasing its mechanical properties, making it possible to obtain more durable and form-preserving structural elements. At the same time, it offers structural solutions that provide strength without compromising aesthetics in architectural designs where large openings must be crossed. Laminated timbers exhibit superior properties, especially in terms of bending resistance, shaping ability, and crack resistance, and are therefore widely used in many different engineering applications such as bridges, roof beams, and sports hall frames. However, in recent years, the tendency to create hybrid structures with different materials has increased to further increase the existing performance [12-19].

The most important of these hybrid structures is the combination of fiber-reinforced polymers with wood materials. Fiber-reinforced polymers are composite materials reinforced with different types of fibers (glass, carbon, aramid, etc.) that provide high mechanical strength and rigidity despite their low density [20, 21]. These materials generally contain thermoset resins such as epoxy, polyester, or vinyl ester as the matrix phase, and the bond between this matrix and the fiber determines the overall strength of the structure [22]. Due to their properties such as high chemical resistance, long-term performance under fatigue, and corrosion resistance, FRPs are widely used in many high-tech fields such as aviation, automotive, defense industry, marine, and sports equipment. These qualities have brought the use of FRPs to the fore in the construction sector in recent years, especially in structural reinforcement and strength-increasing works [23-25].

Reinforcement of wooden structural elements with fiber-reinforced polymers is one of the most striking innovations in this field. Due to its natural structure, wood is affected by various environmental conditions (humidity, temperature changes, biological deterioration, etc.), and its mechanical properties may decrease over time [26,27]. Traditional wooden elements require various interventions to maintain structural integrity, especially in loading conditions such as bending, tension, and compression. The use of FRPs with wood is not only limited to increased strength; it also allows for the construction of lighter, more flexible, and longer-lasting structures. Their lower weight compared to traditional steel or concrete reinforced systems creates advantages in terms of ease of transportation and assembly; they stand out as an important alternative especially in restoration of historical structures or wooden architectural applications where aesthetics is at the forefront [28, 29]. In addition, the integration of composite reinforcements into the structure can contribute to the improvement of seismic performance by increasing the energy absorption capacity of the structure. Various studies on the reinforcement of wood laminated timber (glulam) with fiber reinforced polymers (FRP) show that this method significantly increases structural performance [30-33].

The reinforcement of glulam beams using fiber-reinforced polymers has been extensively explored in recent decades. One of the early implementations of FRP in timber structures involved the restoration of damaged hardwood utility poles in the mid-1990s using e-glass/epoxy laminates. Similarly, FRP composites were employed to strengthen timber piles, as demonstrated by Lopes Anido et al. (2003) [34]. Their study created hybrid glued-laminated timber elements by embedding thin layers of E-glass/epoxy composite between wooden laminations. Micelli et al. (2005) [35] investigated how the inclusion of CFRP rods could enhance the performance of glulam beams. Their findings revealed that the beams' ultimate load capacity and stiffness improved by 26–82% and 8–19%, respectively. Complementing this, De et al. (2005) [36] conducted pull-out tests on CFRP rods bonded to glulam using epoxy resin to evaluate the effectiveness of the bond. Their research considered various factors such as rod surface texture, bonded length, and wood grain orientation, which later informed the development of a localized bond-slip model. In another contribution, Johnsson et al. (2006) [37] performed four-point bending tests on ten glulam specimens, each reinforced with rectangular pultruded CFRP bars. Their results, benchmarked against analytical models, indicated a significant enhancement in short-term flexural load capacity ranging between 49% and 63%. Further advancements in timber reinforcement include Gentry's (2011) [38] proposal to use transversely

placed FRP pins across glulam layers to improve shear resistance. Test outcomes showed that glulam specimens reinforced in this way exhibited more consistent mechanical behavior compared to their unreinforced counterparts. Additionally, Gilfillan et al. (2003) [39] examined Sitka spruce beams reinforced with both steel and composite materials under short- and long-term mechanical loading. Their experiments demonstrated that the incorporation of FRP materials notably increased the structural strength of the beams. Ghoroubi et al. (2022) [40] developed a generalized material model for wood-to-wood joints by experimentally analyzing the load-displacement behavior of connections with varying lengths, using both adhesives and mechanical anchors. The model enhances the accuracy of structural analyses involving such joints when implemented in finite element software. Karagoz Isleyen et al. (2023) [41] investigated the impact response of glued timber beams reinforced with CFRP strips. Through dynamic testing and numerical modeling with ABAQUS, the study demonstrated that FRP reinforcement significantly improves the structural performance of wooden beams under rapid loading conditions.

As a result, the use of fiber-reinforced polymers together with wood structures enables the integration of modern engineering solutions into traditional wood construction systems; it is considered an important innovative approach both in new building designs and in the reinforcement of existing structures. In this context, the effect of composite structures to be obtained by strategically positioning fiber-reinforced polymers in laminated timbers, especially on bending performance, is of great importance. In this study, the effects of different types of FRPs placed between laminated timbers on the bending properties of laminated timbers were experimentally investigated.

2. Material and Methods

2.1. Material

The spruce wood (*Picea abies*) used in the preparation of composite beams was supplied by Yuceer Kereste located in Isparta Province. In the selection of the timber, care was taken to ensure that it was not subject to physical and microorganism damage. To be used in the production of composite beams, 20x100x1300 mm spruce timbers were obtained by sawing with a circular sawing machine. After the beams were stacked, they were kept in the air conditioning room with 20±2°C temperature and 65±5% relative humidity conditions until they reached 12% humidity. The characteristics of the spruce wood species used in the study are given in Table 1.

Table 1. Mechanical properties of spruce timber according to DIN 1052:2008 [42] (values in MPa)

Properties	Value
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Bending	11
Tensile (Parallel)	8.5
Tensile (Vertical)	0.2
Compression (Parallel)	8.5
Compression (Vertical)	2.5 - 3
Modulus of Elasticity (Parallel)	11,000
Modulus of Elasticity (Vertical)	350
Shear Modulus	550

The image of carbon, aramid, and glass FRP polymer fabrics used between the layers to improve the mechanical properties of glulam composite beams is given in Figure 1. FRP fabrics and chemical materials used for bonding were supplied by UNALTEKNIK® company [43].

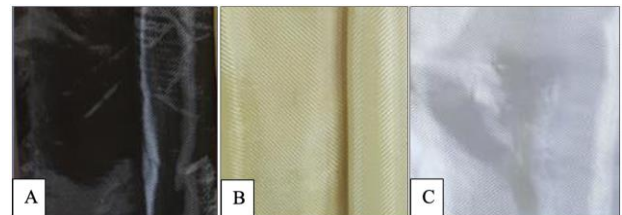


Figure 1. FRP fabrics, (A): Carbon, (B) Aramid, (C) Glass

In the control samples, Polyvinyl acetate (PVAc-D4) glue was used to bond the layers. The manufacturer's recommendations were followed in bonding the layers. Technical specifications for use of the glue are given in Table 2.

Table 2. Technical specifications for use of the glue

Technical Properties	Value
pH	2.5
Adhesion strength	27.6 N/mm ²
Viscosity (20°C)	14000±1000 MPa
Density	1.1±0.02 g/cm ³
Gluing time (at 21°C)	5-6 minutes

In the reinforcement stage with fiber-reinforced polymers, a primer and epoxy adhesive specially produced for FRP fabrics were used.

2.2. Method

2.2.1. Preparation of test samples

The test samples were prepared according to the standard "TS EN 408: 2010+A1: 2014-04 Construction Timber and Glued Laminated Timber - Determination of Some Physical and Mechanical Properties". PVAc-D4 adhesives were used during the production of composite beams from 20 mm thick air-dried solid timber. 3-layer composite beams were produced, with interlayers reinforced with carbon, aramid, and glass fabrics and without interlayer (control). While producing control samples, glue solution was applied

to both surfaces of the layers with a brush at a rate of 180-200 gr/m². The application of FRP fabrics to the intermediate layers was carried out in several stages. First, the FRP fabrics to be used were cut with a pair of scissors, considering the dimensions of the surface to be applied. Before starting the FRP application, the wooden surface was cleaned with a brush, and dust and dirt were removed and made clean. Then, a primer coat was applied to the surface with a low-viscosity epoxy resin, filling the pores of the wood and increasing its adhesion ability. After the primer had set for approximately 2 hours, the epoxy adhesive was applied evenly to the area where the fabric would be placed. The epoxy solution was applied to the solid bonding surfaces with a roller and at a rate of 200 g/m². Then, the fiber fabric was carefully placed on the surface without creating wrinkles or air bubbles. The fabric was pressed with a roller to ensure that it completely adhered and settled on the surface. Finally, epoxy was applied to the fabric again to ensure that the fibers were completely saturated, and a transparent, shiny surface was obtained. Figure 2 shows the stages of FRP application to layered composite intermediate layers.



Figure 2. FRP application stages (A) Sizing the FRP fabrics, (B) Applying primer to the surface, (C) Pouring the epoxy adhesive into the mixing container, (D) Applying adhesive to the surface, (E) Placing the FRP fabric on the surface, (F) Applying the same application to the second intermediate layer

Temperature and humidity control are important in this process. The application should generally be carried out between 15-25°C. In the bonding process, after the surfaces are glued and waited for 5-6 minutes (open time), the press pressure; approximately 1.2 N/mm², the pressing time; 8 hours (closed time) was applied cold, by adjusting the hydraulic press machine with pressure indicator to apply 1.2 N/mm² pressure cold. The schematic view of the beams prepared within the scope of the study is given in Figure 3.

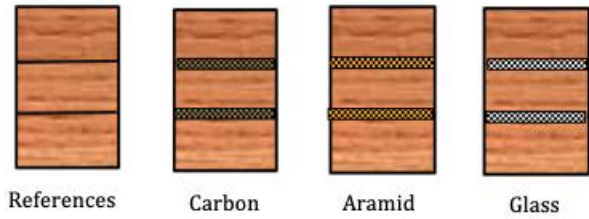


Figure 3. Schematic view of the cross-sections of the produced beams

Within the scope of the study, experiments were carried out on a total of 12 beams by producing 3 beam elements from each. The properties and codes of the produced beams are given in Table 2.

Table 2. Properties and codes of produced beams

Code	Layer Number	Glue type	Reinforcement	FRP Type
UR	3	PVAc-D4	-	-
C-R	3	PVAc-D4	+	Carbon
A-R	3	PVAc-D4	+	Aramid
G-R	3	PVAc-D4	+	Glass

2.2.2. Conducting experiments

In this study, the experiments of the beams subjected to bending tests were carried out in Süleyman Demirel University Natural and Industrial Research and Application Center. The beams were subjected to a static 4-point bending test with a loading rate of 8 mm/min by GB/T 26899-2011[44]. Bending loading persisted until either a sudden increase in loading, signifying failure, was detected by the loading instrument, or substantial damage was visually observed. To prevent the timber from crushing, supports and loading points, constructed from steel cylinders with a diameter of 20 mm, were utilized for beam testing. Both unreinforced and reinforced beams underwent testing following the same experimental procedure as the initial tests. This was done to ensure a fair comparison of the beam capacities. The image of the beams subjected to bending placed in the bending apparatus is shown in Figure 4 (A). The load-displacement results obtained because of the experiments are recorded on the computer given in Figure 4 (B). Maximum load-carrying capacity, bending strength, and elasticity modulus values were obtained from the obtained load-displacement graphs.

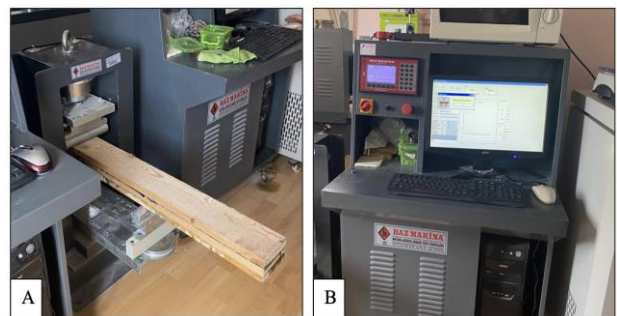


Figure 4. (A) Placing the sample in the device, (B) Computer screen where the results are read

Equation 1 and Equation 2 are used to determine the modulus of elasticity (MOE) and flexural strength (MOR) from the bending test results [45]:

$$MOE = \frac{\Delta P (l - s)(2l^2 + 2ls - s^2)}{8\Delta ybh^3}$$

$$MOR = \frac{3P_{max}(l - s)}{2bh^2}$$

Where Δy is the corresponding displacement of ΔP , b is the width of the specimen, h is the depth P_{max} is the maximum load, l is the span of the specimen between supports, and s is the span between the loads. ΔP is the difference between the upper and lower loads in the proportional limit.

3. Results and Discussion

In this study, a total of 12 samples were studied, 3 from each series in 4 different series. The load-displacement curves of each sample produced in the study are given in Figure 5. MOE and MOR values obtained because of subjecting composite beams to bending tests are given in Figure 6 and Figure 7.

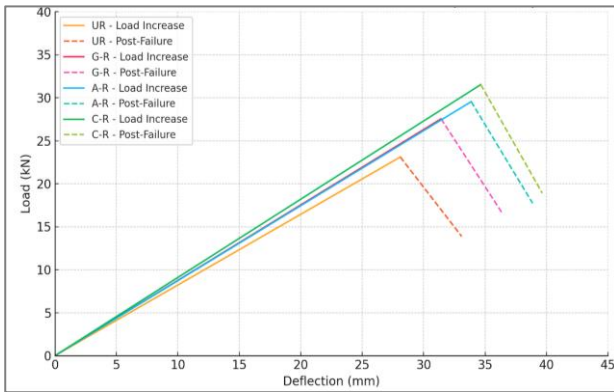


Figure 5. Load-displacement curves

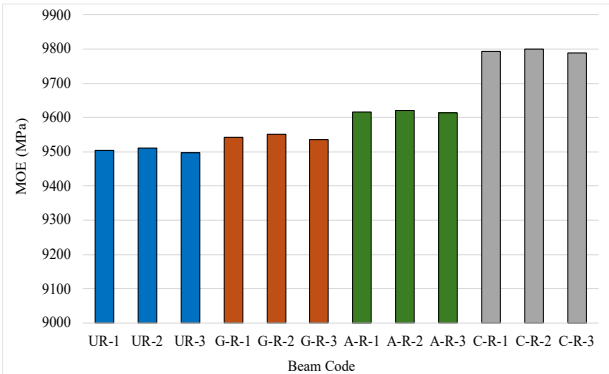


Figure 6. MOE values of composite beams

Figure 6 presents the comparative values of modulus of elasticity (MOE) of wood composite samples reinforced with different types of reinforcement and unreinforced. Samples were tested with three repetitions and the average MOE values for each group are shown in the form of a column chart. Unreinforced

samples (UR-1, UR-2, UR-3) have an average MOE value of approximately 9500 MPa. This value stands out as the lowest level compared to all other reinforced groups. This shows that fiber reinforcement makes a positive contribution to the modulus of elasticity. Glass fiber reinforced samples (G-R-1, G-R-2, G-R-3) show a slight increase compared to unreinforced samples, with the MOE value being approximately 9550 MPa. This increase reveals that the contribution of glass fiber has a limited but positive effect on elasticity. Aramid fiber-reinforced samples (A-R-1, A-R-2, A-R-3) reached an MOE value of approximately 9610 MPa. This value is higher compared to glass fiber-reinforced samples, indicating that aramid fiber increases the elastic modulus more significantly. The samples with the highest MOE value were observed in the carbon fiber reinforced group (C-R-1, C-R-2, C-R-3). The samples exhibited an MOE value of approximately 9800 MPa, indicating an increase of approximately 3% compared to the unreinforced samples. This result shows that carbon fiber is the most effective reinforcement material in increasing the elastic modulus.

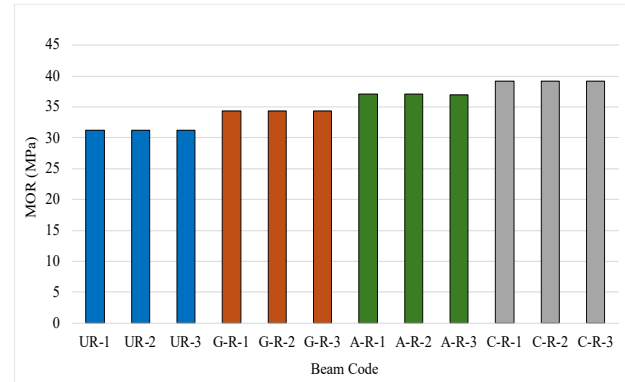


Figure 7. MOR values of composite beams

The flexural strength (MOR) values in the figure show significant differences between reinforced and unreinforced wood composite samples with different reinforcement materials. Unreinforced samples (UR series) have an average MOR value of approximately 31 MPa, which is the lowest among all samples. In glass fiber reinforced samples (G-R series), MOR values are approximately 34.5 MPa. This shows that glass fiber reinforcement is effective in increasing flexural strength, but the contribution is limited. There is an increase of approximately 11% compared to unreinforced samples. Aramid fiber reinforced samples (A-R series) exhibit a higher flexural strength compared to glass fiber samples, with an average MOR value of 37 MPa. An increase of approximately 19% compared to unreinforced samples shows that aramid fiber makes a more effective contribution to the composite structure. Carbon fiber reinforced samples (C-R series) show an average MOR value of 39 MPa, and the highest bending strength is obtained in this group. This situation reveals that carbon fiber is the most effective reinforcement material in increasing structural strength. An improvement of approximately

26% was achieved compared to unreinforced samples. Karaman (2021) [46] investigated the bending moment resistance of T-type, two-pin dowel joints. Joints made with dowels obtained from Scotch pine (*Pinus sylvestris*), hornbeam (*Fagus orientalis*), chestnut (*Castanea sativa*), and oak (*Quercus petraea*) were tested after being reinforced with basalt and fiberglass knitted fabrics. It was observed that single- and double-layer reinforcements made with fiber-reinforced fabrics increased the mechanical performance of furniture fasteners. The highest bending moment values were obtained in samples using oak dowels, and it was determined that oak dowels provided 13% higher bending moment resistance than hornbeam dowels, 32% higher than chestnut dowels, and 43% higher than Scotch pine dowels, respectively. Furthermore, among the reinforcement types, the highest bending moment resistance was found in samples reinforced with basalt knitted fabric, while the lowest resistance was found in unreinforced (control) samples. In general, according to the results of the bending tests, it was determined that the wood type was 3% effective, the dowel type was 43% effective, and the reinforcement fabric type was 72% effective. In another study, Karaman et al. (2021) [47] aimed to determine the four-point bending strength and modulus of elasticity in bending of laminated materials obtained from black pine wood reinforced with aramid fiber and individually bonded with epoxy or polyurethane adhesives. As a result of tests performed on samples prepared by TS 5497 EN 408 (2006) standard, it was determined that the highest static bending strength value (83.94 N/mm²) was obtained in samples prepared with aramid fiber reinforcement in interlayers and using epoxy glue. Similarly, the highest value in terms of modulus of elasticity in bending was also determined to be in samples with interlayer epoxy and aramid fiber reinforcement (10311.62 N/mm²). In addition, it was observed that samples prepared in the direction parallel to the gluing line exhibited higher mechanical performance compared to those in the perpendicular direction. It has been demonstrated that larch laminated wood materials reinforced with aramid fiber can be used as structural elements in the construction industry. In another study, Karaman (2024) [48] investigated the effects of sessile oak (*Quercus petraea*) laminated timber reinforced with basalt fabric (BFRPWF) and plaster mesh (PSM) on air-dry density and compressive strength parallel to the grain. Single-component polyurethane (PUR) adhesive was used as the adhesive, and the reinforcement materials were placed between the wood layers. Three different sample groups were tested in the study: unreinforced laminated oak timber (LOL), BFRPWF-reinforced laminated oak timber (LOL-BFRPWF), and PSM-reinforced laminated oak timber (LOL-PSM). The findings revealed that both air-dry density and compressive strength increased with reinforcement applications. In particular, it was determined that the

samples in the LOL-BFRPWF group exhibited higher mechanical performance than the samples in the PSM-reinforced and control groups. Karaman (2024) [48] study shows that laminated oak timber reinforced with BFRPWF and PSM offers a potential use in both the furniture industry and building materials. It is also seen that similar results were obtained by Yıldırım et al. (2018) [49], Karaman and Yıldırım (2021) [50] and Yıldırım et al. (2021) [51]. The average maximum load-carrying capacity, maximum displacement, MOE, and MOR values of each series are given in Table 3.

Table 3. Average Max. load, max. displacement, MOE and MOR values

Beams Code	Max Load (kN)	Max Deflection (mm)	MOE (MPa)	MOR (MPa)
UR	23.10	28.10	9504	31.24
G-R	27.54	31.42	9543	34.39
A-R	29.54	33.87	9617	37.04
C-R	31.52	34.65	9794	39.21

In this study, the mechanical performances of unreinforced (UR) and beam specimens reinforced with different fiber reinforcements (glass fiber: G-R, aramid fiber: A-R, carbon fiber: C-R) were comparatively investigated. The obtained data revealed that all reinforced specimens showed significant improvements in terms of both carrying capacity and deformation ability compared to the unreinforced reference specimen. While the maximum load carrying capacity was 23.10 kN in the UR specimen, this value increased by 19%, 28% and 36% in the G-R, A-R and C-R specimens, respectively, reaching 27.54 kN, 29.54 kN and 31.52 kN. Similarly, an increase was also observed in the maximum deflection values; this reveals the effect of reinforcement applications on increasing the ductility of the beams. Limited but stable increases were recorded in all reinforced specimens in terms of modulus of elasticity (MOE); The highest value was obtained in the carbon fiber reinforced sample with 9794 MPa. When evaluated in terms of modulus of rupture (MOR), the most remarkable increase was observed in the C-R sample with a rate of 25%.

4. Conclusion

In this study, the mechanical performances of unreinforced (UR) and reinforced beams with different fiber reinforcements were evaluated comparatively. The results obtained are given below.

- Fiber reinforcement significantly improved the important mechanical properties of the beams such as modulus of elasticity (MOE), fracture strength (MOR), load-carrying capacity, and deflection. Reinforced samples exhibited a significant increase in performance in all tests compared to unreinforced reference samples.

- The obtained data in terms of modulus of elasticity show that fiber reinforcement contributes to the rigidity of the beams. In unreinforced samples, the average MOE value remained at the lowest level, while in fiber-reinforced groups, the MOE values of glass, aramid, and carbon fibers increased significantly, respectively. Glass fiber-reinforced samples showed a limited but positive increase compared to unreinforced samples, providing an improvement of approximately 1-2% in the modulus of elasticity. In aramid fiber samples, this increase became more pronounced, and an improvement of approximately 3% was observed. The samples with the highest modulus of elasticity were found in the carbon fiber reinforced group, which showed an increase of approximately 3-4% compared to the unreinforced samples. These findings reveal that carbon fiber is the most effective material in increasing the modulus of elasticity.
- The analyses made in terms of MOR show that fiber reinforcement significantly increases the bending strength. While the average MOR value was at the lowest level in unreinforced samples, glass fiber-reinforced samples provided a certain improvement by increasing this value by approximately 11%. Aramid fiber-reinforced samples reached a higher MOR value compared to glass fiber samples, showing an increase of approximately 19%. Carbon fiber-reinforced samples achieved the highest MOR value among all groups and provided an improvement of 26% compared to unreinforced samples. This result shows that carbon fiber is the most effective fiber type in increasing the bending strength.
- Glass and aramid fibers also can increase the bending strength, but carbon fiber makes a more significant contribution in this area.
- The effect of fiber reinforcement was also observed in the evaluations made in terms of carrying capacity. The carrying capacity of unreinforced samples increased by 19% compared to glass fiber-reinforced samples, 28% compared to aramid fiber-reinforced samples, and 36% compared to carbon fiber-reinforced samples. These findings show that fiber reinforcement plays an important role in increasing the carrying capacity and that carbon fiber is the material that increases this capacity the most.
- Increase in maximum deflection values was observed, which shows that fiber reinforcements contribute to increasing the ductility of the beams.

In conclusion, this study shows that fiber reinforcement provides significant benefits, especially in structural reinforcement applications. Carbon fiber stood out as the most effective reinforcement material by showing the highest performance in all tests. Although glass and aramid fibers provided certain improvements in terms of elastic modulus and

fracture strength, respectively, they were not as effective as the performance increase provided by carbon fiber. These findings emphasize that the selection of reinforcement material to be used in structural elements should be made carefully according to the targeted performance properties. The use of fiber reinforcements offers great advantages, especially in structural elements where bearing capacity and bending strength are important. In addition, it is concluded that fiber reinforcements are an effective method for improving the mechanical properties of composite structures and have significant potential in various application areas.

Acknowledgment

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Declaration of Ethical Code

In this study, we undertake that all the rules required to be followed within the scope of the "Higher Education Institutions Scientific Research and Publication Ethics Directive" are complied with, and that none of the actions stated under the heading "Actions Against Scientific Research and Publication Ethics" are not carried out.

References

- [1] Fengel, D., Wegener, G. 1984. Wood: chemistry, ultrastructure, reactions. Berlin and New York: De Gruyter Press.
- [2] Guo, J., Song, K., Salmén, L., Yin, Y. 2015. Change soft wood cellwalls in response to hygro-mechanical steam treatment. CarbohydrPolym, 115: 207-14.
- [3] Florian, M.L.E. 1990. Scope and history of archaeological wood. In: Rowell R M, Barbour R J, editors. Archaeol. Wood Prop. Chem. Preserv. Washington, D. C: American Chemical Society; 3-32
- [4] Lippke, B.R., Bowyer, J., MeilJ. 2004. CORRIM : life-cycle environmental perfor- mance, (June 2014).
- [5] Nepal, P., Skog, K.E., McKeever, D.B., Bergman, R.D. 2016. Abt KL, Abt RC. Carbon mitigation impacts of increased softwood lumber and structural panel use for nonresidential construction in the United States. Forest Prod J, 66(1-2):77-87.
- [6] Amiri, A., Ottelin, J., Sorvari, J., Junnila, S. 2020. Cities as carbon sinks: classification of wooden buildings. Environmental Research Letters.
- [7] Leskinen, P., Cardellini, G., González García, S., Hurmekoski, E., Sathre, R., Seppälä, J., et al. 2018. Substitution effects of wood-based products in

- climate change mitigation. From Science to Policy, 7(November), 28.
- [8] Gutowski, T. G., Sahni, S., Allwood, J. M., Ashby, M. F., Worrell, E. 2013. The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*.
- [9] Van Ruijven, B. J., Van Vuuren, D. P., Boskaljon, W., Neelis, M. L., Saygin, D., Patel, M. K. 2016. Long-term model-based projections of energy use and CO₂ emissions from the global steel and cement industries. *Resources, Conservation and Recycling*, 112, 15–36.
- [10] Yang, T.-H., Wang, S.-Y., Tsai, M.-J., Lin, C.-Y. 2009. The charring depth and charring rate of glued laminated timber after a standard fire exposure test. *Building and Environment*, 44(2), 231–236.
- [11] Issa, C. A., Kmeid, Z. 2005. Advanced wood engineering: glulam beams. *Construction and Building Materials*, 19(2), 99–106.
- [12] Madhoushi, M., Ansell, M. P. 2004. Experimental study of static and fatigue strengths of pultruded GFRP rods bonded into LVL and glulam. *International Journal of Adhesion and Adhesives*, 24(4), 319–325.
- [13] Guan, Z. W., Rodd, P. D., Pope, D. J. 2005. Study of glulam beams pre-stressed with pultruded GRP. *Computers and Structures*, 83(28-30), 2476–2487.
- [14] Zhang, J., Hu, X., Sun, Q., Zhang, Y., Zhu, W., Li, L. 2020. Experimental study on seismic performance of glulam-concrete composite beam-to-column joints. *Composite Structures*, 236, 111864.
- [15] Wang, M., Song, X., Gu, X., Zhang, Y., Luo, L. 2015. Rotational behavior of bolted beam-to-column connections with locally cross-laminated glulam. *Journal of Structural Engineering*, 141(4), 04014121.
- [16] Bulleit, W. M., Sandberg, L. B., Woods, G. J. 1989. Steel-reinforced glued laminated timber. *Journal of Structural Engineering*, ASCE, 115(2), 433–444.
- [17] Daniel, H., Habashneh, M., Rad, M. M. 2022. Reliability-based numerical analysis of glulam beams reinforced by CFRP plate. *Scientific Reports*, 12(1), 13587.
- [18] He, M. J., Wang, Y. X., Li, Z., Zhou, L. A., Tong, Y. C., Sun, X. F. 2022. An experimental and analytical study on the bending performance of CFRP-reinforced glulam beams. *Frontiers in Materials*, 8, 802249.
- [19] Isleyen, U. K., Ghoroubi, R., Mercimek, O., Anil, O., Erdem, R. T. 2021. Behavior of glulam timber beam strengthened with carbon fiber reinforced polymer strip for flexural loading. *Journal of Reinforced Plastics and Composites*, 40(17-18), 665–685.
- [20] Biscaia, H. C., Chastre, C., Borba, I. S., Silva, C., Cruz, D. 2016. Experimental evaluation of bonding between CFRP laminates and different structural materials. *Journal of Composites for Construction*, 20(3).
- [21] Daniel, H., Habashneh, M., Rad, M. M. 2022. Reliability-based numerical analysis of glulam beams reinforced by CFRP plate. *Scientific Reports*, 12(1), 13587.
- [22] Dong, Z. Q., Wu, G., Zhao, X. L., Zhu, H., Shao, X. X. 2019. Behaviors of hybrid beams composed of seawater sea-sand concrete (SWSSC) and a prefabricated UHPC shell reinforced with FRP bars. *Construction and Building Materials*, 213, 32–42.
- [23] Gomez, S., Svecova, D. 2008. Behavior of split timber stringers reinforced with external GFRP sheets. *Journal of Composites for Construction*, 12(2), 202–211.
- [24] Hay, S., Thiessen, K., Svecova, D., Bakht, B. 2006. Effectiveness of GFRP sheets for shear strengthening of timber. *Journal of Composites for Construction*, 10(6), 483–491.
- [25] He, M. J., Wang, Y. X., Li, Z., Zhou, L. A., Tong, Y. C., Sun, X. F. 2022. An experimental and analytical study on the bending performance of CFRP-reinforced glulam beams. *Frontiers in Materials*, 8, 802249.
- [26] Kilincarslan, S., Şimşek Türker, Y. 2021. Experimental investigation of the rotational behaviour of glulam column-beam joints reinforced with fiber reinforced polymer composites. *Composite Structures*, 262.
- [27] Kilincarslan, S., Şimşek Türker, Y. 2019. The Effect of Strengthening With Fiber Reinforced Polymers on Strength Properties of Wood Beams. 2nd International Turkish World Engineering and Science Congress, pp. 8-14.
- [28] Cheng, F., Hu, Y. 2011. Nondestructive test and prediction of MOE of FRP reinforced fast-growing poplar glulam. *Composites Science and Technology*, 71(8), 1163–1170.
- [29] Corradi, M., et al. 2021. Local FRP reinforcement of existing timber beams. *Composite Structures*, 258, 113363.
- [30] Donadon, B. F., et al. 2020. Experimental investigation of glued-laminated timber beams with vectran-FRP reinforcement. *Engineering Structures*, 202, 123–134.
- [31] Mizuta, Y., et al. 2019. Bending stiffness and strength of reinforcement arrangements for

- CFRP reinforced glulam (AFRW). Mokuzaï Gakkaishi, 65(3), 148–157.
- [32] Simsek Turker, Y., Kilincarslan, S., and Avcı, M. 2024. Enhancement of mechanical properties in FRP-reinforced glulam column-beam connections: a FEM approach. *GeoStruct Innovations*, 2(1), 10–20.
- [33] Tajik, N., et al. 2024. Explainable XGBoost machine learning model for prediction of ultimate load and free end slip of GFRP rod glued-in timber joints through a pull-out test under various harsh environmental conditions. *Asian Journal of Civil Engineering*, 25(1), 141–157.
- [34] Lopez-Anido, R., Michael, A., Sandford, T.C. 2003. Experimental characterization of FRP composite wood pile structural response by bending tests. *Mar Struct*, 16, 257, 74.
- [35] Micelli, F., Scialpi, V., La Tegola, A. 2005. Flexural reinforcement of glulam timber beams and joints with carbon fiber-reinforced polymer rods. *Journal of Composites for Construction*, 4(9), 337–347.
- [36] De Lorenzis, L., Scialpi, V., La Tegola, A. 2005. Analytical and experimental study on bonded-in CFRP bars in glulam wood. *Composite Part B: Engineering*, 36(4), 279–289.
- [37] Johnsson, H., Blanksvard, T., Carolin, A. 2006. Glulam members strengthened by carbon fibre reinforcement. *Materials and Structures*, 40, 47–56.
- [38] Gentry, T. R. 2011. Performance of glued-laminated timbers with FRP shear and flexural reinforcement. *Journal of Composites for Construction*, 15(5), 861–870.
- [39] Gilfillan, J. R., Gilbert, S. G., Patrick, G. R. H. 2003. The use of FRP composites in enhancing the structural behavior of timber beams. *J Reinf Plastics Compos*, 22(15), 1373–1388.
- [40] Ghoroubi, R., et al. 2022. Experimental investigation of bonding behavior of anchorage timber-to-timber joint. *Archives of Civil and Mechanical Engineering*, 22, 1–16.
- [41] Isleyen, U.K., et al. 2023. Investigation of impact behavior of glulam beam strengthened with CFRP. *Structures*, 51, 196–214.
- [42] Deutsches Institut für Normung. 2008. DIN 1052:2008-12: Design of timber structures – General rules and rules for buildings. Beuth Verlag.
- [43] Unaltechnik. 2023. Unaltechnik ürün kataloğu 2023. <https://www.unaltechnik.com/>. Ünaltechnik Yayınları.
- [44] GB/T 26899-2011. 2011. Standardization Administration of China. GB/T 26899-2011: General code for design of timber structures. China Standards Press.
- [45] Gao, Y., Zhang, L., Chen, H., Li, X. 2015. Structural performance of modern timber buildings under seismic loads. *Journal of Structural Engineering*, 141(4), 04014123.
- [46] Karaman, A. 2021. Bending moment resistance of t-type joints reinforced with basalt and glass woven fabric materials. *Maderas. Ciencia y tecnología*, 23.
- [47] Karaman, A., Yildirim, M. N., Tor, O. 2021. Bending characteristics of laminated wood composites constructed with black pine wood and aramid fiber reinforced fabric. *Wood Research*, 66(2), 309–320.
- [48] Karaman, A. (2024). Determination of air-dry density and compression strength parallel to the grains of basalt fiber-reinforced polymer (BFRP) woven fabrics and plaster mesh (PSM) reinforced glued laminated oak lumber. *Turkish Journal of Forest Science*, 8(1), 42–52.
- [49] Yıldırım, M. N., Tor, Ö., Karaman, A. (2018). The bending moment resistance of corner joints reinforced with glass fiber polymer. *Kastamonu University Journal of Forestry Faculty*, 18(3), 350–356.
- [50] Karaman, A., Yıldırım, M. N. (2021). Effects of wood species of the dowels and fiber woven fabric types on bending moment resistance of l-shaped joints. *Wood Industry and Engineering*, 3(2), 12–22.
- [51] Yildirim, M. N., Karaman, A., Zor, M. (2021). Bending characteristics of laminated wood composites made of poplar wood and GFRP. *Drvna industrija*, 72(1), 3–11.