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Determination of the Effects of Fiber-Reinforced Polymer Types and Wooden Dowel Species on the Tensile Strength Perpendicular to the Fibers of Wooden Materials

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ABSTRACT

Tensile strength is the resistance of the wood material to two forces applied in opposite directions and trying to break and separate the fibers. This study was carried out to determine the tensile strength perpendicular to the fibers of beech lumber reinforced with basalt fiber reinforced polymer (BFRP), glass fiber reinforced polymer and plaster mesh (PSM) and joined with beech dowel (BD), oak dowel (OD) and black pine dowel (BPD). Beech (*Fagus orientalis* Lipsky), Black pine (*Pinus nigra* Arnold) and oak (*Quercus petraea* Lieble) wooden were used as wooden dowels. Polyvinyl acetate (PVAc-D4) were used as the adhesive. The BFRP, GFRP, and PSM were added as one layer of reinforced materials. The experimental reinforced with BFRP, GFRP, and PSM were tested in the four different locations unreinforced, reinforced lumber with BFRP, GFRP, and PSM. Tests were performed on the experimental samples to investigate the tensile strength perpendicular to fiber (┴σt). The test results showed that the reinforcement process increased the (┴σ). The ┴σt value of samples reinforced with BFRP was 11%, 52%, and 65% higher than reinforced with GFRP, unreinforced, and reinforced PSM, respectively. The ┴σt value of samples joined with oak dowel was 7%, 14%, and 23% higher than those reinforced with beech, black pine, and control, respectively. Accordingly, the BFRP and oak dowel (OD) have been the potential to serve as options for reinforced wood structural.

Keywords: Tensile strength; Wooden dowel; BFRP; PVAc-D4; GFRP; PSM; Beech; Oak; Black pine; Wood material.

1. Introduction

Wood is a sustainable material that is completely compatible with nature, easy to recycle, has a very good strength compared to its density compared to other building elements, is compatible with other building materials, and can be very long-lasting when used correctly. For wood material structures to survive, it is important to use the right material, protect the material from moisture, and use a carrier material with sufficient cross-sectional area [1]. Because wood is a heterogeneous and anisotropic material, its mechanical properties differ from those of other building materials [2]. Thus, it is a high-strength material. Its resistance to bending is higher than other building elements. The breaking time of a wooden beam under load is quite long. The physical properties of wood are important in terms of strength when wood is used as a building element. In addition, factors such as the type of wood, direction and angle of the fibers in a tree section, and moisture content of the wood can affect its strength. Wood is a material with high bearing capacity, simple joint details, low weight, and a positive architectural effect. It is a very light material despite its sufficient strength. Because of the lightness of the material, the dead load of wooden buildings decreased, and the dimensions of the foundation and other load-bearing elements were reduced. Owing to its lightness, transportation is cheap, assembly machinery is required less, and assembly is easy, quick, and economical. Wooden structural elements, which are easy to assemble, can be connected to each other by interlocking, glued, and combined with dowels, nails, bolts, screws, and metal sheets [3].

The quality of adhesion in glues depends on the fluidity of the glues, which have desired properties such as penetrating both surfaces of the wood material, distributing homogeneously on the applied surface, forming layers, and wetting the surfaces [4]. The effectiveness of glue is expected to depend on its viscosity, molecular weight, surface penetration, amount of solid matter, pH ratio, and application method; the adhesion results also will depend on the wood material, type, density, surface roughness and cleanliness [5]. The heterogeneous distribution of the glue on the surface where it is applied negatively affects cohesion and causes the wood material joints to open [6]. During the processing of wood material, the roughness of the surfaces due to the wood structure negatively affects adhesion [7]. Sanded surfaces generally show more effective adhesion than planed surfaces in wood materials [8]. Strong adhesion is achieved by properly processing the wood surface with cutters, applying the adhesive evenly over the entire surface, and cold-pressing the wooden elements closed together [9].

Fiber-reinforced polymers exhibit several advantageous properties, including high mechanical strength, non-conductive lightweight composition, reduced recycling requirements, and corrosion resistance. FRP has been employed for decades to enhance the structural integrity and augment the structural strength of concrete structures [10]. FRP have been used in bridge coatings, I-beam manufacturing, wooden beams and columns, restoration applications, and all types of strengthening and reinforcing joints owing to their strength properties [11]. Structural composite lumber can be reinforced with synthetic fibers to effectively improve its structural properties [12]. In addition, FRP strengthening can enhance the bending stiffness and ultimate bearing capacity of wood beams. Currently, various types of FRPs are available for structural reinforcement, including Basalt FRP (BFRP), Glass FRP (GFRP), Aramid FRP (AFRP), and Carbon FRP (CFRP) [13].

Dowel joints are widely used in furniture frame construction, both as (load-bearing structure) connections and simple locators for parts. Joints constructed with dowels may be subjected to withdrawal, bending, shearing, and tensional forces. However, the individual dowel pins used in the joints are only subjected to withdrawal and shear forces [14]. To apply dowel-type joints efficiently, the key thing is to understand their mechanical behavior when undergoing the load (e.g., load-slip relation, stress distributions, ultimate strength, and failure modes). The mechanical behavior of wooden joints is a complex problem governed by several geometric, material and loading parameters (e.g. wood species, fastener diameter, end distances, edge distances, spacing, number of fasteners, fastener/hole clearances, friction and loading configuration) [15].

The tensile strengths of beech dowels with straight and grooved bodies of different lengths and diameters on oak, beech, and Scots pine wood were investigated. As a result, it was reported that the highest tensile strength in longitudinal joints was obtained with dowels of 8 mm diameter and 36 mm length in oak [16]. Dowel tensile strength values of wooden joints prepared using dowels obtained from ash (*Fraxinus excelsior* Lipsky) and chestnut (*Castanea sativa* Mill.), and oak (*Quercus petraea* Lieble) were also investigated. According to the test results, the highest dowel tensile strength value was obtained in the test specimens prepared with ash dowel and polyvinyl acetate (PVAc-D4) glue, the lowest dowel tensile strength value was obtained in the test specimens prepared using polyurethane (PU-D4) glue with chestnut dowel [17]. Regarding the tensile strength perpendicular to the fibers, joints reinforced with BFRP, GFRP, and PSM are not applied, and it is considered that there is a deficiency in the literature. Reinforcement with BFRP, GFRP, and PSM-reinforced joints in structural lumber is new research topic.

1.1. Objectives of the Study

The following are the objectives of this study: (1) Determination of tensile strength perpendicular to the fibers of beech wood material reinforced with BFRP, (2) Determination of tensile strength perpendicular to the fibers of beech wood material reinforced with GFRP, (3) Determination of tensile strength perpendicular to the fibers of beech wood material reinforced with PSM, (4) Determination of tensile strength perpendicular to the fibers of beech wood material joined with Oak dowels, (5) Determination of tensile strength perpendicular to the fibers of beech wood material joined with Beech dowels, and (6) Determination of tensile strength perpendicular to the fibers of beech wood material joined with Black pine dowels.

This study aimed to determination of the effects of fiber-reinforced polymer types (BFRP, GFRP, and PSM) and wooden dowel species (Oak, Beech, and Black pine dowel) on the tensile strength perpendicular to the fibers of wooden materials.

2. Materials and Methods

2.1. Materials

Beech wood (*Fagus orientalis* L.), which is used widely in the wood construction industry, was used as the wooden material. The lumber pieces were randomly selected from Yenice-Karabuk timber merchants in Turkey (Figure 1a). Careful attention was paid to the fact that the wood material used in the experimental studies was not subjected to physical damage, mechanical impact, or biological harm. It is a material with a full-dry density (D_0) of 0.630 g/cm^3 and, air-dry density (D_{12}) of 0.660 g/cm^3, and its tensile strength perpendicular to fibers ($\perp\sigma t$) is 7 N/mm^2 [18].

The wood of beech (*Fagus orientalis* Lipsky), Oak (*Quercus petraea* Lieble), and Black pine (*Pinus nigra* Arnold) are used extensively in the wood construction sector and were used as the dowel material for these experiments. The special emphasis was put on the selection of wood material. Accordingly, non-deficient, proper, knotless, normally grown (without zone line, reaction wood, decay, insect and mushroom damages) wood materials were selected. The wood dowels were prepared with a cylindrical shape in nominal dimensions of 8 mm × 50 mm (Figure 1b).

The polyvinyl acetate (PVAc-D4) was obtained from Kronen Furniture Glue Accessory Industrial Products Industry and Trade Limited Company in Turkey (Figure 1c). The technical properties of the PVAc-D4 were as follows: density of 1.080 g/cm^3, pH of 3.5 (25 °C), viscosity of 14.000 to 15000 mPa·s (25 °C), application amount of (200 gr/m^2).

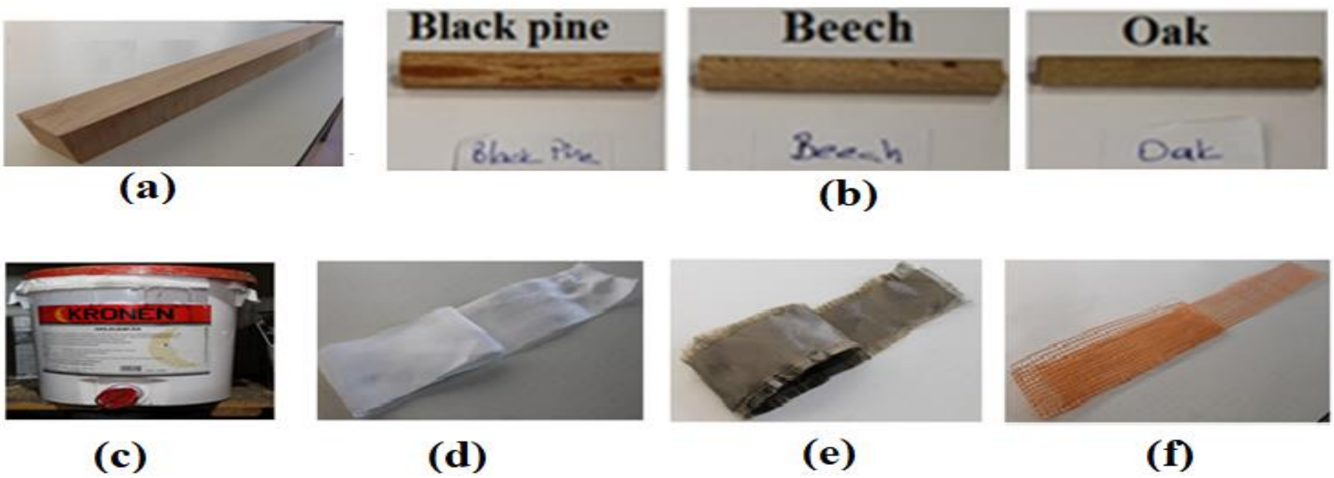

Figure 1. Materials used in experiments: a) Beech wood, b) Wooden dowels, c) PVAc-D4 adhesive, d) GFRP, e) BFRP, and f) PSM

The BFRP and GFRP for 200 gr/m^2 plain materials were obtained from Dost Chemical Industry Raw Material Industry and Trading Company in Turkey (Figure 1d,e respectively). The BFRP and GFRP were prepared by cutting them to a length of 1000 mm and a width of 52 mm. The density of BFRP and GFRP are 2.8 gr/cm^3 and 2.56 gr/cm^3, respectively.

The elasticity modulus, tensile strength, and elongation to fracture of BFRP and GFRP were 8900 and 76000 MPa, 2800 and 2500 MPa, and 3.15% and 3.2%, respectively [19]. The PSM used weighed 160 g/m^2. It was alkali-resistant and orange in color, with a 4 mm × 4 mm mesh pattern (Figure 1f).

2.2. Preparation and Construction of Specimens

In the preparation of the test samples, the wooden materials were sawn using a high-speed circular saw machine to 3 mm thickness, 50 mm width, and 1000 mm length, with annual rings perpendicular to the adhesion surface (Figure 2a). Once stacked, the slats were stored in a temperature-controlled room at a constant temperature of 20 ± 2 °C and a relative humidity of 65 ± 5%. The slats remained in the specified environment until they reached a moisture content of 12%. Test samples were prepared following the guidelines outlined in the TS 5497 EN 408 standard [20]. The PVAc-D4 adhesive was used to prepare the samples.

After the edges and surfaces of the wooden materials were smoothed in the planer machine (Figure 2b), they were brought to the appropriate thickness (2.5 ± 0.1 mm) in the high-speed thickening machine, and the pressing process was started (Figure 2c). For interlayer samples, one layer of reinforced materials (GFRP, BFRP, and PSM) was used as an intermediate support between the solid layers. Approximately 200 g/m^2 of adhesive was used for surface (Figure 2d). The samples, which consisted of two layers, were placed in a hydraulic press (Hydraulic Veneer SSP-80; ASMETAL Wood Working Machinery Industry Inc., Ikitelli, Istanbul, Turkey) at room temperature. The press exerted a pressure of approximately 1.5 N/mm^2 on the samples for 3 h. The test samples were produced at cold pressures of 20 ± 2 °C and 65 ± 5% relative humidity. The pressing of the test samples is shown in Figure 2e.

After the pressing process, one of the edges was smoothed on the planar machine, and test samples were prepared on a high-speed circular saw machine in accordance with the TS ISO 13061-7 standards [21] (Figure 3a,c). On the Vertical Drill Column Stand Lathe Drill machine, appropriate settings were made, and two holes of Ø25 mm and 50 ± 1 mm depth were opened symmetrically in the direction of the part thickness in the middle of the test samples. The test samples were obtained by grading on a horizontal circular machine with a plotter (Figure 3b). In the dowel hole drilling machine, appropriate settings were made for the dowel hole and a dowel hole of Ø8 mm and 50±1 mm depth was drilled on the surfaces of the test samples from the exact center point of the section. Dowels made of beech, oak and black pine wooden materials of Ø8 mm and 50 mm length were placed in the drilled holes without glue (Figure 3c).

The specimens under tensile testing were fabricated as illustrated in Figure 4. Accordingly, three wooden dowel species and three fiber-reinforced polymers (BFRP, GFRP, PSM, and control) and 10 samples of each material (4 × 4 × 10 =160) were used as variables. A total of 160 specimens were constructed in this study. Before testing, all samples were conditioned in a humidity chamber controlled at 20 ± 2 °C and 65% relative humidity (RH) for two weeks.

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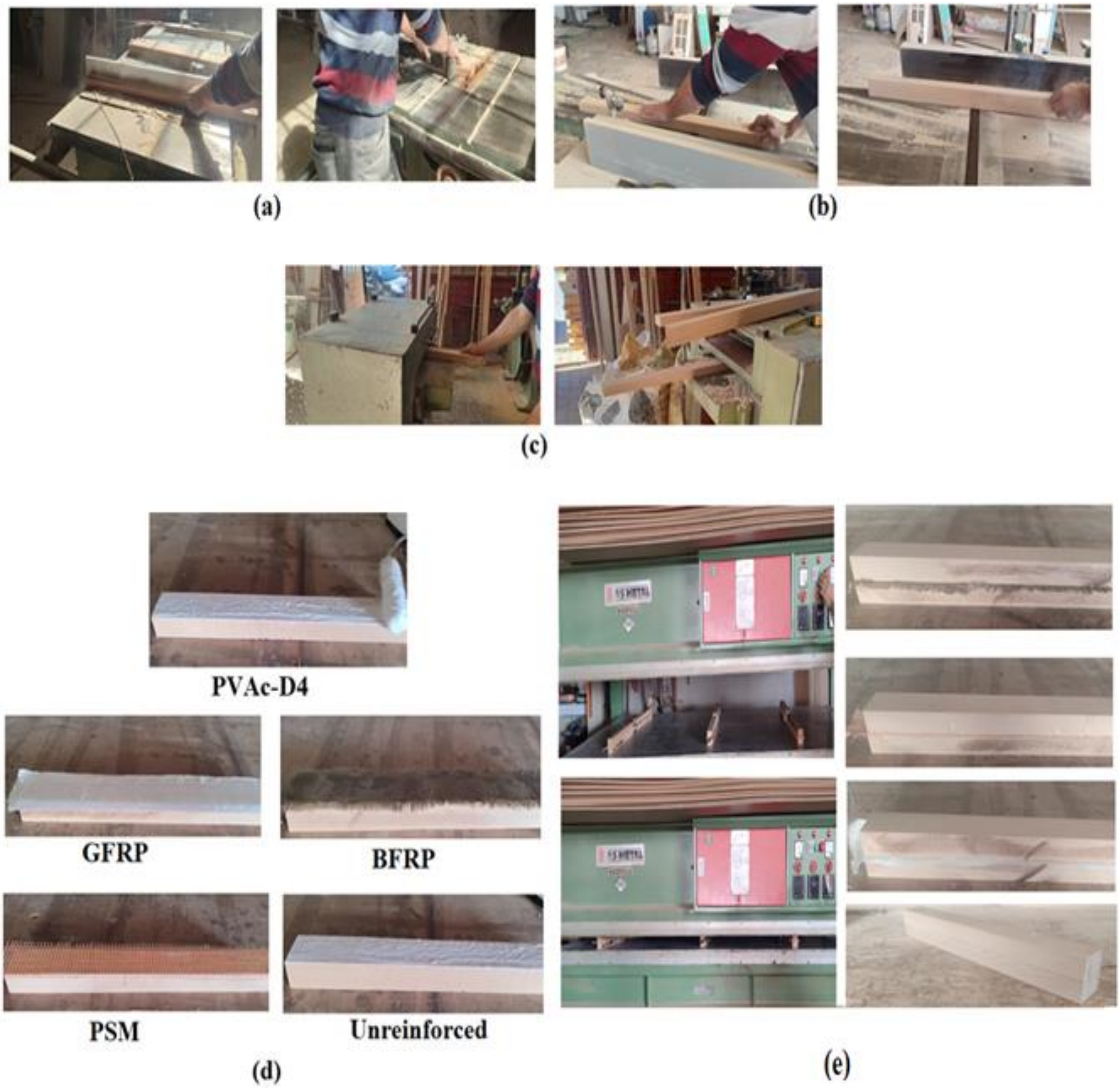

Figure 2. Production stages of test samples

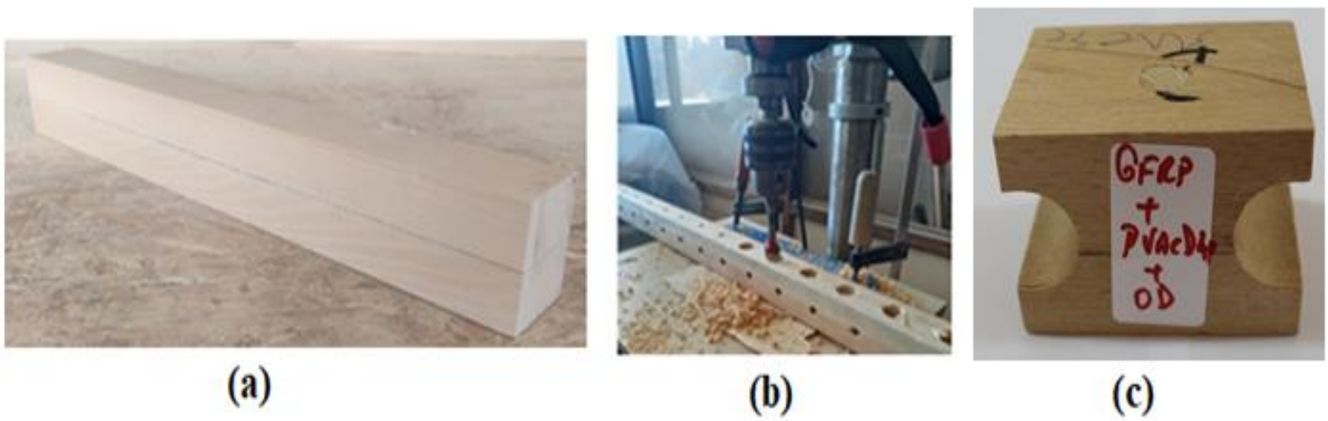

Figure 3. Manufacturing process for experimental samples: a) Slats, b) Hole drilling process, and c) Test samples

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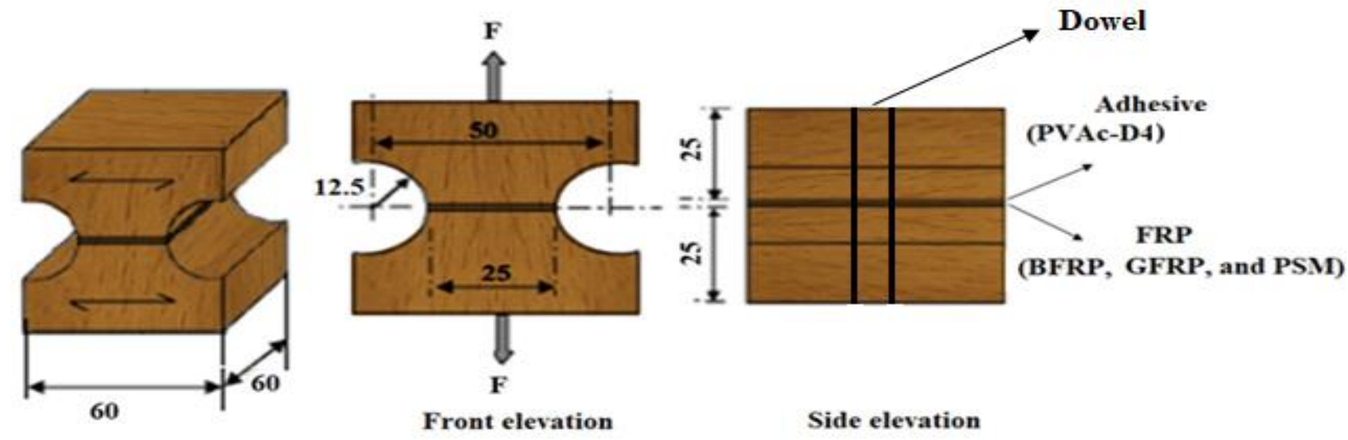

Figure 4. Geometry of specimens in the test (Unreinforced test samples, reinforced with BFRP, GFRP, and PSM test samples (dimensions in mm)

2.3. Mechanical Tensile Tests

For the tensile strength tests, the specimens were tested using an electromechanical universal testing machine (UTM), in the laboratory of Kütahya Dumlupınar University Simav Technical Education Faculty having a capacity of 10 kN, in which they were subjected to a tensile force perpendicular to the substrate wood fibers (Figure 5). According to the TS ISO 13061-7 standard [21], the applied load increased monotonically, due to the crossbar displacement at a rate of 2 mm/min, until the joint rupture. The loading was continued until separation occurred on the surface of the test samples and from the observed load (F_{max}), and the bonding area of the sample (A), the tensile strength perpendicular to fibers ($\perp\sigma t$) was calculated using Equation 1,

$$\perp\sigma t = \frac{F_{max}}{A} \qquad \ldots(1)$$

where $\perp\sigma t$ is the tensile strength perpendicular to fibers (N/mm^2), F_{max} is the ultimate applied force (N), and A is the bonding area of the sample (mm^2).

Figure 5. Apparatus used to hold specimens for the tensile strength perpendicular to fibers tests

2.4. Statistical Analysis

Statistical analysis (Statistical Software, a computer-based statistical package, Minitab, Minitab®18, State College, PA, USA) was performed to examine the data according to the analysis of variance (ANOVA) with the Duncan test ($p < 0.05$).

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3. Results

The mean values $^{\perp}\sigma t$ under tension of the experimental samples with their standard deviation and coefficients of variation are presented in Table 1.

Table 1. Mean values of the $^{\perp}\sigma t$ of joints and their coefficients of variation (N/mm^2)

FRP Types	Wooden Dowel Species	Mean	SD	COV (%)
Unreinforced	Control	2.80	0.19	6.80
	Black pine (BPD)	3.04	0.20	6.69
	Beech (BD)	3.21	0.21	6.58
	Oak (OD)	3.46	0.24	7.02
PSM	Control	2.60	0.11	4.29
	Black pine (BPD)	2.79	0.12	4.25
	Beech (BD)	2.98	0.14	4.61
	Oak (OD)	3.14	0.15	4.68
GFRP	Control	3.82	0.25	6.55
	Black pine (BPD)	4.14	0.30	7.24
	Beech (BD)	4.42	0.29	6.52
	Oak (OD)	4.74	0.32	6.85
BFRP	Control	4.25	0.11	2.50
	Black pine (BPD)	4.65	0.19	4.09
	Beech (BD)	4.92	0.12	2.53
	Oak (OD)	5.25	0.14	2.69

SD: Standard deviation, COV: Coefficient of variation, No-SMT: Unreinforced samples, $^{\perp}\sigma t$: tensile strength perpendicular to fibers.

According to Table 1, when interactions of the FRP types, and wooden dowel species were compared, the highest $^{\perp}\sigma t$ value was obtained for reinforced BFRP in the oak dowel samples (5.25 N/mm^2). The lowest $^{\perp}\sigma t$ value was obtained for reinforced PSM in the control samples (2.60 N/mm^2).

The results of the two-way ANOVA analysis of the FRP types and wooden dowel species on the tension strength perpendicular to the fibers of the experimental samples under the tension load are listed in Table 2.

According to the analysis of variance, as presented in Table 2, the effects of the main factors, including FRP types (A) and wooden dowel species (B), were found to be statistically significant. In contrast, two-way interactions of FRP types × wooden dowel species (A×B) were insignificant at the level of 0.05. The Tukey's test was performed to determine these differences. The $^{\perp}\sigma t$ mean according to the independent effects of test variables are given in Table 3.

Table 2. Summary of the ANOVA Results for ┴σt

Source	Sum of Square	df	Mean Square	F	Sig.
Corrected Model	112.667[a]	15	7.511	178.754	.000
Intercept	2265.853	1	2265.853	53923.823	.000
FRP Types (A)	98.656	3	32.885	782.623	.000
Wooden dowel species (B)	13.247	3	4.416	105.083	.000
A×B	.764	9	.085	2.021	.041
Error	6.051	144	.042		
Total	2384.571	160			
Corrected Total	118.718	159			
R Squared = .949 (Adjusted R Squared = .944)					

df: Degrees of freedom, [a]FRP types (BFRP, GFRP, PSM, and Unreinforced), and [b] Wooden dowel species (Oak, Beech, Black pine, and Control).

Table 3. Independent Effects of Test Variables on Mean Values of ┴σt of Joints (N/mm^2)

Source		┴σt	SD	HG
FRP types	BFRP	4.77	0.14	A
	GFRP	4.28	0.29	B
	Unreinforced	3.13	0.21	C
	PSM	2.88	0.13	D
Wooden dowel species	Oak (OD)	4.15	0.21	A
	Beech (BD)	3.88	0.19	B
	Black pine (BPD)	3.65	0.20	C
	Control	3.37	0.17	D

┴σt: tensile strength perpendicular to fibers, HG: Homogeneity groups.

For the FRP types, the highest ┴σt value was obtained in BFRP (4.77 N/mm^2), and the lowest was in the PSM (2.88 N/mm^2). The ┴σt value according to reinforced FRP declined in the order to BFRP, GFRP, unreinforced, and PSM. The ┴σt value of samples reinforced with BFRP was 11%, 52%, and 65% higher than those reinforced with GFRP, unreinforced, and reinforced PSM, respectively. In the literature, some studies reported that BFRP has higher tensile strength and modulus of elasticity than GFRP [22,23,24,25].

According to the wooden dowel species, the best results were obtained for test samples with oak dowels. The ┴σt value of samples reinforced with oak dowel was 7%, 14%, and 23% higher than those reinforced with beech, black pine, and control, respectively. The reasons for this are the density differences of the wood materials, structural properties, mechanical properties, and improved bonding strength. The density of oak wood was higher than that of other wood samples used in the experiments. This may be due to the thick cell walls of oak wood, the large number of trahe, narrow lumen space, high material density, the thin lumen of the cell walls in black pine, and the low material density. An excess density may have caused the surface areas in contact with each other to grow and increase the number of molecules involved in adhesion; hence, the molecules adhere to each other by creating a greater adhesion force.

In addition, in trees with excess density, hydrogen bridges formed between the cellulose molecules of the wood material and the hydroxyl groups (OH) of the glue are thought to be more excessive. In a study conducted to determine the performance of dowel fasteners with plywood and particleboard materials, oak dowels showed high values in plywood joining [26]. When the studies conducted in the literature are examined, it is seen that the dowel tensile resistance of high-density wood materials is high [27,28,29].

4. Conclusions

This study investigated the tensile strength perpendicular to fibers of timber joined with a wooden dowel and reinforced with basalt BFRP, GFRP, and PSM using PVAc-D4.

According to the overall results, the experimental samples reinforced with BFRP and joined with an oak dowel demonstrated the best properties among all the tested samples. The highest tensile strength perpendicular to fibers value was obtained from oak dowels and reinforced with BFRP. At the same time, the lowest tensile strength perpendicular to the fibers value was obtained from control samples and reinforced PSM.

On the empirical findings regarding the technical characteristics of BFRP as support materials and oak as wooden dowel, the tensile strength perpendicular to fibers of the wood material was observed to be improved. Given the substantial enhancements in the resistance properties of the intermediate filling material utilized in reinforced wood materials, it is advisable to prioritize high-strength properties in wood furniture and structural timber materials. In wooden structures where the tensile strength value perpendicular to the fibers is important, the use of BFRP and an oak dowel as the wooden dowel type can be recommended.

5. Future Studies

(i) It may be recommended to investigate the determination of tensile strength perpendicular to the fibers of wood material reinforced with aramid FRP (AFRP), (ii) It may be recommended to investigate the determination of tensile strength perpendicular to the fibers of wood material reinforced with CFRP, (iii) It may be recommended to investigate the determination of tensile strength perpendicular to the fibers of wood material reinforced with jute fabric, and (iv) It may be recommended to investigate the determination of tensile strength perpendicular to the fibers of wood material reinforced with joined with GFRP rods, BFRP rod, and CFRP rods.

6. Limitations

Due to some limitations such as insufficient lab-server facilities and lack of financial support, the real data can’t be applied for this analysis. However, the methodological process and the features of the results would be similar if the real data set were used.

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Declarations

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This study did not receive any grant from funding agencies in the public, commercial, or not–for–profit sectors.

Competing Interests Statement

The author has not declared any conflict of interest.

Consent for publication

The author declares that he consented to the publication of this study.

Authors' contributions

Author’s independent contribution.

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