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ORIGINAL ARTICLE

Numerical and experimental behavior of fiber reinforced polymer type and layer number effect on the flexural properties of heat-treated black pine wood

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Abstract Heat treatment is one of the environmentally friendly methods applied to improve the structural properties of wooden materials. While heat treatment improves some properties of wood material, it also negatively affects its mechanical properties depending on the heat treatment conditions applied. The decrease in mechanical properties due to heat treatment limits the use of wood material in various applications requiring mechanical strength. For this purpose, various fiber-reinforced polymers have been used in recent years. In this study, it was aimed to experimentally and numerically examine the flexural properties of unheat-treated and heat-treated black pine (*Pinus nigra* Arnold.) wood reinforced 1, 2 and 3 times with carbon, glass and aramid. Following the experimental flexural tests, the samples were modeled and analyzed in the finite element software program. The average flexural strength of the heat-treated sample is 11.72% lower, and the elasticity modulus is 1.23% lower than the unheat-treated sample.It has been determined that carbon-based polymer fabrics, among fiber-reinforced polymer fabrics, have the best reinforcement effect. The flexural strength of the UHT-C-3 sample is 6.1% and the elasticity modulus is 3.52% higher than the UHT-C-1 coded sample. Compared to the sample without reinforcement, flexural strength increased by 30% and elasticity modulus increased by 7%. It is seen that as the number of fiber reinforced polymer layers increases, the flexural properties also increase. When the experimental and numerical analysis results were examined, the flexural strength and modulus of elasticity values gave similar results at the R^2: 0.88–0.99 level. In addition to technologies using kinds of reinforcement evaluated in conservation applications, it may be utilized for numerical analysis in the field of repairing or reinforcing different grades, patterns, and types of reinforcement in already-existing wooden structures.

Keywords Wood materials · FRP · Finite element analysis · Black pine · Flexural properties

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Introduction

Wooden material is a natural, renewable and sustainable building material that has been used for many years due to its many positive properties (Kilincarslan and Simsek Turker 2021; Sutcu and Cambazoglu 2023; Sahin et al. 2020). Wooden material is widely used in various fields due to its positive features such as easy processing, being an economical and aesthetic material, and having high mechanical properties despite its low density (Hill and Wood 2006; Kurtoglu and Sofuoglu 2013; Kurtoglu 2000; Korkut and Hiziroglu 2014; Cigdem and Percin 2023). Due to some structural features and defects of wood material, its mechanical properties decrease, which may limit its use in various structural applications (Uluata 1987; As et al. 2006; Koman et al. 2013). In recent years, efforts to develop environmentally friendly wood modification methods to improve the properties of wood materials and minimize

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their negative properties have been increasing (Rowell 2012; Sandberg et al. 2017). Heat treatment is one of the environmentally friendly methods developed to improve the structural properties of wooden materials (Lee et al. 2018; Çiğdem and Perçin 2023; Kilinçarslan and Turker 2020; Boonstra and Tjeerdsma 2006). The use of heat-treated wood material in structural applications is increasing, and this increases the demand for heat-treated material (Dagbro 2016; Candelier et al. 2016; Jirous-Rajkovic and Maiklecic 2019; Xing et al. 2020). Due to its resistance to environmental influences, heat-treated wood material is used in indoor and outdoor applications such as building exterior cladding, kitchen countertops, bathrooms, garden furniture and sauna interiors (Korkut and Kocaefe 2009). While heat treatment improves some properties of the wooden material, it also negatively affects its mechanical properties (flexural resistance, dynamic flexural, modulus of elasticity in flexural) depending on the heat treatment conditions applied (Chu et al. 2020; Kilincarslan et al. 2020). The decrease in resistance properties due to heat treatment limits the use of wood material in various applications requiring mechanical strength (Kilinçarslan and Simsek Turker 2020).

Studies on strengthening wooden materials have been continuing for many years. The application of fiber-reinforced polymer (FRP) composite materials could offer ways to enhance the subpar mechanical qualities of wood components (Wang et al. 2019; Johns and Lacroix 2000; Plevris and Triantafillou 1992; Triantafillou and Deskovic 1992). In addition, during the past 20 years, a lot of work has been done to restore and strengthen pre-existing buildings using fiber-reinforced polymers, or FRPs. Glass or carbon fiber reinforced polymers (FRPs) have a high strength-to-weight ratio, are resistant to corrosion, and offer design freedom (Yan et al. 2014; Yan and Chouw 2013, 2014). For this purpose, carbon, glass, basalt and aramid-based fiber-reinforced polymers have been used in recent years (Wei et al. 2013; Wdowiak-Postulak 2023, 2022; Wdowiak-Postulak and Brol 2020). The use of fiber reinforcement systems has become a widely applied method to increase the load-carrying capacity and strength properties of wood material (Johnson et al. 2007). In the strengthening of wooden materials, reasons such as improving the load-carrying capacity of building elements by restoring the structures, eliminating damage that may occur due to earthquakes and external effects, preventing premature fatigue and fractures that occur because of insufficient detailing, and compensating for losses in load-carrying capacity due to long-term use (Akgül et al. 2009).

Zhang et al. (2011) strengthened wooden beams with basalt fiber reinforced polymer (BFRP), and the test results showed that there were significant increases in the load-carrying capacity of the reinforced materials. Micelli et al. (2005) investigated the possibility of attaching CFRP rods as reinforcement to glulam beams, keeping the latter case in mind. Test findings showed that adding CFRP rods improved glulam beams' ultimate capacity and stiffness by 26–82% and 8–19%, respectively. In order to assess the bond's performance. Kilincarslan and Simsek Turker (2023) strengthened 20 × 20 × 360 mm solid ash beams with basalt-based fiber-reinforced polymers. They investigated the effect of basalt-based fiber-reinforced polymers on the flexural properties of ash tree beams. A three-point flexural test was applied to wooden beams to determine their flexural properties. As a result of this study, it was determined that the flexural properties of the ash beam reinforced with basalt-based fiber-reinforced polymer composites were better than the reference samples. Johnsson et al. (2007) evaluated a total of ten specimens under four-point flexural from three different series of glulam beams reinforced with rectangular pultruded CFRP bars. The experimental results were compared with analytical models in several aspects. The authors report an average improvement in the short-term flexural load-carrying capacity of 49–63%. Gentry (2011) proposed the use of FRP pins positioned transversely across the plies of glulam to reinforce wood beams in shear. The test findings show that the pinned set of glulams had a much smaller dispersion than the nonpine specimens. Kilincarslan and Simsek Turker (2023) 20 × 20 × 360 mm wooden samples of ash tree species were strengthened with carbon, basalt and glass-based FRP materials. Examined the flexural properties of the unwrapped reference sample and samples reinforced with carbon, basalt and glass-based FRP materials. For this purpose, first performed a three-point flexural test and then compared the obtained results with the numerical results in the ANSYS finite element analysis program. As a result, a good agreement was found between the experimental and numerical results. As a result of the flexural tests, the load-displacement curves, flexural strength values, and elasticity modulus values of the samples were determined. They determined that the sample reinforced with carbon-based FRP polymers had the highest load-carrying capacity value. Kilincarslan et al. (2023) experimentally and numerically examined the flexural properties of solid and glulam beams reinforced with carbon FRP composites. The load-carrying capacity, displacement and modulus of elasticity of glulam beams were higher than solid beams. Although both types of beams were manufactured from the same materials, laminated beams exhibited significantly improved flexural properties. Additionally, strengthening glulam beams with fiber-reinforced polymers showed a significant improvement in flexural performance. Numerical simulations and experimental results performed using the finite element analysis program gave similar results. When the literature is examined, the studies are on the strengthening of unheat-treated laminated timber, especially laminated timber. In recent years, there have been very few studies on strengthening commonly used wooden materials by modifying them with this non-toxic method. There are a limited number of studies, especially on the strengthening of black pine wood. Black pine (*Pinus nigra*) tree has heartwood, its sapwood is wide, its heartwood is narrow, very resinous, the appearance of its annual rings on its head is clear and distinct, and it has a soft structure. Black pine is widely used in the interior and exterior parts of buildings, interior parts of ships and wagons, bridge abutments, mine poles and the packaging industry (Şanıvar and Zorlu 1980). In previous studies conducted on black pine wood; expansion in radial direction 6.57%, volumetric expansion 14.23%, expansion in tangential direction 7.19%, contraction in radial direction 5.69%, contraction in tangential direction 7.12%, volumetric contraction 12.40% (Kardaş 2014), cellulose 48.27%, extractive substance content 8.71%, holocellulose 64.27%, α-cellulose 40.10%, lignin 34.32%, hot water solubility 8.688%, cold water solubility 7.42%, ash content 0.60%, 1% NaOH solubility, 19.75% (Akyürek 2019), static quality value 8.0 (Var and Kardaş 2017), thermal conductivity value was determined as 0.143 W/m.K (Çavuş et al. 2019) and mass loss against Coniophora puteana mushroom after 12 weeks was determined as 43.9% (Lykidis et al. 2013).

In this study, it was aimed to experimentally and numerically examine the flexural properties of unheat-treated and heat-treated black pine wood reinforced 1, 2 and 3 times with carbon, glass and aramid. Following is the remainder of the article. The materials and methods utilized in this study are described in Sect. "Material and methods". The results and discussion on the experimental and numerical study data are described in Sect. "Results and discussion". The paper's conclusion is presented in the last part.

Material and methods

Material properties

One of the greener techniques for enhancing the structural qualities of wood products is heat treatment. The need for heat-treated material is rising as a result of the growing usage of heat-treated wood in structural applications. The heat-treated black pine wood (*Pinus nigra* Arnold.) used in this study was purchased from NASWOOD in the Antalya region. In the selection of wood, care was taken to select materials that did not have defects (knots, fiber curls, etc.). The black pine timbers brought to the laboratory were cut into dimensions of 20 × 20x360 mm. The sawn wood samples were kept in the air-conditioning cabinet under 20 °C (± 2) °C temperature and 65% (± 5) relative humidity conditions in order to reach the same equilibrium moisture content (EMC). After the wooden samples were kept in the air-conditioning cabinet, their moisture content values were measured with an electric moisture meter. Carbon, glass and aramid-based fiber reinforced polymers obtained from UNAL TEKNIK® were used in this study. Technical specifications and application methods of fabrics, epoxy adhesive and primer are available in the company technical sheet. The technical properties of carbon (CFRP), glass (GFRP) and aramid (AFRP) used in this study are given in Table 1. The technical specifications of fiber reinforced polymer fabrics given in Table 1 are available in the products section of UNAL TEKNİK company (Unal Teknik, 2023).

The properties and codes of the black pine samples reinforced with various FRP and FRP layer numbers in this study are given in Table 2. The "−" sign given in Table means "absent" and the "+" sign means present.

Reinforcement application of 22 different series with the features given in Table 2 was made and subjected to flexural test together with the reference sample.

Reinforcement and experimental flexural test

In this study, the reinforcement with FRP fabrics was carried out in 4 stages. Before starting the FRP application, the surfaces of the wooden samples are cleaned. Then, the primer obtained from UNAL TEKNIK® was applied to the surfaces with the help of a roller. After the primer application, the primer was waited for 1–1.5 h for the surface to absorb the primer and to make the application easier. Then, epoxy adhesive, specially developed for fiber reinforced polymers, was applied to the surface with the help of a roller. The epoxy adhesives used are the joining of FRP fabrics and wood material for the purpose of joining the layers. Previously cut and prepared fiber reinforced polymers were wrapped on the adhesive applied surface. The strengthened fiber reinforced polymers were kept under

Table 1 Technical specifications of the carbon, glass and aramid FRP composite

FRP material	Carbon	Glass	Aramid
Weight (g/m^2)	300	300	300
Modulus of Elasticity (GPa)	230	72	100
Tensile strength (N/mm^2)	4900	3900	3300
Design Section Thickness (mm)	0.166	1.162	0.170
Width (mm)	500	500	500
Elongation at Break (%)	2.1	4.8	4.4

Table 2 Properties and codes of the samples tested

Serial-code	Heat treatment	Reinforcement	FRP type	FRP layer number	Moisture content (%)
UHT	–	–	–	–	11.65
UHT-C-1	–	+	Carbon	1	11.60
UHT-C-2	–	+	Carbon	2	11.46
UHT-C-3	–	+	Carbon	3	11.55
UHT-G-1	–	+	Glass	1	11.62
UHT-G-2	–	+	Glass	2	11.39
UHT-G-3	–	+	Glass	3	11.40
UHT-A-1	–	+	Aramid	1	11.64
UHT-A-2	–	+	Aramid	2	11.57
UHT-A-3	–	+	Aramid	3	11.42
HT	+	–	–	–	11.62
HT-C-1	+	+	Carbon	1	11.61
HT-C-2	+	+	Carbon	2	11.34
HT-C-3	+	+	Carbon	3	11.51
HT-G-1	+	+	Glass	1	11.48
HT-G-2	+	+	Glass	2	11.32
HT-G-3	+	+	Glass	3	11.31
HT-A-1	+	+	Aramid	1	11.34
HT-A-2	+	+	Aramid	2	11.25
HT-A-3	+	+	Aramid	3	11.31

appropriate laboratory conditions for one week to perform flexural tests. Flexural strength tests are carried out on $20 \times 20 \times 360$ mm specimens prepared in accordance with TS ISO 13061-2. In the flexural tests, the loading speed is set as 6 mm/min constant speed, and the experiments are carried out. The span of the support points is taken as 300 mm in the experiments. After carrying out the experiments, flexural strength and elasticity modulus values were determined. As a result of flexural tests of wooden samples, flexural strength and elasticity modulus values were determined. After the experiments were carried out, modeling was done in the finite element software program and the beams were analyzed.

Fine element analysis

Numerical simulations were executed using the ANSYS 18.1 Standard Solver and the finite element method. Models were developed for both unreinforced and reinforced beams, ensuring that the geometries and loading 161 configurations of these models accurately represented the experimentally tested beams. End conditions were set with pinned and roller supports to confine the vertical movement of the beams. A 25 mm rectangular mesh was selected during the modeling phase. To accurately simulate the simply supported boundary conditions, restrictions were imposed on select nodes within the beam model. Utilizing the SOLID45 element, a model was constructed for the timber, an element renowned for 3-D modeling of solid structures. This element encompasses eight nodes, each equipped with three degrees of freedom across the x, y, and z dimensions. Despite SOLID45's extensive capabilities, encompassing plasticity, stress stiffening, and large deflection among others, capturing the intricate anisotropic behavior of timber remains challenging. Therefore, orthogonal elastic properties were introduced into the software to approximate the response of the wood. The modeling of FRP was undertaken using SOLID65, an eight-node element with three degrees of freedom at each node. Chosen for its capability to forecast tension cracking and compression crushing, SOLID65 is typically employed for modeling reinforced composites including CFRP, concrete, and geological rocks. Given that FRP materials predominantly undergo minute plastic deformation, they were presumed to have linear elastic properties culminating in a brittle failure. The simplified modeling approach highlighted FRP materials as displaying uniaxial linear isotropic behavior. Considering the material properties and underlying assumptions, SOLID65 emerged as an apt choice for the accurate representation of their performance. Both wood and FRP were represented as solid finite elements, possessing eight nodes and reduced integration. A mesh of higher granularity was generated around the lamination areas proximate to the FRP reinforcement, which was the principal site for stress transmission from the FRP plate to the glulam. The "tie constraint" was employed to delineate the bond between wood/epoxy/FRP interfaces. Representative illustrations of these modeled beams can be found in Fig. 1.

It should be noted that a linear load, uniformly distributed across the width of the beam, was utilized. Vertical displacement increments were progressively employed for the static small displacement analysis until the pre-specified failure condition was achieved.

Results and discussion

Numerical analysis and experimental test results

The flexural properties of heat-treated black pine wood samples were examined experimentally and numerically. As a result of numerical analysis, displacement values obtained because of single point loading were observed and images of these values are given in Figs. 2, 3 and 4.

The elasticity modulus and flexural strength values obtained because of experimental and numerical single-point loading are given in Figs. 5 and 6.

The average flexural strength of the HT sample is 11.72% lower, and the elasticity modulus is 1.23% lower than the UHT sample. The highest flexural strength and elastic modulus values were seen in samples reinforced with carbon-based fiber-reinforced polymers. When the samples reinforced with carbon-based fiber reinforced polymers are examined; The flexural strength of the UHT-C-3 sample is 1.48% and the elasticity modulus is 2.84% higher than the UHT-C-2 coded sample. Compared to the UHT-C-1 sample, its flexural strength is 6.1% higher and its elastic modulus value is 3.52% higher. Similar results were obtained for heat-treated samples. In these beams, the flexural strength and elasticity modulus values of three-layer reinforced samples are higher than those of 1-layer and 2-layer reinforced samples. Glass-based fiber reinforced polymers had the lowest impact. The flexural strength of the UHT-G-3 sample is 1.11% higher and the elasticity modulus is 0.12% higher than the UHT-G-2 sample. The flexural strength of the UHT-G-3 sample is 7.2% higher and the elasticity modulus is 1.19% higher than the UHT-G-1 sample. Similar results were obtained for heat-treated samples; the flexural properties of 3-layer reinforced samples are higher than those of 1-layer and 2-layer reinforced beams. When the properties of glass-based FRP reinforced beams are compared with UHT and HT samples, it is seen that especially the UHT-G-3 sample increases its flexural strength by 11.34% and its elasticity modulus by 3.59% compared to the UHT sample. It is seen that the HT-G-3 sample increases its flexural property by 19.2% and its elasticity modulus by 4.10% compared to the HT sample. In samples reinforced with aramid-based FRP, flexural strength and elasticity modulus values were higher than glass-based FRP and lower than carbon-based FRP. When samples reinforced with aramid-based FRP are examined; The flexural strength of the UHT-A-3 sample is 1.22% higher and the elasticity modulus is 0.62% higher than the UHT-A-2 sample. The flexural strength and elasticity modulus values of the UHT-A-2 sample are 4.45% and 0.69% higher, respectively, than the UHT-A-1 sample. When the results obtained were evaluated, it was seen that the final results were related to the properties of the FRP polymers used for reinforcement. It has been observed that the final bending properties of the beams have low values, especially due to the low elasticity modulus of the glass-based FRP polymer fabric. ANSYS and numerical analysis

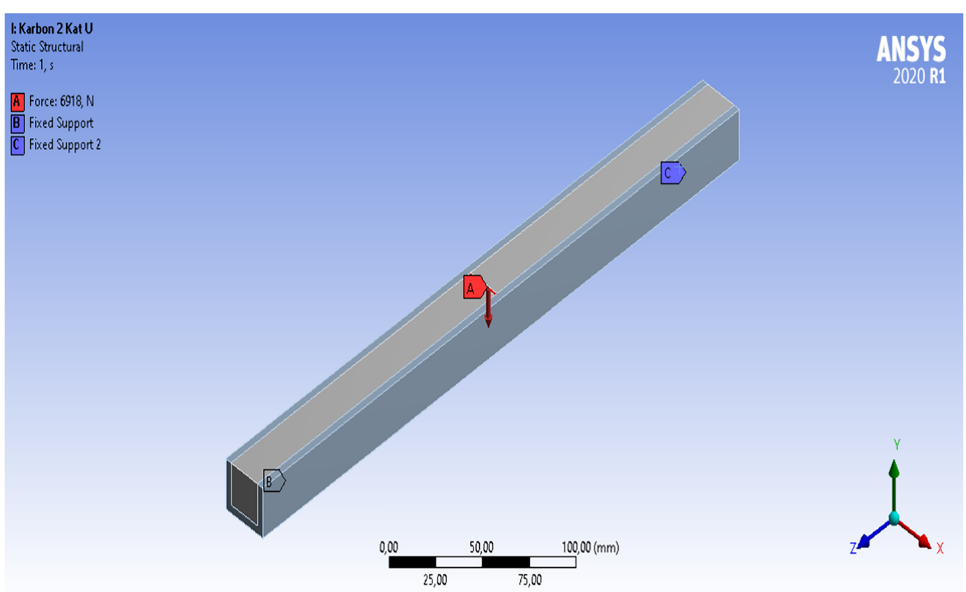


Fig. 1 Beams modeled in a finite element analysis program

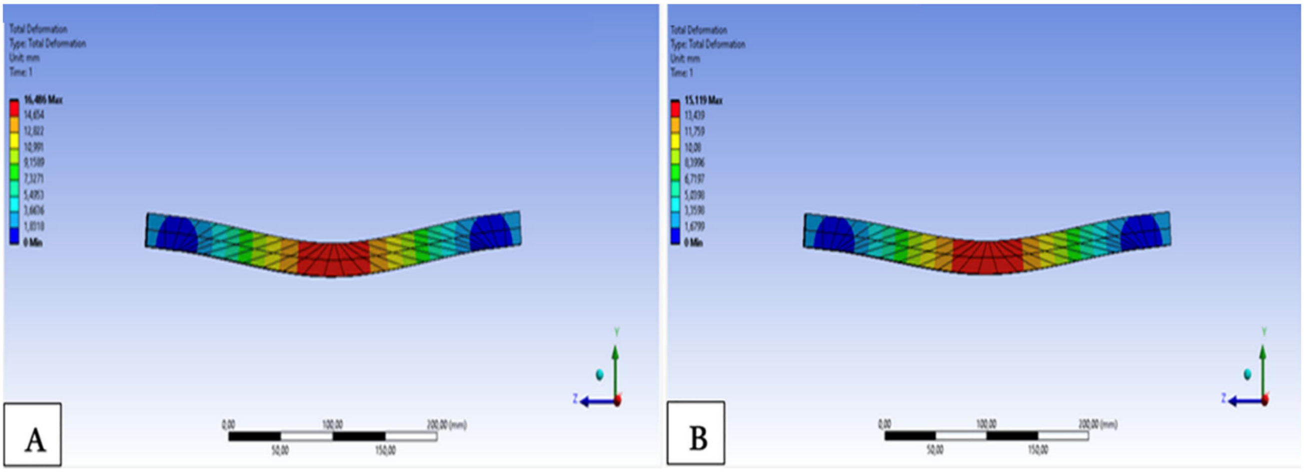


Fig. 2 ANSYS FEM analysis of samples, **A**: UHT sample, **B**: HT sample

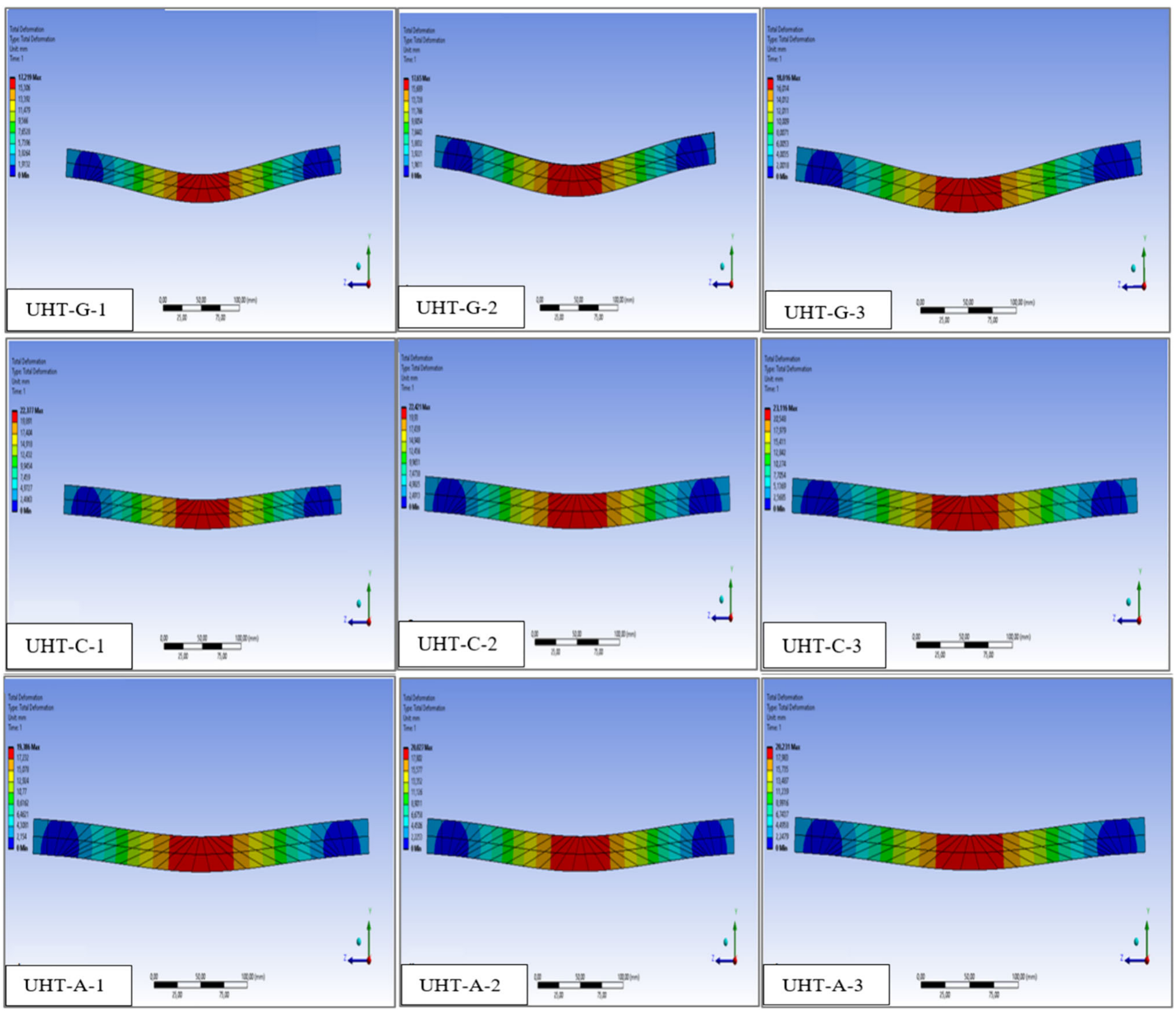


Fig. 3 ANSYS FEM program analysis of UHT samples

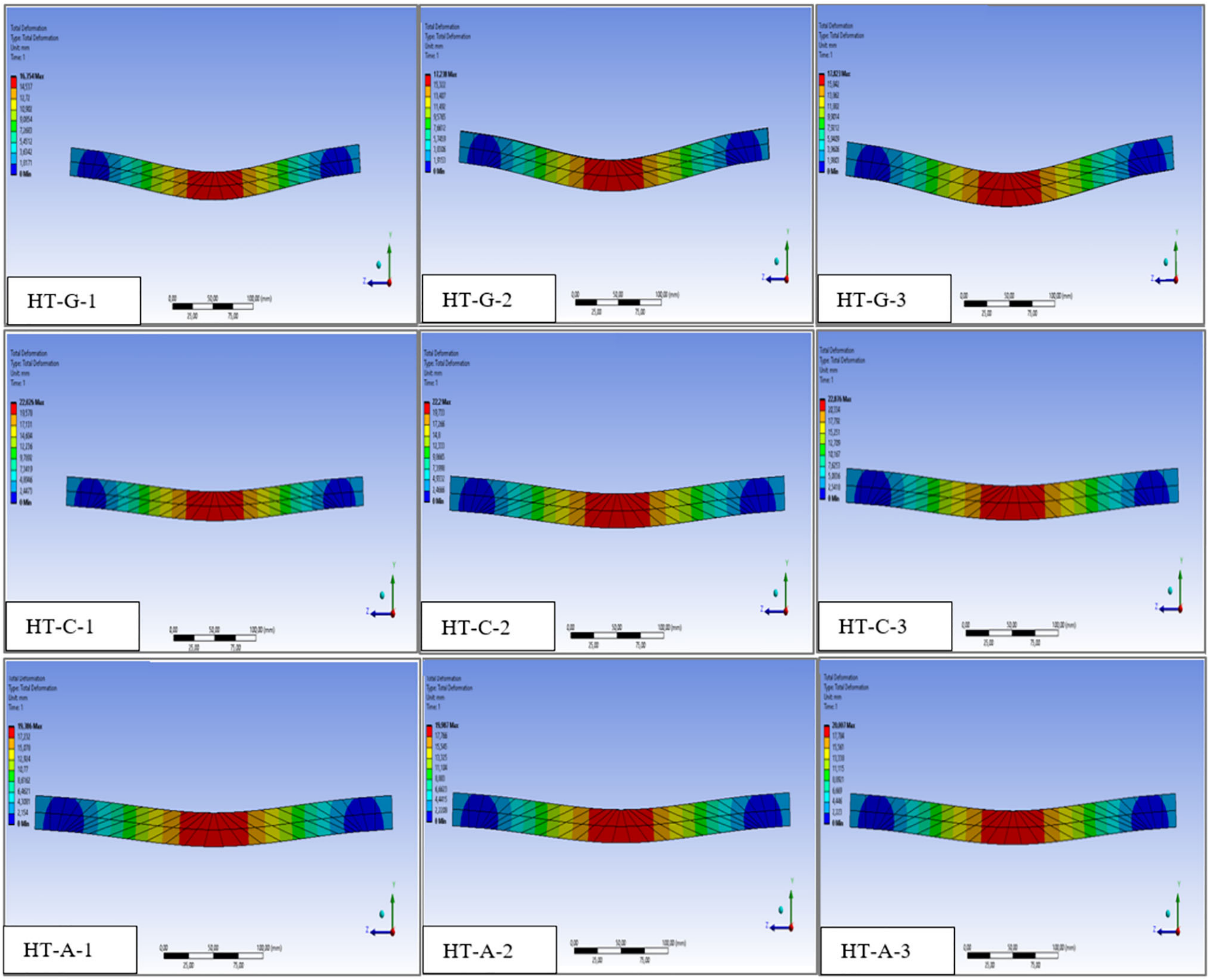
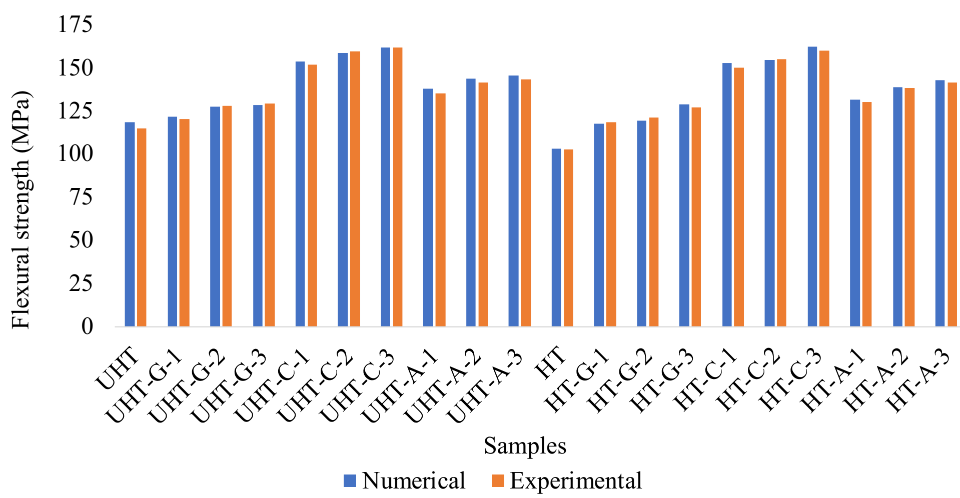


Fig. 4 ANSYS FEM program analysis of HT samples

Fig. 5 Flexural strength values because of experimental and numerical flexural tests



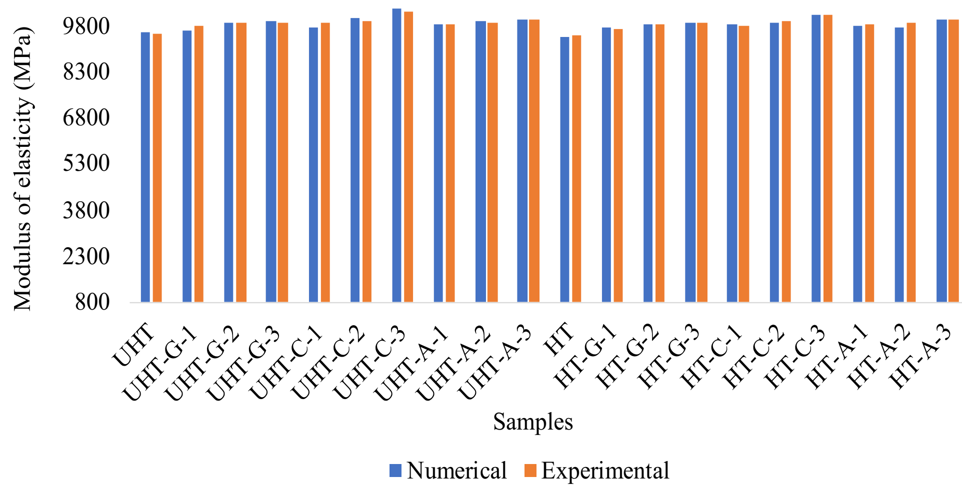


Fig. 6 Modulus of elasticity values from experimental and numerical flexural tests

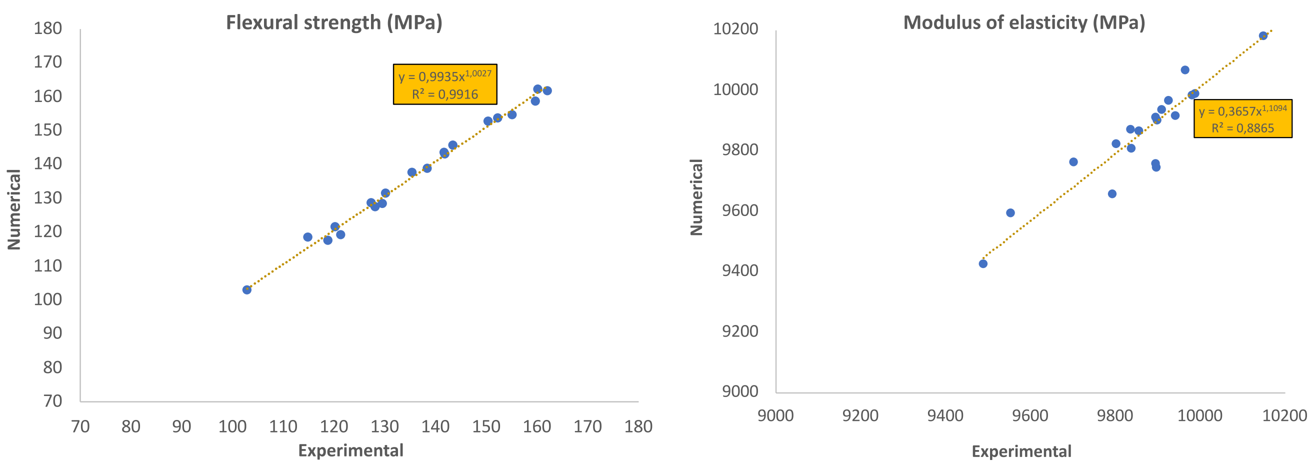


Fig. 7 Correlation coefficient (R^2) values comparing experimental and ANSYS of flexural strength and modulus of elasticity

results are very compatible with each other. Correlation coefficient (R^2) values comparing experimental and ANSYS findings are given in Fig. 7. Consequently, this study has found that, with the application of heat treatment, there is a slight decrease in the mechanical properties of the wooden material, while its dimensional stability and resistance to external factors increase. In this study, it was determined that the flexural properties of heat-treated beams could be increased by strengthening with fiber-reinforced polymers. In addition, it has been determined that the flexural properties of the beams increase with the increase in the number of wrappings in reinforcement techniques with fiber-reinforced polymers. However, it has been determined that the best results are obtained with two-layer wrapping. The results obtained in this study overlap with previous studies conducted by researchers.

When the experimental and numerical analysis results were examined, the flexural strength values gave similar results at the R^2:0.99 level. It was determined that the elasticity modulus values gave similar results at the R^2:0.88 level. Therefore, it can be seen that numerical analyzes were carried out successfully in the strengthening of black

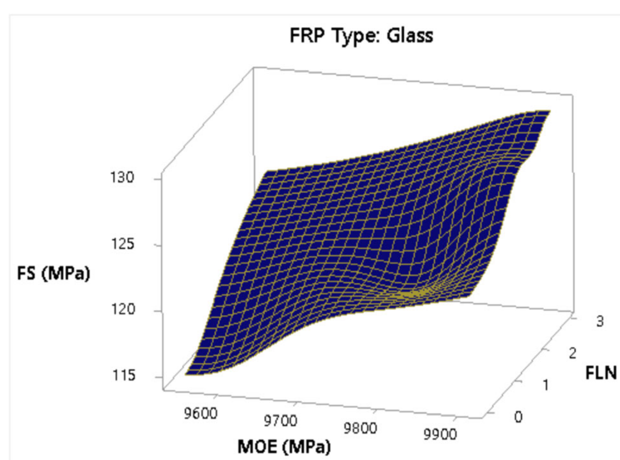


Fig. 8 Relationship between FLN and MOE and FS (UHT Samples, FRP Type: Glass)

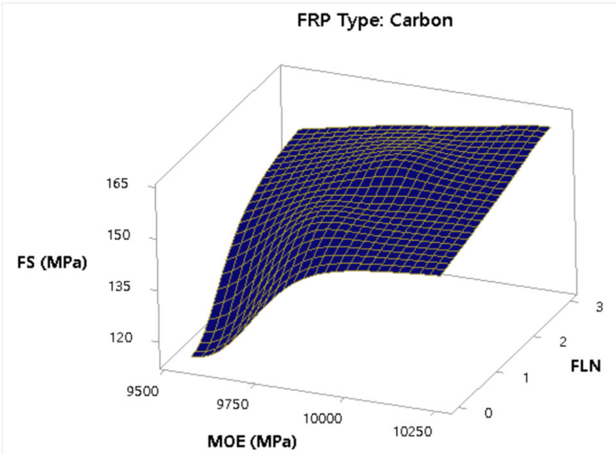


Fig. 9 Relationship between FLN and MOE and FS (UHT Samples, FRP Type: Carbon)

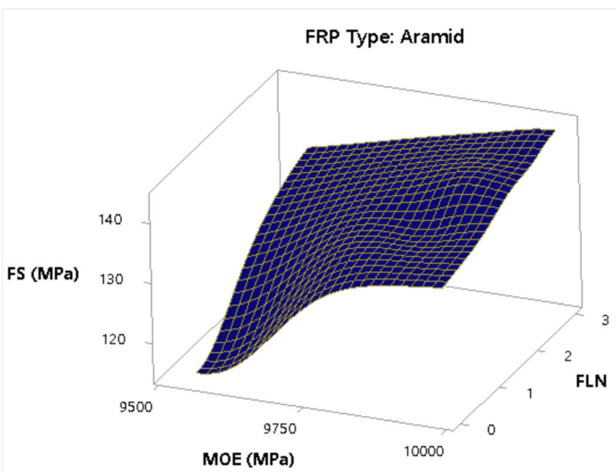


Fig. 10 Relationship between FLN and MOE and FS (UHT Samples, FRP Type: Aramid)

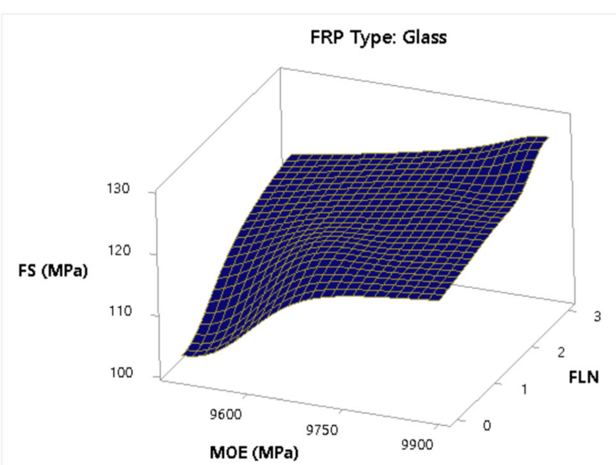


Fig. 11 Relationship between FLN and MOE and FS (HT Samples, FRP Type: Glass)

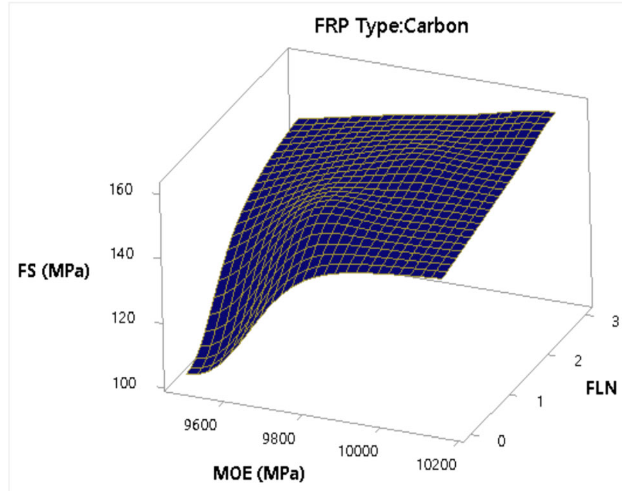


Fig. 12 Relationship between FLN and MOE and FS (HT Samples, FRP Type: Carbon)

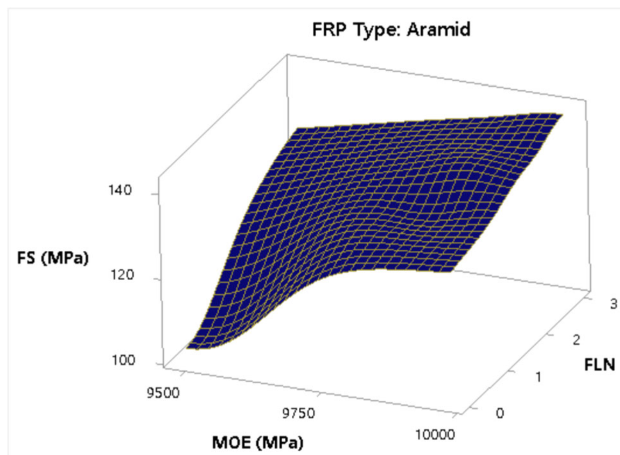


Fig. 13 Relationship between FLN and MOE and FS (HT Samples, FRP Type: Aramid)

pine wood samples. It has been determined that the results can be obtained without performing the tests on the beams of the simulated larch wood type. 3D graphics showing the relationship between FRP fabric type, FRP layer number, elasticity modulus and flexural strength are given in Figs. 8, 9, 10, 11, 12, and 13.

When Figs. 8, 9, 10, 11, 12, and 13 were examined, it was determined that flexural strength and elasticity values increased with the increase in the number of FRP layers. In general, it is seen that more efficient values are obtained with 2-layer reinforcement in all heat-treated and unheat-treated samples.

Conclusion

Increased strengthening efficiency has been achieved with FRP fabric materials with high flexural properties. The highest flexural strength and elastic modulus values were obtained in samples reinforced with carbon-based fiber-reinforced polymers. The lowest reinforcement effect was achieved with glass-based fiber reinforced polymers. Wooden beams are damaged due to cracks occurring in the tension zone. In unreinforced members, these were mostly cracks that occurred in the deformation zone. It is the damage that occurs in the pressure zone of reinforced elements due to crack propagation and crushing. Among the reinforcements made with different number of layers, the reinforcement made with 3 layers of FRP gave the highest flexural properties. However, when the results were evaluated, it was determined that 2 layers of reinforcement may be sufficient for FRP application. Numerical models gave similar values to the experimental test results. The difference between the results of numerical and experimental analysis is due to the heterogeneity of the wood material, such as allowed knots, cracks or deviations in the wood fibers. The above research results can be used for numerical analysis in the field of repair or reinforcement of various grades, patterns and types of reinforcement in existing wooden structures, as well as for technologies using the tested types of reinforcement in conservation application. The experimental studies together with the simulation model verified by them provide a valuable source of input data for the design and selection of FRP type and FRP Layer number.

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