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Experimental and Numerical Study on Strengthening Timber Beams Using Carbon and Glass Fibers

Eksperimentalna i numerička studija ojačavanja drvenih greda upotrebom ugljikovih i staklenih vlakana

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ABSTRACT • *This research investigates the flexural behavior of laminated spruce timber beams strengthened with carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) composites. A total of 28 specimens, fabricated in accordance with TS EN 408+A1 standards, comprising twelve CFRP reinforced, twelve GFRP reinforced, and four unreinforced control beams, were subjected to four-point bending tests. Three distinct reinforcement configurations rods, plates, and fabrics were systematically applied and comparatively evaluated. The results consistently demonstrated that CFRP reinforcements significantly outperformed GFRP counterparts in enhancing stiffness and flexural strength. Among the reinforcement types, double carbon rods and wide CFRP plates exhibited the most pronounced improvements, while spiral-wrapped CFRP fabrics showed superior performance relative to flat fabric applications. Additionally, the study highlights the critical influence of reinforcement configuration on the mechanical response of timber beams and underscores the impact of inherent wood defects on experimental outcomes. Complementary numerical simulations conducted using ANSYS software corroborated the experimental findings, thereby validating the effectiveness of the proposed reinforcement strategies for timber rehabilitation.*

KEYWORDS: *fiber reinforced polymer (FRP); timber beams; strengthening; laminate; ANSYS*

SAŽETAK • *U radu je predstavljeno istraživanje savijanja lameliranih drvenih greda od smrekovine ojačanih polimernim kompozitima s ugljikovim vlaknima (CFRP) i staklenim vlaknima (GFRP). U skladu sa standardom TS EN 408+A1, ukupno je izrađeno 28 uzoraka: 12 uzoraka ojačanih CFRP-om, 12 uzoraka ojačanih GFRP-om i četiri neojačane kontrolne grede. Na uzorcima je provedeno ispitivanje savijanja u četiri točke. Sustavno su primijenjena i usporedno ocijenjena tri različita sustava ojačanja: šipke, ploče i tkanine. Rezultati su dosljedno pokazali da u povećanju krutosti i čvrstoće na savijanje ojačanje CFRP-om znatno nadmašuje GFRP ekvivalente. Dvostruke ugljikove šipke i široke CFRP ploče pokazale su najveća poboljšanja, dok su za spiralno omotane*

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CFRP tkanine utvrđene superiorne performanse u usporedbi s primjenom ravnih tkanina. Osim toga, u studiji se ističe znatan utjecaj sustava ojačanja na mehanički odziv drvenih greda i naglašava utjecaj inherentnih grešaka drva na eksperimentalne rezultate. Komplementarne numeričke simulacije provedene uz pomoć ANSYS softvera potvrdile su eksperimentalne rezultate, čime je ujedno potvrđena i učinkovitost predloženih sustava ojačanja za poboljšanje svojstava drvenih konstrukcija.

KLJUČNE RIJEČI: *polimer ojačan vlaknima (FRP); drvene grede; ojačanje; laminat; ANSYS*

1 INTRODUCTION
1. UVOD

Wood has long been used as a principal structural material due to its favorable mechanical properties and environmental sustainability. As a lightweight, renewable, and biodegradable resource, timber offers excellent thermal and acoustic insulation, making it suitable for energy-efficient and eco-friendly construction (Ramage *et al*., 2017). Moreover, its inherent flexibility and ductility provide notable advantages in seismic applications, as demonstrated in recent studies on displacement-based seismic design of timber structures (Loss *et al*., 2018). The development of engineered wood products, such as glued laminated timber (glulam) and laminated veneer lumber (LVL), has further improved the structural reliability and expanded the applicability of timber in both contemporary and traditional architecture (Abed *et al*., 2022; Wang *et al*., 2021).

Despite these benefits, timber's organic nature makes it vulnerable to environmental degradation caused by moisture, UV radiation, insect infestation, and fungal decay, all of which can compromise long-term structural performance (Jirouš Rajković and Miklečić, 2021; Bazli *et al*., 2022). Flexural members, especially timber beams, are particularly susceptible to fatigue and cracking under cyclic or dynamic loading conditions frequently encountered in seismic zones. To address these challenges, fiber-reinforced polymer (FRP) composites have emerged as a highly effective reinforcement strategy, enhancing the durability and load-bearing capacity of timber elements (Çankal *et al*., 2023).

Among modern strengthening techniques, the application of FRP composites, especially carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP), has gained considerable attention. These materials are characterized by high tensile strength, low density, corrosion resistance, and ease of application (Li *et al*., 2022). When externally bonded to timber beams, particularly in the form of CFRP sheets or plates, FRP reinforcements have been shown to significantly enhance flexural stiffness, ultimate load capacity, and post-elastic behavior without introducing a substantial increase in structural dead load (Zhao *et al*., 2024). Numerous experimental studies have confirmed the effectiveness of FRP reinforcement in timber structures. Fiorelli and Dias (2003) reported notable improvements in bending strength and stiffness of glulam beams strengthened with CFRP plates, while Borri *et al*. (2011) observed enhanced ductility and delayed crack propagation in beams reinforced with GFRP. Similarly, D'Ambrisi *et al*. (2014) demonstrated improved structural performance in aged timber floor systems strengthened using externally bonded CFRP sheets.

Several previous studies have investigated the strengthening of timber and laminated wood elements using fiber-reinforced polymer (FRP) materials, primarily focusing on specific reinforcement concepts and limited cross-sectional configurations. Novosel *et al*. (2021) examined the structural performance of bidirectional oak-wood laminations reinforced with carbon-fiber (CFRP) implants, reporting significant improvements in stiffness and load-bearing capacity; however, their work was restricted to implant-based reinforcement within a predefined laminated cross-section. In a subsequent study, Novosel *et al*. (2023) extended this approach to standard and prestressed glass-fiber (GFRP) implants, confirming the efficiency of implant reinforcement while remaining confined to a single wood species and a specific internal reinforcement technique. In addition, Alsheghri and Akgül investigated the use of FRP plates as substitutes for steel sheets in timber structural joints, emphasizing joint performance, corrosion resistance, and material efficiency rather than the global flexural strengthening of timber beams. Their study addressed connection behavior rather than beam-level structural response and did not consider comparative strengthening layouts within the same timber member. In addition, Alsheghri and Akgül (2021) investigated the use of FRP plates as substitutes for steel sheets in timber structural joints, emphasizing joint performance, corrosion resistance, and material efficiency rather than the global flexural strengthening of timber beams. Their study addressed connection behavior rather than beam-level structural response and did not consider comparative strengthening layouts within the same timber member.

In contrast to these studies, the present research proposes a different and more comprehensive cross-sectional strengthening design for laminated timber beams, allowing direct comparison of multiple reinforcement strategies within a unified experimental and numerical framework. Specifically, the study investigates externally bonded FRP fabrics**,** near-surface mounted (NSM) FRP rods, and NSM FRP plates/strips, using both CFRP and GFRP materials. This comparative cross-sectional approach enables a systematic evaluation of the influence of reinforcement type, geometry, and placement on flexural behavior, stiffness enhancement, and failure mechanisms, thereby addressing key limitations identified in previous research.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

In this study, a total of 28 timber beam specimens were prepared, including 12 beams reinforced with carbon fiber-reinforced polymer (CFRP), 12 beams reinforced with glass fiber-reinforced polymer (GFRP), and 4 unreinforced control specimens. All beams were fabricated from spruce wood (*Picea* spp.) and machined to standardized dimensions of 90 mm × 150 mm × 2500 mm to ensure geometric consistency and structural relevance under flexural loading.

The control group consisted of two glued-laminated timber (Glulam) beams and two solid (non-laminated) spruce beams, allowing direct comparison between laminated and solid wood configurations without reinforcement. The FRP reinforcements were bonded using a high-performance epoxy resin, which served both as the adhesive agent and polymer matrix, ensuring effective stress transfer between the timber substrate and the composite reinforcement.

All specimens were tested under four-point bending in accordance with relevant international standards to evaluate flexural strength, stiffness, and failure behavior. This experimental program enabled a systematic assessment of the influence of wood configuration and reinforcement type on the flexural response of timber beams. In parallel, three-dimensional finite element analyses (FEA) were conducted using ANSYS software to numerically simulate the bending behavior and to support interpretation of the experimental results.

2.1 Materials
2.1. Materijali

2.1.1 Glued-laminated timber (Glulam)
2.1.1. Lamelirane drvene grede

Glued-laminated timber (Glulam) is a structural engineered wood product manufactured by bonding multiple timber lamellae with structural adhesives under controlled pressure, resulting in a composite member characterized by enhanced load-bearing capacity, dimensional stability, and reduced susceptibility to defects commonly associated with solid sawn timber (Wang *et al.*, 2021). In this study, Glulam elements were produced from *Picea orientalis* (spruce), a softwood species recognized for its straight grain, low density, and favorable adhesive bonding performance. Due to its homogeneous anatomical structure and widespread availability in Turkey as well as Central and Northern Europe, *Picea orientalis* is commonly used in the production of engineered wood products, including Glulam and cross-laminated timber (CLT) (Öztürk *et al.*, 2017). The physical and mechanical properties of the timber were determined through standardized laboratory tests and are summarized in Table 1.

2.1.2 Fiber-reinforced polymers (FRP)
2.1.2. Polimeri ojačani vlaknima

In this study, two types of fiber-reinforced polymers (FRP) were used to strengthen timber beams: carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP). These materials are

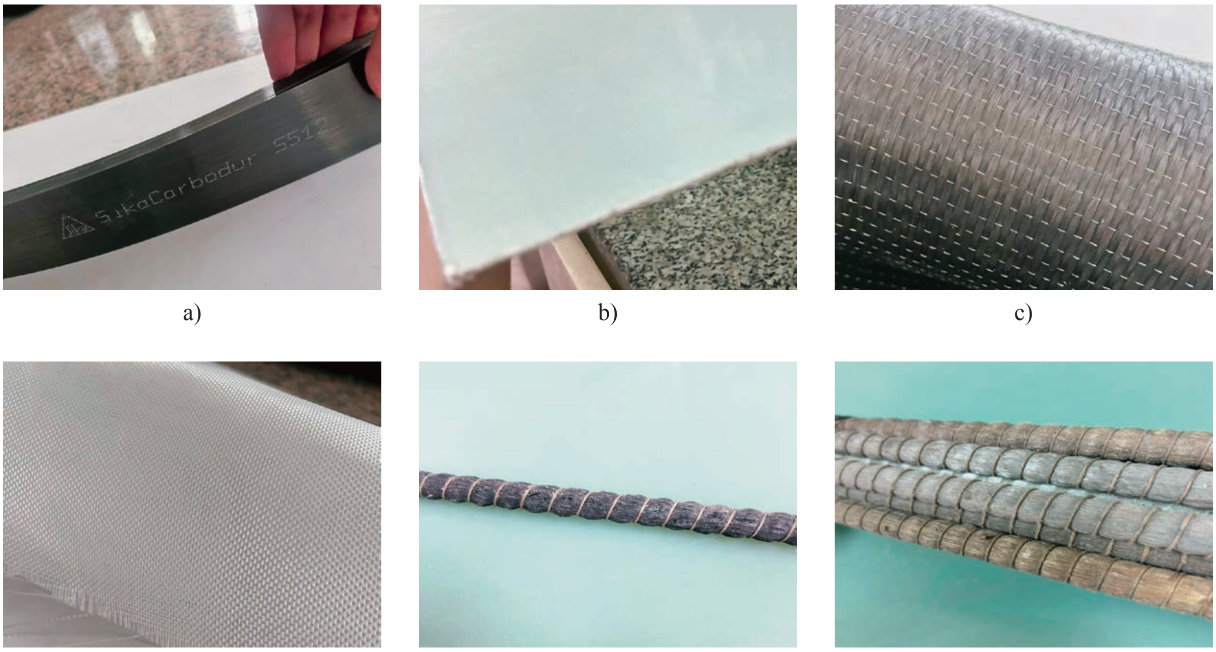
Table 1 Mechanical and physical properties of wood
Tablica 1. Mehanička i fizička svojstva drva

Property *Svojstvo*	***Picea* wood** *Smrekovina*	**Range in literature** *Raspon u literaturi*	**Standard/Reference** *Standard/Referenca*
Physical properties / *Fizička svojstva*			
Moisture content, % *sadržaj vode,* %	12.7	10-15	TS EN 13183-1:2012
Density, g/cm^3 *gustoća,* g/cm^3	0.42	0.38-0.45	TS ISO 13061-2
Specific gravity *specifična gustoća drva*	0.43	0.38-0.45	**TS ISO 13061-3:**2017
Mechanical properties / *Mehanička svojstva*			
Young's modulus MOE, MPa *Youngov modul elastičnosti,* MPa	10345.8	9000–12000	TS ISO 13061-4:2022
Compressive strength (fc,0), MPa *čvrstoća na tlak (fc,0),* MPa	29.152	C27=28	TS ISO 13061-17 EN 338
Compressive strength (fc,90), MPa *čvrstoća na tlak (fc,90),* MPa	2.948	2-5	TS ISO 13061-5
Tensile strength, MPa *čvrstoća na vlak,* MPa	60.217	40-90	TS ISO 13061-6 ASTM D143-14

renowned for their high tensile strength, lightweight nature, and resistance to environmental degradation, making them particularly suitable for structural reinforcement applications (Saad and Lengyel, 2022).

The reinforcement was applied in different forms, including rods, panels, and fabrics, to investigate how each configuration influences the performance of the strengthened timber beams. The main objective of this research was to evaluate and compare the flexural behavior of timber beams reinforced with various FRP forms through four-point bending tests.

The mechanical and physical properties of the CFRP and GFRP materials used in this research, such as Young's modulus, Poisson's ratio, density, bulk modulus, and shear modulus, were obtained from manufacturer technical datasheets and verified through reliable online sources (Fibertech Composite, 2023; Sika Services AG, 2024; Matek Fiber, 2025a, 2025b; Fiber Market, 2024; Karbontech Tekstil, 2025). These parameters, summarized in Table 2, were used as essential input data for evaluating the contribution of each FRP type to the flexural response of the strengthened



a) b) c)

d) e) f)

Figure 1 Different types and configurations of FRP reinforcement materials used in the study: a) CFRP Strip; b) GFRP Panel; c) CFRP fabric; d) GFRP fabric; e) CFRP rod; f) GFRP rod
Slika 1. Različite vrste i sustavi polimera s vlaknima za ojačavanje drvenih greda ispitivanih u studiji: a) CFRP traka; b) GFRP ploča; c) CFRP tkanina; d) GFRP tkanina; e) CFRP šipka; f) GFRP šipka

Table 2 Mechanical and physical properties of FRP reinforcement materials
Tablica 2. Mehanička i fizička svojstva materijala za ojačavanje drvenih greda

Parameter *Parametar*	**Strip/ Panel** *Traka / Ploča*		**Rod** / *Šipka*		**Fabric** / *Tkanina*	
	Glass panel *Staklena ploča*	Carbon strip *Karbonska traka*	Glass rod *Staklena šipka*	Carbon rod *Karbonska šipka*	Glass fabric *Staklena tkanina*	Carbon fabric *Karbonska tkanina*
Poisson`s ratio *Poissonov omjer*	0.23	0.30	0.20	0.25	0.22	0.25
Young`s modulus, MPa *Youngov modul,* MPa	70000	165000	90000	200000	70000	230000
Density, g/cm^3 *gustoća,* g/cm^3	2.5	1.6	2.2	1.5	2.5	1.8
Bulk modulus, MPa *modul stlačivosti,* MPa	35000	137500	40000	15000	30000	50000
Shear modulus, MPa *modul smičnosti,* MPa	25000	63400	25000	15000	30000	30000
Thickness, mm *debljina,* mm	1.5	1.2	D=10	D=10	1	1

timber beams. Figure 1 illustrates the different FRP reinforcement forms employed in this study, including (a) CFRP strip, (b) GFRP panel, (c) CFRP fabric, (d) GFRP fabric, (e) CFRP rod, and (f) GFRP rod.

2.1.3 Adhesive
2.1.3. Ljepilo

An epoxy resin was used as the bonding agent between the fiber-reinforced polymer (FRP) sheets and the glued-laminated timber (Glulam) surfaces. Vaněrek *et al*. (2017) reported that epoxy adhesives exhibit high adhesion capacity, mechanical strength, and resistance to moisture and chemical exposure, making them suitable for durable FRP–wood bonding. The two-component system, consisting of resin (A) and hardener (B), was applied uniformly to ensure full surface contact and minimize the risk of debonding. The technical properties of the epoxy adhesive used in this study are provided in Table 3, and its components are shown in Figure 2.

Table 3 Technical data of epoxy resin
Tablica 3. Tehnički parametri epoksidnog ljepila

Parameter / *Parametar*	**Value** / *Vrijednost*
Elastic modulus, MPa *modul elastičnosti,* MPa	3800
Density, g/cm^3 *gustoća,* g/cm^3	1.31
Compressive strength, MPa *čvrstoća na tlak,* MPa	80

Figure 2 Scalica epoxy adhesive system resin (A) and hardener (B)
Slika 2. Epoksidni sustav ljepila Scalica (A) i očvršćivač (B)

2.2 Specimen preparation
2.2. Priprema uzoraka

The preparation and strengthening of the laminated timber specimens followed a structured methodology, as outlined schematically in Figure 3. The process began with the selection of timber based on its strength grade and moisture condition to ensure material uniformity and compliance with required standards. The selected wood boards were then bonded using epoxy adhesive, producing laminated timber elements with consistent structural characteristics.

Subsequently, fiber-reinforced polymer (FRP) systems were prepared using either carbon or glass fibers embedded in a polymer matrix. These composites were manufactured using appropriate fabrication methods and designed to function compatibly with the laminated timber substrate. Epoxy resins served both as the adhesive medium and, where applicable, as part of the composite matrix, enabling efficient stress transfer between the fibers and the wood. Two reinforcement approaches were applied: external surface reinforcement and near-surface internal reinforcement.

In the external method, FRP materials were bonded directly onto the surface of the laminated wood elements, while the near-surface method involved positioning the FRP materials within shallow grooves close to the wood surface before applying epoxy. Each method resulted in reinforced laminated wood elements with distinct reinforcement mechanisms. Finally, the strengthened specimens were subjected to bending tests to evaluate the structural response. The examination focused on load-bearing capacity, stiff-

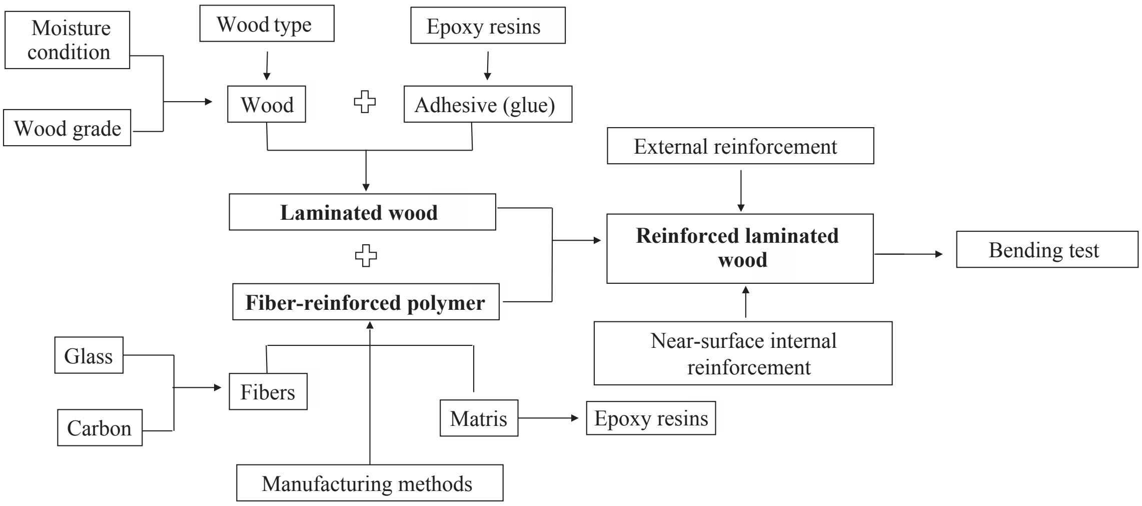


Figure 3 Thesis study flowchart
Slika 3. Dijagram toka istraživanja

ness, and overall performance under flexural loading. This integrated methodology enabled a systematic assessment of how timber type, adhesive selection, fiber material, and reinforcement approach influence the mechanical behavior of reinforced laminated wood.

2.2.1 Preparation of glulam
2.2.1. Priprema lameliranih drvenih greda

The glued-laminated timber (Glulam) elements used in this study were manufactured from spruce wood (*Picea* spp.), selected for its uniform mechanical properties and widespread use in structural applications. All timber materials were sourced from a certified supplier to ensure consistency, quality, and compliance with relevant standards.

The Glulam panels were fabricated by bonding five individual spruce laminae, each 30 mm thick, using an epoxy-based adhesive. After lamination, the panels were cut into standardized beam specimens with final dimensions of 90 mm × 150 mm × 2500 mm using a precision cutting system.

Prior to testing, the specimens were conditioned to achieve a target moisture content of approximately 12 %. The moisture content of each specimen was measured using a handheld moisture meter to ensure consistency across all samples. All conditioning and testing procedures were carried out under controlled laboratory conditions, with ambient temperature maintained between 20-23 °C and relative humidity between 50-60 %.

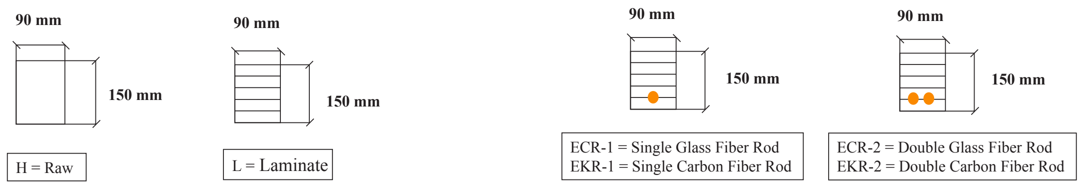
2.2.2 Application of FRP reinforcement
2.2.2. Primjena FRP ojačanja

The reinforcement process employed two primary configurations: external surface reinforcement and internal reinforcement. Tables 1, 2 and 3 outline the mechanical and physical properties of the materials used in this study, including different forms of glass and carbon fiber composites (plates, rods, and fabrics), as well as wood and epoxy-based adhesives. The fabrication procedures for the reinforced timber columns are illustrated in Figure 4. The detailed steps involved in the implementation of each reinforcement configuration are described below.

For external reinforcement, the surfaces of the Glulam beam specimens were carefully sanded and thoroughly cleaned to remove dust, grease, and other contaminants that could adversely affect the adhesive bond. A two-component epoxy adhesive was prepared in accordance with the manufacturer’s instructions and applied uniformly to the prepared surfaces. Subsequently, Fiber-Reinforced Polymer (FRP) fabrics, either Carbon (CFRP) or Glass (GFRP), were bonded to the beam surfaces. Two different fabric configurations were adopted. In Configuration 1, the fabric was applied in a helical pattern at an angle of 45° relative to the longitudinal axis of the beam, orienting the fibers diagonally to improve crack control and enhance flexural performance. In Configuration 2, the fabric was applied with fibers aligned parallel and perpendicular to the beam’s longitudinal axis (0°/90°), aiming to increase flexural stiffness and load-carrying capacity under bending. The original 1 m wide fabric rolls were cut to an appropriate width to ensure full coverage of the beam surfaces. In both configurations, the fabrics were applied in two layers with a lap length of 120 mm to ensure adequate bonding and to prevent premature debonding or delamination. The same two-component epoxy adhesive was used both for laminating the timber layers forming the Glulam beams and for bonding the external FRP reinforcement. The laminated beams were initially cured for one week, followed by an additional one-week curing period after the application of FRP fabrics. Consequently, the total curing duration for the externally reinforced beam specimens was two weeks before conducting the flexural tests. A cross-sectional view of the externally reinforced beam specimens is presented in Figure 4a.

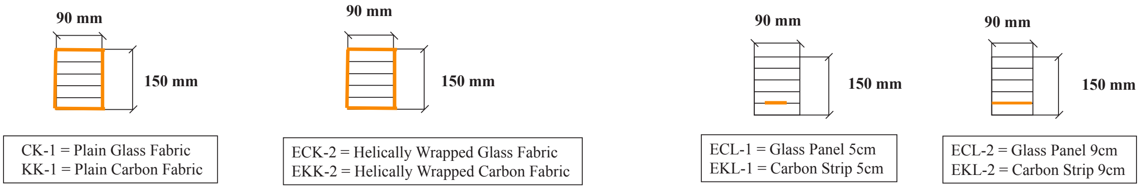
The internal reinforcement of the Glulam beams was implemented using the near-surface mounted (NSM) technique by embedding FRP materials between the fourth and fifth laminae. Two different NSM reinforcement configurations were adopted. FRP Rods: Precision-cut grooves with dimensions of 12 mm × 12 mm were formed along the tensile zone of the beams. In the first configuration, a single FRP rod (carbon or glass) was installed, while in the second configuration, two parallel FRP rods were embedded to enhance flexural stiffness and bending capacity. The rods were bonded using a two-component epoxy adhesive, and the specimens were cured under the same conditions as those applied to the externally reinforced beams. A schematic cross-sectional view of the rod-reinforced specimens is shown in Figure 4b. FRP Strips/Panels: Continuous FRP strips or panels (carbon or glass) were embedded between the fourth and fifth laminae along the beam length. Two different strip/panel widths were considered: 5 cm for the first configuration and 9 cm for the second configuration. The strips/panels were bonded using epoxy adhesive to provide continuous internal reinforcement and to improve the flexural performance of the beams. A cross-sectional representation of both strip/panel configurations is presented in Figure 4c.

The preparation and strengthening stages of the laminated timber beams are illustrated in Figure 5. First, the wooden specimens were selected, cut, and surface-polished to ensure dimensional accuracy and improve bonding quality. Fiber reinforcements were then applied using rods, sheets, and fabrics bonded with epoxy adhesive. Finally, the beams were compressed during the curing stage to ensure full adhesion between the wood and fiber components before testing.



a) Surface reinforcement
a) Površinsko ojačanje

b) Internal reinforcement near the surface by rod
b) Unutarnje ojačanje šipkom blizu površine



c) Internal reinforcement near the surface by panel/strip
c) Unutarnje ojačanje pločom/trakom blizu površine

d) Raw material sample and wood laminate
d) Lamelirano drvo bez ojačanja

Figure 4 Design sample shapes for wood laminates
Slika 4. Načini ojačanja lameliranog drva

a) Wooden specimens used
a) Uzorci drva

b) Softening and polishing wood
b) Priprema površine drva

c) Bonding process of wood and fiber rods
c) Lijepljenje drva i šipki od vlakana

d) Bonding process of wood and fiber sheets
d) Lijepljenje drva i ploča od vlakana

e) Bonding process of wood and fiber fabrics
e) Lijepljenje drva i tkanine

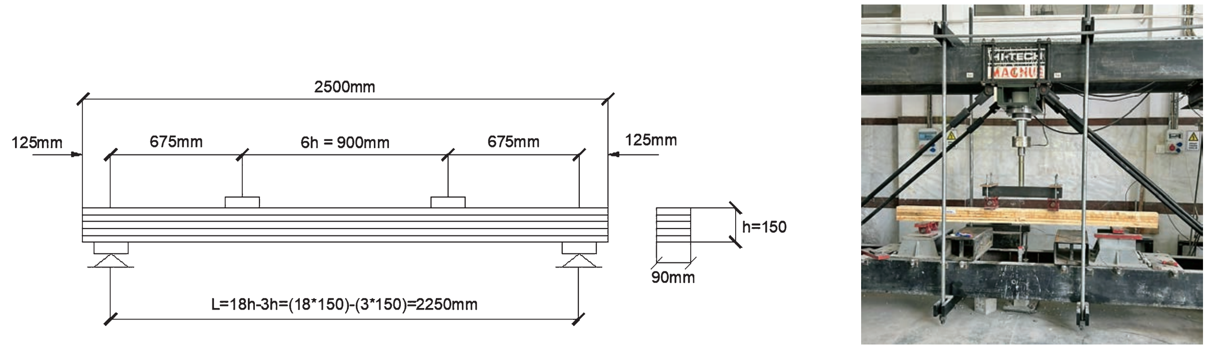
f) Application of compression on the specimens
f) Prešanje uzoraka

Figure 5 Preparation and manufacturing of beams
Slika 5. Proces pripreme i izrade greda

3 LABORATORY AND FINITE ELEMENT ANALYSIS

3. LABORATORIJSKA ANALIZA I ANALIZA KONAČNIH ELEMENATA

The application of fiber-reinforced polymers (FRPs) for strengthening wooden beams has attracted considerable research interest in recent years, owing to their high strength-to-weight ratio, resistance to corrosion, and ease of installation. Among the various FRP types, glass fiber-reinforced polymers (GFRP) and carbon fiber-reinforced polymers (CFRP) have demonstrated significant potential in enhancing the flexural performance of timber beams. GFRP is recognized for its cost efficiency, whereas CFRP offers superior mechanical properties, including higher stiffness and tensile strength, making it more suitable for demanding structural applications. This study focuses on evaluating the flexural behavior of wooden beams strengthened with GFRP and



a) Test sample dimensions
a) Dimenzije uzoraka

b) Bending test
b) Ispitivanje savijanja

Figure 6 Dimensions of bending test specimen
Slika 6. Dimenzije uzoraka za ispitivanje savijanja

CFRP, utilizing both experimental bending tests and numerical modeling through finite element analysis (FEA) performed using ANSYS software.

3.1 Laboratory experiments
3.1. Laboratorijska ispitivanja

The four-point bending test is a method used to evaluate the flexural strength and behavior of laminated materials. The test specimens had dimensions of 90 mm × 150 mm × 2500 mm (thickness × width × length) (see Figure 6). This study investigates how the mechanical properties of laminated wood panels change when reinforced with different types of fibers, specifically glass fiber and carbon fiber. A total of 28 laminated wood specimens were tested: 12 reinforced with glass fiber, 12 with carbon fiber, and 4 unreinforced specimens serving as control samples. The testing procedure was conducted in accordance with the Turkish standard TS EN 408 + A1, which specifies the methods for determining the mechanical properties of timber structures.

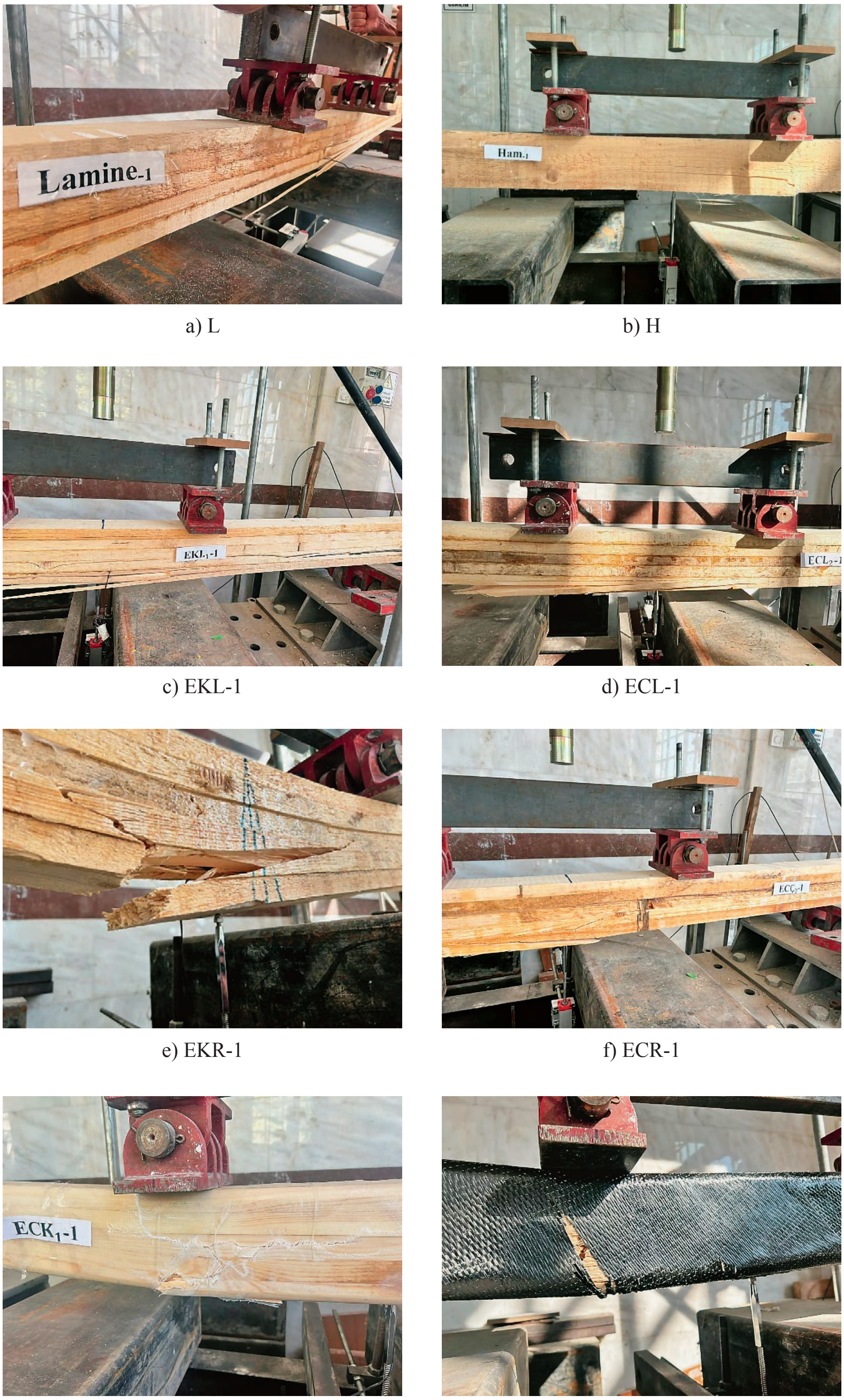
3.1.1 Experimental result – Failure modes of wooden beams under bending loads
3.1.1. Rezultati laboratorijskog ispitivanja – načini loma drvenih greda pri savijanju

In structural systems, wooden beams exhibit various failure behaviors under bending loads, including cracking, fiber separation, and ultimate rupture behaviors influenced by factors such as fiber orientation, geometric characteristics, and internal defects (Brougui and Szabó, 2022). To enhance the mechanical performance of timber, fiber-reinforced polymer (FRP) composites specifically carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) have been increasingly applied as strengthening methods. These materials are prized for their high tensile strength, low weight, and environmental durability, and they have been shown to effectively improve flexural capacity, stiffness, and ductility in timber beams (Saad and Lengyel, 2022). In this study, the failure behaviors of wooden beams under bending loads were investigated, and the effects of FRP reinforcement were evaluated based on the experimental findings. The bending tests revealed distinct failure patterns between unreinforced and FRP-strengthened wooden beams. Unreinforced specimens generally exhibited brittle behavior, characterized by tensile cracking in the bottom fibers and, in some cases, longitudinal splitting or local failures near knots. In laminated and solid wood samples, cracks developed in the lower layers due to tensile stress, and in some cases, severe crushing occurred in the top compression zones. In contrast, beams strengthened with CFRP or GFRP showed improved performance and modified failure mechanisms. Specimens reinforced with CFRP or GFRP rods primarily failed due to localized delamination or partial rupture in the tension zone, along with visible cracking in the lower layers. Beams with FRP plates (either 5 cm or 9 cm wide) demonstrated crack development across multiple layers, with some showing signs of shear-induced or tension-induced collapse in the lower regions. The most ductile behavior was observed in specimens wrapped with carbon or glass fabrics, either in spiral or straight configurations. These beams typically failed by rupture in the bottom layer and tearing in the external FRP fabric, indicating effective redistribution of stress and delayed failure. Overall, FRP strengthening significantly altered the failure modes from brittle to more ductile and enhanced the flexural capacity of the wooden beams. Figure 7 illustrates various failure modes observed in the tested specimens.

3.1.2 Experimental result – Analysis of flexural behavior in wooden beam specimens under loading perpendicular to fibers
3.1.2. Rezultati laboratorijskog ispitivanja – analiza savijanja uzoraka drvenih greda pod opterećenjem okomito na vlakanca

To analyze the structural behavior of the samples, force-displacement relationships were plotted under loading conditions, as illustrated in the following figures.

Figure 8 illustrates the force–displacement behavior of the tested Glulam beam specimens, revealing


a) L

b) H

c) EKL-1

d) ECL-1

e) EKR-1

f) ECR-1

g) ECK-1

h) EKK-2

Figure 7 Failed conditions of test specimens
Slika 7. Pregled lomova ispitnih uzoraka

clear performance differences among reinforcement types and configurations. Beams reinforced with carbon rods (ECR-1 and ECR-2) exhibit higher stiffness and peak load capacity compared to those reinforced with glass rods (EKR-1 and EKR-2), reflecting the superior mechanical properties of carbon fibers. Furthermore, specimens strengthened with double rods demonstrate a more pronounced increase in load-bearing capacity than single-rod configurations, confirming the positive contribution of increased reinforcement area. All strengthened beams outperform the unreinforced specimens (H and L), indicating a substantial enhance-

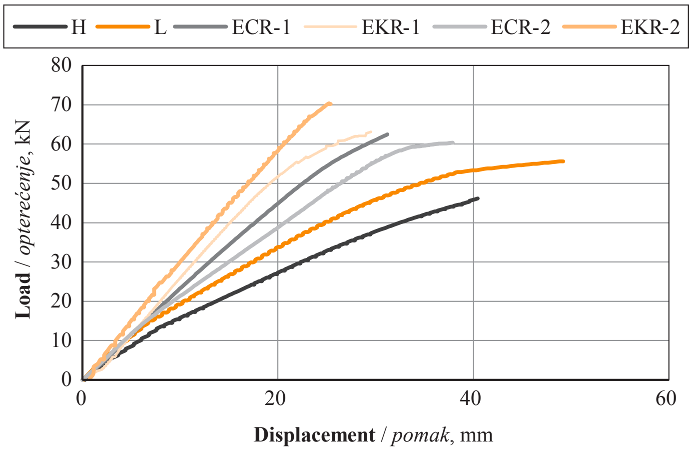


Figure 8 Load versus displacement curves for tested specimens (carbon and glass rod reinforcement)
Slika 8. Krivulje opterećenja u odnosu prema pomaku za ispitane uzorke (ojačane ugljikovim i staklenim šipkama)

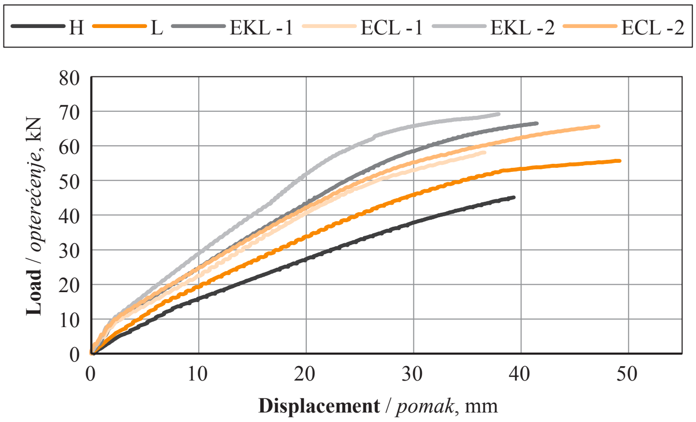


Figure 9 Load versus deflection curves for tested specimens (carbon and glass strip/panel reinforcement)
Slika 9. Krivulje opterećenja u odnosu prema pomaku za ispitane uzorke (ojačane ugljikovim i staklenim trakama/pločama)

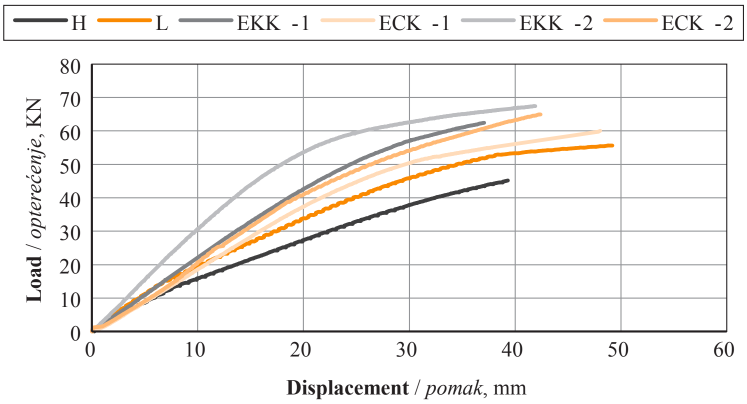


Figure 10 Load versus deflection curves for tested specimens (carbon and glass fiber fabric reinforcement)
Slika 10. Krivulje opterećenja s obzirom na pomak za ispitane uzorke (ojačane ugljikovim i staklenim tkaninama)

ment in flexural resistance and deformation performance due to FRP reinforcement.

Figure 9 presents the load–deflection behavior of Glulam beam specimens reinforced with carbon and glass strips/panels. The curves indicate that carbon-reinforced specimens (ECL) achieved greater stiffness and higher ultimate load capacity than glass-reinforced specimens (EKL), confirming the superior mechanical efficiency of carbon composites under flexural loading.

In addition, partial reinforcement using 5 cm strip width demonstrated a more effective structural response compared to specimens fully reinforced with 9 cm strips. This trend suggests that optimal reinforcement width can enhance flexural behavior while reducing material use, reflecting a more efficient stress distribution mechanism.

Figure 10 illustrates the load deflection response of the fabric-reinforced specimens, highlighting the in-

Table 4 Test results of loading
Tablica 4. Rezultati ispitivanja opterećenja

Sample name *Uzorak*	**Symbols** *Oznaka*	***MOE*, MPa**	***MOR*, MPa**
Raw wood / *masivno drvo*	H	10537.57	68.37
Laminated wood / *lamelirano drvo*	L	13449.22	82.39
Single glass fiber rod / *jednostruka šipka od staklenih vlakana*	ECR-1	15666.21	92.57
Single carbon fiber rod / *jednostruka šipka od karbonskih vlakana*	EKR-1	17840.11	96.67
Double glass fiber rod / *dvostruka šipka od staklenih vlakana*	ECR-2	17158.42	91.63
Double carbon fiber rod / *dvostruka šipka od karbonskih vlakana*	EKR-2	19612.65	103.98
Glass sheet 5 cm / *staklena ploča debljine 5* cm	ECL-1	16869.06	89.48
Glass sheet 9 cm / *staklena ploča debljine 9* cm	ECL-2	17514.72	97.13
Carbon sheet 5 cm / *karbonska ploča debljine 5* cm	EKL-1	18078.72	98.52
Carbon sheet 9 cm / *karbonska ploča debljine 9* cm	EKL-2	19857.21	103.70
Helically wrapped glass fabric *spiralno omotana tkanina od staklenih vlakana*	ECK-2	15613.52	95.81
Plain glass fabric / *obična tkanina od staklenih vlakana*	ECK-1	13958.21	88.55
Plain carbon fabric / *obična tkanina od karbonskih vlakana*	EKK-1	14598.10	89.89
Helically wrapped carbon fabric *spiralno omotana tkanina od karbonskih vlakana*	EKK-2	16814.90	99.85

fluence of reinforcement configuration and material type. Beams strengthened with two-layer spiral fabrics (ECK-2 and EKK-2) exhibited higher stiffness and greater ultimate load capacity compared to straight-form fabric reinforcement (ECK-1 and EKK-1), demonstrating the efficiency of spiral wrapping in improving composite action and delaying crack propagation. Additionally, carbon fabric reinforcement resulted in superior flexural performance relative to glass fabric reinforcement, as reflected by higher peak loads and improved deformation capacity. All reinforced specimens showed marked enhancement over the unreinforced reference beams (H and L), confirming the effectiveness of fiber fabric strengthening in increasing flexural resistance.

3.1.3 Experimental result – Bending test
3.1.3. Rezultati laboratorijskog ispitivanja – ispitivanje savijanja

According to the bending test results summarized in Table 4, all FRP-reinforced specimens exhibit higher modulus of elasticity (*MOE*) and modulus of rupture (*MOR*) than the raw wood (H) and laminated wood (L) references, which recorded the lowest values. Among the rod-reinforced beams, the double carbon fiber rod specimen (EKR-2) achieved the highest *MOR* (103.98 MPa) and a markedly increased *MOE*, outperforming both single carbon rod (EKR-1) and glass rod configurations (ECR-1, ECR-2).

For strip/panel reinforcement, the 9 cm carbon sheet (EKL-2) provided the highest *MOE* (19857.21 MPa) and a *MOR* comparable to EKR-2, indicating the strong efficiency of carbon plates, particularly at greater widths. Carbon sheets (EKL-1, EKL-2) also exceeded their glass counterparts (ECL-1, ECL-2) in both *MOE* and *MOR*. In the fabric group, helically wrapped carbon fabric (EKK-2) showed superior performance relative to glass fabrics (ECK-1, ECK-2), confirming the beneficial effect of both carbon material and spiral wrapping. Overall, the results demonstrate that carbon-fiber reinforcement, especially in double-rod and wide-plate configurations, provides the most effective enhancement of flexural stiffness and strength.

Figure 11 illustrates the comparative variation of the modulus of elasticity (*MOE*) and modulus of rupture (*MOR*) for unreinforced and FRP-reinforced timber beam specimens subjected to four-point bending. The unreinforced specimens (H and L) exhibit the lowest *MOE* and MOR values, confirming the limited stiffness and flexural capacity of untreated and non-reinforced timber. In contrast, all FRP-strengthened specimens demonstrate a clear improvement in both stiffness and strength, indicating the effectiveness of composite reinforcement in enhancing flexural performance. Among the reinforced groups, specimens strengthened with carbon-based reinforcements generally show higher *MOE* and *MOR* values than those reinforced with glass fibers, reflecting the higher elastic modulus and tensile strength of CFRP materials. In particular, double-reinforcement configurations and wider plate applications (e.g., EKR-2 and EKL-2) achieve the highest stiffness and load-carrying capacity, highlighting the positive influence of reinforcement amount and geometry. Fabric-based reinforcements also contribute to notable performance gains, although their effectiveness remains slightly lower than that of rod and plate systems.

Overall, the combined presentation of *MOE* and *MOR* in a single figure enables a clear comparison between stiffness enhancement and strength development across different reinforcement types and layouts, demonstrating that both reinforcement material and con-

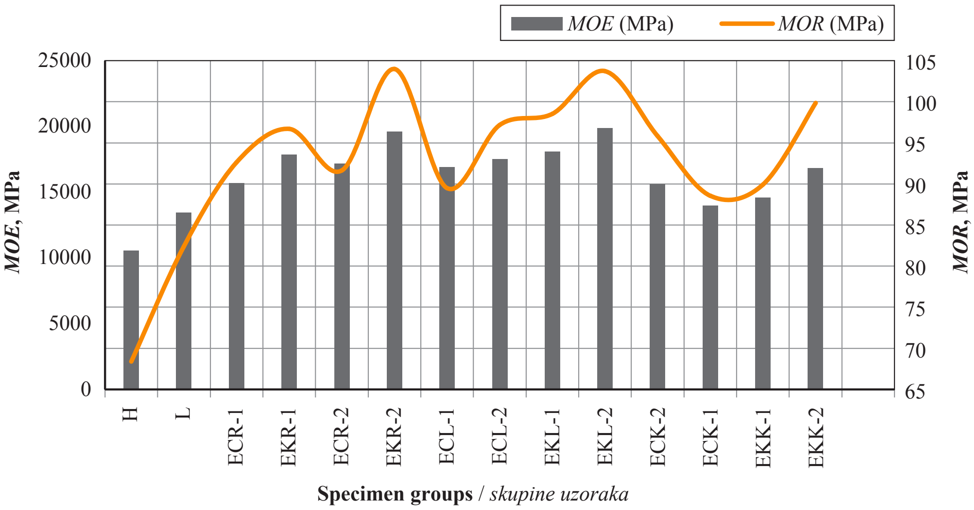


Figure 11 Flexural stiffness and strength (*MOE* and *MOR*) of timber beams with different FRP reinforcement configurations
Slika 11. Krutost i čvrstoća na savijanje (*MOE* i *MOR*) drvenih greda s različitim sustavima FRP ojačanja

figuration play a critical role in the flexural behavior of laminated timber beams.

3.1.4 Numerical analysis: results and discussion

3.1.4. Numerička analiza: rezultati i rasprava

The numerical investigation was carried out using the finite element method implemented in ANSYS in order to replicate the experimental testing conditions and evaluate the structural response of both unreinforced and FRP-reinforced laminated timber beams. Three-dimensional finite element models were developed to represent the exact geometry of the test specimens, ensuring consistency between the numerical simulations and laboratory experiments.

Timber was modeled as a three-dimensional orthotropic elastic plastic material to capture its anisotropic mechanical behavior in the longitudinal, radial, and tangential directions. The orthotropic elastic moduli, shear moduli, and Poisson's ratios were adopted

Table 5 Comparison of laboratory results and software predictions
Tablica 5. Usporedba laboratorijskih rezultata i softverskih predviđanja

Specimen / *Uzorak*	**Experimental** *Eksperimentalno*	**F.E.A**	**Error rate, %** *Pogreška,* %
	Equivalent stress (Lap), MPa *Ekvivalentno naprezanje (Lap),* MPa	Equivalent stress (Ansys), MPa *Ekvivalentno naprezanje (Ansys),* MPa	
Raw wood / *masivno drvo*	46.151	46.612	1 %
Laminated wood / *lamelirano drvo*	55.613	56.169	1 %
Single glass fiber rod *jednostruka šipka od staklenih vlakana*	62.486	65.610	5 %
Single carbon fiber rod *jednostruka šipka od karbonskih vlakana*	63.066	67.481	7 %
Double glass fiber rod *dvostruka šipka od staklenih vlakana*	60.342	62.756	4 %
Double carbon fiber rod *dvostruka šipka od karbonskih vlakana*	70.370	75.804	8 %
Glass sheet 5 cm / *staklena ploča debljine 5* cm	66.503	70.493	6 %
Glass sheet 9 cm / *staklena ploča debljine 9* cm	58.067	62.712	8 %
Carbon sheet 5 cm / *karbonska ploča 5* cm	69.190	75.417	9 %
Carbon sheet 9 cm / *karbonska ploča debljine 9* cm	65.655	69.266	6 %
Helically wrapped glass fabric *spiralno omotana tkanina od staklenih vlakana*	62.437	66.808	7 %
Plain glass fabric *obična tkanina od staklenih vlakana*	60.070	62.473	4 %
Plain carbon fabric *obična tkanina od karbonskih vlakana*	67.396	72.788	8 %
Helically wrapped carbon fabric *spiralno omotana tkanina od karbonskih vlakana*	64.941	70.136	8 %

from established literature for softwood species with comparable physical and mechanical characteristics. The CFRP and GFRP reinforcements were defined as linear orthotropic composite materials with high stiffness along the primary fiber direction. A perfect bond assumption was adopted at the timber FRP interface, implying full strain compatibility and neglecting interfacial slip or debonding.

Quadratic solid elements were employed in the three-dimensional analyses to enhance the accuracy of stress and strain predictions. Both material and geometric nonlinearities were included, and the solution was performed using an incremental–iterative procedure to ensure numerical convergence throughout the loading process. A mesh sensitivity analysis was conducted using element sizes of 5 mm, 10 mm, and 15 mm, and the 5 mm mesh was selected for all subsequent simulations due to its superior agreement with the experimental load–displacement response.

Boundary conditions and loading protocols were defined to replicate the experimental setup. Fixed supports were applied at the specimen base, while displacement-controlled loading was imposed at the loading point. Reaction forces obtained during incremental displacement steps were used to generate numerical load–displacement curves. This analysis methodology ensured reliable numerical predictions and allowed for a direct and consistent comparison with the experimental results.

Table 5 compares the experimental and finite element (FEA) equivalent stress values for all tested specimens. The results show a strong agreement between laboratory measurements and numerical predictions, with error rates ranging from 1 % to 9 %. The smallest deviations were observed for unreinforced and laminated wood specimens, while slightly higher discrepancies occurred in FRP-reinforced configurations, particularly for wider sheets and multi-layer reinforcements. These differences are mainly attributed to the inherent heterogeneity of wood and the idealized assumptions adopted in the numerical modeling, such as perfect bonding between timber and FRP. Overall, the results confirm the reliability and accuracy of the proposed finite element approach.

4 COMPARATIVE PERFORMANCE AND CONFIGURATION-BASED ASSESSMENT OF CFRP AND GFRP REINFORCEMENT SYSTEMS IN LAMINATED TIMBER BEAMS

4. USPOREDBA UČINKOVITOSTI I KONFIGURACIJSKA PROCJENA CFRP I GFRP SUSTAVA OJAČANJA LAMELIRANIH DRVENIH GREDA

The experimental results demonstrated that the application of fiber-reinforced polymer (FRP) materials substantially improved the flexural behavior of laminated timber beams compared to both raw wood and unreinforced laminated specimens. Among the investigated strengthening systems, carbon-based reinforcements consistently outperformed glass-based alternatives in terms of stiffness (*MOE*) and flexural strength (*MOR*).

Reinforcing Elements with CFRP: Carbon fiber reinforced polymer (CFRP) was confirmed as the most effective strengthening material in this study, attributable to its high tensile capacity, lightweight properties, and fatigue resistance. Three types of reinforcement rods, plates/strips, and fabrics were applied, each producing notable gains in mechanical response relative to unreinforced and GFRP-strengthened beams. The double-rod CFRP configuration (EKR-2) yielded the highest enhancement, achieving a modulus of elasticity (*MOE*) of 19,612.65 MPa and a modulus of rupture (*MOR*) of 103.98 MPa, indicating significant increases in both stiffness and load-bearing capacity. Closely following this performance was the 9 cm external CFRP plate (EKL-2), which recorded *MOE* and *MOR* values of 19,857.21 MPa and 103.70 MPa, respectively. This reflects the effectiveness of surface-bonded CFRP plates in distributing tensile stress and improving flexural resistance. Among fabric-based systems, the helically wrapped CFRP fabric (EKK-2) achieved the most favorable results (16,814.90 MPa *MOE*; 99.85 MPa *MOR*), outperforming flat fabric arrangements. The results suggest that wrapping geometry contributes to improved confinement and stress redistribution, reinforcing the suitability of CFRP for flexural strengthening of timber members.

Reinforcing Elements with GFRP: Glass fiber reinforced polymer (GFRP), widely recognized for its cost efficiency and adequate tensile strength, also contributed to measurable improvements in beam performance. Three GFRP systems rods, plates/strips, and fabrics were applied, each demonstrating structural enhancement relative to unreinforced samples, though generally falling below the effectiveness of CFRP. The double GFRP rod configuration (ECR-2) provided the most notable improvement within the GFRP group, reaching an *MOE* of 17,158.42 MPa and *MOR* of 91.63 MPa. These values represent a substantial improvement compared with the control specimens (*MOE* 10,537.57 MPa; *MOR* 68.37 MPa). Among plate-based systems, the 9 cm GFRP plate (ECL-2) achieved superior results (*MOE*: 17,514.42 MPa; *MOR*: 97.13 MPa) compared with the 5 cm plate, demonstrating the influence of increased bonding area on load transfer and stress distribution. For fabric configurations, the spiral-wrapped GFRP fabric (ECK-2) outperformed the flat arrangement (ECK-1), recording an *MOE* of 15,613.52 MPa and *MOR* of 95.81 MPa. This confirms the benefit of wrapping geometry in improving confinement and fiber-to-wood interaction. Although GFRP systems did not match the structural performance of CFRP, the observed improvement highlights GFRP as a viable option for applications requiring moderate-strength enhancement at reduced cost.

*Comparative Analysis of CFRP and GFRP***:** A comparative evaluation revealed clear differentiation in performance between the two FRP types. CFRP consistently generated higher MOE and MOR values due to its superior mechanical properties and more efficient stress transfer mechanisms. For instance, the double CFRP rod system (EKR-2) recorded significantly higher values than the double GFRP rod configuration (ECR-2). However, certain GFRP configurations performed competitively in terms of *MOR*, particularly the 9 cm GFRP plate (ECL-2), which approached the *MOR* values of its CFRP equivalent (EKL-2). These findings indicate that geometric optimization can influence strengthening efficiency, especially regarding flexural capacity. Overall, the comparative results highlight that while CFRP offers maximum performance, GFRP serves as a cost-effective alternative for moderate-strengthening applications.

Reinforcement Configuration Impact: The reinforcement configuration significantly affected structural response across all FRP types. Rod systems, especially double rods, achieved the highest stiffness and strength improvements due to their ability to transfer tensile forces efficiently along the longitudinal axis. Plate systems produced more uniform tensile stress distribution and delayed crack formation, with wider plates demonstrating additional performance gains. Fabric-based systems enhanced ductility and energy absorption, particularly when applied using helical wrapping. Although fabric reinforcements yielded slightly lower stiffness values than rods and plates, the improved confinement effects contributed to favorable post-peak behavior. Collectively, the results emphasize the importance of selecting reinforcement type and geometry based on required stiffness, strength, material efficiency, and economic considerations, particularly in timber rehabilitation and strengthening applications.

5 CONCLUSIONS
5. ZAKLJUČAK

The results of this experimental study clearly demonstrate that the flexural behavior of laminated timber beams can be substantially enhanced through fiber-reinforced polymer (FRP) strengthening. Among the evaluated reinforcement systems, carbon-based materials consistently delivered the highest mechanical performance, achieving superior gains in both stiffness (*MOE*) and strength (*MOR*) compared to glass-based alternatives. Although GFRP offered measurable improvement over unreinforced specimens, its structural contribution remained moderate relative to CFRP. The findings further confirm that reinforcement configuration plays a decisive role in flexural response. Continuous or helical wrapping systems showed greater efficiency than partial, single-direction plate or fabric applications, owing to improved stress distribution and enhanced confinement effects. Similarly, increased reinforcement area, particularly in double-rod (EKR-2) and wide-plate (EKL-2) configurations, significantly elevated load-bearing capacity and deformation resistance. A distinguishing contribution of this study is its comparative assessment of three reinforcement forms (Rods, Strip/Plates, and Fabrics) applied to laminated spruce beams under identical test conditions, providing a comprehensive performance evaluation rather than focusing on a single system. The results indicate that the spiral CFRP fabric configuration (EKK-2) achieved the most ductile response and delayed failure initiation, highlighting the importance of reinforcement geometry in optimizing structural behavior. Minor variations among specimens were largely attributed to natural wood heterogeneity, including knots, grain deviation, and internal micro-defects. Such factors are intrinsic to timber and must be considered in full-scale structural design and material selection. Overall, the study confirms that CFRP reinforcement, particularly when applied in optimized configurations, offers a highly effective solution for increasing the flexural capacity, stiffness, and ductility of timber beams. These outcomes support the broader applicability of advanced FRP systems in timber construction, rehabilitation, and strengthening projects, especially when high performance and long-term durability are required.

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