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Research Article

Experimental and numerical investigation of flexural properties of larch beams reinforced with different layer numbers

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Abstract: Recent applications demonstrated how fiber-reinforced polymer (FRP) composites can improve the structural capabilities of glulam beams, particularly regarding their flexural and shear strength. With the development of precise numerical models, such systems can be optimized. There is currently a dearth of information in the literature on numerical models that can accurately anticipate the nonlinear behavior of low-grade glued laminated timber beams reinforced with FRP. In this study, larch beams were reinforced with carbon fiber reinforced polymer fabric 1, 2 and 3 layers. The effect of the number of floors on the flexural properties of the beams in reinforcement was investigated experimentally and numerically. As a result of the study, the best flexural properties were achieved with 3-layer reinforcement. It was observed that 1- and 2-layer reinforcement compared to the reference beam were also significantly effective. Numerical analyzes gave close values with experimental test results. As a result of comparing the results obtained from the numerical model with the experimental findings, it was concluded that the FRP fabric managed to significantly increase the performance of larch timber. The model is a useful tool for examining the effect of reinforcement coefficient and will be used for optimization of the larch beam.

Keywords: wood beam, flexural properties, larch, FRP, finite element analysis.

1. Introduction

Wood is a common structural material for bridges with short spans and light weight constructions (Johns and Lacroix, 2000; Radford et al., 2002; Buell TW, Saadatmanesh, 2005; Sutcu and Cambazoglu, 2023). Existing timber structures may deteriorate as a result of heightened service loads, aging, and biological attack (Kilincarslan and Simsek Turker, 2021; Sahin et al., 2011; Sahin et al., 2020; Kılıncarslan et al.; 2021). The biological deterioration of timber elements caused by the diffusion of enzymes, for example, is a phenomenon similar to corrosion-induced deterioration of steel or concrete elements, though it differs in mechanism. Repair or strengthening of the damaged timber elements may be advised (Schober and Rautenstrauch, 2005) rather than their pricey replacement. For timber structures, traditional strengthening/reinforcing techniques use steel plates or bars, aluminum plates, or merely timber patches (Mark, 1961; Kilincarslan and Simsek Turker, 2022; Sliker, 1962; Isleyen and Kesik, 2021; Hoyle, 1975). However, using such techniques might result in higher dead loads, transportation costs, and installation costs. Traditional repair techniques typically call for mechanical attachment (such as bolts and nails), which might not work on timber that has deteriorated. When thermal loads are applied, aluminum plates are prone to buckling and steel components are corrosive (Schober and Rautenstrauch, 2005; Mark, 1961; Mohmmed et al., 2020). When improved load-carrying capacity or stiffness are required, the use of fiber reinforced polymer (FRP) composites is a promising upgrade/strengthening method for timber systems. FRP composites are non-corrosive, offer excellent tailor ability, low long-term maintenance costs, and quick site installation (Sliker, 1962; Hoyle, 1975; Aydın et al., 2021; Kabaş et al., 2023; Monsuar et al., 2024; Cankal et al., 2023). They also have favorable strength and stiffness-to-weight ratios. Despite the fact that FRP composites are widely used to reinforce concrete structures (Bulleit and Sandberg, 1989; Simsek Turker and Kilincarslan, 2023; Postulak, 2023; Postulak, 2022) and have more recently been introduced as effective ways to retrofit steel structures (Gilfillan et al., 2003), relatively little information is available for timber applications, such as the interaction between FRP composites and damaged timber elements, the impact of different types of wooden species on the performance of FRP-strengthening systems, and the failure mode of strengthened members.

Micelli et al. (2005) looked into whether CFRP rods might be attached into glulam beams as reinforcement. According to test results, using CFRP rods increased the ultimate capacity and stiffness of glulam beams by 26 to 82% and 8 to 19%, respectively. To examine the bond performance, De Lorenzis et al. (2005) performed pull-out experiments on CFRP rods that had been joined using epoxy resin and glulam components. The length of the bonded joint, the rod's surface pattern, and the direction of the wood fibers with regard to the joint's longitudinal axis were the test variables used. They used the joint test results as the basis for a local bond-slip model. A total of 10 specimens from three distinct series of glulam beams reinforced with rectangular pultruded CFRP bars were tested by Johnsson et al. (2006) under four-point bending. In a number of ways, the experimental findings were contrasted with analytical models. The short-term flexural load-carrying capacity, according to the authors, has increased by an average of 49–63%. Kilincarslan and Simsek Turker (2023) strengthened 20x20x360 mm wooden samples of ash tree species with carbon, basalt and glass-based FRP materials. The bending properties of the unwrapped reference sample and the samples reinforced with carbon, basalt and glass-based FRP materials were examined. For this purpose, firstly, a three-point bending test was performed, and then the obtained results were compared 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. In this study, it was determined that the highest load carrying capacity value belonged to the sample reinforced with carbon-based FRP polymers. Kilincarslan et al., (2023) experimentally and numerically examined the flexural behavior of both solid and glued beams reinforced with “U” shaped carbon FRP composites in the lower layer. Reinforced glued beams were observed to exhibit superior load carrying capacity, displacement, modulus of rupture, and modulus of elasticity compared to their unreinforced solid beam counterparts. Although both types of beams were manufactured from the same materials, the laminated beams exhibited significantly improved flexural properties.

Additionally, adding reinforcement to glued beams showed a significant improvement in flexural performance. The consistency between the numerical simulations performed using the finite element analysis program and the experimental results was noted. This research suggests that wood materials can be accurately represented using numerical tools when reinforced with fiber-reinforced polymer fabrics. Pupsys et al. (2017) reinforced oak wood beams with glass fiber reinforced polymer sheets and found that the reinforcement increased the flexural properties of oak wood beams. Muratoglu (2016) reinforced Eastern beech and Scots pine timbers with carbon FRP and examined the flexural properties of the beams. It was found that the flexural strength of reinforced beams was 108.66% better. More recently, Gentry (2011) suggested a method to strengthen timber beams in shear by using FRP pins put transversely across the glulam's plies. According to test results, the dispersion in the pinned set of glulams is considerably less than it is in the non-pinned specimens. According to the probabilistic distributions derived from the test results, transversely reinforced glulams might be expected to have an acceptable shear stress increase of 50% or higher. In the studies carried out, it is seen that single-layer reinforcement is generally made. FRP polymers are costly products, so the number of layers is important in practice. In application with fiber reinforced polymers, it is necessary to examine the effect of the number of layers on the flexural properties of the beams. Research on the analysis of larch beam bending characteristics is scarce. There are no research on using FRP polymers to simulate and reinforce this kind, which is often utilized, particularly in the timber building business. In this study, it is aimed to investigate the flexural properties of Larch beams reinforced with carbon fiber reinforced polymers in 1 layer, 2 layers and 3 layers.

2. Materials and methods

2.1. Materials

Larch (*Larix decidua* Mill.) beams with a cross section of 80x80 mm and a length of 1400 mm were used. Larch beams were supplied from Nasreddin Forest Products (Naswood) in Antalya organized industrial zone. Care was taken to ensure that the fiber structure of all samples was smooth and that there were no cracks, knots or color defects (fungus, rot, etc.). Prior to the Larch beams being put through the flexural test, an air conditioning cabinet was held at 65% relative humidity until the equilibrium humidity reached 12% at 25°C. An electric humidity meter was used to check the samples' humidity levels after they were placed in the air-conditioning cabinet. Carbon fiber reinforced fabrics were used to strengthen the Larch beams. The carbon-based MasterBrace fabric are sourced from UNAL TEKNIK®. The technical specifications of the carbon fiber reinforced polymer fabric, the primer applied to the wooden surface, and the adhesive are given in Table 1 (BASF, 2022).

Table 1. Technical specifications of materials used for FRP application.

FRP technical properties	
FRP code	600/100 CFS
Weight	300 g/m^2
Material structure	Carbon
Modulus of elasticity (MPa)	230.000
Tensile strength (MPa)	4900
Design section thickness (mm)	0.337
Elongation at treak (%)	2.1
Width (mm)	500
Technical characteristics of the prime	
Mixture density	1.08±0.024 kg/liter
Solid's ratio	%100
Flexural strength (7 days) (TS EN 196)	>20 N/mm^2
Temperature of the floor to be applied	+5^{O}C-30^{O}C
Standby time	-1 ^{O}C 8 hour +32 ^{O}C 25 min
Application thickness	0.1-0.2 mm
Recoat time	Min. 20 hour
Full cure time (+20 ^{O}C)	7 days
Technical characteristics of the adhesive	
Color	Blue
Mixture density	1.02 kg/liter
Viscosity	1500-2500 MPa.s
Compressive strength (7 days)	>60 N/mm^2
Flexural strength (7 days)	>50 N/mm^2
Adhesion strength (7 days)	>3.0 N/mm^2
Recoat time	Min. 20 hours
Full cure time (+20 ^{O}C)	7 days

1, 2 and 3 layers of reinforcement of the larch beams were made with the materials whose technical specifications are given in Table 1. The properties of the tested beams are given in Table 2.

Table 2. Properties of beams (RLN: reinforcement layer number, RT: reinforcement type, RS: reinforcement status, M: moistures).

No	RLN	RT	RS	M (%)	Code
1	-	-	-	11.57	References
2	1	Carbon	+	11.45	L-1-CFRP
3	2	Carbon	+	11.48	L-2-CFRP
4	3	Carbon	+	11.50	L-3-CFRP

Flexural properties of the beams whose properties are given in Table 2 were determined and numerical analyzes were carried out.

2.2. Reinforcement of beams

The reference beam and the beams prepared by strengthening 1, 2, 3 layer number were studied. Reinforcement image of reference beams and beams is given schematically in Figure 1.

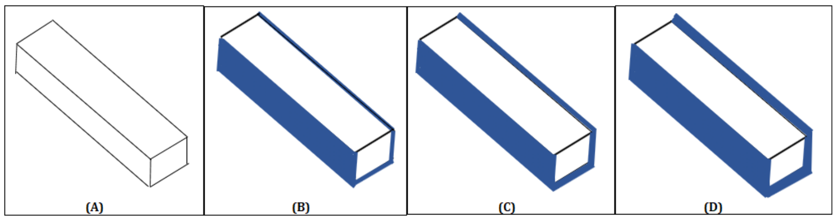

Figure 1. Schematic view of beams (A): Reference beam, (B): 1-layer reinforced beam, (C): 2-layer reinforced beam, and (D): 3-layer reinforced beam.

The surfaces of the timbers to which FRP will be applied are cleaned and then primed. Roll priming is performed to form a thin film layer (0.1-0.2 mm) with an epoxy-based primer developed for the Master Brace® FRP System. After the priming process, the wrapping process is carried out together with the adhesive. A roller is used to apply epoxy adhesive to the prepped surfaces, resulting in a 1 mm thickness. A fibers polymer fabric is placed on the surface by applying a layer of adhesive, stretching it in the direction of its fibers, and air gaps are removed by pressing in the direction of the fibers with a roller, to absorb the adhesive into the fabric (Figure 2).

Figure 2. The image of reinforcement methods with fiber reinforced fabric.

2.3. Experimental test

Beams were kept for at least 7 days and 3-point flexural tests were performed. Experiments were carried out in 3 replica-tions. The real image of the flexural test of the experimental setup are given in Figure 3.

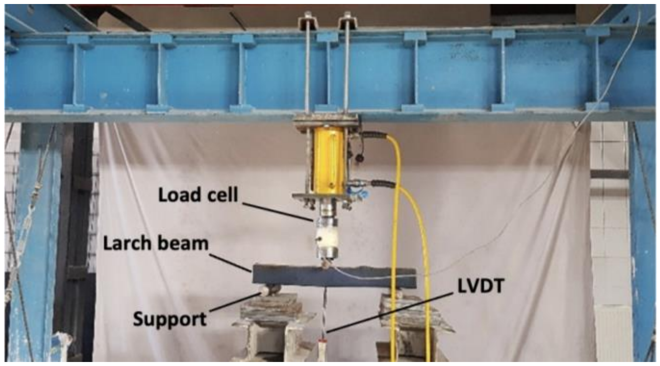

Figure 3. Real image of the bending test experimental setup.

The bending strength according to TS 2474 and the modulus of elasticity in flexural according to TS 2478 were placed in the universal testing machine and the forces obtained from the tests were calculated by substituting them in Equation 1 and Equation 2. Loading is carried out with a constant speed of 6 mm/min where the load cell capacity of the flexural tester is 50 kN, and its rupture is assured. In the experiments, the span of the support points is taken as 1400 mm. Flexural strength (**σ**e) for maximum load at break (F_{max}) and modulus of elasticity (E) (Kasal et al., 2010):

$$\sigma e = \frac{3F_{max}L_s}{2bh^2} \quad (1)$$

$$E = \frac{FLs^3}{4bh^3 f} \quad (2)$$

E : Modulus of elasticity (N/mm²),

F : Difference of applied forces (N),

Ls: Spacing between support points (mm),

b : Width of test sample (mm),

h : Height of test specimen (mm),

f : Displacement amount (mm).

The beams were subjected to flexural experimentally and then numerical analysis was carried out.

2.4. Numerical analysis

The wooden beams are modeled and numerically analyzed in the finite element analysis software ANSYS. Due to wood is an anisotropic material owing to the presence of knots and defects, it is generally modeled as orthotropic material in numerical analysis. The behaviors of wood behaviors are described using the engineering constants such as the modulus of elasticity (MOE) in the longitudinal, radial, and tangential directions (E_x; E_y; E_z), shear modulus (G_{xy}, G_{xz}, G_{yz}), and Poisson's ratio. The wood material properties adopted from literature reports (Cunha et al., 2021; Green et al., 2019) and the authors' research.

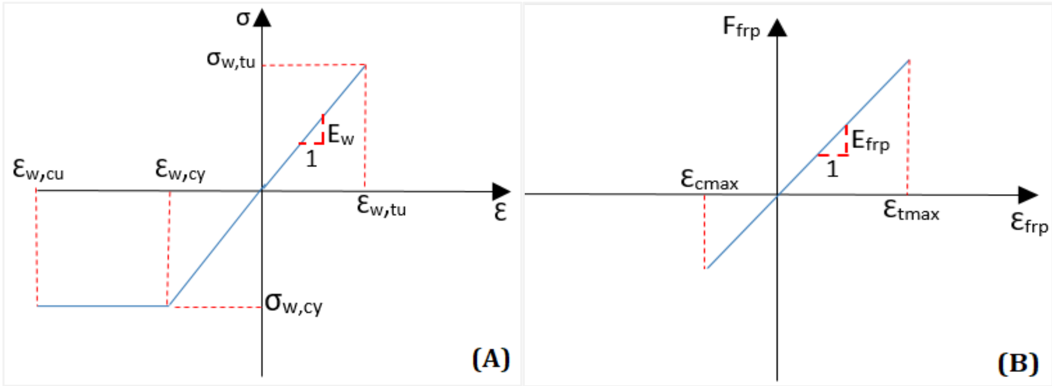

Figure 4. Constitutive law for (A) wood, and (B) fiber reinforced polymer.

The constitutive law for timber (Figure 4) can be expressed by Equations (3) – (5).

$$\sigma_{w,t} = E_w \,.\, \varepsilon_{w,t} \tag{3}$$

$$\sigma_{w,c} = E_w \,.\, \varepsilon_{w,c} \quad \text{if} \quad \varepsilon_{w,c} \leq \varepsilon_{w,cy} \tag{4}$$

$$\sigma_{w,c} = \sigma_{w}, c_y \quad \text{if} \quad \varepsilon_{w,c} > \varepsilon_{w,cy} \tag{5}$$

where $\sigma_{w,t}$, and $\sigma_{w,c}$ are the timber tensile and compressive stress; E_w is the timber modulus of elasticity; $\varepsilon_{w,t}$ and $\varepsilon_{w,c}$ are the tensile and compressive strain in timber; and $\varepsilon_{w,cy}$ is the strain value at yield stress $\sigma_{w,cy}$. The numerical simulation utilizes the ANSYS 2022 R2 Standard Solver in combination with the FEM. Models are created to represent both unenhanced and strengthened beam, guaranteeing that their shapes and applied loads correspond to those tested in experiments. The terminal constraints, which limit vertical displacement, are replicated using pinned and roller supports. A 25 mm square mesh is employed in the modeling phase. It is assumed that there exists an impeccable bond at the interface between timbers and FRP, and the appropriate boundary conditions are applied to the beam model to imitate the constraints of a simply-supported system. The images of the beams modeled in the ANSYS finite element software program in the study are given in Figure 5.

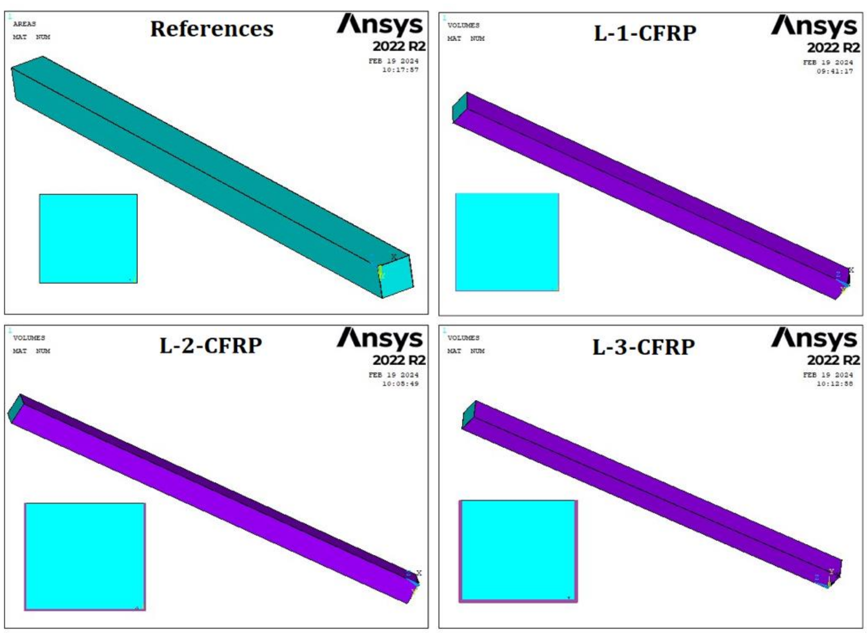

Figure 5. Modeling of beams in a finite element software program.

The timber section makes use of the SOLID45 element, which is tailored for three-dimensional modeling of solid structures and includes eight nodes, each endowed with three degrees of freedom (along the three axes). SOLID45 incorporates abilities like plasticity, stress-induced stiffening, accounting for substantial deflections and strains. Nevertheless, providing a precise portrayal of the complex anisotropic nature of timber is deemed impractical. Instead, the software requires the elastic characteristics of the timber to be entered in an orthogonal format for behavioral simulation.

The SOLID65 element, equipped with eight nodes and allowing three degrees of freedom at each node (in the x, y, and z directions), is utilized to replicate the behavior of fiber-reinforced polymers (FRP). This choice is based on its effectiveness in predicting tension cracking and compression crushing. It finds widespread application in simulating reinforced composites like FRP, concrete, and geological rocks. FRP material is thought to have linear elastic characteristics with brittle failure because to the little plastic deformation it experiences. The FRP materials are simplified by modeling them to have uniaxial linear isotropic behavior. With these considerations and assumptions, the SOLID65 element can accurately replicate their behavior. Additionally, based on the excellent bonding shown during testing, the connections between epoxy and FRP and epoxy and timber are expected to be perfect. All elements were modeled as solid FEM featuring eight nodes and reduced integration. A finer mesh is applied to the laminations near the FRP reinforcement, where stress is transmitted from the FRP plate to the glulam. To represent the bonding between the interfaces of wood, epoxy, and FRP, a “tie constraint” was implemented.

3. Experimental results and analysis

3.1. Failure modes

The failed modes given in the study are the images taken after the maximum load carrying capacity in the flexural test application. Failure modes were examined through these images. The failure modes of reinforced and unreinforced larch beams are given in Figure 6.

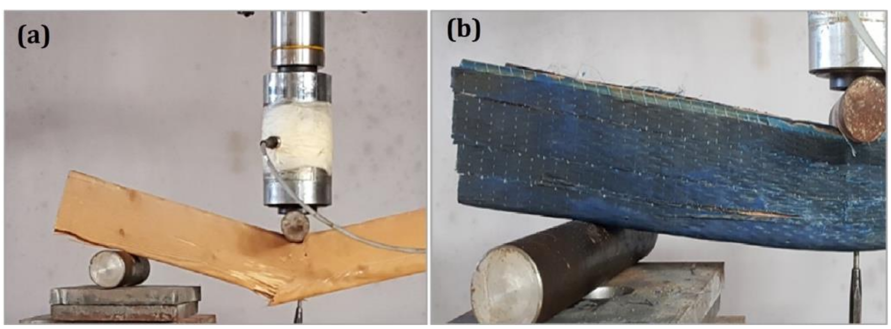

Figure 6. Failure modes (a) unreinforced beam, and (b) reinforced beam.

The failure mode of unreinforced beams was tensile fracture of timber fibers and propagation fracture along timber grains. Sudden, noisy failure occurred at low displacement and load capacities relative to unreinforced beams (Figure 6 (a)). In the reinforced beams, first the beams started to break in the fiber direction, then separations were observed in the FRPs. Even at higher loads and displacements compared to unreinforced beams, small separations were observed (Figure 6 (b)). As can be seen in the figure, the unreinforced beam has completely broken after the maximum load carrying capacity, while the reinforced beam has not yet broken with only slight cracks.

3.2. Experimental and numerical results

Larch beams were reinforced with 1 layer (L-1-CFRP), 2 layers (L-2-CFRP) and 3 layers (L-3-CFRP) of FRP fabric. As a result of the strengthening, the bending properties of the beams were investigated experimentally and numerically.

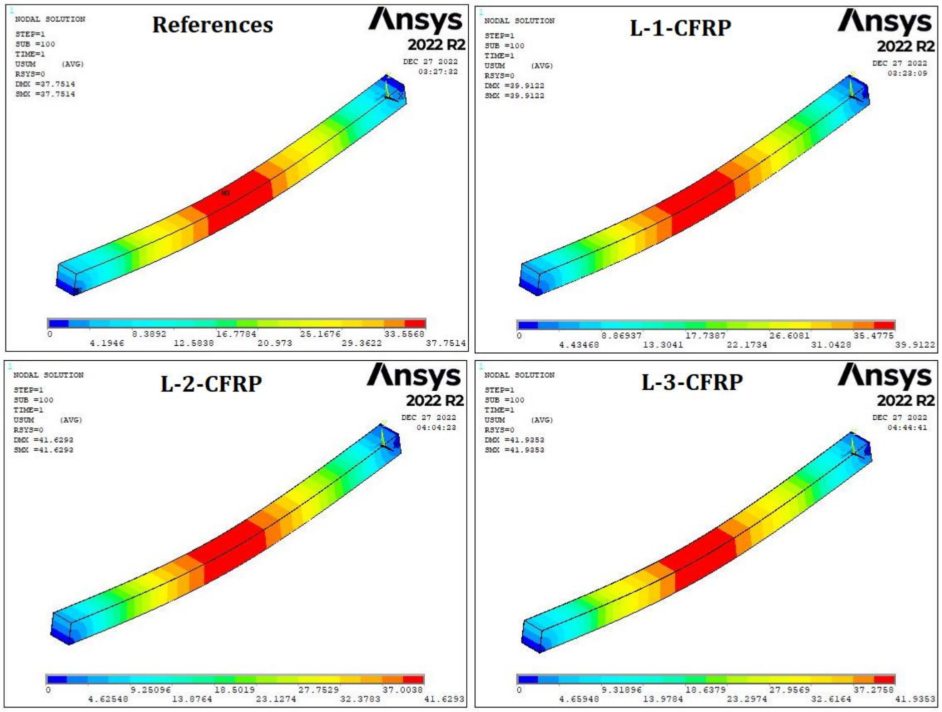

Figure 7. ANSYS software program analysis images.

The highest load carrying capacity (Experimental: 34.79 kN, Numerical: 42.42 kN) and displacement were obtained in the three-layer reinforcement. Compared to the reference beam, the load carrying capacity of the L-3-CFRP coded beam increased by approximately 33.78%, the L-2-CFRP code beam increased by 31.54%, and the L-1-CFRP coded beam increased by 23.55%. Bending strength and modulus of elasticity values of Larch beams are given in Figure 8.

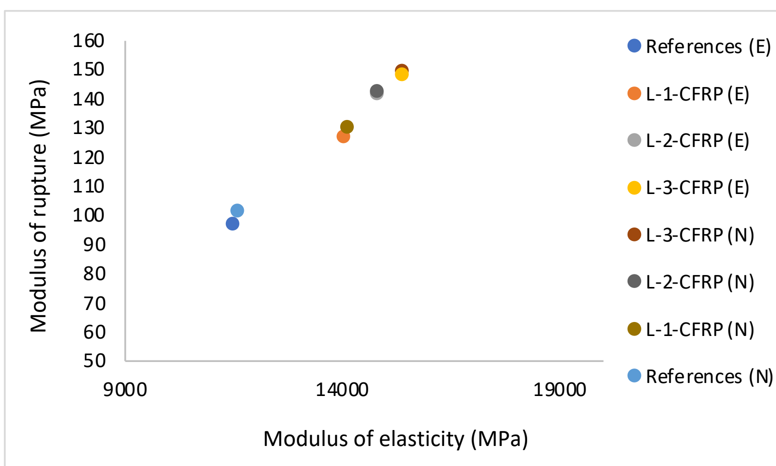

Figure 8. Modulus of rupture and modulus of elasticity values.

The highest flexural strength (Experimental: 148.5 MPa, Numerical: 149.55 MPa) and modulus of elasticity (Experimental: 15365 MPa, Numerical: 15373 MPa) belongs to the L-3-CFRP coded beam. Compared to the reference beam, the flexural strength values of the L-3-CFRP code beam increased by 34.54%, the L-2-CFRP code beam by 31.54%, and the L-1-CFRP code beam by 23.55%. The modulus of elasticity values increased by 25% in the L-3-CFRP coded beam, by 22% in the L-2-CFRP coded beam, and by 28% in the L-1-CFRP coded beam. Figure 9 shows that the experimental results gave values close (Modulus of elasticity R^2: 0.95, Modulus of rupture R^2: 0.97) to the numerical results.

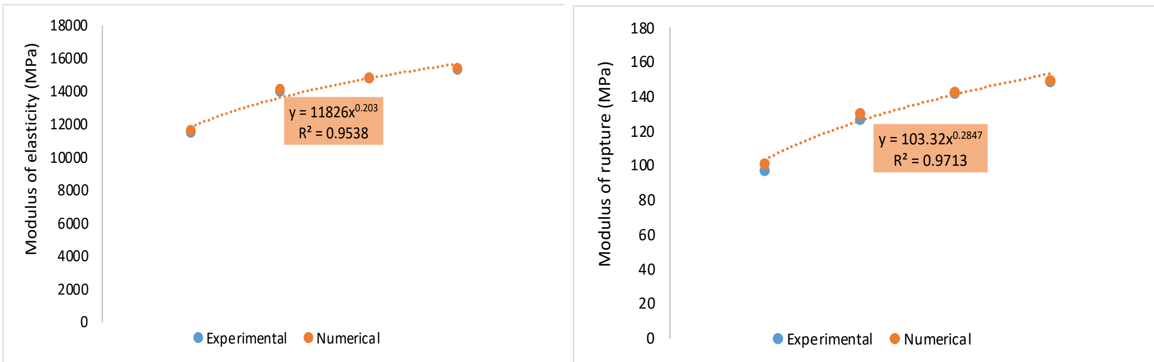

Figure 9. R^2 values of experimental and numerical results.

The graph created in Minitab 18 statistical program to show the relationship between the number of reinforcement stories, bending strength and modulus of elasticity is given in Figure 10.

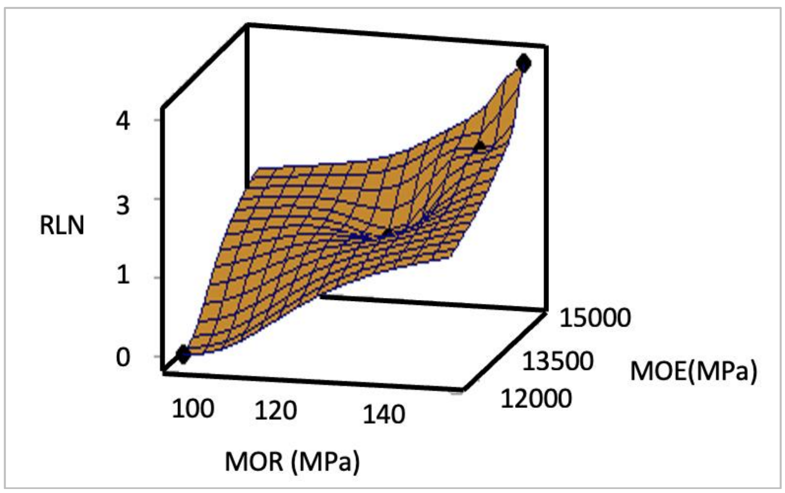

Figure 10. Modulus of rupture and modulus of elasticity values depending on the number of FRP layer (3D graph).

As seen in Figure 10, it was determined that the flexural strength and modulus of elasticity values increased with the increase in the number of reinforcement layers.

4. Conclusions and comments

In this study, larch beams were reinforced with carbon fiber reinforced polymer fabric 1, 2 and 3 layer. The effect of the number of floors on the bending properties of the beams in reinforcement was investigated experimentally and numerically. Clearly explain the main conclusions of your study;

1. Compared to the reference beam, the load carrying capacity of the L-3-CFRP coded beam increased by approximately 33.78%, the L-2-CFRP code beam increased by 31.54%, and the L-1-CFRP coded beam increased by 23.55%. Therefore, when reinforcing with fiber-reinforced polymer fabrics, a couple of reinforcements had a high effect on increasing the flexural properties. In contrast to two-layer reinforcement, it had less of an impact, despite expectations that it would have a bigger impact in three-layer reinforcement.
2. Flexural strength values of the L-3-CFRP code beam increased by 34.54%, the L-2-CFRP code beam by 31.54%, and the L-1-CFRP code beam by 23.55%. The flexural strength of the beams increased with the increase in the number of reinforcement layers. Again, in terms of flexural strength values, the highest flexural strength belongs to triple reinforced beams compared to single layer reinforcement. However, it was determined that there was a significant increase in flexural properties with two layers of reinforcement.

3. The modulus of elasticity values increased by 25% in the L-3-CFRP coded beam, by 22% in the L-2-CFRP coded beam, and by 28% in the L-1-CFRP coded beam.
4. Experimental results gave values close (modulus of elasticity R^2: 0.95, modulus of rupture R^2: 0.97) to the numerical results. As a result, the bending properties of the beams improved with the increase in the number of layers. Numerical analysis results and experimental results gave values close to each other. Therefore, Larch beams reinforced with fiber-reinforced polymer fabrics were simulated, and this model can be used in future studies.

The above research results can be used for numerical calculations in the field of repair or reinforcement at various FRP ply numbers in existing wooden structures, as well as for the tested reinforcement type and ply numbers in protection application. Additionally, the use of FRP can be an effective and common method of repairing beams in the field. Similarly, the successive development of structures reinforced with FRP fabrics is related to the improvement of the properties of composite materials themselves. The greater durability of structures reinforced with FRP fabrics or the avoidance of costs associated with the operation of steel-reinforced structures justify the advisability of using these composites.

Author contributions: All authors contributed to the design of the research, to the analysis of the results, and to the writing of the manuscript.

Conflicts of interest: No conflict of interest was declared by the authors.

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