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Reinforcement of Joints Between LVL Members with GFRP and Finite Element Analysis

Ojačanje spojeva između LVL elemenata polimerima ojačanim staklenim vlaknima i analiza metodom konačnih elemenata

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ABSTRACT • *The goal of this study was to investigate the effect of glass fiber reinforced polymer (GFRP) on joints made of laminated veneer lumber (LVL), through experimental data and evaluation by ANSYS finite element (FE) software. In order to fabricate LVL, veneer from poplar (Populus deltoides Bartr. ex Marsh) with 2.5 mm thickness and PVA adhesive were used. T-shape joints out of LVL were made and two wooden dowels were incorporated as well. Then GFRP was applied to reinforce the joints. GFRP in three grammages (100, 200 and 300 g/m^2) was adhered to joints with epoxy resin. Joints reinforcement was performed by a two-layer reinforcing agent. For comparing the effectiveness, half of the specimens were reinforced on sides and the other half on edges. Specimens were tested in static bending. The results have shown that GFRP had a significant effect on the strength of joints. Reinforced joints on both sides were stronger than those reinforced on edge. Joints reinforced with 300 g/m^2 GFRP were improved by 35 % and 43 %, respectively, compared to 100 and 200 g/m^2 grammage. Failure modes of specimens are dependent on GFRP grammage. The results of FE have shown that the highest concentration of stress and elastic strain was generated in the tension and compression zones of joints.*

KEYWORDS: *veneer lumber; glass fiber reinforced polymer; finite element method; failure modes*

SAŽETAK • *Cilj rada bio je na temelju eksperimentalnih podataka i analize konačnih elemenata (FE) te uz pomoć softvera ANSYS istražiti utjecaj polimera ojačanog staklenim vlaknima (GFRP) na spojeve od lamelirane drvne građe (LVL). Za izradu LVL-a upotrijebljen je furnir drva topole (Populus deltoides Bartr. ex Marsh) debljine 2,5 mm i PVA ljepilo. Izrađeni su T-spojevi od LVL-a i ugrađena su dva drvena moždanika. Zatim je za ojačanje spojeva primijenjen GFRP u tri gramature (100, 200 i 300 g/m^2) tako da je epoksidnom smolom zalijepljen na spojeve. Ojačanje spojeva izvedeno je dvoslojnim armaturnim sredstvom. Radi usporedbe učinkovitosti, polovica uzoraka ojačana je sa strane, a druga polovica na rubovima. Uzorci su ispitani na statičko savijanje. Rezultati su pokazali da GFRP ima značajan utjecaj na čvrstoću spojeva. Spojevi ojačani s obje strane bili su jači od onih ojačanih na rubu. Spojevi ojačani GFRP-om od 300 g/m^2 poboljšani su za 35 % odnosno za 43 % u usporedbi s GFRP-om gramature100 i 200 g/m^2. Načini loma uzoraka ovisili su o gramaturi GFRP-a. Rezultati analize konačnih elemenata pokazali su da se najveća koncentracija naprezanja i elastične deformacije pojavljuje u vlačnoj i tlačnoj zoni spojeva.*

KLJUČNE RIJEČI: *drvna građa; polimer ojačan staklenim vlaknima; metoda konačnih elemenata; načini loma*

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1 INTRODUCTION
1. UVOD

An appropriate solution for utilizing low diameter logs and defects prone wood, developed during past decades, is to convert them into structural composite lumber (SCL). Mechanical properties of SCL products are improved by removing randomly scattered growth defects, thus substantially recovering dimensional stability (Williamson, 2002).

SCL products are increasingly replacing the use of solid wood in construction practices (Harrison and Hindman, 2007). Among these products, LVL has gained more popularity than other SCL items (Aydm *et al.,* 2004; Subhani *et al.,* 2017). LVL seems to be a potential material for replacing solid wood in the construction industry. These types of structure joints on load bearing members meet the requirements of the applicable standards. Uses of connecting hardware for increasing stress carrying capacity of joints made on LVL members in construction has limitations due to the size of the member cross-section. Considering these facts, it seems worthwhile to treat such joints by making use of other technologies for increasing their strength, tensile in particular. Hence, many researchers have studied the effect of using fiber-reinforced polymer on the mechanical properties of engineered wood products.

The application of fiber-reinforced polymer (FRP) composites is a promising solution to upgrade/strengthen LVL (Khelifa *et al.,* 2015). Applications of Glass Fiber Reinforced Polymers (GFRP) elements have grown continuously during the last years, as they became very popular in different areas of the aerospace, automotive, marine, oil and gas and civil construction industries, namely (fiberglass structures): ladders, platforms, handrail systems tank, pipe and pump support and or as a reinforcer in wood productions such as glulam and LSL (Osmannezhad *et al.,* 2014; Landesmann *et al.,* 2015; Moradpour *et al.,* 2018; Zor and Kartal, 2020). Many researchers have investigated the operation of FRP materials for strengthening timber elements in the case of increased service (Triantafillou and Deskovic, 1992; Gentile *et al.,* 2002; Micelli *et al.,* 2005; Dempsey and Scott, 2006; Osmannezhad *et al.,* 2014; Raftery and Whelan, 2014; Rautenstrauch, 2007; Moradpour *et al.,* 2018; Reis *et al.,* 2018; Schober and Rautenstrauch, 2007). Using bonded fiber-reinforced polymer laminates for the strengthening and repair of wooden structural members is an effective and economical method (Schober *et al.,* 2015).

According to Kim and Harries (2010), timber beams strengthened with CFRP improved load-carrying capacity and energy absorption capacity when compared to non-strengthened timber.

Khelifa *et al.* (2015) indicated that the increases of flexural strength for the two different reinforcement schemes with 2 and 3 layers of CFRP composite sheets were 41.82 % and 60.24 %, respectively, with respect to the unreinforced timber beams.

D' Ambrisi *et al.* (2014) found that the application of CFRP plates is very effective for repairing both new and old timber beams and it allows to completely restore and to increase their flexural strength, so CFRP can be used for restoring historical building beams. Also, CFRP can increase the load-carrying capacity of timber beams in bending (De Jesus *et al.,* 2012; Nowak *et al.,* 2013; Khelifa and Celzard, 2014; Andor *et al.,* 2015; Rescalvo *et al.,* 2018) and, it shows a significant increase in ultimate strength, stiffness (Borri *et al.,* 2005; Micelli *et al.,* 2005; Nadir *et al.,* 2016; Yang *et al.,* 2016), and energy absorption capacity (Alhayek and Svecova, 2012). Wei *et al.* (2017) investigated the flexural performance of bamboo scrimber beams strengthened with FRP and observed that the strengthening method had a beneficial effect on promoting the compression behavior in the compression zone of the cross-sections of bamboo beams. Ferreira *et al.* (2017) investigated the failure behavior and repair of delaminated glulam beams; their results indicated that the preventively repaired beams showed significant improvements in resistance and stiffness compared to unrepaired beams, although they failed to achieve the performance of healthy beams. Basterra *et al.* (2017) described internal reinforcement of laminated duo beams of low-grade timber with GFRP sheets and presented it by using relatively low reinforcement ratios (1.07 %, 1.6 %) in the tension zone. They found an average improvement of 12.1 % and 14.7 % in stiffness, and an increase of up to 23 % in moment capacity. Hernandez *et al.* (1997) investigated strengthening of laminated beams of *Liriodendron tulipifera* L. (yellow poplar) with external GFRP reinforcements placed in tension, as well as in tension and compression; these authors determined that tensile reinforcement increased flexural strength, whereas double reinforcement increased flexural stiffness. Qi *et al.* (2017) obtained GFRP-wood sandwich beams with lattice-web reinforcement and tested bending in flatwise and sidewise directions. The results showed that the composite sandwich beams in flatwise bending tests failed under a lower load but yielded a larger deflection than those in sidewise bending tests. It was also shown that with the increase in the number of lattice-webs, pseudo-ductility was found to increase in the flatwise directions but decrease in the sidewise directions. The flexural behavior of glulam beams reinforced with fiberglass and steel wire nets was studied by Uzel *et al.* (2018). The results showed that the use of reinforcement nets at the lamination surfaces increased the ultimate load capacities of the tested beams. Investigation of the sandwich beams reinforced with GFRP as surface skins and inner lattice-webs indicated that implementation of GFRP webs in the sandwich beams considerably improved their flexural performance, in association with a pseudo-ductile failure process and certain residual load-carrying capacity (Shi *et al.,* 2017). The strength and stiffness of glulam beams reinforced with glass and basalt fibers were studied by Thorhallsson *et al.* (2017) and they found that the reinforced glulam beams on the tension side allow a possible reduction of the cross-section or lower timber grade while maintaining the same bending strength and stiffness as for the unreinforced beam. Corradi *et al.* (2017) investigated uncertainty analysis of FRP reinforced timber beams and observed that the FRP reinforcement was effective for both enhancing the beam load-carrying capacity and for reducing strength uncertainties. There are also several studies, which indicate that FRP could be increasing mechanical properties of LVL (Wei *et al.,* 2013; Bal, 2014a, 2014b, Wang *et al.,* 2015; Percin and Altunok, 2017; Subhani *et al.,* 2017).

Many studies examined the effect of FRP on the strengthening of engineering wood products i.e. LVL, LSL, glulam. However, the literature does not provide any significant research results related to reinforcing joints fabricated with engineering wood products. Hence, the aims of this study were as follows: 1) to investigate the effect of GFRP on the bending moment capacity joints made of LVL; 2) to compare the density of GFRP in three levels (100, 200 and 300 g/m^2) on the bending moment capacity of these joints; 3) to compare two reinforcing methods using two layers on the sides and two layers in the edge of joints applied in the connection area between two members; 4) to simulate finite element method for investigating the distribution of stress and strain in these joints.

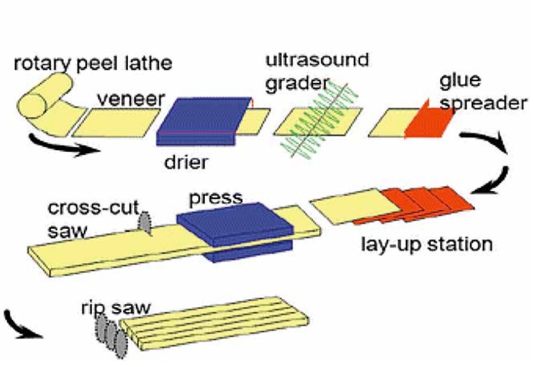


Figure 1 Manufacturing steps of LVL (Buchanan, 2007)
Slika 1. Koraci u proizvodnji LVL-a (Buchanan, 2007.)

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Material
2.1. Materijal

2.1.1 Veneer preparation and LVL manufacturing
2.1.1. Priprema furnira i proizvodnja LVL-a

Rotary cut veneers of poplar logs *(Populus deltoides Bartr. ex Marsh)* were collected from an industrial-scale production. The thickness of the test veneer was 2.3 mm. Veneers were cut into pieces of 2400 mm × 200 mm (length × width), then dried to 6–7 % moisture content. Polyvinyl acetate adhesive was applied to the dried veneer by a manual spreader. The amount of glue per unit area was approximately 200 g/m^2. Nine pieces of glued veneer were stacked with their grain parallel to each other, and then pressed. Press pressure of 1 MPa was applied for 60 minutes. Figure 1 illustrates the process of LVL production.

Some strength properties of experimental LVL, important to this study, were measured according to EN 310 standard, and others were predicted through an existing relationship. Table 1 presents the measured and predicted strength information associated with LVL.

2.1.2 Adhesive
2.1.2. Ljepilo

Two types of adhesives were used in this research, polyvinyl acetate for fabricating LVL and epoxy resin to apply GFRP on target points of test joints. The epoxy consisted of two parts, resin and hardener, which need to be mixed at a ratio of 2:1 in volume. Table 2 presents the strength properties of the adhesive used.

Table 1 Basic properties of wood used in this study
Tablica 1. Osnovna svojstva drva upotrijebljenoga u istraživanju

Parameter *Parametar*	E_L	E_R	E_T	G_{LR}	G_{LT}	G_{RT}	v_{LR}	v_{LT}	v_{RT}	v_{TR}	v_{RL}	v_{TL}
	MPa			MPa								
LVL	11103	1216	599	799	688	133	0.37	0.50	0.67	0.33	0.04	0.027
Hornbeam dowel *moždanik od grabovine*	11215	1212	605	807	695	134	0.37	0.50	0.67	0.33	0.04	0.027

E_L, E_R and E_T – Modulus of elasticity in longitudinal, radial, and tangential directions, respectively / *moduli elastičnosti u uzdužnome, radijalnome i tangentnom smjeru*
V_{LR}, V_{RT} and V_{LT} – Poisson's ratio on longitudinal-radial, radial-tangential, and longitudinal-tangential direction, respectively / *Poissonov omjer za uzdužno-radijalni, radijalno-tangentni i uzdužno-tangentni smjer*
G_{LR}, G_{LT} and G_{RT} – Shear modulus on longitudinal-radial, longitudinal-tangential, and radial-tangential direction, respectively / *modul smicanja za uzdužno-radijalni, radijalno-tangentni i uzdužno-tangentni smjer*

Table 2 Strength properties of adhesives used for making LVL and reinforce joints
Tablica 2. Svojstva čvrstoće ljepila upotrijebljenih za izradu LVL-a i za ojačanje spojeva

Parameter *Parametar*	***E*, MPa**	***G*, MPa**	ν
PVA	400	153	0.3
Epoxy	3500	1346	0.3
GFRP	29000	9615	0.3

E – Modulus of elasticity / *modul elastičnosti*, G – Shear modulus / *modul smicanja*, ν – Poisson's ratio / *Poissonov omjer*

2.1.3 GFRP
2.1.3. GFRP

Woven glass fiber reinforced polymer (GFRP) was provided by Mandegar Basbar Company in Karaj, Iran. Three weight intensities of GFRP were applied on test joints, including 100, 200 and 300 g/m^2. GFRP was cut into two pieces, 140 mm × 100 mm and 140 mm × 20 mm, according to the points of application (joint depths and edges).

2.1.4 Dowel
2.1.4. Moždanik

Commercially available dowel out of hornbeam wood was purchased to incorporate in fabrication test joints, as it is a common joint reinforcer in furniture manufacturing. The dowel was 10 mm in diameter and 80 mm in length with a smooth surface.

2.2 Fabrication of test joints
2.2. Izrada ispitnih spojeva

Produced LVL panels were stored for a two-week period to restore and dissipate any strain energy imposed during pressing. Then panels were cut into stacks 300 mm × 100 mm × 21 mm (length × width × thickness) to be utilized as test joint members. Each joint member received two predrilled holes, 40 mm apart on center for installing dowels. The distance between the centers of the two holes was 50 mm and the diameter of the holes was 0.1 mm larger than the dowel diameter. Dowels were dipped in the adhesive prior to being inserted in holes. The adhesive was applied to the cross-section of joints members as well. T-shape assembled joint remained under clamp pressure for 24-h to let adhesive cure well enough. In total 35 T-shape joints were made. For reinforcing test joints with GFRP, a 2-layer GFRP was glued on the depth sides, and top and bottom edges of each joints. Epoxy was the means to apply GFRP with the weight intensity of 100, 200 and 300 g/m^2 (Figure 2). Five replicates were made for each treatment.

2.3 Method of test loading
2.3. Način opterećenja

All specimens were tested by a computer-controlled Instron testing machine (model 4486). The loading rate was set at 5 mm/min. A point load was

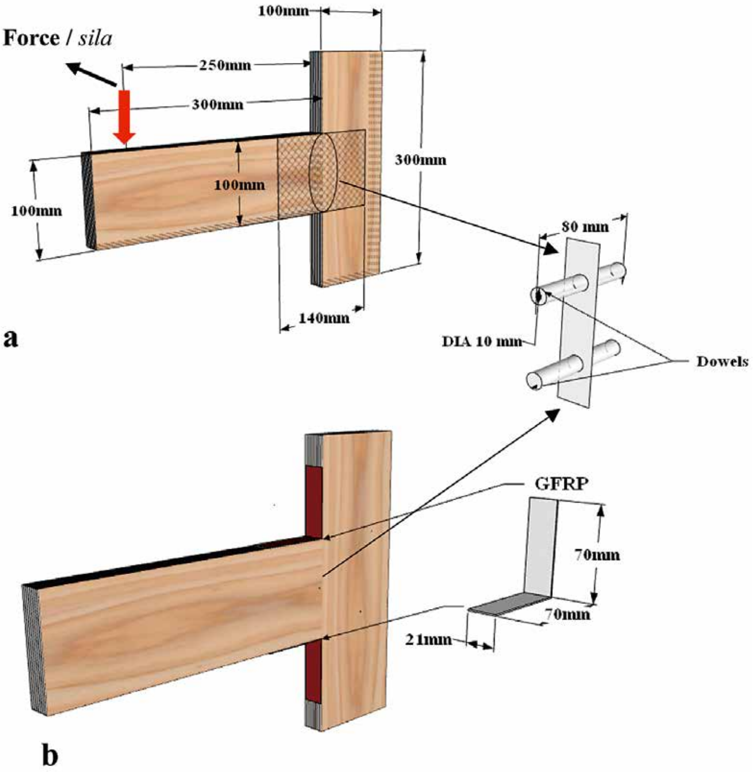


Figure 2 a) Joint reinforced with GFRP by 2 layers on sides (2S), b) joint reinforced with GFRP by 2 layers on upper and bottom edge (2E)
Slika 2. a) Spoj ojačan dvama slojevima GFRP-a sa strane (2S), b) spoj ojačan dvama slojevima GFRP-a na gornjemu i donjem rubu (2E)

applied to the rail member of the joint with the moment arm of 250 mm.

Loading under $M = 0.25 \times P$ (N·m) moment was continued until the joint failure.

2.4 Data analysis
2.4. Analiza podataka

Collected data were first checked for their normal distributions by SPSS software and then refined to determine the effects of variables (grammage, location of applied GFRP), by comparing discrepancies found in mean and standard deviation.

2.5 Finite element modeling
2.5. Modeliranje konačnih elemenata

Ansys workbench 19.1 was used to establish finite element modeling FEM. The geometric size of the FEM was the same as the experimental specimen. For completing strength properties of LVL, relationships between stress and strain were used to calculate others not measured. For mechanical properties of dowels from hornbeam species, average values given in the Wood handbook were adopted (Eqs. 1-9) (Ross, 2010).

$$\sigma_i = E_i \times \varepsilon_i \tag{1}$$

$$\tau_{ij} = G_{ij} \times \gamma_{ij} \tag{2}$$

Where for wood:

$$\varepsilon_L = \frac{1}{E_L}(\sigma_L - \nu_{LR} \cdot \sigma_R - \nu_{LT} \cdot \sigma_T) \tag{3}$$

$$\varepsilon_R = \frac{1}{E_R}(\sigma_R - \nu_{RL} \cdot \sigma_L - \nu_{RT} \cdot \sigma_T) \tag{4}$$

$$\varepsilon_T = \frac{1}{E_T}(\sigma_T - \nu_{TL} \cdot \sigma_L - \nu_{TR} \cdot \sigma_R) \tag{5}$$

$$\gamma_{LT} = \frac{\tau_{LT}}{G_{LT}} \tag{6}$$

$$\gamma_{TR} = \frac{\tau_{TR}}{G_{TR}} \tag{7}$$

$$\gamma_{RL} = \frac{\tau_{RL}}{G_{RL}} \tag{8}$$

Whereas

$$\frac{\nu_{LR}}{E_L} = \frac{\nu_{RL}}{E_R}, \frac{\nu_{LT}}{E_L} = \frac{\nu_{TL}}{E_T}, \frac{\nu_{RT}}{E_R} = \frac{\nu_{TR}}{E_T} \tag{9}$$

Where: E is modulus of elasticity (L: longitudinal, R: radial and T: tangential), G is shear modulus (G_{LR}, G_{LT} and G_{RT}), υ is Poisson's ratio (υ_{LR}, υ_{LT} and υ_{RT}), ε is linear strain in material directions (orthotropic axis), γ is shear strain in material planes (orthotropic planes), σ is linear stress and τ is shear stress.

GFRP and glue lines were referred to as isotropic substances with properties given in Table 2.

Figure 3 illustrates the simulation model of the joint. The tetrahedron method was applied to generate the mesh for joint assembly (Figure 3b$_1$). The developed model included 29735 elements with 124216 nodes. Specific areas of joint such as GFRP, dowel and glue line were meshed with sweep method which is a dense mesh (Figure 3b$_{2,3}$). Interfaces between dowels and hole and between GFRP and joint members were incorporated too.

Boundary conditions reflected experimental specimens, i.e., the force was applied at a point 250 mm on the rail member. Supports were placed in the top, bottom and back of the posting member (Figure 3c).

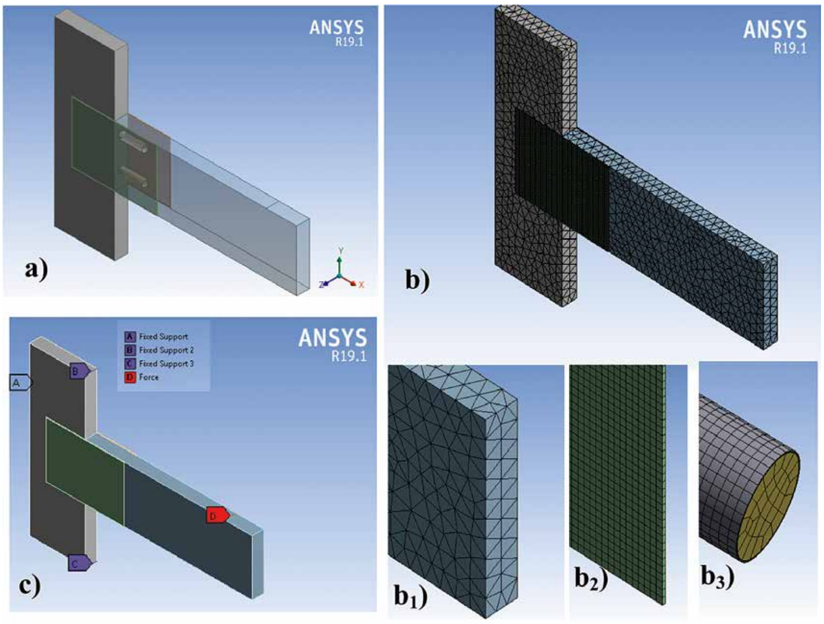


Figure 3 a) Joint modular design, b) FE mesh used for joint, b$_1$) Mesh of joint members, b$_2$) Mesh of GFRP, b3) Mesh of dowel and glue line, c) Boundary conditions

Slika 3. a) Modulirani dizajn spoja, b) FE mreža upotrijebljena za spoj, b$_1$) mreža za spojni element, b$_2$) mreža za GFRP, b$_3$) mreža za moždanik i ljepilo, c) granični uvjeti

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Experimental results
3.1. Eksperimentalni rezultati

The average values of the moment resistance with their standard deviation for types of GFRP and two methods of reinforcing are given in Table 3. This table shows that the highest strength was obtained in joints that were reinforced by GFRP with 300 g/m^2 grammage, while the lowest bending moment resistance was recorded in joints that were not reinforced. The results of multivariable variance analyses of GFRP grammage types, method of reinforcement, and interaction effect between GFRP grammage and the method of reinforcement are given in Table 4.

The analysis of results has indicated that the effects of the main factors (GFRP grammage and method of reinforcement) and their interaction on bending moment resistance were statistically significant at the 1 % significance level.

3.2 Effect of GFRP grammage on bending moment resistance
3.2. Utjecaj gramature GFPR-a na otpor momentu savijanja

Figure 4 shows that the bending moment resistance of joints reinforced with GFRP is significantly higher than that of non-reinforced joints according to Duncan's test. As it can be seen, the bending moment resistance increased with an increase in GFRP grammage. Previous studies in this field have shown that using GFRP materials improves the mechanical properties of timber and the strength of joints (Schober and Rautenstrauch, 2007; De Jesus *et al.,* 2012; Nowak *et al.,* 2013; Raftery and Whelan, 2014; Yildirim *et al.,* 2018).

The highest bending moment resistance was measured for joints reinforced with 300 g/m^2 grammage of GFRP (713 N·m). Average increase in bending moment resistance of joints reinforced by 300 g/m^2 GFRP was 35 % - 43 % as compared to bending moment resistance of joints reinforced by 100 and 200 g/m^2 GFRP, respectively. There were no significant differences between joints reinforced with 100 and 200 g/m^2 GFRP.

3.3 Effect of reinforcing method on bending moment capacity
3.3. Utjecaj metode ojačanja na kapacitet momenta savijanja

As shown in Figure 5, it is obvious that the location of GFRP in reinforced joints had an influence on bending strength and it can be said that the strength of reinforced joints is dependent on the reinforcing method. So, the highest strength was observed in joints reinforced with 2S, the joints being reinforced in depth. Joints reinforced in depth were stronger by 46 % than those reinforced on edges. The main reason for this should be related to the increasing contact zone in the 2S method.

3.4 Failure modes
3.4. Načini loma

In all of the reinforced joints, the fracture was observed in the GFRP zone between two members. An analysis of the failure modes in reinforced joints was investigated and the fracture phenomena observed were divided into three categories. Failure mode in reinforced joints with 100 g/m^2 GFRP grammage oc-

Table 3 Mean bending moment resistance with its standard deviation
Tablica 3. Srednja vrijednost otpora momentu savijanja sa standardnom devijacijom

GFRP grammage *Gramatura GFRP-a*	**Number of specimens** *Broj uzoraka*	**Methods of reinforcement** *Metode ojačanja*	**Bending moment resistance, N m** *Otpor momentu savijanja,* N·m	**Standard deviation** *Standardna devijacija*
100	5	2E	332.150	42.592
	5	2S	392.550	31.631
200	5	2E	369.700	57.453
	5	2S	397.050	53.938
300	5	2E	324.100	46.350
	5	2S	713.100	40.459
Nonreinforced *Neojačan*	5	-	250.000	19.628

Table 4 Univariate analysis of variance for bending moment resistance
Tablica 4. Univarijatna analiza varijance otpora momentu savijanja

Source / *Izvor*	**Sum of squares** *Zbroj kvadrata*	*df*	**Mean square** *Srednja vrijednost kvadrata*	*F*	**Sig.**
Grammage of GFRP / *gramatura GFRP-a*	143806.379	2	71903.190	33.678	0.000*
Methods of reinforcing / *metoda ojačanja*	189408.802	1	189408.802	88.716	0.000*
Grammage of GFRP * Methods of reinforcing *gramatura GFRP-a * metoda ojačanja*	199884.154	2	99942.077	46.811	0.000*

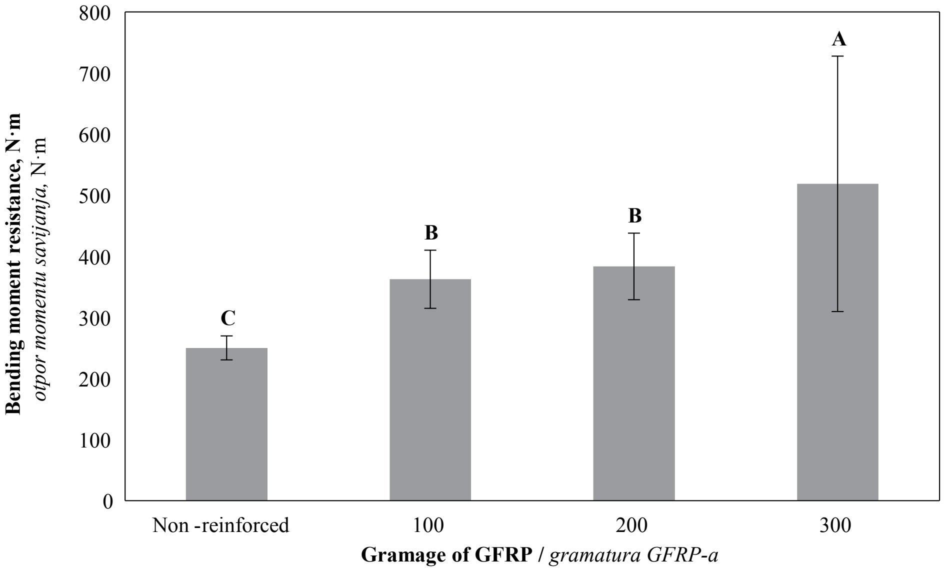


Figure 4 Effect of GFRP grammage on bending moment resistance (bars marked by the same letter are not significantly different according to Duncan's test P < 0.01)
Slika 4. Utjecaj gramature GFRP-a na otpor momentu savijanja (stupci označeni istim slovom ne razlikuju se značajno prema Duncanovu testu uz *P* < 0,01)

curred in tensile mode in GFRP (Figure 6a), and for those reinforced with 300 g/m^2, fracture mode was observed as cracks in GFRP zone (Figure 6c). In the case of reinforced joints with 200 g/m^2 grammage, GFRP combined fracture of two previous modes (tensile mode and fracture mode) was observed (Figure 6b). Mode of failure in reinforced joints by method 2S occurred around the upper connection zone between two members, where it was under tensile stress and the cracking developed along with the connection between two members until the middle of the connection (Figure 7a). However, observations of the mode of failure in reinforced joints by method 2E have shown that the crack occurred at the upper edge of joints exposed to tensile stress. (Figure 7b).

3.5 Finite element modelling
3.5. Modeliranje konačnih elemenata

Since the greatest resistance was obtained from reinforced joint with GFRP of 300 g/m^2 by method 2S, it was selected for the simulation. The analysis of equivalent von Mises stress and elastic strain distribution in reinforced joints revealed that the biggest concentration of stress and elastic strain were generated in the zone of connection between two members. As shown in Figure 8, it can be seen that stress and strain

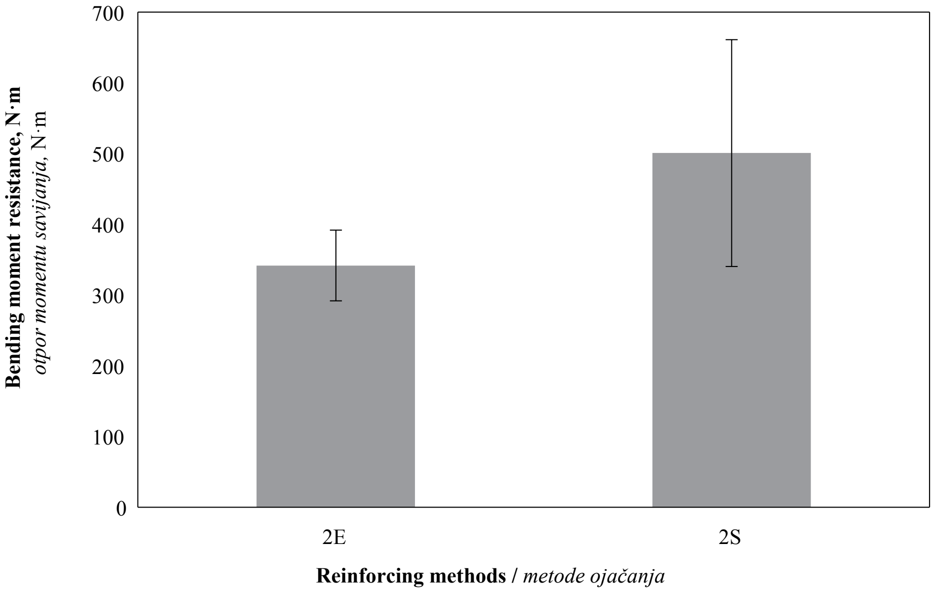
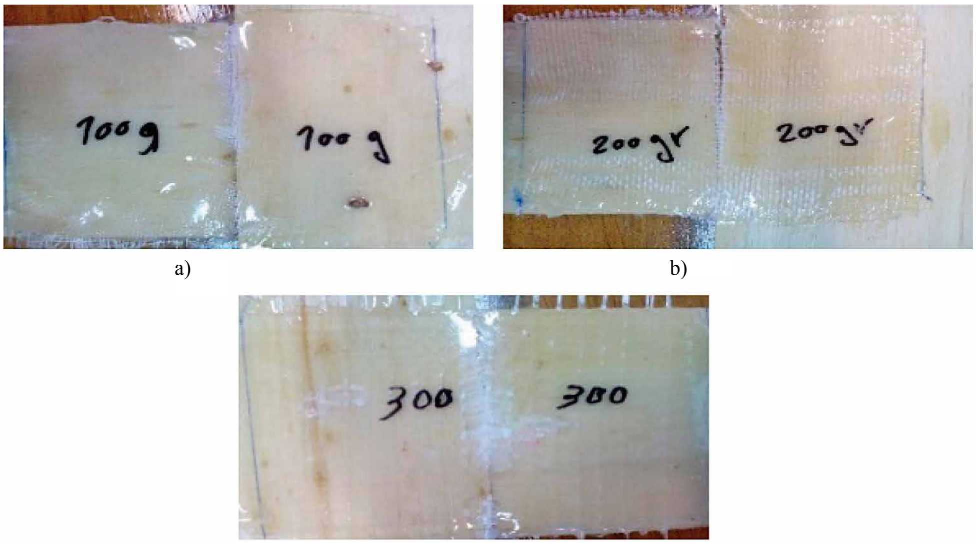
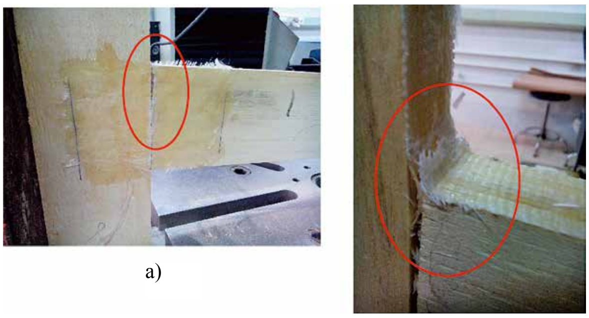


Figure 5 Effect of reinforcing methods on bending moment resistance
Slika 5. Utjecaj metoda ojačanja na otpor momentu savijanja



a) b) c)

Figure 6 Failure modes, a) tensile mode in GFRP (100 g/m^2), b) combined fracture (tensile mode and fracture mode) in GFRP (200 g/m^2), c) fracture mode in GFRP (300 g/m^2)
Slika 6. Načini loma: a) vlačni lom u GFPR-u (100 g/m^2), b) kombinirani lom (vlačni lom i puknuće spoja) u GFPR-u (200 g/m^2), c) puknuće spoja u GFPR-u (300 g/m^2)



a) b)

Figure 7 Failure modes, a) Fracture in reinforced joints by method 2S, b) Fracture in reinforced joints by method 2E
Slika 7. Načini loma: a) lom u spoju ojačanome metodom 2S, b) lom u spoju ojačanome metodom 2E

are concentrated at the extreme fibers at the top and bottom of the joint. The overall simulated stress and strain of the reinforced joints have shown good agreement with the experimental observations.

Also, based on figures extracted from FEM, one can say that failure occurs when principal tensile stress exceeds the ultimate tensile of GFRP. Therefore, it can be concluded that in joints reinforced with GFRP, tensile strength is essential.

This statement is confirmed by the results obtained from the experimental observations made in this study. The stress and strain distribution of GFRP is illustrated in Figure 8. It can be seen that the highest stress and strain occurred in the top middle of GFRP where the fracture initiated in the experiments. According to the results, joints reinforced by GFRP with higher grammages were stronger than those reinforced with lower grammages. This result can be described as increasing tensile strength in GFRP with increasing grammage. In other words, the tensile strength of GFRP is dependent on the grammage and the type of glass fiber, so the higher grammage of GFRP, the higher is the strength. (De la Rosa García *et al.,* 2013; Clausen *et al.,* 2018,).

Stress and strain distribution in the length of the dowels is shown in Figure 9. It can be seen that the distribution of stress and strain was different for each dowel. The highest stress concentration occurred in the upper part of the top dowel and lower part of the bottom dowel. In order to better illustrate the distribution of stress and strain in dowels, a cross-section of dowels is presented (Figure 9) (glue lines are hidden). The upper and bottom dowel received the tensile and compression stress, respectively (Figure 9).

4 CONCLUSIONS
4. ZAKLJUČAK

Results of the experimental investigations have shown that GFRP reinforcing improves the bending moment strength in T-shape joints. In terms of GFRP grammage, results have shown that 300 g/m^2 GFRP had more effect on the strength of joints than 100 and 200 g/m^2 GFRP. Also, the reinforcing method was important for the strengthening of joints, so that joints reinforced by method 2S achieved better results those reinforced by 2E method.

Failure modes of reinforced joints were different, and three modes of failure were observed: tensile modes in 100 g/m^2 GFRP, fracture modes in 300 g/m^2 GFRP, combined fracture (tensile mode and fracture mode) in 200 g/m^2 GFRP.

According to the finite element analysis of reinforced joints, the highest concentration of stress and

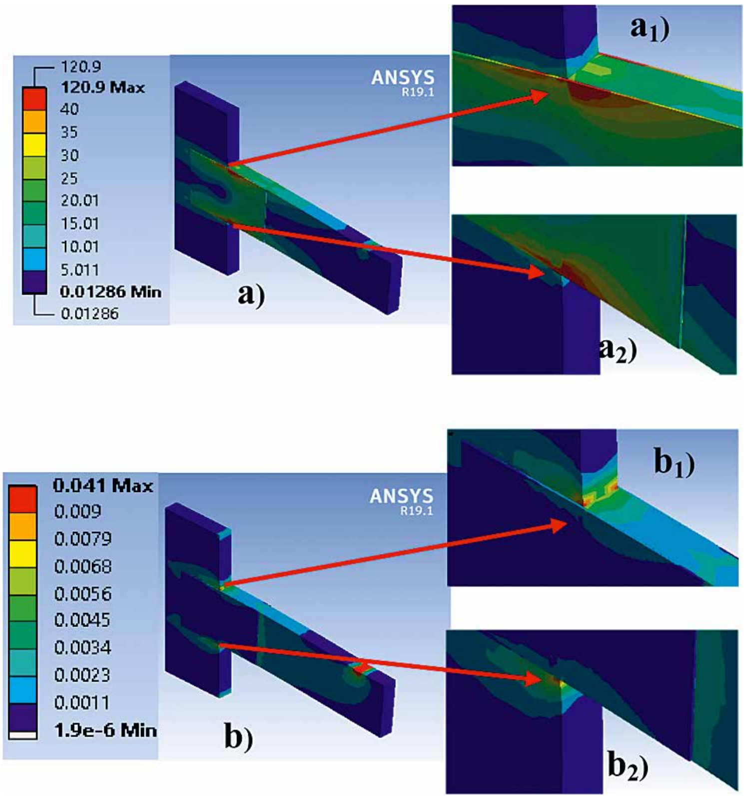


Figure 8 a, b) Distribution of stress and strain in reinforced joint; a_1, b_1) Distribution of stress and strain at the edge of joint; a_2, b_2) Distribution of stress and strain at bottom edge of joint
Slika 8. a), b) Raspodjela naprezanja i deformacija u ojačanom spoju; a_1), b_1) raspodjela naprezanja i deformacija na rubu spoja; a_2), b_2) raspodjela naprezanja i deformacija na donjem rubu spoja

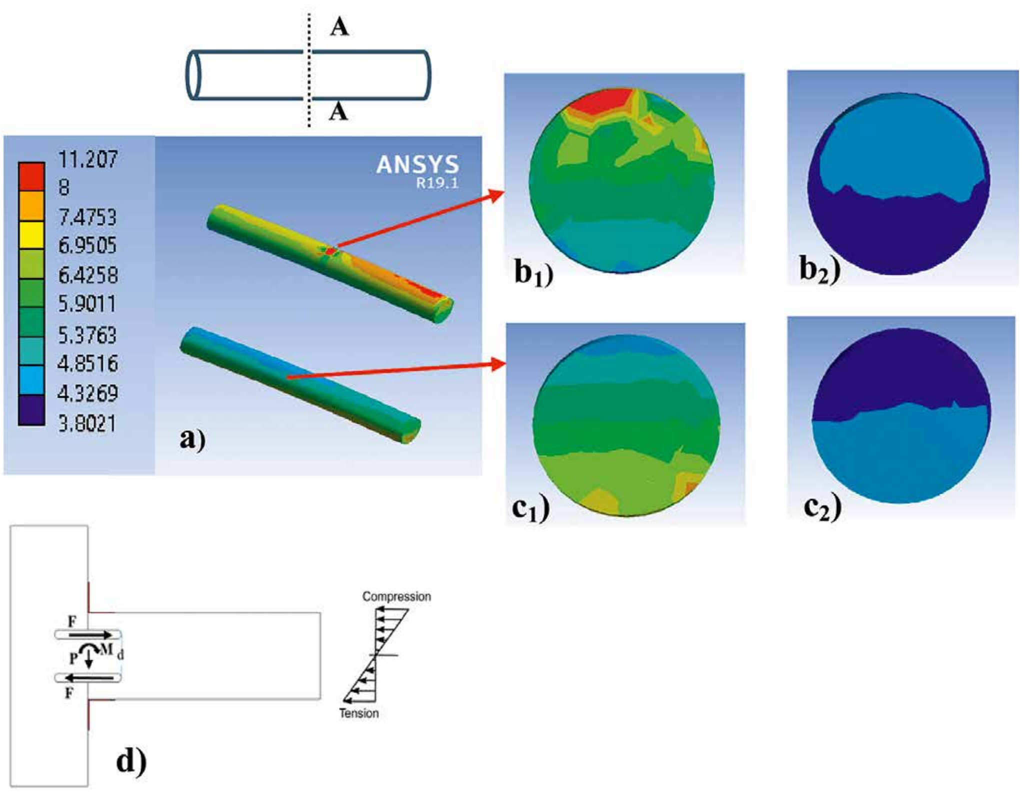


Figure 9 a) Distribution of stress and strain in dowels, b_1, b_2) Distribution of stress and strain in top dowel, c_1, c_2) Distribution of stress and strain in bottom dowel, d) Position of dowels
Slika 9. a) Raspodjela naprezanja i deformacija u moždanicima; b_1), b_2) raspodjela naprezanja i deformacija u gornjem moždaniku; c_1), c_2) raspodjela naprezanja i deformacija u donjem moždaniku; d) položaj moždanika

elastic strain were generated in the zone of connection between two members. In the GFRP zone, the highest stress and strain occurred in the top and bottom middle, which was the main cause of fracture in reinforced joints. The distribution of stress and strain in dowels showed that dowels were affected by different types of stress. Thus, the dowel inserted in the upper part of the joint was stressed in tension, while the bottom dowel was stressed in compression. According to the results of this research, the overall simulated stress and strain of the reinforced joints have shown good agreement with the experimental observation. Further research in this field should focus on studying the performance of the reinforced joints under different loading including tension and compression and different materials i.e., other engineered wood materials and different connectors, such as screws, nails, etc.

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