OJAČANJE DRVENIH GREDA PRIMENOM FRP ŠIPKI

STRENGTHENING OF TIMBER BEAMS USING FRP BARS

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1 UVOD

Drvo kao jedan od najstarijih građevinskih materijala nalazi primenu i u savremenoj građevinskoj praksi zahvaljući tome što predstavlja prirodan, obnovljiv, biorazgradiv i estetski atraktivan materijal. Potreba da se ojačaju drvene konstrukcije može nastati iz različitih razloga, kao što su mehanička oštećenja, destruktivni uticaji okruženja ili povećanje korisnog opterećenja. U ovom kontekstu, razvoj efikasnih metoda ojačanja od velike je važnosti.

Poslednjih godina, primena polimera ojačanih vlaknima (*Fiber Reinforced Polymer* - FRP) u oblasti sanacija i ojačanja građevinskih konstrukcija omogućena je zahvaljujući povećanoj dostupnosti i sve nižoj ceni. FRP materijali su grupa naprednih kompozita u okviru kojih se nalaze vlakna izraženih mehaničkih karakteristika (najčešće staklena ili karbonska) povezana izuzetno čvrstom, hemijski otpornom i trajnom sintetičkom smolom (kao matricom). Ovi kompozitni materijali dostupni su kao gotovi fabrički proizvodi najčešće u formi traka, tkanina ili šipki. Povezivanje FRP ojačanja za konstrukcijske elemente izvodi se uglavnom lepljenjem uz primenu odgovarajućih polimernih lepkova. Ovi materijali se već dugo uspešno koriste pri ojačanju betonskih i zidanih konstrukcija [1,2], dok je njihova primena za ojačanje i sanaciju drvenih konstrukcija još uvek u fazi ispitivanja kako bi se obezbedila pravilna i optimalna

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1 INTRODUCTION

Timber, as one of the oldest structural materials, is still widely used nowadays since it is natural, renewable, biodegradable and aesthetically attractive material. The need for reinforcement of timber structures can be caused by various reasons, such as mechanical damage, destructive effects of the environment or the increase in service loads. Therefore, the development of effective methods of reinforcement is of great importance.

In recent years, the use of Fibre Reinforced Polymers - FRP in the field of repair and strengthening of structures was made possible thanks to the increased availability and lower price. FRP materials are a group of advanced composites comprised of fibres with high mechanical properties (usually glass or carbon fibres) embedded in chemically resistant and durable synthetic resin (as a matrix). These composites are available as finished products, usually in the form of plates, sheets or bars. Bonding of FRP reinforcement to structural elements is mainly performed by gluing with suitable polymer adhesives. In the past years composite materials have been successfully used for the reinforcement of concrete and masonry structures [1,2], while their application for the reinforcement and repair of timber structures is still in the experimental phase in order to ensure their proper and optimal use. FRP com-

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upotreba. FRP kompoziti su idealno ojačanje za drvene elemente zbog njihovih izuzetnih karakteristika, kao što su odlična mehanička svojstva, mala sopstvena težina, izuzetna trajnost, velika mogućnost oblikovanja i fleksibilnost.

U radu je predstavljena upotreba FRP šipki kao materijala za ojačanje drvenih nosača. Postavljanje FRP šipki unutar poprečnog preseka nosača ima nekoliko značajnih prednosti u odnosu na uobičajenu primenu FRP traka sa spoljne strane preseka, kao što su: veća sigurnost pri požaru, bolja estetska svojsta, efikasnija veza drvo–FRP (veća površina lepljenja) i smanjena mogućnost pojave delaminacije ojačanja.

2 FRP KOMPOZIT

Zavisno od zahtevanih fizičkih i mehaničkih karakteristika, kao i od ekonomskih razmatranja, FRP kompoziti mogu biti sačinjeni od različitih tipova vlakana i polimernih matrica, i prilagođeni tako da obezbede potrebnu nosivost i krutost u željenim pravcima. U okviru kompozita vlakna i matrica zadržavaju svoj fizički i hemijski identitet, a ipak zajedno proizvode određena svojstva koja ne mogu biti dostignuta kada deluju samostalno.

2.1 Vlakna

Izbor vlakana umnogome utiče na karakteristike kompozita. Za primenu u građevinarstvu dominiraju tri tipa veštačkih vlakana: karbonska, staklena i aramidna, a u poslednje vreme primenu nalaze i prirodna bazaltna vlakna. Vlakna imaju različite karakteristike, uključujući i cenu, što čini jednu vrstu više pogodnom od druge vrste za različite namene. Sva vlakna imaju generalno veliki kapacitet nosivosti (veći od običnog čelika) i linearno elastično ponašanje do loma. U tabeli 1 su prikazane osnovne karakteristike vlakana.

Staklena vlakna imaju dobre mehaničke karakteristike, visoku hemijsku otpornost i odlična izolaciona svojstva uz nisku cenu u odnosu na druge tipove vlakana. Nedostaci ovih vlakana jesu relativno nizak modul elastičnosti, mala otpornost na zamor, osetljivost na habanje i na vlagu, kao i sklonost ka deformacijama tečenja.

Karbonska vlakna imaju visoke mehaničke karakteristike u pravcu vlakana i znatno niže u poprečnom pravcu. Prednosti karbonskih vlakana jesu dobar odnos između čvrstoće i težine, odlična trajnost, dobra reološka svojstva, otpornost na zamor. Najveći nedostatak karbonskih vlakana jeste njihova cena.

Aramidna vlakna imaju najmanju zapreminsku masu i najveću čvrstoću na zatezanje naspram zapreminske mase u poređenju sa staklenim i karbonskim vlaknima. Kompoziti sa aramidnim vlaknima imaju dobru otpornost na dinamička i udarna opterećenja. Aramidna vlakna imaju visoku termičku stabilnost i dobru hemijsku otpornost. Mane aramidnih vlakana jesu nepostojanost na povišenim temeperaturama, kao i osetljivost na vlažnost i UV zračenje.

Bazaltna vlakna imaju odličnu otpornost na koroziju i hemijske uticaje. Po svom ponašanju najsličnija su staklenim vlaknima, pa se često koriste kao zamena za njih. Najveća prednost ovog tipa vlakana jeste u tome

posites are the perfect reinforcement for timber elements due to their exceptional characteristics, such as excellent mechanical properties, low weight, good durability, availability in different shapes and flexibility.

The paper presents the use of FRP bars as reinforcement materials for timber beams. Placing the FRP bars within a cross-section of the beams has several important advantages over traditional use of FRP plates on the outer sides of the beams, such as greater fire safety, better aesthetic appearance, more efficient timber-FRP bond (greater gluing surface) and decreased possibility of delamination.

2 FRP COMPOSITES

Depending on the required physical and mechanical properties, as well as economic factors, FRP composites can be made from various types of fibres and polymer matrices and they can be adapted to provide the required load carrying capacity and stiffness in desired directions. Within the composite, fibres and matrices keep their physical and chemical identity, yet together they produce certain properties that cannot be achieved when they are used separately.

2.1 Fibres

The choice of fibres greatly affects the characteristics of the composite. In civil engineering three types of fibres are mainly used: carbon, glass and aramid; lately the natural basalt fibres are also applied. The fibres have different properties and prices, which makes one type more suitable than the other for different purposes. All fibres generally have a large load carrying capacity (greater than steel) and linear elastic behaviour up to failure. Table 1 shows the main fibre properties.

Glass fibres have good mechanical properties, high chemical resistance, excellent insulating properties and low cost compared to other types of fibres. Disadvantages of these fibres are relatively low modulus of elasticity, low fatigue resistance, sensitivity to abrasion and moisture, as well as tendency to creep deformations.

Carbon fibres have high mechanical properties in fibre direction and much lower in transverse direction. The advantages of carbon fibres are good strength to weight ratio, excellent durability, good rheological properties and fatigue resistance. The greatest disadvantage of carbon fibres is their price.

Aramid fibres have the lowest weight and the highest tensile strength to weight ratio compared to glass and carbon fibres. Composites with aramid fibres have good resistance to dynamic and impact loads. Aramid fibres have high thermal stability and good chemical resistance. Main flaws of aramid fibres are sensitivity to high temperatures, moisture and UV radiation.

Basalt fibres have excellent resistance to corrosion and chemical influences. These fibres are most similar to glass fibres and are often used as a substitute for them. The biggest advantage of basalt fibres is that they are natural material and therefore the negative impacts on the environment during production and use of these fibres are reduced to minimum.

što su prirodan materijal, pa su negativni uticaji na životnu sredinu tokom proizvodnje i upotrebe ovih vlakana svedeni na minimum.

Tabela 1. Poređenje prosečnih vrednosti karakteristika vlakana [3–6]
Table 1. Comparison of average fiber properties [3–6]

Vlakna *Fibres*	Zapreminska masa *Density* (g/cm^3)	Modul elastičnosti *Modulus of elasticity* (GPa)	Čvrstoća na zatezanje *Tensile strength* (MPa)
Staklena *Glass*	2,6	70-80	2000-3500
Karbonska *Carbon*	1,75-1,95	240-760	2400-5100
Aramidna *Aramid*	1,45	62-180	3600-3800
Bazaltna *Basalt*	2,8	90	4800

2.2 Matrica

Matrica je vezivni materijal, sa osnovnim zadatkom da drži vlakna zajedno i sačuva njihovu orijentaciju. Takođe, matrica ima ulogu da štiti vlakna od uticaja okruženja i mehaničkog habanja. Veoma je važno da matrica bude hemijski i termički kompatibilna s vlaknima, kao i da ima malu zapreminsku masu kako ne bi povećavala težinu kompozita [7]. Najčešće korišćeni polimer za FRP materijale u građevinarstvu je epoksid. Poliester ili vinilester se takođe upotrebljavaju. U Tabeli 2 prikazane su osnovne karakteristike matrica.

2.2 Matrix

Matrix is a bonding material, with the main task to hold the fibres together and preserve their orientation. Also, matrix has a role to protect fibres from environmental influences and abrasion. It is very important that the matrix is chemically and thermally compatible with the fibres, and that it has a small density in order to prevent the increase of weight of the composite to the great extend [7]. The most commonly used polymer for FRP materials in construction is epoxy. Polyesters and vinylesters are also used. Table 2 shows the main properties of the matrix.

Tabela 2. Karakteristike matrica [6]
Table 2. Matrix properties [6]

Materijal *Material*	Zapreminska masa *Density* (g/cm^3)	Modul elastičnosti *Modulus of elasticity* (GPa)	Čvrstoća na zatezanje *Tensile strength* (MPa)
Epoksid *Epoxy*	1,1-1,4	2,0-6,0	35-130
Poliester *Polyester*	1,1-1,5	1,2-4,5	40-90
Vinilester *Vinylester*	1,5	3,0-4,0	65-90

2.3 Kompozit

Karakteristike FRP materijala ne mogu se predvideti jednostavnim sumiranjem karakteristika njegovih sastavnih delova. Vlakna i matrica deluju komplementno da obezbede željene karakteristike obe komponente. Na primer, većina matrica na bazi polimera ima malu čvrstoću na zatezanje, ali izuzetnu tvrdoću i savitljivost, dok tanka vlakna imaju veliku čvrstoću na zatezanje, ali oseljivost na oštećenja. Generalno, karakteristike FRP kompozita zavise od karakteristika materijala vlakana i matrice, orijentacije vlakana (kod šipki obično vlakna postavljena u jednom pravcu), zapreminskog udela vlakana, i tako dalje.

Pultruzija je tehnologija koja se uglavnom koristi za proizvodnju FRP šipki, koje mogu biti u obliku kružnog ili kvadratnog poprečnog preseka, glatke ili

2.3 Composite

The properties of FRP materials cannot be predicted by simple summation of the characteristics of its component parts. The fibres and matrix act complementary so as to provide the desired characteristics of both components. For example, most polymer-based matrices have a low tensile strength, but excellent toughness and flexibility, whereas thin fibres have a high tensile strength, but they are sensitive to damage. Generally, the properties of FRP composites depend on material characteristics of fibre and matrix, fibre orientation (in the case of bars fibres are usually oriented in one direction), the percentage of fibres in the composite, etc.

Pultrusion is a technology that is generally used for production of FRP bars. Bars can have a circular or rebraste kao i peskarene (slika 1).

square cross section, and they can be smooth or ribbed, as well as sand-coated (Figure 1).

Slika 1. Tipovi FRP šipki
Figure 1. Types of FRP bars

2.4 Lepkovi

Ako nije postignut pravilan spoj između FRP kompozita i drveta neće se ostvariti spregnuto dejstvo i prevremeni lom može se dogoditi pri apliciranju većeg opterećenja. Stoga, uspešna primena FRP kompozita na konstrukcijske elemente zahteva da visokokvalitetni, trajni spoj bude ostvaren između dva različita materijala. Implementacija FRP ojačanja obično zahteva upotrebu lepkova. Postoji nekoliko prednosti primene lepljenog spoja, kao što su: mogućnost povezivanja različitih materijala, obezbeđivanje velike krutosti, ravnomerno raspodeljeno opterećenje i tako dalje. S druge strane, lepkovi su osetljivi na uslove sredine, kao što je vlažnost, i nisu pogodni kada su izloženi visokim temperaturama (otpornost na požar).

Postoji mnogo tipova prirodnih ili sintetičkih lepkova (elastomeri, termoplastični, termostabilni lepkovi) koji se mogu koristiti. Ipak, izbor odgovarajućeg lepka treba da bude načinjen na bazi raspoložive podloge i izabrane vrste FRP šipki. U okviru tehničkih listova za FRP proizvode, proizvođači obično navode koji lepak treba upotrebiti zavisno od konstrukcije koja se ojačava. Najpodesniji lepkovi za kompozitne materijale jesu lepkovi na bazi epoksida. Ovi lepkovi imaju određene prednosti kao što su dobre karakteristike popunjavanja pora na spojnim površinama, ograničeno skupljanje tokom vremena očvršćavanja, sposobnost očvršćavanja na ambijentalnim temperaturama i zahtevanje samo minimalnog pritiska u procesu spajanja.

2.4 Adhesives

If proper connection between FRP and timber is not achieved composite effect is unlikely to be accomplished and premature failure can occur. Therefore, successful application of FRP composites in structural elements requires the achievement of high-quality, durable connection between the two materials. Implementation of FRP reinforcement usually requires use of adhesives. There are several advantages of adhesives, such as the ability to connect different materials, high stiffness, uniformly distributed load, etc. On the other hand, the adhesives are sensitive to environmental factors such as humidity and they are unsuitable when exposed to high temperatures (low fire resistance).

There are many types of natural or synthetic adhesives (elastomers, thermoplastic, thermosetting adhesives) that can be used. However, the suitable adhesive should be chosen based on the material properties of the structure and the type of FRP bars. As part of the technical data sheets for FRP products, manufacturers usually specify which adhesive should be used depending on the structure that is being reinforced. The most suitable adhesives for composite materials are epoxy-based adhesives. These adhesives have certain advantages such as good filling of the pores of bonding surfaces, limited shrinkage during curing, the ability to cure at ambient temperatures and they require only minimal pressure in the process of bonding.

3 OJAČANJE DRVENIH ELEMENATA IZLOŽENIH SAVIJANJU

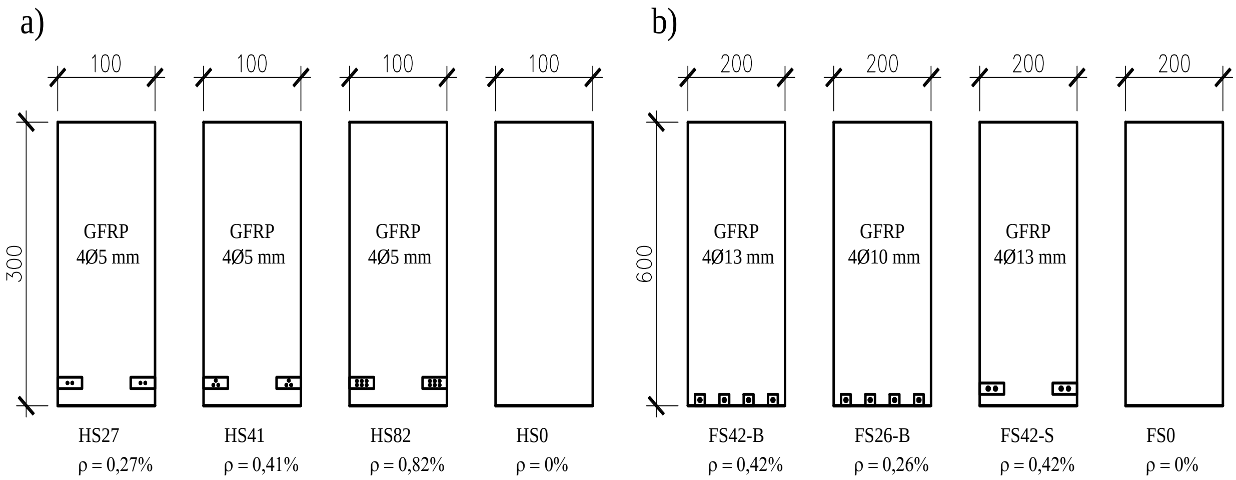
Kod drvenih elemenata napregnutih na savijanje, inicijalni lom nastaje uglavnom u zategnutoj zoni u blizini kvrga, defekta ili na mestima poprečnog nastavka lamela kod lepljenih lameliranih nosača. Lom usled zatezanja drveta izloženog savijanju je krt, nasumičan i teško predvidiv. Stoga, drveni nosači se uglavnom ojačavaju na zategnutoj strani, čime se povećava nosivost i krutost na savijanje i postiže znatno duktilniji lom u pritisnutoj zoni. Ojačanje postavljanjem šipki blizu površine u pripremljene proreze ne menja visinu nosača dok istovremeno štiti šipke od spoljašnjih uticaja. U različitim radovima do sada je ispitivano ponašanje monolitnih i lepljenih lameliranih drvenih nosača ojačanih FRP šipkama. U nastavku su prikazana neka od istraživanja.

3 STRENGHTENING OF TIMBER ELEMENTS SUBJECTED TO BENDING

In timber elements subjected to bending, initial failure occurs mainly in the tensile zone near knots, defects or finger joints of glued laminated beams. Tensile failure of timber is brittle, random and difficult to predict. Therefore, the timber beams are usually reinforced at tension side, which increases load carrying capacity and flexural stiffness. Also, this type of reinforcement allows for ductile failure in the compressive zone to be achieved. Positioning the bars near the surface in the prepared slots does not change the height of the beam and protects the bars from environmental influences. Various researchers so far have investigated the behaviour of solid and glued laminated timber beams reinforced with FRP bars. Some of the experimental investigations are presented in this paper.

Gentile, *Svecova* i *Rizkalla [8]* sproveli su eksperimentalno ispitivanje s ciljem procene ponašanja na savijanje trideset godina starih drvenih nosača (Duglasova jela) ojačanih šipkama na bazi staklenih vlakana (GFRP). Dvadeset dve grede (10x30x430 cm) isečene iz glavnih nosača starog drvenog mosta, od kojih je 15 ojačanih, ispitano je na savijanje. Grede su bile ojačane GFRP šipkama postavljenim u zategnutoj zoni sa bočnih strana (slika 2a). Uticaj površine ojačanja u poprečnom preseku bio je razmatran kroz tri procenta ojačanja: 0,27, 0,41 i 0,82%. Pored greda, četiri cela glavna nosača mosta (20x60x1040 cm), od kojih su tri ojačana, ispitano je s ciljem utvrđivanja uticaja efekata veličine uzorka na rezultate ojačanja. Ovi nosači su ojačani GFRP šipkama, koje su postavljene u zategnutoj zoni s donje strane preseka ili s bočnih strana (slika 2b). Procenti ojačanja kod nosača bili su 0,26 i 0,42%.

Gentile, Svecova and Rizkalla [8] conducted an experimental testing in order to assess flexural behaviour of 30-year-old timber beams (Douglas fir) reinforced with glass fibre reinforced polymer (GFRP) bars. Twenty two beams (10x30x430 cm) cut from the old timber bridge stringers, from which 15 were reinforced, were tested in bending. The beams were reinforced with GFRP bars positioned in tension zone on the sides of the beam (Figure 2a). Reinforcement percentages in the cross section were: 0.27, 0.41 and 0.82%. In addition, four whole timber bridge stringers (20x60x1040 cm), three of which were reinforced, were examined to investigate the size effect on the performance of strengthening technique. These beams were reinforced with GFRP bars, which were positioned in tension zone of the cross-section at the bottom or on the sides (Figure 2b). Percentages of reinforcement for stringers were 0.26 and 0.42%.



Slika 2. Poprečni preseci ispitanih ojačanih i neojačanih uzoraka [8]
Figure 2. Crossections of reinforced and unreinforced beams [8]

Istraživanje je pokazalo da su GFRP šipke efikasna tehnika ojačanja na savijanje monolitnih drvenih nosača. Slično ponašanje, u smislu oblika loma, dijagrama opterećenje–ugib, raspodele dilatacija i granične čvrstoće, zabeleženo je kod obe grupe ispitanih uzoraka. Nije evidentiran nikakav efekat veličine uzorka. Za procente ojačanja između 0,27 i 0,82%, granično opterećenje se povećalo 48–60%. Ojačanjem nosača prosečna vrednost granične dilatacije zatezanja drveta povećala se za 64%, što pokazuje da prisustvo ojačanja znatno umanjuje uticaj defekata u drvetu. Osim toga, kod 60% ojačanih uzoraka zabeleženi oblik loma je duktilni lom u pritisnutoj zoni.

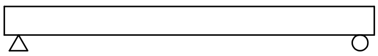
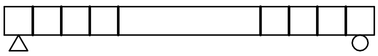
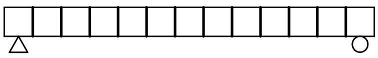
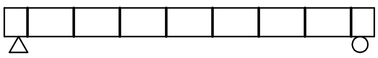
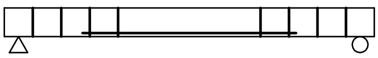
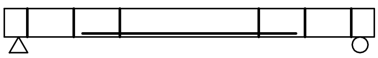
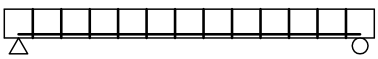
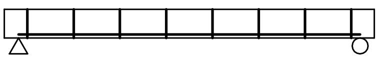
Svecova i *Eden [9]* sproveli su istraživanje kako bi doprineli razvoju praktične metodologije ojačanja postojećih drvenih mostova primenom GFRP šipki. Povod za ovo istraživanje jeste težnja da se umesto skupe zamene starih i oštećenih drvenih mostova ojačaju postojeće konstrukcije i na taj način im se produži upotrebni vek. Eksperimentalni program obuhvatio je ispitivanje na savijanje do loma 45 drvenih greda (Duglasova jela), isečenih iz glavnih nosača drvenih mostova oblasti Manitoba u Kanadi. Grede su bile dimenzija 10x30x200 cm. Generalno, dve šeme

The research showed that the GFRP bars are effective flexural strengthening technique for solid timber beams. Similar behaviour in terms of failure modes, load-deflection, strain distribution and ultimate strength was observed in both groups of tested beams. Size effect of the beams was not recorded. For reinforcement ratios between 0.27 and 0.82%, ultimate load increased 48-60%. Average tensile strain value increased by 64%, indicating that the presence of reinforcement significantly reduces the influence of defects in timber. In addition, in 60% of reinforced beams ductile failure in the compressive zone was recorded.

Svecova and Eden [9] carried out a research to contribute to the development of reinforcement techniques of existing timber bridges by using GFRP bars. The reason behind this study was the tendency to shift from costly replacements to strengthening of existing structures and thus to extend their service lives. The experimental program included testing in bending of 45 timber beams (Douglas fir), cut from the timber bridge stringers from Manitoba area in Canada. The dimensions of the beams were 10x30x200 cm. Overall, two reinforcement schemes were used in the test program. The first group, Group S, included 16 beams ojačanja primenjene su u okviru programa ispitivanja. Prva grupa, Grupa S, obuhvatila je 16 greda, koje su ojačane samo vertikalnim šipkama (prečnika 16 mm) kao ojačanjem na smicanje, dok je druga grupa od 20 greda, Grupa SF, pored vertikalnih imala i ojačanja u vidu dve horizontalne šipke sa bočnih strana (prečnika 5 mm), što je predstavljalo kombinaciju ojačanja na savijanje i na smicanje. Položaj i rastojanje vertikalnih šipki, kao i dužina horizontalnih šipki jesu parametri koji su varirani. Rezultati ispitivanja ojačanih greda upoređeni su s rezultatima ispitivanja grupe od devet neojačanih greda (Grupa C). Program eksperimentalnog ispitivanja dat je u tabeli 3.

that were reinforced only with vertical bars (diameter 16 mm) as shear reinforcement. The second group of 20 beams, SF Group, in addition to the vertical reinforcement had two horizontal bars positioned on the sides (diameter 5 mm), which was a combination of flexural and shear reinforcement. The position and spacing of vertical bars, as well as the length of the horizontal bars were the parameters that were varied. The test results of reinforced beams were compared with the results of 9 unreinforced beams (Group C). The program of experimental tests is given in Table 3.

Tabela 3. Program eksperimentalnog ispitivanja [9]
Table 3. The program of experimental tests [9]

Oznaka uzoraka *Beam label*	Šema ojačanja *Reinforcement scheme*	Broj uzoraka *Number of beams*
C		9
S-S150		5
S-C150		6
S-C300		5
SF-S150		5
SF-S300		5
SF-C150		5
SF-C300		5

Eksperimentalno ispitivanje dovelo je do sledećih zaključaka:

– upotreba GFRP šipki pokazala se kao primenljiva za ojačanje drvenih greda;

– optimalno rastojanje vertikalno postavljenih šipki za povećanje smičuće nosivosti treba da bude jednako širini poprečnog preseka;

– grede ojačane samo na smicanje pokazale su povećanje nosivosti od 33%, dok su kombinovano ojačane grede pokazale povećanje od 47% do 52%;

– upotreba kombinovanog ojačanja uzrokuje lom u pritisnutoj zoni, kome prethode velike deformacije, što može poslužiti kao upozorenje pre loma grede;

– upotreba ojačanja smanjuje prirodnu varijabilnost mehaničkih karakteristika drveta u različitim pravcima;

– veze između GFRP, lepka i drveta nisu pokazale znake popuštanja pre nastupanja loma čitave grede;

– dijagrami kombinovano ojačanih greda opterećenje–ugib pokazali su duktilno ponašanje, pri čemu je 60% greda imalo dva puta veće ugibe pri lomu u odnosu na neojačane grede.

Istraživanje *Amy* i *Svecova [10]* predstavlja nastavak eksperimentalnog programa ojačanja glavnih nosača

The research has led to the following conclusions:

– Use of GFRP bars proved to be feasible for reinforcing timber beams;

– Optimal spacing between vertical shear bars is equal to the width of the cross section;

– Shear reinforced beams have shown an increase in load carrying capacity of 33%, while both shear and flexural reinforced beams showed an increase of 47% to 52%;

– Using both flexural and shear strengthening of timber increased the strength of the beams and also introduced compressive failure accompanied by large deflections before it, which served as warning of impending failure;

– Introduction of both flexural and shear reinforcement reduced the inherent strength variability of timber;

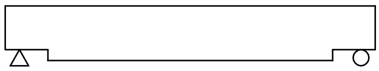
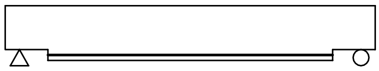
– Bonds between GFRP, timber and epoxy showed no signs of fracture before the failure of the entire beam;

– Load–deflection curves of beams from group SF became pseudo-ductile with 60% of tested beams experiencing twice the amount of deflection compared with control beams.

drvenih mostova. Sva istraživanja do tada su sprovedena na pravougaonim gredama bez zasečenih krajeva. Međutim, većina drvenih nosača u okviru mostova u kanadskoj oblasti Manitoba imala je redukovanu visinu na krajevima. Zbog koncentracije napona na mestu nagle promene visine, na zasečenim delovima nosača, ovaj eksperimentalni program obuhvatio je ojačanje zasečenih drvenih nosača. Ukupno 26 drvenih nosača (10x40x340 cm) ispitano je na savijanje do loma: osam neojačanih (kontrolnih) uzoraka (Grupa C), 12 ojačanih horizontalnim GFRP šipkama (prečnika 12 mm) u oblasti najvećih napona savijanju u zategnutoj zoni (Grupa F) i šest ojačanih horizontalnim GFRP šipkama u zategnutoj zoni i kosim GFRP šipkama, pod uglom od 60º prema horizontalnoj ravni, kao ojačanje na smicanje (Grupa FD). Program eksperimentalnog ispitivanja dat je u tabeli 4.

The research of Amy and Svecova [10] represents further investigation of timber bridge stringers reinforcement. All previous research in this area was conducted on rectangular beams, without dapped ends. However, the majority of timber bridge stingers in Manitoba (Canada) have dapped ends. Because of the stress concentration at daps, this experimental program investigated flexural strengthening of dapped timber stringers. A total of 26 timber beams (10x40x340 cm) were tested in bending to failure: 8 unreinforced (control) stringers (group A), 12 stringers reinforced with GFRP bars (diameter 12 mm) in tensile region (Group F) and 6 stringers reinforced with GFRP bars in tensile zone and GFRP dowel bars inclined at an angle of 60º to the horizontal plane for shear reinforcement (Group FD). The program of experimental tests is given in Table 4.

Tabela 4. Program eksperimentalnog ispitivanja [10]
Table 4. The program of experimental tests [10]

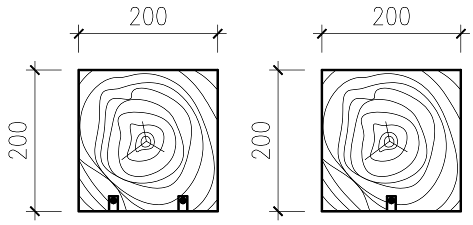
Grupa uzoraka *Beam group*	Šema ojačanja *Reinforcement scheme*	Broj uzoraka *Number of beams*
C		8
F		12
FD		6

Primena samo ojačanja na savijanje ne preporučuje se za zasečene nosače, jer je dominantan smičući lom na zasečenom delu, koji znatno redukuje nosivost nosača. Usled primene ojačanja i na savijanje i na smicanje za ovaj tip nosača povećalo se granično opterećenje za 22%, uz promenu oblika loma (pritisak upravno na vlakna u pritisnutoj zoni). Duktilnost nosača je, takođe, povećana primenom GFRP ojačanja. Znatno veće povećanje duktilnosti zabeleženo je kod nosača ojačanih i na savijanje i na smicanje u odnosu na nosače ojačane samo na savijanje.

Borri, Corradi i *Grazini [11]* su teorijski i eksperimentalno ispitivali ojačanja postojećih drvenih elemenata izloženih savijanju primenom FRP materijala. Kako bi utvrdili krutosti, nosivosti i duktilnosti ojačanih drvenih greda, dvadeset greda dimenzija 20x20x400 cm ispitano je u okviru eksperimentalnog dela. Pored uzoraka ojačanih karbonskim tkaninama, ispitano je i pet drvenih greda ojačanih karbonskim šipkama (CFRP). U zategnutoj zoni, blisko donjoj površini, postavljena je jedna ili dve šipke, prečnika 7,5 mm (slika 3). Dodatno, jedna greda je ojačana s dve prednapregnute karbonske šipke.

The use of flexural reinforcement only is not recommended for dapped beams because shear failures at daps can occur and reduce the ultimate strength of the beam significantly. The use of both flexural and shear reinforcement for this type of beams has led to an increase in ultimate load of 22%, with a change of failure mode (compression perpendicular to the grain in the compressive zone). Ductility of stringers was also improved by GFRP reinforcement. Beams with both flexural and shear reinforcement had significantly greater ductility increase compared to those with only flexural reinforcement.

Borri, Corradi and Grazini [11] have theoretically and experimentally investigated the strengthening of existing timber elements subjected to bending with FRP materials. In order to determine the stiffness, load carrying capacity and ductility of reinforced timber beams, 20 beams (20x20x400 cm) were experimentally tested. In addition to the beams reinforced with carbon fibre reinforced polymer (CFRP) sheets, 5 timber beams reinforced with CFRP bars were tested. In tensile zone, close to the bottom surface, one or two bars with a diameter of 7.5 mm were placed (Figure 3). In addition, one beam was reinforced with two prestressed carbon bars.



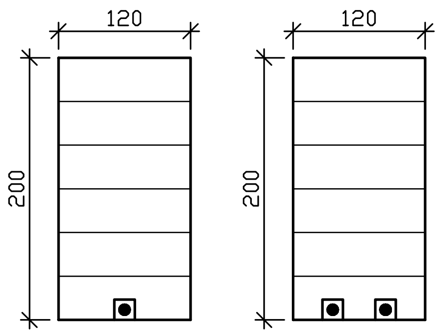
Slika 3. Šeme ojačanja greda s karbonskim šipkama [11]
Figure 3. Schemes for beams with CFRP bar reinforcement [11]

U oba slučaja ojačanja s karbonskim šipkama zabeleženo je povećanje nosivosti i krutosti (28,9% i 22,0% za slučaj jedne šipke, odnosno 52,0% i 25,5% za slučaj dve šipke). Međutim, grede ojačane karbonskim šipkama pokazale su manje duktilno ponašanje od greda ojačanih karbonskim tkaninama, kao i u poređenju s neojačanim gredama. Pozitivan efekat izazvan prisustvom šipki nije bio dovoljan da ograniči lokalna oštećenja i premosti lokalne defekte u drvetu. Prednaprezanje CFRP šipki nije vodilo ka bilo kakvom značajnijem poboljšanju u poređenju s neprednapregnutim ojačanjem. Kako se radilo o malom broju uzoraka, autori preporučuju dalja eksperimentalna ispitivanja s različitim vrstama drveta i većim brojem greda.

Micelli, Scialpi i *La Tegola [12]* razmatrali su mogućnost upotrebe šipki na bazi karbonskih vlakana (CFRP) kao ojačanja lepljenih lameliranih drvenih nosača. Šest nosača od lepljenog lameliranog drveta (smreka), od čega četiri ojačana, ispitano je na savijanje. Nosači (12x20x500 cm) su ojačani karbonskim šipkama prečnika 12,5 mm (jednom ili dve) postavljenim u zategnutoj zoni, u neposrednoj blizini donje površine (slika 4).

In both cases of the beams reinforced with CFRP bars an increase in maximum load and stiffness was recorded (28.9% and 22.0% in the case of one bar, and 52.0%, and 25.5% in the case of two bars). However, the beams reinforced with CFRP bars have shown less ductile behaviour when compared to the beams reinforced with CFRP sheets, as well as compared to unreinforced beams. The positive effect caused by the presence of bars was insufficient to limit raptures and bridge local defects in timber. Prestressing CFRP bars did not lead to any significant improvement compared to regular reinforcement. Since the number of specimens was small, the authors recommended further research with different types of wood and a larger number of beams.

Micelli, Scialpi and La Tegola [12] investigated the possibility of using CFRP bars as a reinforcement for glued laminated timber beams. Six glued laminated timber (spruce) beams, out of which four were reinforced, were tested in bending. Specimens (12x20x500 cm) were reinforced with CFRP bars with a diameter of 12.5 mm (one or two bars) in the tensile zone, close to the bottom surface (Figure 4).



Slika 4. Poprečni preseci ojačanih nosača [12]
Figure 4. Crossections of reinforced beams [12]

Eksperimentalni rezultati su pokazali da se postavljanjem CFRP šipki sa zategnute strane poprečnog preseka može značajno poboljšati nosivost i krutost nosača. Za procente ojačanja 0,51% i 1,03%, zabeleženo je povećanje graničnog momenta od 26% i 82%, odnosno povećanje krutosti od 8% i 19% u odnosu na neojačane nosače. Oblici loma i eksperimentalni podaci pokazali su odlične karakteristike spoja između dreveta i karbonskih šipki. Lom kako neojačanih, tako i ojačanih nosača zavisio je pre svega od čvrstoće drveta na zatezanje.

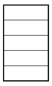
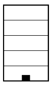
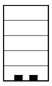
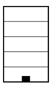
Johnsson, Blanksvard i *Carolin [13]* su istraživali ojačanje nosača od lepljenog lameliranog drveta

Experimental results showed that CFRP bars positioned in tensile zone can significantly improve ultimate moment and stiffness of the beam. For reinforcement ratios of 0.51% and 1.03%, an increase in the ultimate moment was recorded 26% and 82%, and an increase in stiffness 8% and 19% compared to unreinforced beams. Failure modes and experimental data showed excellent bond properties between timber and bars. Failure of both unreinforced and reinforced beams depended primarily on the tensile strength of timber.

Johnsson, Blanksvard and Carolin [13] explored pomoću CFRP šipki. Posebna pažnja bila je usmerena ka utvrđivanju potrebne minimalne dužine sidrenja ojačanja, pri kojoj neće doći do pojave prevremenog loma. Ukupno je ispitano deset lepljenih lameliranih nosača (smreka), porečnog preseka 9x22,5 cm i dužine 350 cm. Karbonske šipke (pravougaonog poprečnog preseka, 10x10 mm) postavljene su unutar preseka, u neposrednoj blizini donje površine. Program eksperimentalnog ispitivanja dat je u tabeli 5.

reinforcing glued laminated timber beams using CFRP bars. Special attention was given to the minimum anchoring length of reinforcement that will not cause premature failure. A total of 10 glulam beams (spruce) were tested (9 x 22.5 x350 cm). CFRP bars (rectangular, 10 x 10 mm) were placed inside the cross section near the bottom surface. The program of experimental tests is given in Table 5.

Tabela 5. Program eksperimentalnog ispitivanja [13]
Table 5. The program of experimental tests [13]

Serija uzoraka *Beam series*	Tip *Type*	Ojačanje *Reinforcement*	Broj uzoraka *Number of beams*
1		Bez ojačanja *No reinforcement*	3
2		1 šipka centralno postavljena u zategnutoj zoni, celom dužinom nosača *1 bar centrally positioned in tensile zone, along the beam's length*	3
3		2 šipke simetrično postavljene u zategnutoj zoni, celom dužinom nosača *2 bars symmetrically positioned in tensile zone, along the beam's length*	3
4		1 šipka centralno postavljena u zategnutoj zoni, kraće dužine *1 bar centrally positioned in tensile zone, shorter length*	1

Rezultati su pokazali da pored povećanja nosivosti na savijanje od 40 do 60% i povećanja krutosti od 5 do 25% ovaj metod ojačanja menja tip loma iz krtog u zatežućoj zoni u duktilni lom u pritisnutoj zoni. Kao posledica duktilnog ponašanja ojačanih nosača, ugib u sredini nosača pri lomu povećao se do 80%. Rezultati eksperimentalne i teorijske analize dužine sidrenja CFRP šipke pokazali su da je minimalna potrebna dužina 150 mm.

Raftery i *Whelan [14]* su u svom radu istraživali različite dispozicije ojačanja lepljenog lameliranog drveta niže klase sa GFRP šipkama (slika 5). Ispitano je pet nosača svake serije s rasponom od 342 cm i dimenzijama poprečnog preseka 9,6x19 cm. Kao što se može videti na slici 5, ispitivan je uticaj upotrebe više šipki manjeg prečnika naspram šipki većeg prečnika, zatim oblik proreza u koji se postavljaju šipke, kao i ojačanje u obe zone (pritisnuta i zategnuta zona) nosača. Procenti ojačanja za razmatrane šeme ojačanja iznosili su redom: 1,05; 1,4; 1,4 i 2,8%.

Zaključci dobijeni eksperimentalnim ispitivanjem su sledeći:

– veći kapacitet nosivosti i veća krutost dostižu se primenom kružnih u odnosu na kvadratne proreze za postavljanje šipki usled smanjenja koncentracije napona na ivicama proreza;

– upotreba više šipki manjih prečnika nije pokazala poboljšanje u nosivosti i krutosti bez obzira na povećanje površine lepljenja između lepka i šipki;

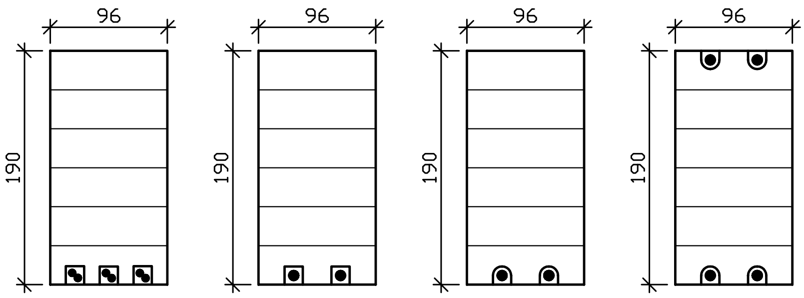
The results showed that in addition to flexural capacity increase of 40-60% and an increase in stiffness of 5-25% this method changes the type of failure from brittle in tensile zone to ductile failure in compressive zone. As a result of ductile behaviour of the reinforced beams, the mid-span deflection at failure increased up to 80%. The results of experimental and theoretical analysis of the anchoring length of CFRP bars showed that the minimum required length was 150 mm.

Raftery and Whelan [14] explored different arrangements of reinforcing low-grade glulam beams using GFRP bars (Figure 5). Five beams of each series with a span of 342 cm and cross section dimensions of 9.6x19 cm were tested. As it can be seen in Figure 5, they inspected the use of multiple bars with smaller diameter against the bars with larger diameter, shape of the grooves where bars were placed and reinforcement in both compressive and tensile zone of the beam. The reinforcement ratios for different schemes were, respectively: 1.05; 1.4; 1.4 and 2.8%.

The conclusions obtained by experimental tests were as follows:

– Greater ultimate moment capacity and stiffness were achieved with the use of circular routed out grooves in comparison with square grooves for the reinforcement, due to the reduction of stress concentration at the edges of the groove;

– The use of multiple smaller diameter bars per groove showed no improvement in strength and stiffness regardless to the increase of the bond surface area between adhesive and bars;



Slika 5. Poprečni preseci ojačanih nosača [14]
Figure 5. Cross sections of reinforced beams[14]

– ojačani nosači dostigli su duktilni lom u pritisnutoj zoni za razliku od neojačanih koji su krti lom dostizali u zategnutoj;

– s većim procentom ojačanja postiže se i veće iskorišćenje mehaničkih svojstava drveta u pritisnutoj zoni;

– upotreba procenta ojačanja od 1,4% u zategnutoj zoni dovela je do povećanja krutosti od 11,2% i nosivosti od 68%, dok je ojačanje od 1,4% u zategnutoj i 1,4% u pritisnutoj zoni dovelo do povećanja krutosti od 22% i nosivosti od 98,5%.

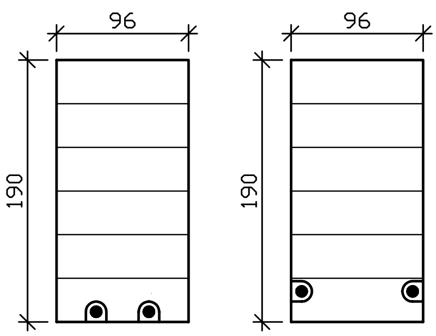
Raftery i *Kelly [3]* su istraživali primenu šipki na bazi bazaltnih vlakana (BFRP). U svom radu su pokazali da BFRP šipke imaju nešto bolje karakteristike od GFRP šipki. Ispitano je pet nosača svake serije sa rasponom od 342 cm i dimenzijama poprečnog preseka 9,6x19 cm. Rezultati ojačanja su dosta slični onim koji se dobijaju ojačavanjem GFRP šipkama. Pored postavljanja ojačanja na donjoj zategnutoj strani nosača, ispitano je i postavljanje šipki u proreze sa strane (slika 6), što je povoljnije sa estetske strane. Međutim, ovako postavljeno ojačanje daje manje povećanje nosivosti nosača, jer položaj ojačanja nije optimalan u odnosu na neutralnu osu poprečnog preseka.

– Reinforced beams have reached the ductile failure in the compressive zone in comparison with the unreinforced beams that reached brittle tensile failure;

– With higher reinforcement percentages greater utilisation of mechanical properties of timber in the compressive zone was achieved;

– The use of reinforcement percentage of 1.4% in the tensile zone has led to an increase in stiffness of 11.2% and ultimate moment capacity of 68%, while the reinforcement of 1.4% in the tensile and 1.4% in the compressive zone has led to an increase in stiffness of 22% and ultimate moment capacity of 98.5%.

Raftery and Kelly [3] investigated the use of basalt fibre reinforced polymer (BFRP) bars. In this paper it was shown that BFRP bars have a somewhat better performance than the GFRP bars. Five beams of each series with a span of 342 cm and the cross section dimensions 9.6x19 cm were tested. The results of reinforcement are quite similar to those obtained from reinforcing with GFRP bars. In addition to positioning the reinforcement on the bottom tensile side of the beams, positioning the bars into slots on the sides was also investigated (Figure 6), which is aesthetically more favourable. However, this provided a lesser increase in the ultimate moment capacity, because the position of the bars was not optimal in relation to the neutral axis of the cross section.

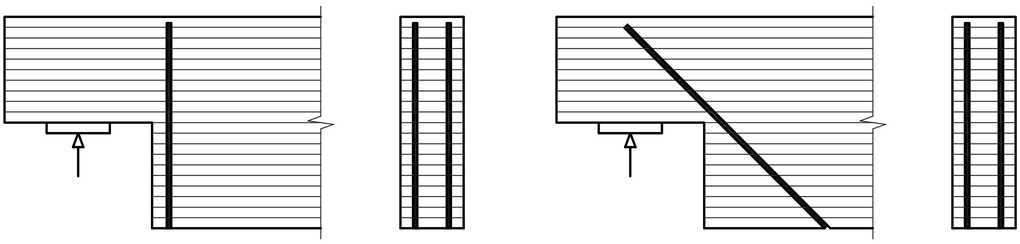


Slika 6. Poprečni preseci ojačanih nosača [3]
Figure 6. Cross sections of reinforced beams [3]

Lokalno ojačanje drvenih nosača različitim vrstama FRP šipki prikazali su *Franke*, *Franke* i *Harte [15]*. U slučaju kada se oslanjanje nosača izvodi s redukovanom visinom nosača iznad oslonca, koncentracije napona koje se javljaju u uglu uzrokuju otvaranje pukotina na

Local reinforcement of timber beams using FRP bars was investigated by Franke, Franke and Harte [15]. In the case of notched end beams, the stress concentration at the corner of the notch leads to crack initiation and rapid crack propagation, which can result in a sudden tom mestu i njihovu brzu progresiju kroz poprečni presek elementa, što može izazvati lom. Pored smičućih napona javljaju se i naponi zatezanja upravni na vlakna. Predložene metode ojačanja prikazane su na slici 7 [15]. Ojačanje je postavljeno upravno na vlakna ili pod uglom od 45°.

brittle failure of the beam. In addition to shear stress, high tensile stress perpendicular to the grain occurs. The proposed reinforcement methods are shown in Figure 7 [15]. Reinforcement was positioned perpendicular to the grain or at an angle of 45° to the beam axis.



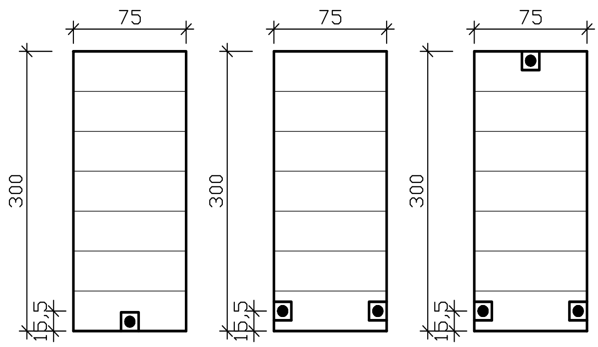
Slika 7. Ojačanje na mestu redukovane visine nosača – neposredno uz oslonac [15]
Figure 7. Reinforcement arrangements for notches [15]

Primena ojačanja pod uglom od 45° dala je znatno bolje rezultate, pre svega zbog velikih smičućih napona u ovim presecima. Pored povećanja nosivosti, ojačanje ovog tipa omogućilo je i duktilniji lom nosača. Istraživanje je pokazalo da FRP šipke treba da budu postavljene što bliže uglu zasecanja, pri čemu je veoma važno da uslov o minimalnim rastojanjima bude zadovoljen.

Yang i grupa autora [16] su istraživali ojačanje lepljenolameliranih nosača sa GFRP šipkama, GFRP i CFRP trakama i čeličnim šipkama. Nosači dimenzija poprečnog preseka 7,5x30 cm ispitivani su na savijanje. Ukupno 46 nosača dužine 6 m i raspona 5,7 m eksperimentalno je testirano. Konfiguracija ojačanja šipkama prikazana je na slici 8. Dobijeni rezultati su upoređeni sa analitički određenim vrednostima.

The use of reinforcement at an angle of 45° showed significantly better results, primarily due to high shear stresses. In addition to enhanced load carrying capacity, the reinforcement allowed for less brittle failure modes of the beams to occur. Research has shown that FRP bars should be placed as close as possible to the notch corner, while also satisfying the requirements for minimum edge distance and spacing of the bars.

Yanget al.[16]investigated reinforcement of glulam beams with GFRP bars, GFRP and CFRP plates and steel bars. Beams with cross section dimensions of 7.5x30 cm were tested in bending. Total of46 beams with a length of 6 m and 5.7 m span were experimentally tested. Configuration of the reinforcement bars is shown in Figure 8. The results were compared with analytically obtained values.



Slika 8. Šeme ojačanja greda s karbonskim šipkama [16]
Figure 8. Schemes for beams with CFRP bar reinforcement [16]

Eksperimenti su pokazali da s povećanjem procenta ojačanja raste nosivost, krutost, maksimalni ugib u sredini nosača, kao i duktilnost nosača. Postavljanje ojačanja i u pritisnutoj zoni umanjuje duktilnost i nelinearno ponašanje u poređenju s gredama ojačanim samo u zategnutoj zoni. Takođe, ojačanje u pritisnutoj zoni dovodi do vrlo malog povećanja kapaciteta nosivosti u odnosu na iste nosače ojačane samo u zategnutom delu preseka.

Experiments have shown that with the increase in reinforcement percentages ultimate load, stiffness, maximum mid-span deflection, and ductility of the beam increases. Introduction of compressive reinforcement reduced ductility and nonlinear behaviour in comparison with the beams reinforced only in the tensile zone. Also, compressive reinforcement led to a very small increase in the load carrying capacity compared to the same beam reinforced only in the tensile zone.

4 ANALITIČKI PRORAČUN

4.1 Proračunski model

Razvoj proračunskog modela kojim se može odrediti krutost i granična nosivost ojačanih nosača važan je za optimalnu upotrebu FRP šipki, kao i za njihovu širu primenu. Proračun drvenih konstrukcija obično se sprovodi prema teoriji dopuštenih napona usled anizotropnog i složenog ponašanja drveta kao materijala. Kod drvenih nosača izloženih savijanju inicijalni lom nastaje uglavnom u zetegnutoj zoni, a ponašanje drveta se predstavlja jednostavnim linearno-elastičnim modelom. Dodavanjem kompozitnih materijala drvenim elementima, veza napon-dilatacija u poprečnom preseku se menja, pa pri proračunu treba uzeti u obzir i plastično ponašanje drveta u pritisnutoj zoni. Kako bi se što bolje prikazalo ponašanje ojačanih drvenih nosača, nelinearnost mora biti izražena u analitičkom modelu.

Na osnovu dosadašnjih ispitivanja [16] prikazan je teorijski model s ciljem predviđanja ponašanja drvenih nosača ojačanih FRP šipkama. Analitičkim proračunom se određuje moment savijanja u najopterećenijem preseku nosača za određeni nivo dilatacije zatezanja ivičnih drvenih vlakana.

Osnovne pretpostavke modela su:

– poprečni preseci pri deformaciji ostaju ravni;

– lepljeni sloj između šipke i drveta je idealan;

– ponašanje drveta je linearno-elastično pri zatezanju i elasto-idealno plastično pri pritisku;

– ponašanje FRP ojačanja pri zatezanju je linearno-elastično;

– uticaj slabljenja poprečnog preseka usled plastifikacije se zanemaruje.

Ojačani drveni nosač se ponaša linearno-elastično do dostizanja dilatacije tečenja drveta na gornjoj ivici preseka. Kada dilatacija pritiska pređe granicu elastičnosti javlja se plastifikacija pritisnute zone i pomera se neutralna osa. Ponašanje nosača nakon toga je plastično do loma, dostizanjem graničnog napona zatezanja na donjoj ivici ili loma usled dostizanja granične dilatacije pritiska na gornjoj ivici drvenog preseka.

Idealizovana raspodela dilatacija i napona po visini ojačanog nosača poprečnog presekaojačanog FRP šipkama ukupne površine poprečnog b/h preseka A_f prikazana je na slici 9.

Ako su dilatacije ε_{wt} i ε_{wcy} poznate (eksperimentalno utvrđene ili standardom definisane) iz uslova kompatibilnosti mogu se odrediti karakteristične dilatacije u poprečnom preseku:

4 THEORETICAL ANALYSIS

4.1 Proposed model

Development of theoretical model that can determine the stiffness and ultimate moment capacity of reinforced beams is important for optimal use of FRP bars, as well as their wider application. Design of timber structures is usually performed according to allowable stress design due to anisotropic and complex behaviour of timber as a material. For timber beams exposed to bending initial failure occurs mainly in tensile zone and timber behaviour is presented by simple linear-elastic model. By adding a composite material to timber element stress-strain relationship in cross section changes, therefore the design should take into account plastic behaviour of timber in the compressive zone. In order to accurately describe the behaviour of reinforced timber beams, nonlinearity must be considered in the analytical model.

Based on previous research [16] a theoretical model was developed in order to predict the behaviour of timber beams reinforced with FRP bars. Analytical design determines ultimate moment capacity of the beam for a known ultimate tensile strain of edge timber fibres.

Basic assumptions of the model are:

– The cross sections under deformation remain plane;

– Bond layer between bars and timber is ideal;

– he behaviour of timber is linear-elastic in tension and elastic-perfectly plastic in compression;

– Behaviour of FRP reinforcement in tension is linear elastic;

– The weakening of the cross section due to plasticization is not taken into account.

Reinforced timber beam acts linear elastic until it achieves yielding of timber at the top of the beam. When the compressive strain exceeds ultimate elastic strain plasticization of compressive zone occurs and there is a shift of neutral axis. Behaviour of the beam after that is plastic until it reaches the tensile failure at the bottom or failure caused by the ultimate compressive strain at the top of the cross section.

Idealised stress and strain distribution through the height of the beam (dimensions b/h) reinforced with FRP bars with cross section of A_f is shown in Figure 9.

For known strains ε_{wt} and ε_{wcy} (experimentally obtained or defined in the standard) characteristic strains can be determined from compatibility conditions:

$$\varepsilon_{wc} = \left(z_3 + z_2\right) / z_2 \cdot \varepsilon_{wcy}$$

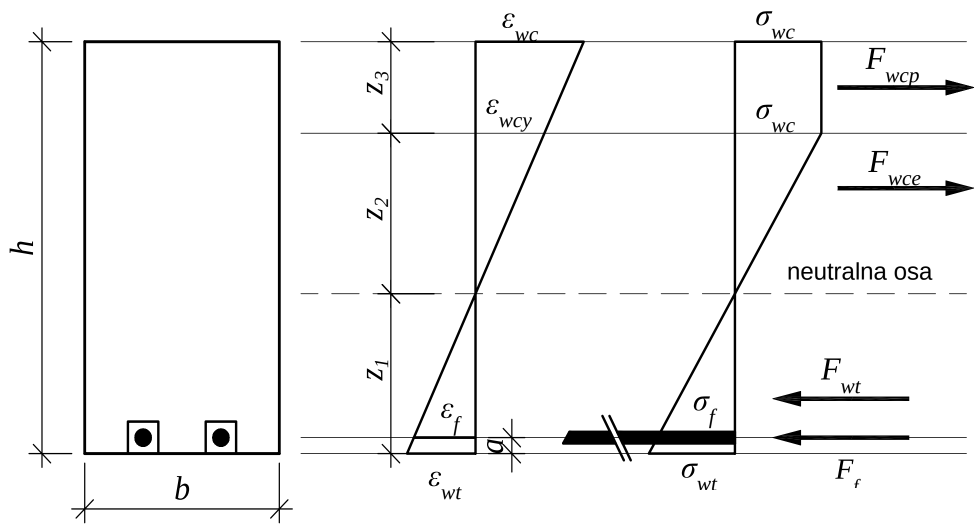
$$\varepsilon_f = \left(z_1 - a\right) / z_1 \cdot \varepsilon_{wt}$$

sa

with

$$z_2 = \varepsilon_{wcy} / \varepsilon_{wt} \cdot z_1$$

$$z_3 = h - \left(z_1 + z_2\right)$$



Slika 9. Raspodela napona i dilatacija u okviru poprečnog preseka
Figure 9. Stress and strain distribution in the cross section

gde je:

ε_{wt} – dilatacija zatezanja na donjoj ivici drvenog preseka;

ε_{wcy} – dilatacija plastičnog tečenja drveta;

ε_{wc} – dilatacija pritiska na gornjoj ivici drvenog preseka;

ε_f – dilatacija zatezanja u FRP šipkama;

z_1 – rastojanje neutralne ose do donje ivice drvenog preseka;

z_2 – rastojanje neutralne ose do zone plastifikacije drvenog preseka;

z_3 – visina zone plastifikacije drvenog preseka;

a – rastojanje od donje ivice drvenog preseka do težišta FRP šipki;

Za poznate dilatacije, vrednosti napona se mogu izračunati prema poznatim vezama napon–dilatacija:

where:

ε_{wt} –tensile strain of timber at the bottom;

ε_{wcy} – compressive yield strain of timber;

ε_{wc} – compressive strain of timber at the top;

ε_f – tensile strain of FRP bars;

z_1 – distance of neutral axis from bottom of the cross section;

z_2 – distance of neutral axis from plasticized zone of timber;

z_3 – height of plasticized zone of timber;

a – distance from the bottom of cross section to the centroid of FRP bars;

For known strains, stress values can be calculated through known stress-strain relationships:

$$\sigma_{wt} = E_w \cdot \varepsilon_{wt}$$
$$\sigma_{wc} = E_w \cdot \varepsilon_{wcy} = f_{wc}$$
$$\sigma_f = E_f \cdot \varepsilon_f$$

gde je:

σ_{wt} – napon zatezanja na donjoj ivici drvenog preseka;

σ_{wc} – napon pritiska u okviru zone plastifikacije drvenog preseka;

σ_f – napon zatezanja u FRP šipkama;

E_w – modul elastičnosti drveta pri savijanju;

E_f – modul elastičnosti FRP šipke;

f_{wc} – čvrstoća drveta na pritisak;

where:

σ_{wt} – tensile stress in timber at the bottom;

σ_{wc} – compressive yield stress in timber;

σ_f – tensile stress in FRP bars;

E_w – timber modulus of elasticity in bending;

E_f – FRP bars modulus of elasticity;

f_{wc} – compressive strength of timber;

Položaj neutralne ose određuje se iz uslova ravnoteže unutrašnjih sila:

The position of neutral axis is determined from internal forces equilibrium equations:

$$F_{wcp} + F_{wce} = F_f + F_{wt}$$

gde su unutrašnje sile definisane u skladu s dijagramima napona u poprečnom preseku:

where internal forces are defined in accordance to the stress configuration in the cross section:

$$F_{wcp} = z_3 \cdot b \cdot \sigma_{wc}$$
$$F_{wce} = 0,5 \cdot z_2 \cdot b \cdot \sigma_{wc}$$
$$F_{wt} = 0,5 \cdot z_1 \cdot b \cdot \sigma_{wt}$$
$$F_f = A_f \cdot \sigma_f$$

Rezultujući moment savijanja može se izračunati kao suma momenata unutrašnjih sila oko neutralne ose:

Ultimate moment can be calculated as a sum of moments from internal forces around neutral axis:

$$M_u = \frac{2}{3} \cdot z_1 \cdot F_{wt} + (z_1 - a) \cdot F_f + \left(z_2 + \frac{z_3}{2} \right) \cdot F_{wcp} + \frac{2}{3} \cdot z_2 \cdot F_{wce}$$

Krutost na savijanje ojačanih nosača može se izračunati koristeći teoriju kruto spregnutih preseka za linearno-elastično stanje. Plastične deformacije ne razmatraju se jer se krutost koristi za proveru graničnog stanja upotrebljivosti. Položaj neutralne ose u odnosu na težište drvenog preseka, odnosno ojačanja z_w i z_f (slika 10) računaju se prema izrazima:

Flexural stiffness of reinforced beams can be calculated using the theory of composite cross sections in the linear-elastic state. Plastic deformations are not considered because the stiffness is used for serviceability limit states. The position of the neutral axis with respect to the centroid of timber cross section and reinforcement, z_w and z_f (Figure 10) is calculated as follows:

$$z_w = \frac{E_f \cdot A_f \cdot \left(\frac{h}{2} - a \right)}{E_w \cdot A_w + E_f \cdot A_f}$$
$$z_f = \frac{h}{2} - a - z_w$$

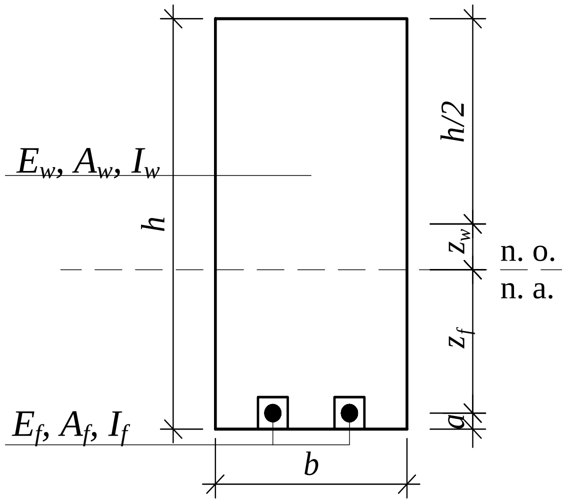
Krutost na savijanje može se izračunati prema sledećem izrazu:

Flexural stiffness is calculated as follows:

$$EI = E_w \cdot I_w + E_f \cdot I_f + E_w \cdot A_w \cdot z_w^2 + E_f \cdot A_f \cdot z_f^2$$

gde su A_w i A_f površine poprečnih preseka drveta i ojačanja, a I_w i I_f su sopstveni momenti inercije poprečnog preseka drveta i ojačanja.

where A_w and A_f are areas of cross section of timber and reinforcement, and I_w are I_f are moments of inertia of timber and reinforcement.



Slika 10. Geometrijske karakteristike poprečnog preseka potrebne za proračun krutosti
Figure 10. Geometry properties of the cross section necessary for stiffness calculation

4.2 Verifikacija proračunskog modela

Verfikacija predloženog analitičkog modela izvršena je poređenjem sa eksperimentalno dobijenim rezultatima iz istraživanja sprovedenog u [16]. Da bi se usvojeni model primenio, potrebno je poznavati vrednosti napona i dilatacija koje definišu konstitutivne modele materijala. Zato je izbor adekvatnih vrednosti za granične napone drveta najbitnija tačka proračuna. Mehaničke karakteristike za drvo i GFRP šipke korišćene u proračunu date su u tabeli 6.

4.2 Verification of theoretical model

Verification of proposed analytical model was done through comparison with experimental results obtained from a research carried out in [16]. In order to implement the model it is necessary to know the values of stresses and strains that define the constitutive models of materials. Thus, the selection of appropriate values of ultimate timber stresses is the most important step of the calculation. The mechanical properties of timber and GFRP bars used in the calculation are given in Table 6.

Tabela 6. Mehaničke karakteristike materijala [16]
Table 6. Mechanical properties of materials [16]

Karakteristika *Property*		Vrednost *Value*
ε_{wtu}	Granična dilatacija zatezanja pri savijanju drveta *Ultimate tensile strain of timber in bending*	3,56‰
ε_{wcy}	Dilatacija plastičnog tečenja drveta *Compressive yield strain of timber*	3,35‰
ε_{wcu}	Granična dilatacija pritiska drveta *Ultimate compressive strain of timber*	12‰
f_{wc}	Čvrstoća drveta na pritisak *Compressive strength of timber*	36 MPa
E_w	Modul elastičnosti drveta pri savijanju *Timber modulus of elasticity in bending*	10760 MPa
E_f	Modul elastičnosti GFRP šipke Ø12 *Ø12 GFRP barmodulus of elasticity*	35300 MPa
E_f	Modul elastičnosti GFRP šipke Ø16 *Ø16 GFRP barmodulus of elasticity*	30400 MPa

Prilikom modeliranja drveta kao materijala uzeta je u obzir činjenica da je granični napon zatezanja pri lomu usled savijanja veći nego pri lomu usled aksijalnog zatezanja. Takođe, granični napon zatezanja može biti efikasno povećan primenom FRP ojačanja.Veći naponi pri lomu ukazuju na veće dilatacije pri lomu. Shodno rezultatima merenih dilatacija, usvojeno je povećanje granične dilatacije zatezanja, date u tabeli 6 za 30% usled prisustva GFRP šipki [16].

The fact that tensile stress at failure in bending is higher than tensile stress at failure in tension should be taken into account in timber material modelling. In addition, ultimate tensile stress can be effectively increased by addition of FRP reinforcement. Higher stress at failure points to higher strain at failure. Based on the results of measured strains, a 30% increase in the ultimate tensile strain given in Table 6 is adopted due to the presence of the GFRP bars [16].

U tabeli 7 prikazane su vrednosti eksperimentalnih rezultata za granični moment i krutost na savijanje i vrednosti ovih veličina prema analitičkom proračunu. Analiza je uključila grede s procentima ojačanja 0,5% (serija GR0.5), 1% (serija GR1.0) i 1,8% (serija GR1.8) ojačanja.

Table 7 shows experimental and analytical values for ultimate moment and flexural stiffness. The analysis included beams with reinforcement percentages of 0.5% (series GR0.5), 1% (series GR1.0) and 1.8% (series GR1.8).

Tabela 7. Poređenje eksperimentalnih i teorijskih rezultata
Table 7. Comparison of experimental and theoretical results

Test serija *Test series*	Eksperimentalno ispitivanje *Experimental results*	Analitički proračun *Analytical results*	Razlika (%) *Difference (%)*
Granični moment savijanja (kNm) *Flexural capacity(kNm)*			
GR0.5	53,8	56,0	4,1
GR1.0	54,5	58,4	7,2
GR1.8	61,8	60,9	1,5
Krutost na savijanje *EI* (10^3 kNm^2) *Flexural stiffness EI* (10^3 kNm^2)			
GR0.5	2,12	1,89	10,8
GR1.0	2,10	1,96	6,7
GR1.8	2,16	2,03	6,0

Kao što se vidi iz rezultata, analitički proračun daje zadovoljavajuće predviđanje, što znači da može biti primenjen u realnim proračunskim situacijama. Odstupanja koja se javljaju između vrednosti dobijenih u eksperimentalnom ispitivanju i analitičkim proračunom mogu se objasniti malim brojem uzoraka na kojima su izvršeni eksperimenti (tri po seriji), zatim prirodnom varijabilnošću karakteristika drveta i kvalitetom izvođenja ojačanja. Takođe, na rezultate utiče i faktor povećanja graničnih dilatacija čiji uticaj je potrebno dodatno istražiti.

As it is seen from the results analytical model provides good predictions, which means it can be successfully employed for the design of reinforced timber beams. Differences between the values obtained from the experiment and analytical calculation can be explained by a small number of experimental samples (three per series), natural variability of timber properties and processing quality. Also, the results are dependent from ultimate strain modification factor whose influence needs further examination.

5 ZAKLJUČAK

Istraživanja u oblasti ojačanja drvenih konstrukcija primenom FRP šipki postala su aktuelna poslednjih godina i još uvek su malobrojna u odnosu na istraživanja ojačanja primenom FRP traka. U ovom radu su prikazana sva značajnija eksperimentalna ispitivanja koja se bave ovom temom, s ciljem upoznavanja naučne i stručne javnosti s mogućnostima primene FRP šipki kao ojačanja drvenih nosača. Pored toga, dat je i proračunski model kojim se može odrediti krutost i granična nosivost ojačanih nosača.

Primena FRP šipki kao materijala za ojačanje drvenih elemenata pruža velike mogućnosti kod sanacije postojećih konstrukcija, ali i kod projektovanja novih objekata. Ova tehnika omogućava značajno povećanje nosivosti i krutosti ojačanih konstrukcijskih elemenata. Takođe, čini konstrukciju pouzdanijom, redukujući mogućnost pojave krtog loma. Prisustvo FRP ojačanja sprečava otvaranje pukotina, ograničava lokalna oštećenja i premošćava lokalne defekte u drvetu.

Bez obzira na visoke mehaničke karakteristike i druge pogodnosti, posebnu pažnju treba obratiti na pitanje trajnosti, funkcionalnosti i ekonomičnosti, što se postiže pravilnim izborom i primenom odgovarajućeg

5 CONCLUSION

Studies of FRP bars as reinforcement for timber structures have become popular in recent years and there are still a small number of them compared to studies of FRP plates as timber structures reinforcement. This paper presents all significant experimental tests that deal with this topic, with the aim of informing the scientific and professional public with the possibilities of application of FRP bars as reinforcement of timber beams. In addition, theoretical model that determines the stiffness and ultimate moment capacity of reinforced beams is given.

The use of FRP bars as reinforcement for timber elements provides many possibilities for rehabilitation of existing structures, but also for the design of new structures. This method allows for a significant increase in strength and stiffness of reinforced structural elements. In addition, the structure is more reliable due to the reduced possibility of brittle failure. The presence of the FRP reinforcement prevents cracks initiation, limits local damages and bridges local defects in timber.

Despite high mechanical properties and other benefits of this reinforcement method, special attention should be paid to the issue of sustainability, functionality sistema. Buduća istraživanja treba da utvrde uticaj tipa, položaja i površine ojačanja na nosivost i krutost drvenih elemenata kako za granično stanje nosivosti, tako i za granično stanje upotrebljivosti. Osim toga, da bi ovaj metod ojačanja bio praktičan i ekonomičan za svakodnevnu primenu, potrebno je usavršiti proračunski postupak i implementirati ga u odgovarajući standard.

and profitability which could be achieved by proper selection and use of an appropriate system. Future research should determine the effects of type, position and percentage of reinforcement on load carrying capacity and stiffness of timber elements for both the ultimate limit state and serviceability limit state. In addition, in order to make this method practical and economical for everyday use, the design model should be improved and implemented in appropriate standards.

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REZIME

OJAČANJE DRVENIH GREDA PRIMENOM FRP ŠIPKI

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Potreba da se ojačaju drvene konstrukcije usled oštećenja ili promene namene objekata dovela je do razvoja savremenih metoda ojačanja i upotrebe novih materijala u tu svrhu. Poslednjih godina, upotreba polimera ojačanih vlaknima (FRP) u oblasti sanacija i ojačanja građevinskih konstrukcija omogućena je zahvaljujući povećanoj dostupnosti i sve nižoj ceni. U radu se razmatra mogućnost primene FRP šipki kao materijala za ojačanje drvenih nosača. Ojačanjem drveta kompozitima na bazi karbonskih, staklenih ili bazaltnih vlakana mogu se obezbediti bolje karakteristike, kao što su poboljšana nosivost, krutost i duktilnost. Takođe, u radu je opisan i proračunski model razvijen za predviđanje nosivosti i krutosti drvenih nosača ojačanih FRP šipkama.

Ključne reči: drveni nosači, ojačanje, FRP kompoziti, FRP šipke

SUMMARY

STRENGTHENING OF TIMBER BEAMS USING FRP BARS

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The growing need for the reinforcement of timber beams (required due to deterioration or damage to the material or change of use) has led to the development of new methods of reinforcement with modern materials. In the recent years the use of fibre reinforced polymers (FRP) as reinforcement materials for structures has been made possible thanks to the increased availability and lower costs. This paper presents FRP bars as products for strengthening timber structures. Strengthening timber with glass, carbon and basalt FRP can provide better features of timber beams, such as improved load capacity, rigidity and ductility. Also, the paper describes the theoretical model developed in order to predict the flexural capacity and flexural stiffness of timber beams reinforced with FRP bars.

Key words: timber structures, strengthening, FRP composites, FRP bars