EKSPERIMENTALNO ISPITIVANJE OJAČANIH LEPLJENO LAMELIRANIH DRVENIH NOSAČA SA REDUKOVANOM VISINOM PRESEKA

EXPERIMENTAL TESTING OF REINFORCED END-NOTCHED GLULAM BEAMS

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1 UVOD

Nosači s redukovanom visinom preseka od monolitnog i lepljeno lameliranog drveta vrlo su zastupljeni u građevinskoj praksi. Mesto nagle promene visine poprečnog preseka nosača predstavlja slabu tačku u konstrukciji, te se preporučuje njeno izbegavanje. Međutim, postoje brojni razlozi za redukciju visine elementa. Najčešći razlog za to jeste ograničenje visine iznad oslonaca, ali postoje i drugi, poput poboljšanja bočne stabilnosti nosača, ostvarivanja veze elemenata itd. [1]. U svim ovim slučajevima, neophodan je adekvatan proračun nosača s redukovanom visinom preseka.

Kapacitet nosivosti nosača znatno je umanjen, kao rezultat koncentracije napona na mestu redukcije visine preseka. Redukcija visine preseka na zategnutoj strani elementa izaziva pojavu napona zatezanja upravno na vlakna koji, zajedno sa smičućim naponima, može da izazove pojavu pukotina, tipično od mesta nagle promene visine (slika 1). Pukotine su nepoželjna pojava sa estetske tačke gledišta, ali su takođe veoma opasne po konstrukciju, jer propagacija pukotine s porastom nivoa opterećenja može dovesti do loma. Ojačanje nosača s redukovanom visinom preseka je ekonomično rešenje kako bi se povećala nosivost.

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1 INTRODUCTION

Notched solid timber and glued laminated timber (glulam) beams are very common in structural engineering practice. Notches represent a weak spot in structure, and it is advisable to avoid them. However, there are various reasons for beam notching. The most common one being limitation in construction height at the supports, and others such as: stabilization of structural elements against lateral buckling, intersection of members and joint details etc. [1]. Adequate design of notched beams is necessary in these cases.

The load carrying capacity of timber beams is considerably reduced as a result of stress concentration around the notch. Notches made on the tension side induce tensile stresses perpendicular to grain which, accompanied by shear stresses, can cause longitudinal splitting typically starting at the notch corner (Figure 1). Cracks are unattractive appearance from aesthetic point of view, but are also very dangerous from structural perspective because crack propagation as the load level increases can lead to a failure of a beam. Reinforcement of such members is a cost-effective alternative for enhancing the load carrying capacity of structures in service.

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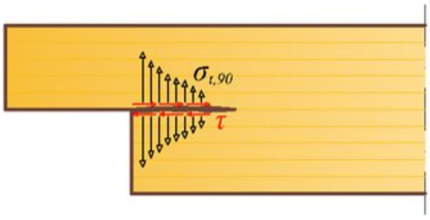
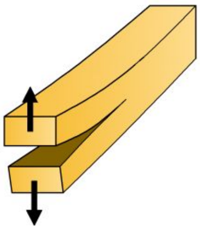


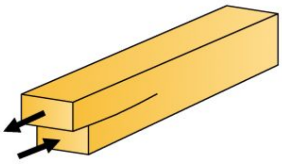
Slika 1. Koncentracija napona na mestu redukcije visine preseka
Figure 1. Stress concentration at the notched end of a beam

Naponsko stanje u okolini pukotine može se opisati različitim oblicima loma. Oblik loma 1 je otvaranje pukotine usled zatezanja upravano na ravan pukotine – slika 2 (a). Oblik loma 2 predstavlja smicanje u ravni gde površine pukotine klizaju jedna po drugoj – slika 2 (b). Kombinacija prethodna dva oblika loma predstavlja kombinovani lom, kao što je prikazano na slici 2 (c). Iako se pojavljuju oba napona (smicanje i zatezanje upravno na vlakna), otvaranje pukotina očigledan je mehanizam loma na mestu nagle promene visine preseka i izazvan je zatezanjem upravno na vlakna drveta. Zbog toga, oblik loma 1 jeste najčešći način loma kod nosača s redukovanom visinom preseka [2]. Međutim, obično postoji i komponenta smičućeg napona, koju treba imati u vidu.

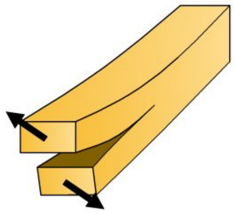
The stress state at a crack can be described by different fracture modes. Mode 1 is a tensile opening mode characterized by separating of crack surfaces in the direction that is perpendicular to them - Figure 2(a). Mode 2 represents in plane shear mode where crack surfaces slide one over the other - Figure 2(b). The combination of the previous two modes is a mixed mode fracture, as shown in Figure 2(c). Although both stresses (shear and tension perpendicular to grain) appear, crack opening is an apparent failure mechanism of a notch and it is caused by tension perpendicular to grain. Therefore, Mode 1 fracture is the most common failure mode of end-notched timber beams [2]. However, shear component usually exists and it should be also taken into consideration.



a) Oblik loma 1
a) *Mode 1 fracture*



b) Oblik loma 2
b) *Mode 2 fracture*



c) Kombinovani oblik loma
c) *Mixed mode fracture*

Slika 2. Oblici loma [1]
Figure 2. Fracture modes [1]

Mesta nagle promene visine nosača treba ojačati kako bi se izbegao krti lom i povećala nosivost. Postoje različite tehnike ojačanja, koje se uglavnom zasnivaju na sprečavanju pojave očekivanih pukotina. Parametri kao što su lakoća ugradnje, vidljivost ojačanja, jednostavnost proračuna i ekonomska isplativost važni su za odabir metode ojačanja. Različiti tipovi elemenata (šipke [3], zavrtnji [4,5], ploče i tkanine [6]) i materijala (materijali na bazi drveta, čelika, napredni kompozitni materijali, kao što su polimeri na bazi karbonskih i staklenih vlakana [7,8]) uspešno se koriste kao ojačanje drvenih nosača s redukovanom visinom preseka.

U proteklim decenijama, mnogi istraživači bavili su se drvenim nosačima s redukovanom visinom preseka i očigledno je da ojačanje i sanacija ovakvih elemenata predstavljaju veoma važnu temu u oblasti drvenih konstrukcija. U svojoj doktorskoj disertaciji, Jockwer [1] je dao detaljnu analizu različitih proračunskih pristupa neojačanih, ali i ojačanih greda s redukovanom visinom preseka. Franke, Franke i Harte [9] bavili su se metodama povećanja nosivosti drvenih greda,

Notched ends of beams should be reinforced so as to avoid brittle failure and increase load carrying capacity of the beams. There are various types of strengthening techniques which are mainly based on preventing the expected cracks. Parameters such as ease of installation, invisibility of reinforcement, simplicity of design approach and cost are all important for determining the strengthening method. Different types of elements (rods [3], screws [4,5], plates and sheets [6]) and materials (wood-based materials, steel, advanced composite materials like carbon or glass fibre based polymers [7,8]) have been successfully used as reinforcement of notched timber beams.

In the past decades, many researchers have dealt with notched timber beams and it is obvious that notched beam strengthening and repair represents very important topic in the field of timber structural design. In the PhD thesis Jockwer [1] gave a thorough analysis of different design approaches of both unreinforced and reinforced notched beams. Franke, Franke and Harte [9]dealt with methods for repair of structural performance uključujući i one s redukovanom visinom preseka. U svom radu, Oudjene i grupa autora [10] predstavljaju numerički pristup za modeliranje neojačanih i ojačanih greda s redukovanom visinom preseka. Dietsch [11] je govorio o neophodnosti novih proračunskih metoda za ojačanje drvenih greda i o njihovoj implementaciji u okviru Evrokoda 5 [12], naglašavajući važnost adekvatnog analitičkog proračuna.

U ovom radu prikazani su eksperimentalni rezultati ispitivanja nosača s redukovanom visinom preseka iznad oslonaca koji su ojačani zavrtnjima. Zavrtnji su efikasno rešenje za ojačanje iz aspekta cene, lakoće i brzine ugradnje [13], zbog čega su izabrani u ovom istraživanju. Pet neojačanih i deset ojačanih nosača s redukovanom visinom preseka iznad oslonaca ispitano je na savijanje do loma, uz razmatranje dve različite šeme ojačanja. Rezultati u pogledu ponašanja opterećenje–deformacije, oblika loma, granične nosivosti i krutosti upoređeni su za ispitane serije. Izvedeni su zaključci o efikasnosti zavrtanja kao ojačanja.

2 EKSPERIMENTALNO ISPITAVANJE

Eksperimentalno istraživanje sprovedeno je u Laboratoriji za ispitivanje konstrukcija, na Građevinskom fakultetu, Univerziteta u Beogradu. Pet neojačanih (serija U) i deset ojačanih (Serija R) nosača s redukovanom visinom preseka iznad oslonaca ispitani su na savijanje do loma. Neojačani nosači korišćeni su kao kontrolna serija. Ojačanje je izvedeno zavrtnjima. Pet ojačanih nosača imalo je zavrtnje postavljene upravno u odnosu na podužnu osu nosača (Serija R-s90), a pet je imalo zavrtnje postavljene pod uglom od 45° u odnosu na podužnu osu nosača (Serija R-s45).

Lepljeno lamelirani nosači su klase čvrstoće GL22h [15], a izrađeni su od drvene građe (smreke) klasifikovane kao klasa čvrstoće C22 prema EN 338 [14]. Pre eksperimentalnog ispitivanja, nosači su čuvani na temperaturi T = 20 ± 2 ºC i relativnoj vlažnosti od RH = 65 ± 5%. Posle ispitivanja, sadržaj vlage meren je na različitim mestima u okviru svakog nosača pomoću digitalnog vlagomera. Sadržaj vlage u testiranim nosačima varirao je od 11,0% do 11,9%.

Ukupna dužina nosača iznosila je 4.000 mm, dok su dimenzije poprečnog preseka bile 100 x 220 mm. Svaki nosač sastavljen je od sedam lamela debljine 32 mm. Na zasečenim krajevima, visina nosača smanjena je na 110 mm (za pola), a dužina zaseka bila je 250 mm. Kao ojačanje u ovom istraživanju, korišćeni su tradicionalni zavrtnji za drvo prečnika 10 mm i dužina 200 mm za Seriju R-s90 i 250 mm za Seriju R-s45 (slika 3). Dužina zavrtnja u navoju iznosila je 125 mm i 160 mm, respektivno. Prema proizvođaču, upotrebljeni zavrtnji su klase čvrstoće 5.6. Dva zavrtnja u jednom redu postavljena su blizu oba kraja nosača s redukovanom visinom preseka kod oslonaca. Uslovi za minimalna međusobna i ivična rastojanja zavrtanja su zadovoljeni, pri čemu je ojačanje postavljeno što bliže mestima nagle promene visine preseka.

of timber beams, including the ones with notches. In paper Oudjene et al. [10] presented a numerical approach for modelling both unreinforced and reinforced notched beams. Dietsch [11]talked about the necessity of new design approaches of strengthened timber beams, including strengthening of notches, and implementation of these in a new section of Eurocode 5 [12], emphasizing the importance of adequate analytical design.

This paper presents experimental results of end-notched glulam beams that were reinforced with screws. Screws are economic and time-efficient solution for reinforcement and they can be easily applied [13], which is the reason why they were chosen in this study. Five unreinforced and ten reinforced end-notched glulam beams were tested in bending to the point of failure, with two different reinforcement schemes considered. The results in terms of load-deformation relationship, failure mode, ultimate load carrying capacity and stiffness were compared between tested beam series. The conclusions on effectiveness of screws as a reinforcement method were made.

2 EXPERIMENTAL TESTING

The experimental research was conducted at the Laboratory of Structures, Faculty of Civil Engineering, University of Belgrade. Five unreinforced (Series U) and ten reinforced (Series R) notched glulam beams were tested in bending to the point of failure. Unreinforced beams were used as a control series. Reinforcing was performed with screws. Five reinforced beams had screws installed perpendicular to beam axis (Series R-s90) and five had screws positioned at an angle of 45° to beam axis(Series R-s45).

The glulam beams were made from spruce timber classified in the strength class C22 according to EN 338 [14], making the beams class GL22h [15]. Before the tests were performed, the beams were conditioned at a temperature of T = 20 ± 2 ºC and a relative humidity of RH = 65 ± 5%. After testing, moisture content was measured in each beam using a digital hygrometer at different locations. The moisture content in tested beams varied between 11.0% and 11.9%.

The overall length of the beams was 4000 mm and the cross section was 100 x 220 mm. Each beam was composed of seven 32 mm thick laminations. At the notched ends, the height of the beams was reduced to 110 mm (by half) and the length of notches was 250 mm. The reinforcement selected in this study was traditional wood screws with a diameter 10 mm and length of 200 mm for Series R-s90 and 250 mm for Series R-s45(Figure 3). Threaded part of screws was 125 mm and 160 mm, respectively. According to the manufacturer the steel grade of screws was 5.6. Two screws in one row were positioned near the both notched ends of the beams. The requirements for minimum screw edge distances and spacing were satisfied while keeping the reinforcement as close as possible to the notch corners.

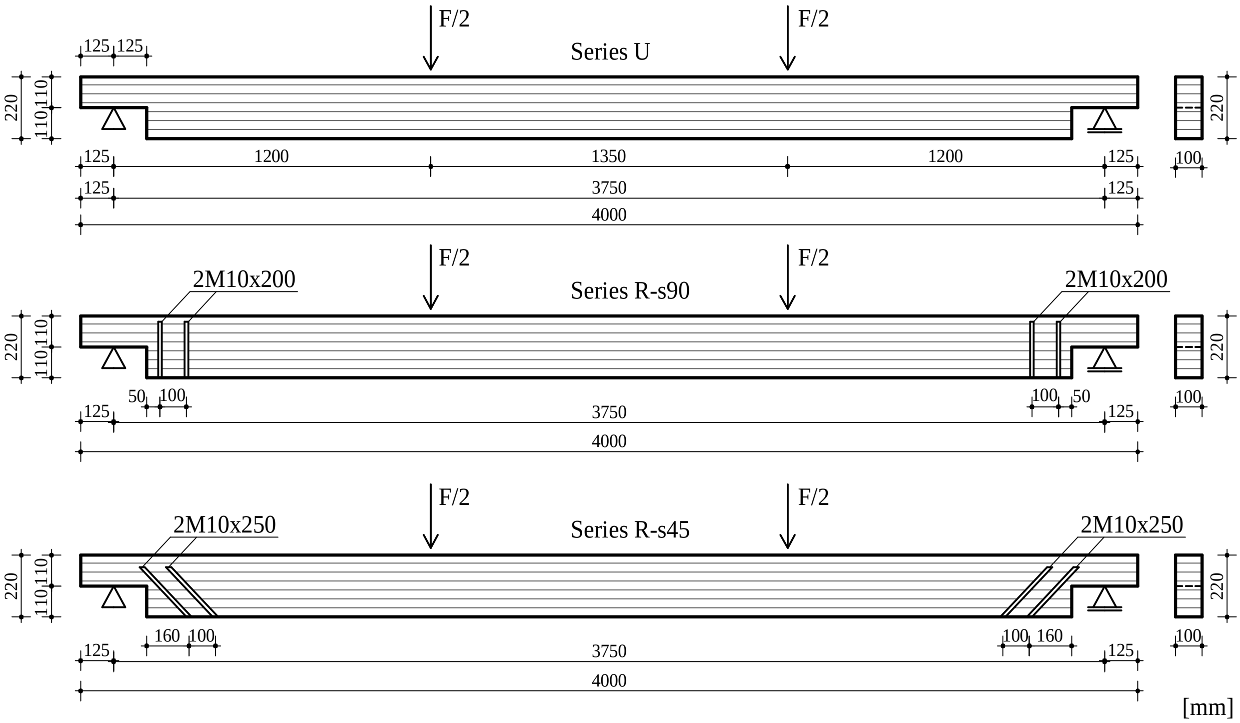
Slika 3. Zavrtnji za ojačanje
Figure 3. Screws used as reinforcement

Svi nosači izloženi su savijanju, u skladu sa EN 408 [16]. Proste grede raspona 3.750 mm ispitane su do loma pod koncentrisanim opterećenjem u dvema tačkama. Rastojanje između tačaka nanošenja opterećenja bilo je 1.350 mm, dok je rastojanje od sile do oslonca iznosilo 1.200 mm. Nosači su bili oslonjeni na valjkasta ležišta, koja su takođe postavljena na mestima unošenja opterećenja. Efekti lokalnih oštećenja na osloncima i na mestima unošenja koncentrisanih sila su minimizirani postavljanjem čeličnih pločica.

Šematski prikaz konfiguracije ispitivanja na savijanja za Seriju U, Seriju R-s90 i Seriju R-s45 prikazan je na slici 4, dok je na slici 5 prikazana postavka eksperimentalnog ispitivanja.

All beams were subjected to bending test in accordance with EN 408 [16]. The beams were tested to failure under monotonic load in four-point bending configuration over a simply supported span of 3750 mm. The distance between two loading points was 1350 mm, while the distance from the loading points to the supports was 1200 mm. The specimens were supported on roller bearings at the ends. Roller bearings were also used at the load application points. The effects of local indentation at load application and support positions were minimized by placing steel plates.

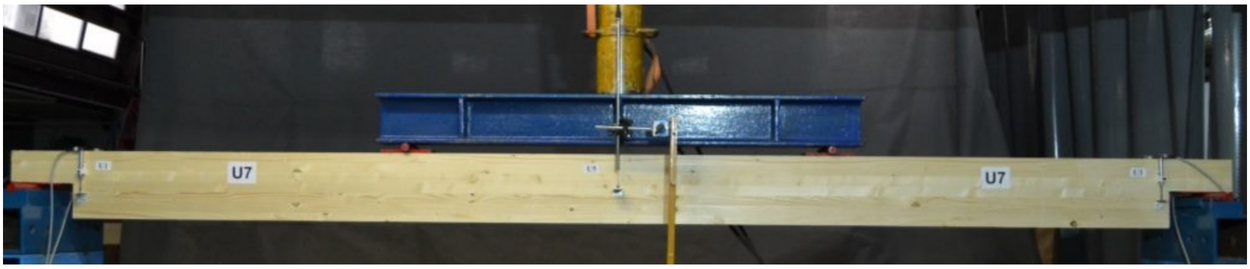
A schematic illustration of the bending test configuration for Series U, Series R-s90 and Series R-s45 is shown in Figure 4, while Figure 5 shows experimental test set-up.



Slika 4. Geometrija i opterećenje greda
Figure 4. Geometry and loading of the beams

Kod nosača predviđenih za ojačanje, posebna pažnja posvećena je ugradnji zavrtanja. Priprema uzoraka Serije R prikazana je na slici 6. Rupe za zavrtnje su vrlo pažljivo izbušene do prečnika 8 mm, s približnom dužinom bušenja 200 mm i 250 mm. Zavrtnji su postavljeni pomoću moment ključa.

When considering the specimens that were going to be reinforced special attention was put on inserting the screws. The preparation of Series R specimens is shown in Figure 6. The holes for screws were pre-drilled very carefully to a diameter of 8 mm, with approximately drilling length of 200 mm and 250 mm. The screws were inserted using a moment wrench.



Slika 5. Postavka eksperimenta
Figure 5. Experimental test set-up

Slika 6. Priprema ojačanih uzoraka
Figure 6. Preparation of reinforced specimens

Opterećenje je aplicirano do loma pomoću hidrauličke prese i mereno doznom. Opterećenje je transformisano s jedne tačke na dve tačke, pomoću čeličnog profila. Monotono statičko opterećenje nanošeno je kontrolisanom brzinom od 4 kN u minuti, kako bi se izazvao lom neojačanih nosača za približno pet minuta. Ojačani nosači testirani su sa istom brzinom opterećenja kako bi se obezbedila uporedivost rezultata ispitivanja. Lom ojačanih nosača postignut je za oko deset minuta.

Elektronski ugibomeri (LVDT) korišćeni su za merenje ugiba u sredini raspona nosača, kao i za merenje otvaranja pukotina na mestima nagle promene visine preseka. Podaci o ugibima sa LVDT-ova i odgovarajući podaci o opterećenju sa dozne zabeleženi su pomoću akvizacionog sistema. Sopstvena težina hidrauličke prese i čeličnog profila uzeti su u obzir. Ovo dodatno opterećenje iznosilo je 1,3 kN.

The load was applied monotonically using a hydraulic jack until the failure occurred and recorded with a compression load cell. The load was transformed from one point to two points with a steel beam. Monotonic static load was applied in a stroke-controlled rate of 4 kN per minute, so as to cause the failure of the unreinforced beams in approximately 5 minutes. The reinforced beams were tested with the same load rate in order to ensure a fair comparison of test results. The failure of the reinforced beams was achieved in about 10 minutes.

Linear variable differential transducers (LVDTs) were used for the measurement of mid-span deflection of the beams as well as the measurement of crack opening in notch details. The deformation data from LVDTs and corresponding load data from a loading cell were recorded by a computerized data acquisition system. Self-weight of hydraulic jack and steel beam were added to the recorded load. This additional load was 1.3 kN.

3 REZULTATI I DISKUSIJA

3.1 Ponašanje opterećenje–ugib i oblici loma

Ponašanje opterećenje–ugib do loma ispitanih nosača prikazano je na slikama 7 i 8.

Efekti redukcije visine preseka na mehaničke karakteristike lepljeno lameliranih drvenih nosača su značajni. Svi ispitani neojačani nosači (Serija U) pokazali su linearno ponašanje do loma. Lom je nastupio na mestima nagle promene visine usled prekoračenja napona na zatezanje upravno na vlakna, kao što je prikazano na slici 9. Otvaranje pukotina (oblik loma 1) na mestu nagle promene visine očigledan je mehanizam loma neojačanih nosača. Međutim, smicanje u ravni pukotine (oblik loma 2) takođe je imalo značajan uticaj. Zbog krte prirode ponašanja drveta pri zatezanju i

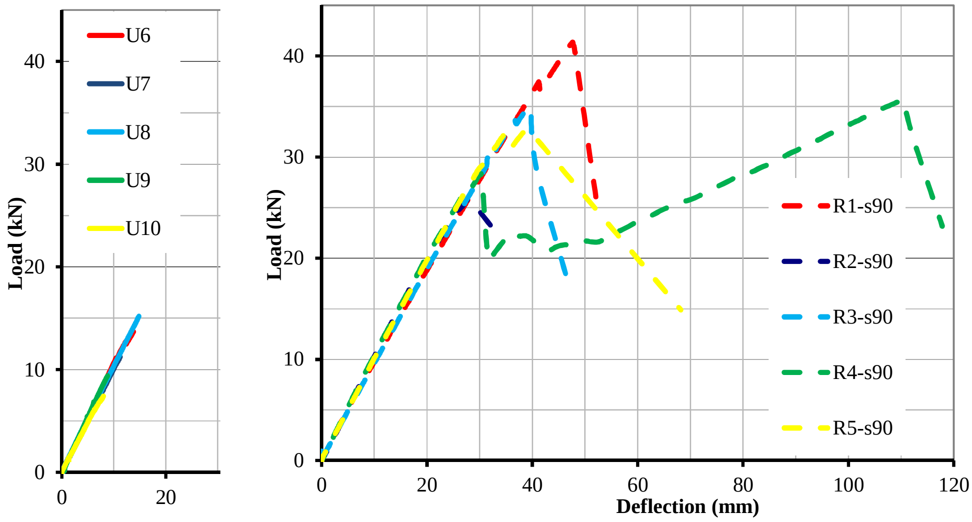
3 RESULTS AND DISCUSSION

3.1 Load-deflection behaviour and failure modes

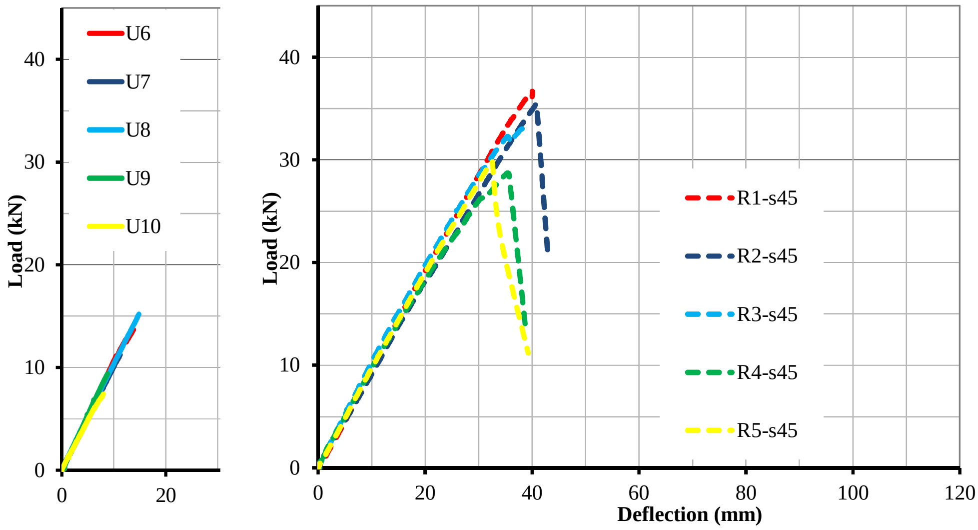
The load-deflection behaviour to the failure of tested beams is shown in Figures 7 and 8.

The effects of the notches on the mechanical properties of glulam beams are significant. All tested beams with unreinforced notches (Series U) exhibited linear load-deflection behaviour until the point of failure. Beams failed at the notch details due to excessive tensile stress perpendicular to grain, as it is shown in Figure 9. Crack opening (Mode 1 fracture) at the notch corner was the obvious failure mechanism of unreinforced notched beams. However, crack shearing (Mode 2 fracture) also had a considerable influence. Due to brittle nature of wood behaviour in tension and in smicanju, lom nosača Serije U bio je iznenadan i bez znakova upozorenja. Pre dostizanja graničnog opterećenja, primećeno je vrlo malo otvaranje pukotina. Nakon razvijanja inicijalne pukotine na mestu redukcije visine preseka, došlo je do nekontrolisanog rasta pukotina. To je uzrokovalo razdvajanje preseka na dva dela (gornji i donji). Putanja pukotine bila je uglavnom pravolinijska, a površine pukotine bile su ravne.

shear, failure of Series U beams was sudden without warning signs. Prior to ultimate load, only very little crack opening was observed. After the development of initial crack at the notch corner, uncontrollable crack growth occurred. This led to a separation of the cross-section in two parts (upper and lower). The crack path was generally clear and straight.



Slika 7. Krive opterećenje-ugib za grede Serije U i Serije R-s90
Figure 7. Load-deflection curves for Series U and Series R-s90 beams



Slika 8. Krive opterećenje-ugib za grede Serije U i Serije R-s45
Figure 8. Load-deflection curves for Series U and Series R-s45 beams

Slika 9. Tipični mehanizam loma greda Serije U
Figure 9. Typical failure mechanism of Series U beams

Ojačani nosači s redukovanom visinom preseka (Serija R) u suštini su imali linearno ponašanje do loma. Devet od deset nosača doživelo je krti lom. Jedan od nosača imao je pad nosivosti, ali je nastavio da nosi opterećenje do loma. Iako je granično opterećenje povećano, ojačanje nije bilo dovoljno da se promeni oblik loma iz kombinovanog usled zatezanja upravno na vlakna i smicanja u lom usled savijanja. Slika 10 prikazuje tipičan lom ojačanih nosača.

Reinforced notched beams (Series R) essentially experienced linear behaviour up to the point of failure. Nine out of ten beams failed in a brittle way. One of the beams had a drop in the load carrying capacity, but continued to carry the load until failure was reached. Although ultimate load was improved, the reinforcement was insufficient to change the failure mode from combined tensile perpendicular to grain and shear to bending failure. Figure 10 shows typical failure of reinforced beams.

Slika 10. Tipični mehanizam loma ojačanih greda – Serija R
Figure 10. Typical failure mechanism of reinforced beams – Series R

Uprkos intervenciji ojačanja, inicijacija pukotina na mestu nagle promene visine preseka se ne može sprečiti. Može se videti da je iniciranje pukotina započelo na relativno niskim vrednostima opterećenja. Ovo se može objasniti veoma malim kapacitetom deformacije drveta pri zatezanju upravno na vlakna. Prekomerno otvaranje pukotina ograničeno je ojačanjem. S daljim opterećivanjem, stabilan rast pukotine propraćen je smicanjem u ravni pukotine. Pri lomu, došlo je do nestabilnog rasta pukotina i znatnog porasta smicanja u ravni pukotine. Može se pretpostaviti da je smicanje dominantan mehanizam loma. U najvećem broju slučajeva, lom je propraćen izvlačenjem zavrtanja.

Vertikalno postavljeni zavrtnji opterećeni su na kombinovano naprezanje paralelno i upravno na ravan smicanja. Na zavrtnjima su postojale jasne plastične deformacije koje ukazuju na to da je formiran plastični zglob u području loma, u slučaju nosača Serije R-s90. Motivacija za postevljanje zavrtanja pod uglom bila je da oni budu aksijalno opterećeni (na zatezanje), u pravcu u kome pokazuju najveću krutost. Zbog toga se očekivalo da nosači Serije R-s45 imaju mnogo veću nosivost, ali zbog nedovoljne dužine sidrenja zavrtanja, oni su doživeli lom ranije nego nosači Serije R-s90. Pošto tradicionalni zavrtnji zahtevaju prethodno izbušene rupe za ugradnju, bolji rezultati u slučaju ojačavanja i sanacije drvenih konstrukcija mogu biti postignuti pomoću samougrađujućih zavrtanja.

Despite the reinforcement intervention, initial cracking of the notch corner cannot be prevented. It can be seen that crack initiation started at relatively low loads. This can be explained by the very small deformation capacity of wood before the tensile strength perpendicular to grain is exceeded. Excessive crack opening was limited by the reinforcement. With further loading the stable crack growth was accompanied by sharing of the crack. At failure, unstable crack growth occurred and crack shearing increased considerably. It can be assumed that the shear failure was dominant failure mechanism. In most cases, failure was accompanied by withdrawal of the screws.

At the notch corner vertical reinforcement screws were subjected to combined loading parallel and perpendicular to the shear plane. There were clear plastic deformations in the reinforcement indicating that plastic hinge was formed in the fracture region in the case of these beams. The idea of inclined screws was to load the reinforcement axially (in tension), the direction in which they demonstrate the highest stiffness. Therefore, Series R-s45 beams were expected to have much higher load carrying capacity, but due to insufficient anchorage length of the screws, they failed even earlier than the beams from Series R-s90. Since conventional screws require pre-drilled holes for installation, better results could be achieved with self-tapping screws for reinforcing and strengthening procedures of timber structures.

3.2 Kapacitet nosivosti, deformabilnost i krutost

Rezultati eksperimentalnih ispitivanja u pogledu nosivosti, deformabilnosti i krutosti za tri serije nosača dati su u tabeli 1. Granično opterećenje uzeto je kao maksimalna sila koja je izazvala lom nosača. Srednji ugib uzet je kao vrednost koja odgovara graničnom opterećenju. Krutost na savijanje izračunata je iz linearnog dela krive opterećenje–ugib za svaki nosač, korišćenjem jednačine za ugib u sredini proste grede opterećene u dvema tačkama:

3.2 Load carrying capacity, deformability and stiffness

The results of experimental tests in terms of load carrying capacity, deformability and stiffness for the three series of beams are given in Table 1. The ultimate load was taken as a maximum force, which caused the failure of the beams. The mid-span deflection was taken as the value that corresponded to the ultimate load. The bending stiffness was calculated from liner part of the load-deflection curve of each beam, using the mid-span deflection equation for four-point bending:

$$EI = \frac{1}{48}\frac{\Delta F(3l^2 - 4c^2)c}{\Delta w} \quad (1)$$

gde je
E – modul elastičnosti;
I – moment inercije;
$\frac{DF}{Dw}$ – nagib krive opterećenje-ugib između 10% i 40% graničnog opterećenja;
l – raspon grede;
c – rastojanje između oslonca i koncentrisane sile.

U tabeli 1 prikazana su poređenja graničnog opterećenja, ugiba u sredini i krutosti na savijanje za ojačane nosače (Serija R-s90 i Serija R-s45) i neojačane nosače (Serija U).

where:
E – modulus of elasticity,
I – moment of inertia,
$\frac{DF}{Dw}$ – slope of load-deflection curve between 10% and 40% of ultimate load,
l – beam span,
c – distance between support and load application point.

Comparisons in relation to ultimate load, mid-span deflection and bending stiffness for the reinforced beams (Series R-s90 and Series R-s45) and unreinforced beams (Series U) are also reported in Table 1.

Tabela 1. Eksperimentalni rezultati
Table 1. Experimental results

Nosač *Beam*	**Granično opterećenje** *Ultimate load* F_{ult} **(kN)**	**Ugib u sredini za granično opt.** *Mid-span deflection for ultimate load* **w (mm)**	**Krutost na savijanje** *Bending stiffness* **EI (kNmm^2 x 10^8)**
Serija U / *Series U*			
U6	15,0	13,8	9,03
U7	12,7	12,1	8,85
U8	16,7	15,1	9,55
U9	10,7	8,8	9,91
U10	8,7	8,0	8,60
Srednja vrednost / *Average*	12,8	11,5	9,19
SD	3,2	3,1	0,53
CV	25,2	26,6	5,8
Serija R-s90 / *Series R-s90*			
R1-s90	42,7	47,7	8,46
R2-s90	29,8	27,8	10,46
R3-s90	36,3	39,7	8,63
R4-s90	37,0	110,4	9,32
R5-s90	34,0	39,2	9,14
Srednja vrednost / *Average*	35,9	52,9	9,20
SD	4,7	32,9	0,79
CV	13,0	62,1	8,5
Poređenje sa Serijom U *Comparison with Series U* (%)	180,5	360	-

Serija R-s45 / *Series R-s45*			
R1-s45 R2-s45 R3-s45 R4-s45 R5-s45	38,0 36,7 34,6 30,0 31,1	40,1 40,8 38,9 59,1 32,6	9,01 8,29 9,19 8,54 8,83
Srednja vrednost / *Average*	34,1	42,3	8,77
SD	3,5	9,9	0,36
CV	10,1	23,5	4,1
Poređenje sa Serijom U *Comparison with Series U* (%)	166,4	267,8	-

Neojačani nosači s redukovanom visinom preseka iznad oslonca (Serija U) imali su prosečno granično opterećenje od 12,8 kN. Nosivost nosača znatno je smanjena zbog nagle promene visine preseka. Veliki koeficijent varijacije (25,2%) u slučaju graničnog opterećenja greda Serije U se može objasniti prirodnom varijabilnošću karkteristika drveta kao materijala. Uvođenje ojačanja na mestima nagle promene visine preseka nosača dovelo je do poboljšanja nosivosti. Ojačani nosači imaju prosečno granično opterećenje od 35,9 kN i 34,1 kN, za zavrtnje postavljene pod uglovima od 90° i 45°. Svi ojačani nosači pokazali su povećanje graničnog opterećenja u poređenju sa opterećenjem nosača bez ojačanja. Ovo povećanje iznosilo je 180,5% i 166,4%. Neojačani nosači s redukovanom visinom preseka potpuno su izgubili nosivost nakon iniciranja pukotine. S druge strane, ojačani nosači nastavili su da nose opterećenje nakon inicijalnog otvaranja pukotine. Međutim, nedovoljna dužina sidrenja nije dozvolila da ojačani nosači dožive lom usled savijanja, pošto je izvalačenje zavrtanja nastupilo pre dostizanja nosivosti koju bi imali nosači bez redukovane visine preseka kod oslonaca.

Ojačani nosači pretrpeli su veće deformacije pre loma u poređenju s neojačanim. Prosečno izmereni ugib u sredini pri graničnom opterećenju bio je 52,9 mm, 42,3 mm i 11,5 mm za nosače Serije R-s90, Serije R-s45 i Serije U, redom. Ojačani nosači pokazali su 3,6–4,6 puta veće ugibe u sredini pri graničnom opterećenju. Dakle, zavrtnji su doprineli poboljšanju deformabilnosti nosača.

Svi nosači imali su slične vrednosti krutosti na savijanje. Ovo je očekivano s obzirom na to da primenjeno ojačanje nije namenjeno poboljšanju krutosti. Serija R-s45 imala je malo nižu vrednost koja se može objasniti varijabilnošću svojstava, što je karakteristično za drvo kao materijal.

The unreinforced notched beams (Series U) had an average ultimate load of 12.8 kN. The load carrying capacity of the beams was considerably reduced due to presence of notches. High coefficient of variation (25.2%) in ultimate load for Series U beams can be explained by natural variability in timber properties. Introduction of reinforcement at the notched ends of the beams resulted in improvement in load carrying capacity. The reinforced beams obtained an average ultimate load of 35.9 kN and 34.1 kN, for screws positioned at the angles of 90° and 45°, respectively. All reinforced beams showed an increase in ultimate load when compared with the loads recorded for the beams without reinforcement. This increase was 180.5% and 166.4%. Unreinforced notched beams completely lost their load carrying capacities after the first crack developed. On the other hand, reinforced beams continued to carry the load after initial cracking. However, insufficient anchorage length did not allow for the reinforced beams to fail in bending, since the withdrawal of the screws occurred before the beams reached the load carrying capacity of beams without notches.

The reinforced beams underwent large deformations before the failure when compared with the unreinforced ones. Average measured mid-span deflection at ultimate load was 52.9 mm, 42.3 mm and 11.5 mm for beams of Series R-s90, Series R-s45 and Series U, respectively. At failure, the reinforced beams exhibited 3.6 – 4.6 times larger mid-span deflections. Hence, screws helped improve the deformability of the beams.

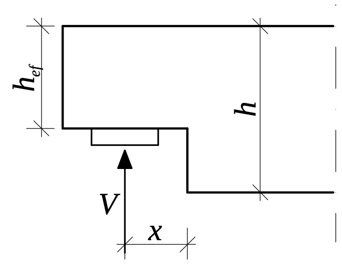
All the beams had similar bending stiffness values. This was expected since the applied reinforcement was not meant to improve the bending stiffness. Series R-s45 had a bit lower value, which can be explained by the variability in timber properties that generally exists when this material is in question.

4 NUMERIČKA ANALIZA

Proračun nosača s redukovanom visinom preseka dat je u Evrokodu 5 [12]. Za nosače s pravougaonim poprečnim presekom i orijentacijom vlakana u pravcu dužine nosača, smičući napon na mestu redukcije visine preseka računa se koristeći efektivnu (redukovanu) visinu nosača h_{ef} (slika 11).

4 NUMERICAL ANALYSIS

The design of notched timber beams is given in Eurocode 5 [12]. For beams with rectangular cross-sections and grain that runs parallel to the length of the member, the shear stresses at the notched support should be calculated using the effective (reduced) height h_{ef} of the beam (Figure 11).



Slika 11. Greda sa redukovanom visinom kod oslonca
Figure 11. End-notched beam

Neophodno je zadovoljiti sledeću nejednakost:

The following expression should be satisfied:

$$t = \frac{1,5V}{b_{ef}\,h_{ef}} \leq k_v\, f_v \qquad (2)$$

gde je:

V – smičuća sila;

t – smičući napon;

f_n – čvrstoća na smicanje;

b_{ef} – efektivna širina nosača $b_{ef} = k_{cr} b$;

za pravogaoni poprečni presek $k_{cr} = 0,67$

h_{ef} – efektivna visina nosača;

k_n – faktor redukcije kojim se uzima u obzir koncentracija napona na mestu nagle promene visine preseka:

za redukciju visine na suprotnoj strani od oslonca: $k_n = 1$;

za redukciju visine na istoj strani kao oslonac:

$$k_v = \frac{k_n}{\sqrt{h}\left(\sqrt{a(1-a)} + 0,8\frac{x}{h}\sqrt{\frac{1}{a} - a^2}\right)} \leq 1;$$

h – visina nosača;

x – rastojanje reakcije oslonca do mesta redukcije visine preseka;

$$a = \frac{h_{ef}}{h}$$

$$k_n = \begin{cases} 5 & \text{za monolitno drvo} \\ 6,5 & \text{za lepljeno lamelirano drvo} \end{cases}$$

Analitički proračun sproveden je za ispitane grede. Kako bi se uporedili eksperimentalni i analitički rezultati, uzimaju se karakteristične vrednosti čvrstoća. Karakteristična čvrstoća na smicanje za lepljeno lameliran drvo klase GL22h je

$$f_{n,k} = 3,5\frac{N}{mm^2}.$$

Faktor k_n usvojen je za lepljeno lamelirano drvo $k_n = 6,5$. Faktor k_n sračunat je za $a = 0,5$, $x = 125\ mm$, $h = 220\ mm$:

$$k_v = \frac{6,5}{\sqrt{220}\left(\sqrt{0,5(1-0,5)} + 0,8\frac{125}{220}\sqrt{\frac{1}{0,5} - 0,5^2}\right)} = 0,398$$

Sračunata vrednost graničnog opterećenja za neoja-

where:

V – shear force

t –shear stress

f_n –shear strength

b_{ef} – effective beam width $b_{ef} = k_{cr} b$

for rectangular cross-section $k_{cr} = 0.67$.

h_{ef} –effective beam height

k_n – reduction factor which takes into account stress concentration at the notch:

for notches at the opposite side to the support: $k_n = 1$

for notches on the same side as the support:

$$k_v = \frac{k_n}{\sqrt{h}\left(\sqrt{a(1-a)} + 0.8\frac{x}{h}\sqrt{\frac{1}{a} - a^2}\right)} \leq 1$$

h – beam height

x – the distance from line of action of the support reaction to the corner of the notch

$$a = \frac{h_{ef}}{h}$$

$$k_n = \begin{cases} 5 & \text{for solid timber} \\ 6.5 & \text{for glued laminated timber} \end{cases}$$

Analytical calculations are performed for tested beams. In order to compare the experimental and analytical results, characteristic values for strengths were adopted. Characteristic value of shear strength for glulam class GL22h is

$$f_{n,k} = 3.5\frac{N}{mm^2}.$$

Factor k_n is taken for glued laminated timber $k_n = 6.5$. Factor k_n is calculated for $a = 0.5$, $x = 125\ mm$, $h = 220\ mm$:

$$k_v = \frac{6.5}{\sqrt{220}\left(\sqrt{0.5(1-0.5)} + 0.8\frac{125}{220}\sqrt{\frac{1}{0.5} - 0.5^2}\right)} = 0.398$$

The calculated value of ultimate load for unreinforced čane nosače prema Evrokodu 5 iz Jednačine 2 jeste:

$$F_{ult} = \frac{2}{1,5} k_v \cdot f_{v,k} \cdot b_{ef} \cdot h_{ef} = 13,7\,kN$$

Kada se uporedi s prosečnom eksperimentalnom vrednošću za Seriju U, koja je iznosila 12,8 kN, može se videti da predloženi metod proračuna premašuje granično opterećenje za 7,0%. Može se zaključiti da ovaj proračunski pristup zanemaruje pojavu smicanja u ravni pukotine, koje se javlja na mestu redukcije visine preseka, uzimajući u obzir samo vertikalnu komponentu koja izaziva zatezanje upravno na vlakna drveta.

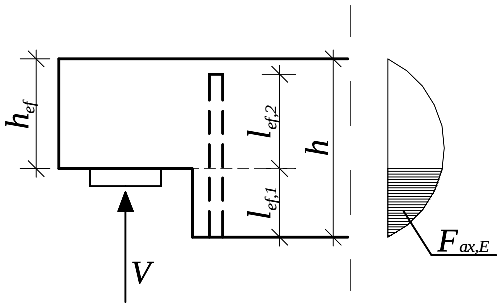
Proračun nosača s redukovanom visinom preseka kod oslonca, dat u Evrokodu 5, ne predviđa proračun mogućih ojačanja. Kao dodatak Evrokodu 5, Nemački nacionalni aneks [17] predlaže metod proračuna ojačanja (slika 12). Ovaj pristup baziran je na ideji da se napon koji se javlja na mestu nagle promene visine nosača raspodeljuje između ojačanja i drveta putem faktora k_a.

notches according to Eurocode 5 from Eq. 2 is:

$$F_{ult} = \frac{2}{1.5} k_v \cdot f_{v,k} \cdot b_{ef} \cdot h_{ef} = 13.7\,kN$$

When compared with the average experimental value for Series U, which was 12.8 kN, it can be seen that the suggested design method overestimated the ultimate load by 7.0%. It can be noted that this design approach ignores the in-plane shear, which appears at the notch, taking into account only the vertical component that causes tensile stress perpendicular to grain of timber.

The design of end-notched shear stress given in the Eurocode 5 does not provide the calculation of possible reinforcement. In addition to Eurocode 5, the German National Annex [17] proposes reinforcement design method at the notch (Figure 12). This design approach is based on the idea that the stress which apperas around the notch is divided between reinforcement and timber using factor k_a.



Slika 12. Vertikalno ojačanje grede sa redukovanom visinom kod oslonca [18]
Figure 12. Vertical reinforcement of end-notched beam [18]

Maksimalna smičuća sila kod oslonca nosača s redukovanom visinom:

Maximum shear force at the support of end-notched beam:

$$\max V = \frac{2}{3} b_{ef} \cdot h_{ef} \cdot f_v] \quad (3)$$

U ovom radu zavrtnji su usvojeni kao ojačanje i deo sile koji oni preuzimaju može se sračunati prema izrazu:

In this paper screws are selected as reinforcement and and part of the load carried by screws can be calculated as follows:

$$F_{ax,E} = k_a V \quad (4)$$

uz uslov:

$F_{ax,E} \le n_{ef} F_{ax,R}$

gde je:

V – smičuća sila;

with condition:

$F_{ax,E} \le n_{ef} F_{ax,R}$

where:

V – shear force

$$k_a = 1,3\left[3(1-a)^2 - 2(1-a)^3\right] \quad (5)$$

$$a = \frac{h_{ef}}{h} \quad (6)$$

$F_{ax,E}$ – aksijalna sila u zavrtnjima;

n – broj zavrtanja;

$F_{ax,R}$ – kapacitet zavrtnja na čupanje.

Za ojačane nosače, karakteristična vrednost kapaciteta zavrtnja na čupanje usvaja se prema [18]:

$F_{ax,E}$ – axial force in screws

n – number of screws

$F_{ax,R}$ – screw withdrawal capacity

For reinforced beams the screw withdrawal capacity was adopted according to [18]:

$$F_{ax,R} = f_{ax,90} \cdot d \cdot l_{ef} \quad (7)$$

gde je:

$f_{ax,90}$ – čvrstoća vertikalnog zavrtnja na čupanje upravno na vlakana;

d – prečnik zavrtnja;

l_{ef} – dužina sidrenja dela zavrtnja u navoju.

Čvrstoća vertikalnog zavrtnja na čupanje upravno na vlakana je

$$f_{ax,90} = 9{,}8 \frac{N}{mm^2}$$

prema [18], usvojeno na osnovu vrednosti datih u literaturi. Vrednost kapaciteta vertikalnog zavrtnja na čupanje za prečnik zavrtnja $d = 10\ mm$ i dužinu sidrenja $l_{ef} = 90\ mm$ jeste:

$$F_{ax,R} = f_{ax,90} \cdot d \cdot l_{ef} = 8{,}82\,kN$$

Ako se zanemari koeficijent $k_a\ (k_a = 1)$, s pretpostavkom da zavrtnji nose svo opterećenje, granično opterećenje za nosače ojačane vertikalnim zavrtnjima prema [18] jeste:

$$F_{ult} = 2V = 2nF_{ax,R} = 35{,}3\,kN$$

Ova pretpostavka je validna, s obzirom na to da je testiranje vršeno do loma, a ne za eksploataciono opterećenje. Drvo gubi nosivost pri iniciranju pukotine na mestu nagle promene visine preseka, a zavrtnji nastavljaju da nose opeterećenje do loma. Razlika u odnosu na eksperimentalnu vrednost, koja je iznosila 35,9 kN, jeste 1,7%.

Za zavrtnje pod uglom od 45° u odnosu na podužnu osu nosača, čvrstoća zavrtnja na čupanje uzeta je kao

$$F_{ax,45} = 0{,}86 \cdot f_{ax,90}$$

prema [18]. Vrednost kapaciteta kosog zavrtnja na čupanje za prečnik zavrtnja $d = 10\ mm$ i dužinu sidrenja $l_{ef} = 94\ mm$ jeste:

$$F_{ax,R} = 0{,}86 \cdot f_{ax,90} \cdot d \cdot l_{ef} = 7{,}92\,kN$$

Ponovo, ako se zanemari koeficijent k_a, s pretpostavkom da zavrtnji nose svo opterećenje, granično opterećenje za nosače ojačane kosim zavrtnjima jeste:

$$F_{ult} = 2V = 2nF_{ax,R} = 31{,}7\,kN$$

Razlika u odnosu na eksperimentalnu vrednost, koja je iznosila 34,1 kN, jeste 7,0%.

Uočava se dobro slaganje analitičkih i eksperimentalnih rezultata za nosivost ojačanih nosača. Kako je proračun baziran na konceptu da ojačanje prihvata samo vertikalnu komponentu sile koja izaziva zatezanje upravno na vlakna drveta, analitičke vrednosti niže su od eksperimentalnih.

where:

$f_{ax,90}$ – withdrawal strength perpendicular to the grain for vertical screws

d – screw diameter

l_{ef} – anchorage length of the threaded part

The withdrawal strength perpendicular to the grain for vertical screws is taken as

$$f_{ax,90} = 9.8 \frac{N}{mm^2}$$

according to [18], which is adopted based on various literature sources. The value for vertical screw withdrawal capacity for screw diameter $d = 10\ mm$ and anchorage length $l_{ef} = 90\ mm$ is:

$$F_{ax,R} = f_{ax,90} \cdot d \cdot l_{ef} = 8.82\,kN$$

If factor k_a is ignored $(k_a = 1)$, with the assumption that the screws carry the entire load the ultimate load for vertically reinforced notches according to [18] is:

$$F_{ult} = 2V = 2nF_{ax,R} = 35.3\,kN$$

The made assumption is valid, because the tests were carried out to the point of failure and not for the service loads. Timber part of the cross-section in this case loses its load-carrying capacity with crack initiation at the notch, and screws continue to carry the load to failure. The difference from experimentally obtained average value, which was 35.9kN, is 1.7%.

For screws positioned at an angle of 45° to beam axis, the withdrawal strength is taken as

$$F_{ax,45} = 0.86 \cdot f_{ax,90}$$

according to [18]. The value for inclined screw withdrawal capacity for screw diameter $d = 10\ mm$ and anchorage length $l_{ef} = 94\ mm$ is:

$$F_{ax,R} = 0.86 \cdot f_{ax,90} \cdot d \cdot l_{ef} = 7.92\,kN$$

Again, if factor k_a is ignored, with the assumption that the screws carry the entire load, the ultimate load for notches reinforced with inclined screws is then:

$$F_{ult} = 2V = 2nF_{ax,R} = 31.7\,kN$$

The difference from experimentally obtained average value, which was 34.1 kN, is 7.0%.

There is a good agreement between analytical and experimental results for reinforced beams load-carrying capacity. Since the design method is based on the concept that reinforcement carries only the vertical force component that causes tensile stress perpendicular to grain of timber, analytical values underestimate the ultimate load.

5 ZAKLJUČCI

Eksperimentalno ispitivanje sprovedeno u ovom radu uključivalo je ispitivanje na savijanje 15 lepljeno lameliranih drvenih nosača s redukovanom visinom preseka iznad oslonaca do tačke loma (pet neojačanih i deset ojačanih). Zavrtnji su odabrani kao ojačanje. Uticaji ojačanja procenjeni su u smislu ponašanja opterećenje–ugib, oblika loma, nosivosti i krutosti ojačanih nosača, koji su upoređeni s neojačanim nosačima. Takođe, sprovedeno je poređenje sa analitičkim rezultatima. Izvedeni su sledeći zaključci:

– Lom lepljeno lameliranih drvenih nosača s redukovanom visinom preseka iznad oslonaca opterećenih na savijanje nastaje usled koncentracije napona na mestu redukcije visine. Nosivost ovih nosača definisana je prekomernim otvaranjem pukotina. Krt lom tipičan je za neojačane nosače s redukovanom visinom preseka iznad oslonaca.

– Inicijalno otvaranje pukotine ne može se sprečiti ojačanjem. Međutim, pomoću ojačanja pojava loma znatno se odlaže.

– Ojačanje sprečava prekomerno otvaranje pukotina na mestu nagle promene visine preseka. Ipak, konačni lom ojačanih nosača usled prevelikog rasta pukotina uzrokovan je smicanjem.

– Ojačanjem zavrtnjima povećava se nosivost i deformabilnost lepljeno lameliranih drvenih nosača s redukovanom visinom preseka iznad oslonaca.

– Na mestu nagle promene visine preseka, zavrtnji upravni na podužnu osu nosača izloženi su kombinovanom paralelnom i upravnom opterećenju u odnosu na ravan pukotine. Prema tome, ojačanje s visokom čvrstoćom i krutošću u oba pravca neophodno je radi postizanja najboljeg efekta ojačanja.

– Zavrtnji postavljeni pod uglom od 45° u odnosu na podužnu osu nosača dominantno su opterećeni u aksijalnom pravcu. Posebnu pažnju treba posvetiti dužini sidrenja ovih zavrtanja.

– Kako bi se poboljšalo sidrenje, generalno se preporučuje primena samougrađujućih zavrtanja umesto klasičnih koji zahtevaju prethodno bušenje rupa.

– Predložena metoda proračuna u Evrokodu 5 precenila je granično opterećenje neojačanih nosača za 7,0%.

– Kada je reč o ojačanim nosačima, ako se usvoji pretpostavka da svo opterećenje primaju zavrtnji, postoji dobro slaganje rezultata s proračunom datim u Nemačkom nacionalnom aneksu za Evrokod 5.

– Ovo istraživanje daje uvid u mogućnosti ojačanja drvenih nosača s redukovanom visinom preseka. Ono može biti dobra osnova za dalja istraživanja efikasnosti drugih vrsta ojačanja, kao što su šipke od polimera na bazi karbonskih i staklenih vlakana. Takođe, rezultati dobijeni ispitivanjem mogu biti korisni u izradi odgovarajućih analitičkih modela drvenih nosača s redukovanom visinom preseka. Postojeće metode proračuna treba revidirati, jer zanemaruju složeno naponsko stanje koje se javlja na mestu nagle promene visine preseka.

5 CONCLUSIONS

The experimental procedure performed in this research included bending tests of 15 notched glulam beams to the point of failure (five unreinforced beams and ten reinforced ones). The screws were selected as reinforcement. The effects of reinforcing were evaluated in terms of load-deflection behaviour, failure mode, ultimate load carrying capacity and stiffness of reinforced beams, which were compared with the unreinforced notched beams. In addition, comparison with analytical design method was made. The following conclusions were drawn:

– Notched glulam beams when subjected to bending failed due to stress concentration at the notch corner. The load carrying capacity of these beams is defined by excessive crack opening. Brittle failure mechanism is typical for unreinforced notched beams.

– Initial cracking of the notch corner cannot be prevented by the reinforcement. However, by using reinforcement at the notches failure is delayed significantly.

– The reinforcement prevents excessive crack opening at the notch corner. Nevertheless, final failure of the reinforced notches due to excessive crack growth is caused by crack shearing.

– Reinforcing intervention of notched glulam beams with screws increases the load carrying capacity and deformability.

– At the notch corner, reinforcement screws perpendicular to beam axis are subjected to combined parallel and perpendicular to the crack surface loading. Hence, reinforcement with high strength and stiffness in both directions is required to achieve the best reinforcing effect.

– Reinforcement screws inclined at an angle of 45° to beam axis are dominantly loaded in the axial direction. Special attention should be paid to the anchorage length of these screws.

– Generally, in order to improve anchorage, self-tapping screws are recommended to be used instead of the pre-drilled screws.

– The suggested design method in Eurocode 5 overestimated the ultimate load of unreinforced beams 7.0%.

– As for reinforced beams, if the assumption that the entire load is carried by screws is made, there is a good agreement with the proposed design method in the German National Annex to Eurocode 5.

This research gives an insight into reinforcing possibilities of notched timber members. It can be a good basis for further investigation of the effectiveness of other types of reinforcement like carbon or glass fibre based polymer bars. In addition, results obtained from tests can be useful in developing appropriate analytical design models for notched timber beams. Existing design methods should be revised, as they overlook the complex stress state around the notch area

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REZIME

EKSPERIMENTALNO ISPITIVANJE OJAČANIH LEPLJENO LAMELIRANIH DRVENIH NOSAČA SA REDUKOVANOM VISINOM PRESEKA

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Redukcija visine drvenih nosača kod oslonaca znatno umanjuje kapacitet nosivostielementa. U ovom radu je predstavljeno eksperimentalno ispitivanje lepljenih lameliranih drvenih nosača sa redukovanom visinom preseka kod oslonaca opterećenih na savijanje, sa i bez ojačanja. Kao ojačanje upotrebljeni su zavrtnji za drvo, postavljeni pod uglomod 90° i 45° u odnosu na podužnu osu nosača. Neojačni nosači su doživeli krti lom usled otvaranja pukotine i njene propagacije. Ove pukotine su rezultat prekoračenj a čvrstoće drveta na zatezanje upravno na vlakna i čvrstoće drveta na smicanje. Ispitivanje je pokazalo da se upotrebom zavrtanja može povećati kapacitet nosivosti i deformabilnosti posmatranih nosača. Međutim, primena zavrtanja kao ojačanja nije dovela do promene oblika loma iz krtog u duktilni lom usled savijanja. Lom usled smicanja je bio dominantan oblik loma kod ojačanih nosača. Takođe, analitički proračun je izvršen prema Evrokodu 5 kako bi se rezultati uporedili sa eksperimentalnim ispitivanjem.

Ključne reči: zasek, lepljeno lamelirano drvo, zavrtnji, ojačanje, eksperimentalno ispitivanje

SUMMARY

THE POSSIBILITY OF USING BLAST FURNACE SLAG AS CONCRETE AGGREGATE

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Notches made at the ends of timber beams significantly decrease load carrying capacity of a structural member. This paper presents an experimental research on bending behaviour of end-notched glulam beams, with and without reinforcement. Screws for timber were used as reinforcement, positioned at angles of 90° and 45° to the longitudinal beam axis. The unreinforced beams failed due to crack opening and its propagation in a brittle manner. Cracks that appeared in the notch details resulted from combined excessive tensile stresses perpendicular to grain and shear stresses. This study shows that reinforcing the beams at the notched ends can improve their load carrying capacity and deformability. However, applied screws did not help the beams achieve ductile failure in bending. The shear failure was dominant failure mechanism for reinforced beams. In addition, analytical calculations were performed in accordance with Eurocode 5 so as to compare the results with experimental research.

Key words: notch, glulam, screws, reinforcement, experimental investigation