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Comparison and Investigation of the Behavior of Reinforced Wooden Beams with Notches at the Ends

Istraživanje i usporedba ponašanja ojačanih drvenih greda s urezima na krajevima

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ABSTRACT • *When manufacturing wooden beams for spanning, notches are often formed at the ends. Under load, stresses develop at these notches, often causing cracks and beam failure. This study theoretically and experimentally investigated methods to reinforce such beams. Two types of calibrated beams were tested: solid timber and glued laminated beams. In experimental tests, beams were fixed in a machine to simulate mid-span "three-point" bending. Parallel theoretical evaluations followed EN 1995-1-1: Eurocode 5 and STR 2.05.07:2005 design standards. For each beam type, three groups of specimens were prepared: unreinforced, end-reinforced with dowels, and end-reinforced with plywood strips. All beams failed similarly: cracks formed at the notches and grew until the beam lost the load-bearing capacity. Failure behavior differed from typical bending tests, but the mechanical properties of unreinforced beams depended on cross-section. Dowel reinforcement effectiveness theoretically increased with the number of dowels, though excessive dowels risked splitting the wood. In tested beams, dowels nearly doubled the load capacity (6.5–24.0 kN on average). Plywood strip reinforcement improved resistance by up to 10 kN, equivalent from several percent to 2.5 times the original capacity.*
Beams with end notches, used in spans, can be evaluated under load using EN 1995-1-1: Eurocode 5 and STR 2.05.07:2005 methods. The study showed that differences between theoretical calculations and experimental results on calibrated structural timber did not exceed 17 %.

KEYWORDS: *timber beam; glulam timber beam; plywood strips; reinforced; strengthening*

SAŽETAK • *Pri proizvodnji drvenih greda velikih raspona na njihovim se krajevima često formiraju urezi. Pod opterećenjem se na tim urezima stvaraju naprezanja, što nerijetko uzrokuje pukotine i lom grede. U ovoj su studiji teorijski i eksperimentalno istraživane metode ojačanja tih greda. Ispitane su dvije vrste kalibriranih greda: grede od masivnog drva i lamelirane lijepljene grede. U eksperimentalnim ispitivanjima grede su učvršćene u stroju kako bi se simuliralo savijanje u tri točke na sredini raspona. Za paralelne teorijske procjene primijenjeni su standardi za projektiranje EN 1995-1-1: Eurocode 5 i STR 2.05.07:2005. Za svaku vrstu grede pripremljene su tri skupine uzoraka: neojačane grede, grede s čeonim ojačanjem moždanicima i grede s čeonim ojačanjem letvicama*

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furnirske ploče. Sve su grede pucale na sličan način: pukotine su nastajale na urezima i širile se sve dok greda nije izgubila nosivost. Ponašanje loma razlikovalo se od tipičnih ispitivanja savijanja, ali mehanička svojstva neojačanih greda ovisila su o njihovu presjeku. Učinkovitost ojačanja moždanicima teorijski se povećavala s brojem moždanika, iako je prevelik broj moždanika značio i rizik od cijepanja drva. Na testiranim gredama moždanici su gotovo udvostručili nosivost (u prosjeku 6,5 – 24,0 kN). Ojačanja od furnirske ploče poboljšala su otpornost do 10 kN, što je ekvivalentno iznosu od nekoliko postotaka do 2,5 puta izvorne nosivosti. Nosivost grede s urezima na krajevima može se procijeniti primjenom metoda EN 1995-1-1: Eurocode 5 i STR 2.05.07:2005. Studija je pokazala da razlike između teorijskih izračuna i eksperimentalnih rezultata na kalibriranom građevnom drvu nisu bile veće od 17 %.

KLJUČNE RIJEČI: *drvena greda; lamelirana lijepljena greda; letvice furnirske ploče; ojačanje*

1 INTRODUCTION
1. UVOD

Natural and glued timber are commonly used in construction due to their versatility and relatively straightforward processing. Glued timber is composed of wood chips of various dimensions, bonded together with adhesive, the quality of which is crucial for the properties of the structure and the risk of delamination (Ferreira *et al*., 2017; O'Loinsigh *et al.*, 2012). Structures constructed from glulam timber are stable; however, the wood responds to environmental humidity, which can result in dimensional changes in the wooden elements (Smulski, 2004).

Wooden beams are often used to overlap spans. Structurally, they are frequently cut at their ends. They are formed at the supports, which weakens the structure. The strength of beams cut at the supports diminishes due to transverse stresses, potentially leading to the formation of cracks. In such cases, it is essential to analyse and design the structures carefully. In renovation projects, cut-outs in beams are often prohibited to prevent weakening the structure (Todorovic *et al.*, 2019; Soltis *et al.*, 1998). Possible longitudinal cracks at the ends of beams are classified into three types: the crack surfaces may separate from each other vertically (in a perpendicular direction), horizontally (where shear occurs between the crack surfaces), or as a combination of these two types (Todorovic *et al.*, 2019).

In structural design, the behaviour of beams can be assessed using various methodologies. One of them, described in the standard EN 1995-1-1: Eurocode 5: "Design of timber structures", stipulates that beams with notches should be designed taking into account stress concentrations, which can be ignored in certain cases, e. g. if the bending of the beam does not cause significant tensile stresses. Shear stresses are generated at the supports with notches; therefore the beams must be of a certain height. It is also stated that notches should be made only at the supports, avoiding them in the centre of the beam. Furthermore, if notches are necessary, they should be rounded (Butler, 2002).

To prevent cracks and increase load-bearing capacity, beams can be reinforced. Recently, Şimşek Türker and his colleagues have devoted significant attention to improving the mechanical properties of glulam beam and column connections using FRP (fibre-reinforced polymers) (Şimşek Türker, 2024; Şimşek Türker and Kilincarslan, 2024; Şimşek Türker *et al.*, 2024). Their studies investigated various reinforcement methods, including carbon, glass, basalt, and aramid FRP fabrics, and their effects on connection stiffness, bending strength, and energy dissipation. Experimental tests demonstrated that FRP reinforcement significantly enhances connection performance, with carbon fibre generally proving the most effective and glass fibre the least. Additionally, numerical models were employed to predict beam behaviour, and the results showed high prediction accuracy.

Threaded rods, wood screws, bolts, and various plates made of steel, carbon or fibreglass are used for this purpose. Wood screws used for connecting or reinforcing wooden structures are categorised into full-thread and partial-thread types, chosen according to the specific requirements of each situation. Full-thread wood screws possess a greater load-bearing capacity under axial loads [Aytekin, 2008]. Screws or fully threaded screws can either be glued or simply screwed in. They enhance the resistance of the beam from cracking. There are methodologies for various types of wood, as well as glulam beams and LVL, to assess the behaviour of such reinforced beams under load. In calculations, it is generally assumed that the screws are inserted into the beams perpendicular to the wood grain (Todorovic *et al.*, 2019; Jockwer, 2014).

Occasionally, beams are strengthened using plywood strips. Plywood is a readily processed material with appropriate mechanical properties for reinforcing the ends of beams. It is advisable to use plywood that has a thickness of at least 10 mm, adhered to both sides of the beam. In order to ensure good adhesion to the beam surface, the plywood strips must be well pressed, and nails or wood screws can also be used as fasteners. Epoxy resin or polyvinyl acetate resin-based adhesives can be used for glueing plywood. The choice of adhesive is usually determined by the strength and ecological requirements of the structure (Ebnesajjad and Landrock, 2015; Broughton and Hutchinson, 2001).

Other methods of strengthening the ends of beams are sometimes used. One such methods is the use of fibreglass rods. It is said that this increases the load-bearing capacity of the beam by up to 194 %. Epoxy adhesives are used to bond the rods. Although this method of strengthening beams is effective and durable, these rods are not environmentally friendly and their recycling is difficult (Tao *et al.*, 2023; Todorovic *et al.,* 2019). Another material used is carbon fibre fabric. It is a light and strong material that allows the beams to withstand more than 2.5 times the load. Epoxy glue is used to bond the carbon fibre. This strengthening method is rarely used because it is expensive, environmentally unfriendly, and the glue can take up to 7 days to cure (Ebnesajjad and Landrock, 2015; Broughton and Hutchinson, 2001). Another way to strengthen beams is to use steel threaded rods. They are effective in cutouts where precise load transfer is required. When installing the rods, larger diameter holes need to be drilled to allow for glueing. In this case, the strength of the beam is greatly influenced by the adhesive, the quality of the glueing, and the mechanical properties of the rods. The rods can also be installed at an angle, which allows them to be fixed closer to the edge of the cutout (Branco *et al.*, 2021).

The selection of these beam reinforcement methods is influenced by cost, complexity, and environmental considerations.

Objective of the study: To evaluate the effectiveness of beam end reinforcement and to compare the practically obtained load resistance values with those theoretically calculated ones.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

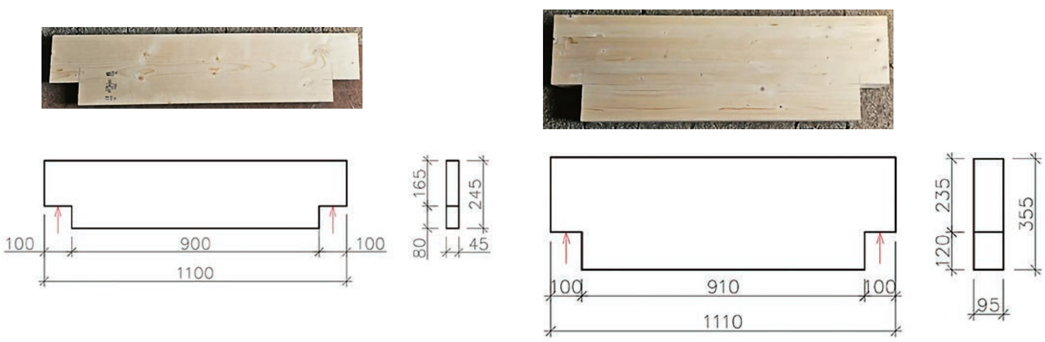
Two types of beams, made of solid and glulam spruce timber, were used for the research. The dimensions of the solid wood beams were 1100 mm × 245 mm × 45 mm, moisture content 11.3-11.8 %, density 457-471 kg/m^3; according to the manufacturer's declaration, they correspond to class C24. The dimensions of the glulam timber beams were 1110 mm × 355 mm × 95 mm, moisture content 11.2-11.5 %, density 478-489 kg/m^3; they correspond to class Gl24C.

The length of the specimens was measured using a ruler with a precision of 1 mm, while the width and thickness were measured with a calliper with a precision of 0.1 mm. The mass of the specimens was determined using scales with a precision of 1 g, and the moisture content was assessed employing an electronic moisture meter, adhering to standard EN 13183-2:2003, EN 13183-2:2003/AC:2004, with a precision of 0.1%. Notches were cut at the ends of the beams with a hand saw. There were 12 beams of both types in total. Their general view and diagram are presented in Figure 1.

Both types of beams were randomly divided into three groups of four pieces each, which were designated as follows: solid wood groups N1, N2, N3, and glulam timber groups GL1, GL2, GL3. The ends of the beams in groups N2 and GL2 were reinforced with wood screws "KLIMAS WKCP", measuring 6x180 mm and 8x240 mm, respectively, while groups N3 and GL3 were reinforced with plywood strips (plywood BB/WG, class 3, manufacturer AS "Latvijas Finieris"). The strips were glued with wood glue "Titebond Original" according to the manufacturer's recommendations. A general view and schemes of these reinforced beams are presented in Figures 2 and 3, respectively.

Before testing, the samples were conditioned in the laboratory for one week at a temperature of 19.5–20.0 °C and a relative humidity ranging from 52 % to 55 %.

The load-bearing capacity of the specimens was determined using the "three-point" scheme. When testing with this method, the sample is placed on two supports and pressed from above at one place (one point) in the middle. The pressure force is increased until the



a) b)

Figure 1 General view and diagram of beams made of solid (a) and glulam timber (b) used for the research
Slika 1. Opći prikaz i dijagram greda od masivnoga (a) i lijepljenog drva (b) izrađenih za istraživanje

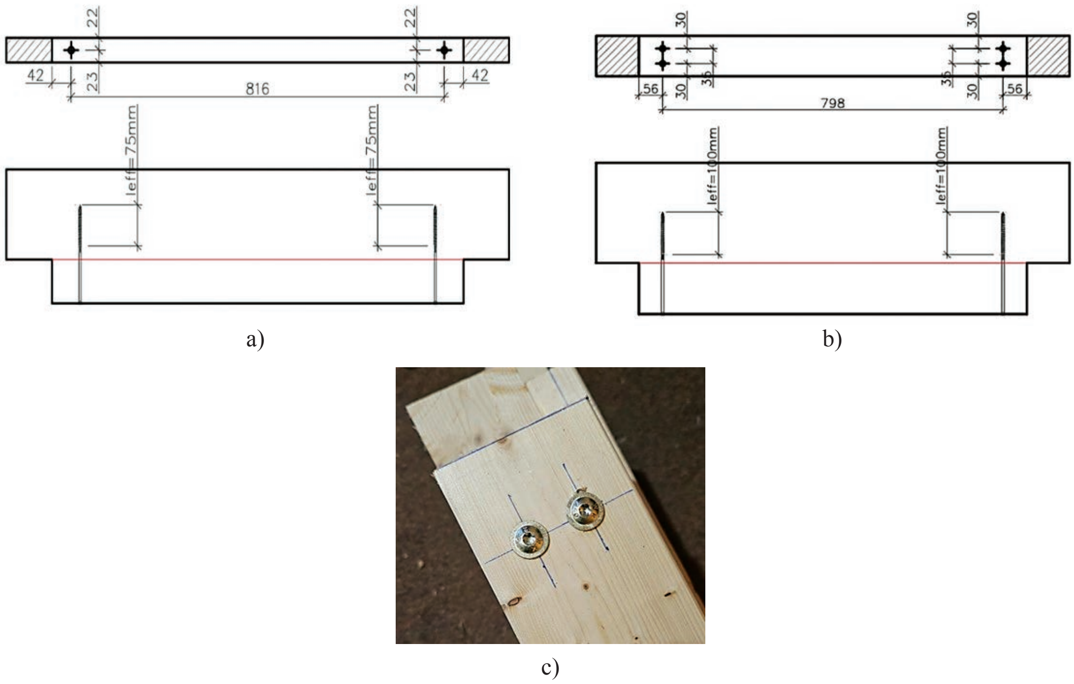


Figure 2 Schemes (a, b) and a general view (c) of solid and glulam timber beams reinforced with wood screws
Slika 2. Sheme (a, b) i opći prikaz (c) masivnih i lijepljenih drvenih greda ojačanih vijcima za drvo

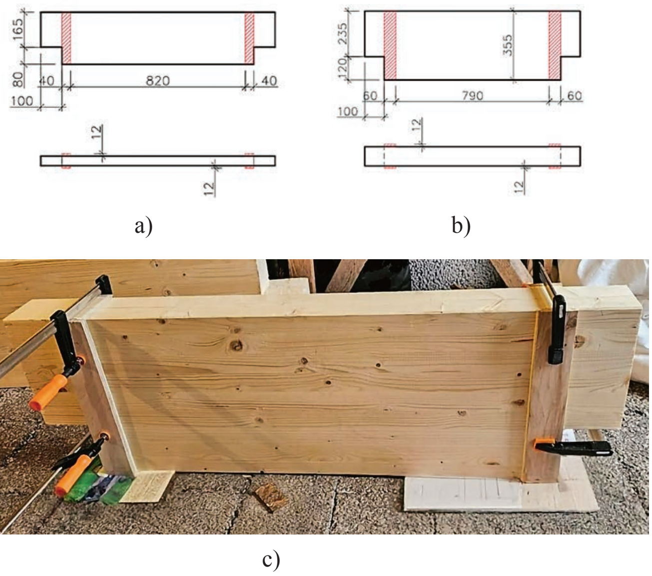


Figure 3 Schemes (a, b) and an overview (c) of solid and glulam timber beams reinforced with plywood strips
Slika 3. Sheme (a, b) i pregled (c) masivnih i lijepljenih drvenih greda ojačanih letvicama od furnirske ploče

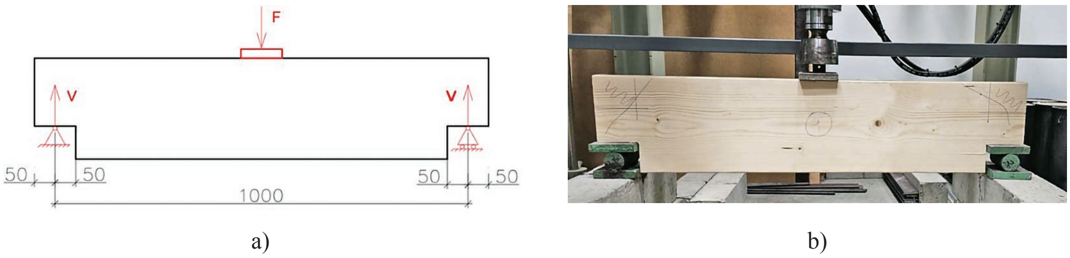


Figure 4 Scheme of the test (a) and general view (b)
Slika 4. Shema ispitivanja (a) i opći prikaz (b)

sample breaks and stops resisting. The distance between the lower supports and the geometric dimensions of the sample are evaluated during the calculation. The tests were carried out in accordance with the standard EN 310:1993. The principal test scheme and general view are presented in Figure 4.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The calculated and practically determined values of load resistance using methods "A" and "B", along with the statistical data assessing the dispersion of these values (standard deviation and coefficient of variation), are presented in Table 1.

First of all, it should be noted that the "false" strength of unreinforced beams differs (column 5). This difference is quite significant (4.15 and 3.66 N/mm^2 or MPa) and is about 12 %. However, this is not related to gluing, but to the dispersion of the mechanical properties and structural features of wood (Wagenführ, 2000; Wood handbook, 2010).

Data analysis showed that the glulam timber beams withstood higher loads than the solid ones (column 4). However, this is attributed to their significantly larger cross-section. To enable a comparison of these values, the load resistance (MPa) was calculated (column 5). Evaluating the nature of the beams failure (both glulam timber and solid beams, when subjected to loads, did not fracture, as is typical in the case of three-point bending, but delamination occurred at the ends with notches) and because they were reinforced, this does not accurately reflect the true bending strength of the material. Nonetheless, in the authors' opinion, it permits a more objective comparison of samples with differing cross-sections. It can be stated that, in the case of unreinforced beams, both glued and solid beams exhibited similar mechanical properties. In terms of MPa, the difference in the average values of the groups was approximately 12 %, which is quite small considering the dispersion of the mechanical properties of wood. Regarding reinforcement with wood screws, it can be concluded that the nature of beam failure significantly influences the number of screws used. Comparatively, in both glulam timber and solid wood beams, the specimens with wood screws endured nearly twice the load compared to those without wood screws. Specifically, when comparing the groups "N2" and "N1", this difference is 1.87 times, and when assessing the groups "GL2" and "GL1", the difference is 1.81 times. However, in terms of absolute values, the average difference with one wood screw is 6.5 kN, and with two screws, it is as much as 24.0 kN. Certainly, the strength properties of wood likely also played a role, but the trend is clear. A markedly different effect was achieved when reinforcing beams with plywood strips. In this instance, for both solid and glued beams, plywood strips "added" several kN (averaging about 8.9 for solid beams and approximately 7.0 kN for glued beams). Based on the nature of the samples breakdown, it can be concluded that this "additional resistance" was influenced by two factors – the area of the strip and the resistance of the wood to delamination. Given that these values are similar, the results were as follows. In terms of relative values, the strength of beams with a larger cross-section increased by about 1.23 times, whereas that of beams with a smaller cross-section increased significantly by 2.20 times.

When comparing the values of the load resistance of beams calculated theoretically with those determined practically, it can be stated that they are simi-

Table 1 Calculated and practically determined values of load resistance using methods "A" and "B" and statistical data assessing the dispersion of values
Tablica 1. Izračunane i praktično određene vrijednosti otpora opterećenju primjenom metoda A i B te statistički podatci prema kojima se procjenjuje raspršenost vrijednosti

Group No. *Broj skupine*	**Force calculated by method A, kN** *Sila izračunana prema metodi A,* kN	**Force calculated by method B, kN** *Sila izračunana prema metodi B,* kN	**Determined force within group, kN** *Sila utvrđena unutar skupine,* kN	**Determined force within group, kN** *Sila utvrđena unutar skupine,* kN	**Standard deviation within group, kN** *Standardna devijacija unutar skupine,* kN	**Variation coefficient within group, %** *Koeficijent varijacije unutar skupine,* %	**Difference between values in columns "2" and "4", %** *Razlika između vrijednosti u stupcima 2. i 4., %*	**Difference between values in columns "3" and "4", %** *Razlika između vrijednosti u stupcima 3. i 4., %*
1	2	3	4	5	6	7	8	9
N1	6.99	6.41	7.48	4.15*	0.38	5.08	6.55	14.30
N2	14.02	-	14.00	7.77**	0.65	4.64	0.14	-
N3	14.71	-	16.42	9.12***	0.70	4.26	10.41	-
GL1	33.00	24.49	29.50	3.66*	1.08	3.66	11.86	16.98
GL2	47.10	-	53.50	6.70**	2.14	4.00	11.96	-
GL3	31.38	-	36.48	4.57***	1.60	4.39	13.98	-

* – When evaluating the nature of the sample failure mode, this represents a false strength of the wood under load (bending).
** – This indicates a false strength of the wood under load, as wood screws affect the outcome.
*** – This signifies a false strength of the wood under load, with the result being influenced by glued plywood.
** – Pri procjeni načina loma uzorka predočuje lažnu čvrstoću drva pod opterećenjem (savijanje).*
*** – Upućuje na lažnu čvrstoću drva pod opterećenjem jer vijci za drvo utječu na rezultat.*
**** – Označava lažnu čvrstoću drva pod opterećenjem, pri čemu na rezultat utječe zalijepljena furnirska ploča.*

a) b)

Figure 5 Predominant failure modes of solid timber (a) and glulam timber (b)
Slika 5. Prevladavajući načini loma punog drva (a) i lijepljenoga lameliranog drva (b)

lar (Table 1, columns 8 and 9). The largest difference was observed in the case of glulam timber unreinforced beams (group GL1), where the values calculated according to STR 2.05.07:2005 "Design of timber structures" (Method "B") and the practical values differed by nearly 17 %. In contrast, the smallest difference was noted for the group of specimens N2, with the values calculated according to EN 1995-1-1: Eurocode 5 "Design of timber structures" (Method "A") differing from the practical values by only 0.14 %. Method "B" does not permit the calculation of the strength properties of reinforced beams, so these were not computed. Overall, by assessing the differences between the calculated and practical values, it can be stated that the values computed by method "A" are closer to those obtained in practice (the difference was 0.14 – 14.0 %). Conversely, the values calculated by method "B" differed from the practical ones by 14.0 – 17.0 %.

The dispersion of results across all groups of specimens was small, with the coefficient of variation ranging from 3.6 % to 5.1 %. This was the smallest for unreinforced glulam timber beams and the largest for unreinforced solid beams (see Table 1, column 7).

Thus, on one hand, both the variability of values within groups and the discrepancies between theoretical and practical values stem from the considerable variation in the mechanical properties of wood as a material. On the other hand, the research used wood calibrated by the manufacturer, and therefore both the variability of values and the discrepancies between theoretical and practical values were relatively small.

General images of the prevailing nature of the collapse of solid and glued timber beams are presented in Figure 5.

The characteristics of beam failure and other defects that occurred under load were analysed individually. Regarding unreinforced beams (groups N1, GL1), both solid and glulam timber beams exhibited the formation of a crack at the beam cutout, leading to collapse once the specified load threshold was attained. When loading beams that are reinforced with wood screws (groups N2 and GL2), the wood fibres are initially compressed beneath the heads of the screws. In the case of solid wood beams, where one screw is installed at each end of the beam, the loads fluctuate within the range of 7.0 to 8.0 kN. In the case of glulam timber beams, two wooden bolts were twisted at the ends, and the forces exerted varied within the range of 21 to 27 kN. Furthermore, as the loads increased, the wooden bolts were extracted, resulting in the formation of cracks at the beam cutouts, similar to the behaviour observed in unreinforced beams. When loading beams reinforced with glued plywood strips (designated as groups N3 and GL3), the wood exhibited nearly simultaneous exfoliation at the adhesive joints that connected the beams to the plywood strips, accompanied by crack formation. It is noteworthy that cohesive failure predominantly occurred through the wood (primarily in the beams) at the adhesive joints.

The dependence of the beam deflection on the load was also evaluated. The curves show the average values of the mentioned groups. They are presented in Figure 6.

We see that both in case of solid timber and glulam timber, the largest deformations were observed in beams reinforced with wood screws. However, these differences are very small and are not related to the strengthening method, but to the viscous-elastic properties of the wood.

Summarising the results obtained, it can be stated that by choosing the right method of reinforcing the ends of the beams, a much stronger structure can be obtained. This has been confirmed by both theoretical calculations and practical research results.

When examining the results in general, in the context of the results obtained by other researchers, it can be stated that the fastening effect depends on the materials and method used. Another important aspect is the prediction of the strength properties of the structure. In many cases, it is complicated not so much by the method of reinforcement itself, but by the unevenness of the wood structure and the dispersion of mechanical properties.

4 CONCLUSIONS
4. ZAKLJUČAK

1. By employing suitable methods for reinforcing the ends of the beams with notches under optimal conditions, the structural strength can be enhanced twofold or more.

2. In the installation of beams with cutouts at their ends–regardless of whether they are constructed

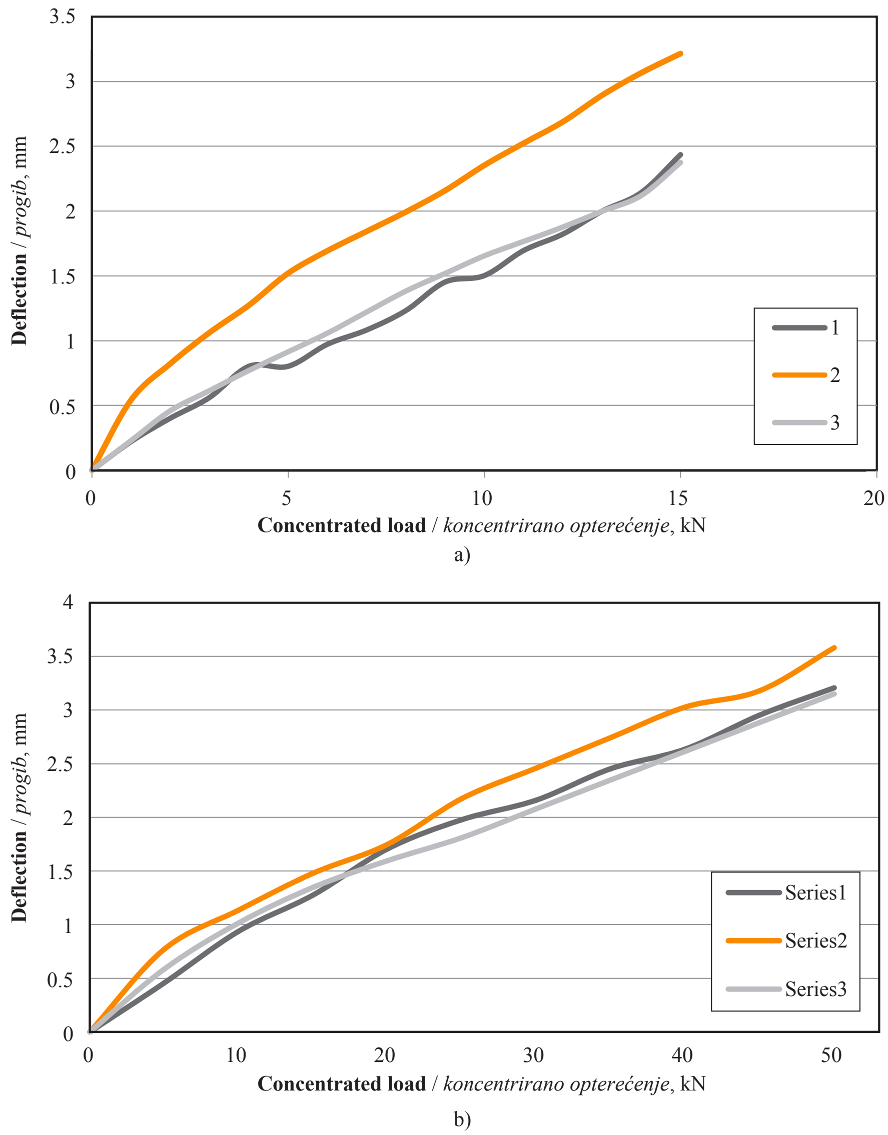


Figure 6 Beam deformations depending on the load: a) solid timber; b) glulam timber: 1 – unreinforced beams; 2 – reinforced with wood screws beams; 3 – reinforced with glued plywood strips beams
Slika 6. Deformacije greda ovisno o opterećenju: a) masivno drvo; b) lijepljeno lamelirano drvo: 1 – neojačane grede; 2 – grede ojačane vijcima za drvo; 3 – grede ojačane zalijepljenim letvicama od furnirske ploče

from solid wood or glulam timber, and irrespective of reinforcement–the nature of potential failure remains consistent. Due to the induced stresses, a crack may develop at the cutout, leading to the delamination of the wood.

3. Unreinforced beams with cutouts at the ends, positioned within the span, demonstrate a load resistance that is contingent upon the cross-sectional area; however, the failure pattern differs from the conventional failure modes associated with "three-point" or "four-point" bending.

4. A highly effective method for strengthening of beams with notched ends involves the use of dowels. An increased quantity of dowels may yield a more pronounced strengthening effect; however, there exists a risk of compromising the integrity of the beam, potentially leading to splitting and diminishing the wood capacity to securely accommodate the dowels. In the instances of the examined beams, their load-bearing resistance exhibited an approximate doubling after the implementation of dowels, with an average increase ranging from 6.5 to 24.0 kN.

5. When using glued plywood strips to reinforce beams with cutouts at the ends, their effect, in absolute terms, does not depend on the beam load resistance and, in specific instances, can increase the resistance by up to 10.0 kN. In the cases examined, this varied from a few percent to nearly 2.5 times.

6. In the assessment of deflection for beams featuring notches at their ends, which are used for installation across spans, the methodologies outlined in the normative documents EN 1995-1-1: Eurocode 5 "Design of Timber Structures" and STR 2.05.07:2005 "Design of Timber Structures" are deemed appropriate. Research indicates that the discrepancies between the theoretically calculated values and those derived from

practical testing of calibrated construction timber did not exceed 17 %. This difference is considered minimal, especially when considering the variability in the mechanical properties of wood.

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