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ФЛЕКСИОНО ЗАЈАКНУВАЊЕ НА ГРЕДИ ОД ЛЕПЕНО ЛАМЕЛИРАНО ДРВО СО КОРИСТЕЊЕ НА НАДВОРЕШНО ПОВРЗАНИ CFRP ПЛОЧИ

РЕЗИМЕ

Идеата за зајакнување на лепени ламелирани дрвени греди (glulam) доаѓа како одговор на потребата за подобрување на механичките карактеристики, како и обезбедување повисока доверливост на овој тип на конструктивни елементи. Овој труд го опишува експерименталниот програм кој го истражува зајакнувањето при свиткување на glulam греди со плочки од пластика зајакната со карбонски влакна (CFRP). Петнаесет греди зајакнати со CFRP на затегнатата страна и пет незајакнати контролни греди се инструментирани и тестирани до лом во конфигурација на свиткување во 4 точки. Механичките карактеристики на зајакнатите греди се споредени со оние од незајакнатите и тоа, однесувањето сила-поместување, типови на лом, ултимативните товари и крутоста.

Клучни зборови: glulam греди, карбонски влакна, зајакнување, тестови на свиткување.

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FLEXURAL STRENGTHENING OF GLULAM BEAMS USING EXTERNALLY BONDED CFRP PLATES

SUMMARY

The idea of strengthening glued laminated timber (glulam) beams came in response to the need to improve the mechanical properties, as well as to ensure higher reliability of this type of structural elements. This paper describes an experimental program which examines the reinforcement in flexure of glulam beams with carbon fibre reinforced plastic (CFRP) plates. Fifteen beams reinforced with CFRP at the tension side and five unreinforced control beams were instrumented and tested to failure in a four-point bending configuration. The mechanical properties of reinforced beams are compared to those of unreinforced beams with regard to the load-deflection behaviour, failure mode, ultimate load capacity and stiffness.

Keywords: glulam beams, carbon fibres, reinforcement, bending tests.

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1. INTRODUCTION

Timber has been used as a building material from the earliest times. Even today, in addition to progress of steel and concrete, timber structures have their own special place in the modern construction industry. Lightweight and relatively high strength, workability, easy of handling and assembly, attractive aesthetic appearance and environmental compatibility are only some of the parameters which effect the successful application of timber structures. However, timber also has a number of disadvantages. Variability in terms of strength and stiffness of wood, caused by the presence of natural defect and variations in growth conditions, make it difficult to predict the behaviour of timber elements at different loads. These problems can be solved with the development of wood-based products by gluing smaller pieces of solid timber such as glued laminated timber (glulam). This technique allows the production of timber elements in which the defects are dispersed, ensuring a final product with more uniform properties, whose dimensions are theoretically unlimited. Capable of spanning greater lengths and carrying greater loads, glulam has advanced the timber as a building material. Although glulam offers significant improvement over sawn timber, its ultimate bending strength often remains limited by strength reducing flaws, such as knots and finger joints, in the tension zone. Tension failure mode is brittle as the timber does not exhibit plastic behaviour under tensile loads. This can even lead to cracks along the timber grain, which will result in terrible destruction of the cross section.

When a timber beam is reinforced at a tension zone, the failure mode for the timber structures may change from tension failure to compressive failure, which is more ductile. In other words, this method increases the tensile capacity of the beam, meaning that the compressive capacity of a timber is utilized at its fullest. As a result, it can be applied in a new construction, as well as in the rehabilitation of existing timber structures. Effective techniques for reinforcing timber can be used to reduce the size of beams and allow for utilization of lower grades of wood. The same strengthening techniques may be used in order to increase the load-carrying capacity of existing timber elements, so that the same elements could support much higher loads when compared to those in the original design of the structure, thus saving money and material needed to replace the structure (Gentile 2000).

In recent years, the increased availability and a reduced cost of fibre reinforced polymer (FRP) materials have aroused interest in research into strengthening timber structures. Fibre reinforced polymers are a relatively new class of composite materials manufactured from artificial fibres and resins. The three fibre types most commonly used in structural applications are glass, carbon and aramid. High stiffness and tensile strength, low weight, easy installation, high durability (no corrosion), electromagnetic permeability, and practically unlimited availability in terms of geometry and size are the main advantages of these composites.

A number of research studies have examined the attractive option of strengthening timber flexural members with fibre reinforced polymer plates. Although this idea has existed for some time the amount of research undertaken in this area remains limited. Much effort was expended to study the short-term response of timber-FRP plates (Fiorelli and Dias 2003; Gilfillan et al. 2003; Borri et al. 2005; Li et al. 2009; Raftery and Harte 2011), the interaction and bond strength of FRP-timber interface (Juvandes and Barbosa 2012), as well as the long-term performance of FRP reinforced timber members (Gilfillan et al. 2003).

This paper describes an experimental investigation of glulam beams reinforced with carbon fibre reinforced polymer (CFRP) plates. Bending behaviour of CFRP-reinforced beams was compared with unreinforced beams that were used as control specimens. Experimental results are presented in terms of load-deflection relationship, failure mode, ultimate load capacity and stiffness.

2. MATERIALS

2.1. Timber

Glulam was manufactured from Spruce (*Picea abies*) timber, of strength class C24 according to EN 338. The timber came from the same stand in order to minimize the influence of the variability in timber properties. The timber stock was initially kiln dried until reaching 18% of moisture content and then conditioned for three months at the relative humidity of 65 ± 5% and at the temperature of 20 ± 2°C. An approximate equilibrium moisture content of 12% was obtained after the conditioning period, and a mean timber density of 427 kg/m^3 was recorded. The average mechanical properties, obtained from preliminary testing compliant with EN 408 (CEN 2010), are reported in Table 1.

Property	Value
Tensile strength parallel to grain (MPa)	27.8
Compression strength parallel to grain (MPa)	36.2
Bending strength (MPa)	42.5
Modulus of elasticity parallel to grain (MPa)	11080

Table 1. Experimental mechanical properties of Spruce timber

Each glued laminated timber beam was obtained by assembling 7 laminations which are 80 mm wide, 30 mm thick and 4000 mm long. The overall dimensions of the beams were 80 x 210 mm by 4000 mm. Laminations of better quality (fewer critical strength reducing defects such as knots, fissures and grain deviation) were placed on the region of the greatest stress. A phenol-resorcinol adhesive was used to glue laminations into the monolith section, where the bonding performed under pressure of 0.5 to 0.8 MPa for the period of 12 h at the temperature of approximately 20°C.

2.2. Fibre reinforced polymer

Fibre reinforced polymer is an advanced composite material which consists of many thin and long fibres embedded in a polymer resin matrix. Fibres provide both load carrying capacity and stiffness to the composite, while the matrix is necessary to hold fibres together and ensure the load among fibers. Composite materials for structural strengthening are available today typically in the form of plates, sheets or bars.

FRP material used in the test program comprised carbon fibres in an epoxy matrix. The carbon fibre plates were provided from Sika Group, a company that has extensive experience in terms of repairing and strengthening of reinforced concrete and masonry structures. The plates used for this research were Sika CarboDur S613 with cross sectional dimension 60 x 1.3 mm. Sika CarboDur is a pultruded carbon fibre reinforced polymer plate designed for the purpose of strengthening concrete, timber and masonry structures. The plates consisted of unidirectional fibres aligned along the longitudinal direction with fibre volume content greater then 68%. The density of this reinforcement is 1.6 g/cm^3.

Property	Value
Experimental results (average)	
Tensile strength (MPa)	2846
Modulus of elasticity (MPa)	165543
Maximum strain (%)	1.79
Provided by Sika	
Tensile strength (MPa)	2800
Modulus of elasticity (MPa)	165000
Maximum strain (%)	1.7

Table 2. Summary of results for tensile test of CFRP plates

Ten samples from CFRP plate were tested in tension with reference to EN 527-5 (CEN 2009) in order to determine its ultimate strength, ultimate strain and modulus of elasticity. Table 2 shows mechanical properties of the CFRP reinforcement. The experimental results for modulus of elasticity, tensile strength and strain at failure are close to the value specified by the manufacturer.

2.3. Adhesive

Epoxy adhesives are well established in civil engineering and it is reported that they are generally considered to be the most suitable for the bonding of composite materials. They have certain advantages such as good gap-filling characteristics, limited shrinkage during curing, ability to achieve full cure at ambient temperatures, and only require low clamping pressures. Consequently, epoxy adhesives are often employed in CFRP–timber bonded connections in the reinforcing timber members.

Property	Value
Tensile strength after 7 days (MPa)	24.8
Elongation at break (%)	1.0
Compression strength after 7 days (MPa)	59.3
Bending strength after 14 days (MPa)	46.8
Modulus of elasticity in bending after 14 days (MPa)	11721

Table 3. Typical data of mechanical properties of epoxy resin (Curing conditions: 23°C and 50% R.H.)

The adhesive used to bond glulam beams and CFRP plates was Sikadur-30, which is a Sika produce. Advantages of this resin are the relative low cost and no odors' emissions during its application. Sikadur-30 is solvent free adhesive based on a combination of epoxy resin and special filler, which is used primarily to bond structural reinforcements to other substrates. It consists of component A (Resin) and B (Hardener). Sikadur-30 is ready to be used when mixing these two components in ratio A: B = 3:1, either by weight or volume. Table 3 shows the mechanical properties of adhesive provided by the manufacturer.

3. EXPERIMENTAL METHOD

3.1. Test program

The experimental investigation was carried out at the Material Testing Laboratory of the Faculty of Civil Engineering, University of Belgrade. The test program involved the fabrication of reinforced glulam beams and testing to failure of both unreinforced and reinforced beams under four-point bending. The results for the unreinforced beams are reported solely for the purpose of quantitatively evaluating the effectiveness of the intervention by making comparison with those results of reinforced beams.

The beams were divided into three series:

1. Series A, which included 5 unreinforced beams;
2. Series B, which included 10 beams reinforced with one 60 x 1.3 x 3600 mm CFRP plate bonded centrally to the tension zone of the beam (reinforcement ratio 0.46%);
3. Series C, which included 5 beams reinforced with two 60 x 1.3 x 3600 mm CFRP plates bonded centrally to the tension zone of the beam (reinforcement ratio 0.93%).

3.2. Reinforced beam fabrication

In the fabrication of reinforced beams, the substrate had to be made first before the composite plates were bonded to tensile face of glulam beams. The timber surface was prepared as suggested in the manufacturer's instructions so that CFRP plates and timber could be properly bonded. To eliminate splinters and dust, a sanding process with sandpaper was applied at those zones where CFRP's systems were planned to be installed, followed by the application of compressed air. CFRP plates were cut to the desired length, and were cleaned properly with acetone (Sika Colma Cleaner) so as to remove any contaminant. Well-mixed Sikadur-30 was applied by using a special "roof-shaped" spatula over the cleaned carbon plate to nominal thickness of 1 mm. The epoxy adhesive was applied over the cleaned and prepared substrate with a trowel to a thickness of approximately 1 mm. Within the open time of the epoxy, the CFRP plate was placed onto the glulam surface. The composites plate was attached starting at one end and applying enough pressure by rubber roller to press out any excess epoxy from the sides of the plate. All excess epoxy was removed from the sides of the CFRP plate. To ensure a proper bonding, the specimens were cured for seven days at room temperature of 20±2°C.

A two-step process was used for five beams with two layers of CFRP at the tension side. One CFRP plate was bonded to the glulam beam, as previously described; then the next CFRP plate was bonded with the same epoxy adhesive. After the first CFRP layer was glued to the glulam beam, the epoxy adhesive was applied only onto the second layer, which was placed on already attached CFRP layer.

3.3. Beam testing

All beams (Series A-C) were subjected to bending test in accordance with EN 408 (CEN 2010). The beams were tested to failure under monotonic load in four-point bending configuration with a simple supported span of 3780 mm (18 times the beams' depth). The two load points were at a distance from their reaction equal to one third of the span. The loading was done by using a loading cell, whose maximum capacity of 250 kN, powered by 350 kN hydraulic jacks. In the test procedure, the load was transformed from one load point to two load points by using the steel beam. Lateral restraints were provided to prevent lateral buckling of the beams. The typical test setup for beams is shown in Fig. 1.

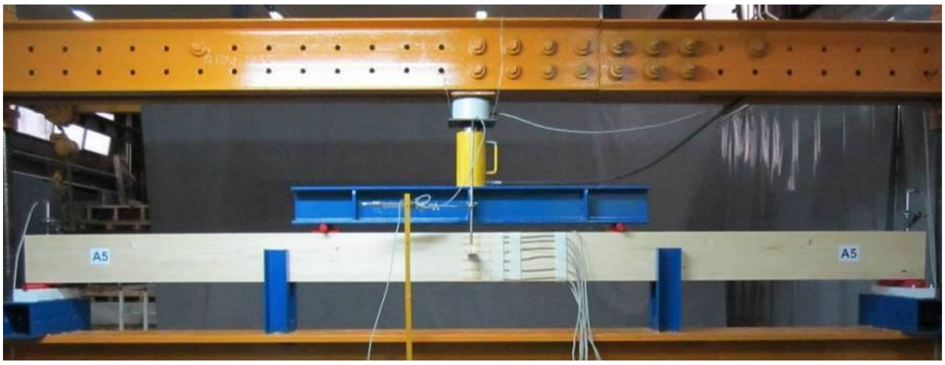

Fig. 1. Beam arrangement during test

The deflections of the beams were measured by using linear variable displacement transducers (LVDTs). Deflection at mid-span was monitored using one LVDT (positioned so as to effect the reading near the neutral axis), while displacement at supports was measured using two LVDTs. Furthermore, strains were monitored at the mid-span of the beam throughout the depth and on the CFRP reinforcement by using strain gauges. Strain data from strain gauges, deformation data from LVDTs and corresponding load data from the loading cell were all recorded by using a computerized data acquisition. Data acquisition was carried out with a frequency of 2 Hz.

The monotonic static load was applied at a stroke-controlled rate of 4.5 kN per minute so as to produce the failure of beams for approximately 10-15 min. Before the tests had been carried out, the specimens were conditioned at the standard environment of relative humidity 65 ± 5 % and at the temperature of 20 ± 2 °C. Soon after the test had been completed, moisture content of a timber was measured with a digital hygrometer at different locations. The moisture content was in the range of 10.8–11.4% in all cases.

4. RESULT AND DISCUSSION

4.1. Load-deflection behaviour and failure mode

The results of load-deflection curves for all beams are shown in Fig. 2.

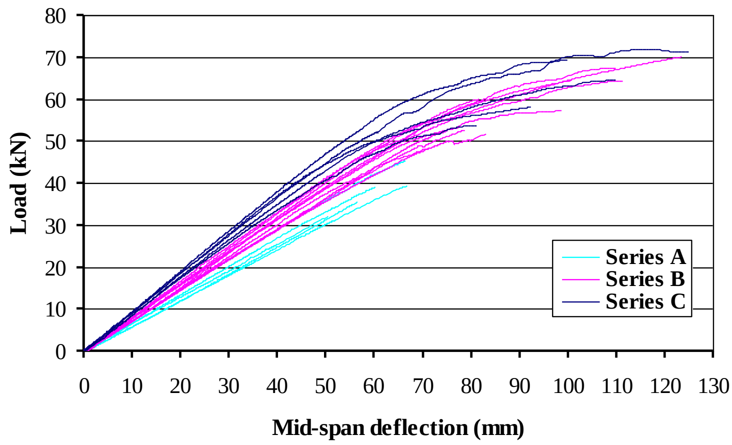

Fig. 2. Load-deflection curves from bending tests

Every unreinforced beam (Series A) failed within the elastic region due to a tension failure of the bottom laminations. Because of the timber's brittle nature when exposed to tension, most beams failed catastrophically without visible failures before reaching ultimate load. Once the timber showed signs of fissures, the cracks promptly developed and in some cases propagated along the timber grain, past the load application points and towards supports as seen in Fig. 3(a). In four out of five specimens, the initial cracking of the timber initiated either at a defect or discontinuity (e.g. knots) in the tension zone, not very far from the mid-span (Fig. 3(b)). One beam failed in clear wood at the bottom lamination (Fig. 3(c)). There was no sign of compressive plasticization at the top lamination in any of unreinforced beams.

Fig. 3. Beam failure modes

Experimental test carried out on reinforced beams, which are reinforced with one CFRP plate (Series B), demonstrated that the most frequent failure mechanism is the one in which tension failure occurs, with or without partial plasticization of the compression zone. Initially the load-deflection response is shown to be linear-elastic up to the local failure induced by presence of defect and discontinuity in the tension zone. Timber yield produced a non-linear response terminated by a sudden drop of the load as a result of timber rupture in the tension zone (Figs. 3(d) and 3(e)). The tough compression face displayed signs of plasticization in the form of a buckled fibre, but it remained intact (Fig. 3(f)). Results indicated that seven out of ten test beams failed at a knot in tension laminations, and two out of ten test beams failed at the bottom lamination due to clear wood tensile failure. Horizontal shear failure occurred in one beam. Sometimes the tension failure in the timber is explosive in nature, pushing off the composite layer as it develops (Fig. 3(e)). The adhesion between timber and composite material failed only after timber rupture.

The beams reinforced with two CFRP plates (Series C) exhibited pseudo-ductile behaviour. Two types of failure mechanisms prevailed for the beams studied here: the timber fracture at the end of the bonded CFRP composites, caused by concentration of shear stresses in the anchorage zone, and timber longitudinal splitting, as shown in Figs. 3(g) and 3(h). The ultimate shear failure was a consequence of a higher reinforcement ratio in the cross section. Higher reinforcement ratio at the cross section prevented normal bending failure and switched failure mode to shear failure, which was quite sudden and brittle. Compressive failure was observed in one of the specimens. Compressive plasticization was highly visible in the compression zone, with distinct crushing of timber (Fig. 3(i)). The bonds between CFRP reinforcement, timber and epoxy remained intact during a test.

The glulam beams reinforced with CFRP plates revealed more non-linear behaviour when compared to unreinforced beams. The CFRP composites act like bridges over the timber defects and make the structural member section more ductile.

4.2. Ultimate load carrying capacity

The ultimate load, maximum bending moment and deflection at a maximum load for the three groups of beams are shown in Table 4.

Series		Maximum load (kN)	Deflection at maximum load (mm)	Maximum bending moment (kNm)	Bending stiffness *EI* (x10^{11} Nmm^2)
A	Mean	38.3	60.0	24.1	6.54
	CoV (%)	17.1	15.4	17.1	9.6
B	Mean	59.1	93.8	37.2	7.73
	CoV (%)	12.4	18.6	12.4	4.9
C	Mean	63.5	99.6	40.0	9.11
	CoV (%)	11.9	13.8	11.9	4.3

Table 4. Summary of experimental results from bending tests

The mean ultimate load of the control unreinforced specimens was 38.3 kN with a coefficient of variation of 17.1%. The large difference between the lowest and highest loads shows the large variability in the strength properties of a timber. When making comparison with unreinforced beams, the reinforced ones failed at much higher loads. The tests carried out on ten specimens with one CFRP plate led to mean ultimate load of 59.1 kN, indicating a 54.3% increase over the control specimens. The mean ultimate load for the five specimens with two CFRP plates was 63.5 kN, indicating an increase of 65.8% over the control specimens. Furthermore, a lower coefficient of variation of approximately 12% is associated with the reinforced beams when compared to 17% in terms of unreinforced beams. This suggests that a reduction in variability of the ultimate load capacity of beams occur by bonding CFRP plate at the tension side.

The load carrying capacity enhancement was not proportional to the amount of reinforcement. The load carrying capacity was enhanced only by cca 20% when the reinforcement ratio was increased twofold (from 0.46% to 0.93%). This phenomenon may be explained by the fact that over-reinforcing a glulam member in flexure results in a shear dominated failure.

4.3. Stiffness

For load-deflection curves shown in Fig. 2, the elastic region up to half the failure load was considered to determine the stiffness for each beam. Linear regression analysis for that region was carried out to calculate the gradient of the slope. The results of bending stiffness for the unreinforced and reinforced glulam beams are shown in Table 4.

Unreinforced beams had a mean stiffness of 6.54 x 10^{11} Nmm^2 with a coefficient of variation of 9.6%. The mean stiffness of Series B beams was 7.73 x 10^{11} Nmm^2 with coefficient of variation of 4.9%, while the mean stiffness of Series C beams was 9.11 x 10^{11} Nmm^2 whose coefficient of variation was 4.3%. The increase in stiffness was 18.1% and 39.2% with respect to unreinforced beams, respectively, in case of one or two CFRP plates. In general, the stiffness enhancement was proportional to the amount of reinforcement.

The introduction of stiffer material at the cross section resulted in increased stiffness of the beams, which in turn resulted in lesser deflection. This low deflection phenomenon is desirable from the point of view of serviceability limit state so as to ensure comfort of timber structures.

5. CONCLUSIONS

Experimental program was conducted in order to investigate the effectiveness of CFRP plates as flexural reinforcement of glulam beams. Two different amounts of CFRP reinforcement were used at the tension side of the glulam section. The bending behaviour of the beams was studied both through their load-deflection characteristics and failure mode.

The unreinforced glulam beams demonstrated linear elastic behaviour and exhibited brittle tensile-flexural failures when compared to pseudo-ductile behaviour of the reinforced beams. The reinforcing influences the plastic behaviour of the beam, which otherwise is not so predominant due to the low tensile strength of the timber. The rupture of the CFRP reinforced glulam beams was always reached due to the crisis of the timber. No bond failure was observed for reinforced beams although a secondary debonding failure of the CFRP occurred in some cases due to push-off of the split timber near mid-span.

The CFRP attached at the tensile side of glulam beams resulted in moderate enhancements in the stiffness, while more significant improvements were obtained in the ultimate load capacity. The amount of reinforcement in the cross section is very important in terms of strength, stiffness and failure modes. The increase in stiffness is obvious as the increasing area of reinforcement basically means introducing stiffer material to the cross section. On the other hand, it can be seen that increase in reinforcement may not necessarily result in increase in strength properties, as the shear failure mode becomes prominent for higher reinforced beams.

The experiments show that the introduction of CFRP reinforcement in the cross section reduces the variability in results. The reinforced specimens were more consistent in their properties and behaviour. This indicates the ability of the CFRP material to reduce the effect of natural defects in timber.

According to current results, it is possible to conclude that the application of externally bonded CFRP plates is a promising solution to reinforce (repair) the glulam beams. Further research is necessary to examine the influence of using different material properties (of timber, reinforcements as well as adhesives) and different geometries on the strength and stiffness of glulam beams for both the serviceability and ultimate limit states. Another point that needs to be further studied is the long-term reliability, especially when considering bond properties.

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