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EXPERIMENTAL INVESTIGATION OF CRACKED END-NOTCHED GLULAM BEAMS REPAIRED WITH GFRP BARS

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ABSTRACT

In this paper, an experimental research on bending behaviour of end-notched glulam beams and their bending behaviour after repairing with glass fibre reinforced polymer (GFRP) bars is presented. Altogether five glulam beams (100 x 220 x 4000 mm) made of spruce timber classified in the strength class C22 were tested. Experiment showed that originally, the beams failed in a brittle manner due to crack opening and its propagation. Cracks in the notch details were a result of excessive tensile stresses perpendicular to grain and shear stresses. Repairing the beams with GFRP bars after their failure completely restored and notably improved their load carrying capacity (average increase of 194%). Failure mechanism after repair changed from the original brittle tensile failure to more ductile failure in bending for most beams, proving the successfulness of the intervention. This study gives an insight in rehabilitation and repair possibilities of existing structures using advanced materials like GFRP bars.

KEYWORDS: Notch, glulam, GFRP bars, spruce, reinforcement.

INTRODUCTION

Notched solid timber and glued laminated timber (glulam) beams represent a frequent occurrence in construction industry. Beams can be notched due to various architectural or structural demands. The most common reason for beam notching is limitation in construction height at the supports, but there are also other reasons such as: stabilization of structural elements against lateral buckling, intersection of members and joint details (Jockwer 2014). Since notches are a weak spot in a structure, they should be avoided altogether. However, that is not always possible and adequate design and analysis of notched beams is very important in these cases.

Stress concentration, which occurs around the notch, causes a considerable reduction of the load carrying capacity of notched timber beams. If a notch is made on the tension side, tensile stresses perpendicular to grain is induced. This stress, accompanied by shear stresses, can cause a crack opening which typically starts at the notch corner (Fig. 1). Aside the fact that cracks are unattractive aesthetically, they are very dangerous structurally, since their propagation as the load level increases can lead to a failure of a beam. Reinforcement of new and repair of existing notched members represents a cost-effective solution for maintenance and enhancement of the load carrying capacity of structures in service, in the cases when notches are unavoidable.

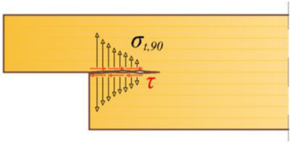
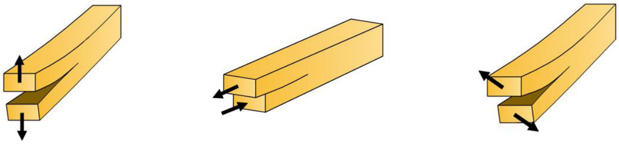


Fig. 1: Crack opening and stress concentration at the notched end of a beam.

Three fracture modes, defined according to Smith et al. (2003), describe the stress state present at a crack. Mode I is characterized by separating of crack surfaces in the direction that is perpendicular to them and it presents a tensile opening mode (Fig. 2a). In Mode II crack surfaces slide one over the other and it is described as an in-plane shear mode (Fig. 2b). A mixed mode fracture is a combination of the previous two modes (Fig. 2c). Although shear stress and tension perpendicular to grain both appear at a notch, crack opening is an apparent failure mechanism and it is caused by tension perpendicular to grain. Therefore, Mode I fracture is the most common failure mode of notched timber beams (Smith et al. 2003). However, shear component usually exists and it should not be ignored. This is especially important for reinforced notched beams as reinforcement is usually designed to overcome tension perpendicular to grain.



a) Mode I fracture *b) Mode II fracture* *c) Mixed mode fracture*

Fig. 2: Fracture modes (Jockwer 2014).

Notched ends of existing beams should be strengthened so that load carrying capacity of a member in question is improved. Reinforcing methods are mainly based on preventing the expected cracks. Various requirements dictate which reinforcing technique will be applied in each unique situation. Installation process, cost, visibility of reinforcement and simplicity of design should all be taken into consideration when determining the adequate reinforcing or repair method. Elements such as rods (Steiger et al. 2015), screws (Bejtka and Blaß 2006, Dietsch and Brandner 2015, Todorović et al. 2018), plates and sheets (André 2011) have all been successfully used for reinforcing and repair of notched timber beams. In addition, different materials such as wood-based materials, steel, advanced composite materials like carbon or glass fibre based polymers (Schober et al. 2015) can be used, depending on demands and possibilities of a given structural problem.

As it is already mentioned, notches are very dangerous for timber members. Therefore, they were a topic of many researches done over the past years. Gustafsson et al. (1998), Asiz and Smith (2008), Rautenstrauch and Franke (2008), Toussaint et al. (2016) all investigated the behaviour of unreinforced notched timber and glulam beams, varying different parameters in search for an adequate design method of these beams. Mohler (1978), Coureau and Cuvillier (2001), Blass and Bejtka (2003) used different kinds of reinforcing techniques in order to improve load carrying capacity of notched beams. Amy and Svecova (2004) and Gomez and Svecova (2008) dealt with flexural and shear reinforcing with GFRP materials of old bridge notched timber beams, proving the effectiveness of their methods. Jockwer (2014) analysed different design approaches of unreinforced and reinforced notched beams in detail. Oudjene et al. (2016) explained numerical modelling of both unreinforced and reinforced notched beams. Dietsch (2016) 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 (2008), underlining the importance of adequate analytical design.

In this paper, emphasis is placed on notches made at the supports – end-notched beams and reinforcement in a form of glued-in glass fibre reinforced polymer bars. GFRP is an advanced material, which more and more often finds its place in timber and structural engineering in general. Glass fibres have good mechanical properties, high chemical resistance, excellent insulating properties and low cost compared to other types of fibres. For these reasons, they were chosen in this study. Bars made out of GFRP are usually utilized as reinforcement of concrete slabs, but lately they are often used in combination with timber. As an example, Gentile et al. (2002), Svecova and Eden (2004), Raftery and Whelan (2014) and Yang et al. (2016) all investigated flexural reinforcement of timber and glulam beams with GFRP bars.

In this research, altogether five end-notched beams were tested twice (original beams without reinforcement and repaired beams). The end-notched beams were originally tested in bending to the point of failure, which occurred due to crack opening and its propagation. After that, the failed beams were repaired using GFRP bars and tested again. The results in terms of load-deformation relationship, failure mode, ultimate load carrying capacity and stiffness were compared between two beam series. The conclusions on effectiveness of GFRP bars as a repair method are made.

MATERIALS AND METHODS

The experimental research was conducted at the Laboratory of Structures, Faculty of Civil Engineering, University of Belgrade. A total of five end-notched glulam beams were tested two times in four-point bending configuration. First time the beams were tested without any reinforcement to the point of failure (series U). After the beams had cracked, they were repaired using GFRP bars and tested again (series S-f90).

The glulam beams were made from spruce timber classified in the strength class C22 according to EN 338 (2009), making the glulam class GL22h, in accordance with EN 10480 (2009). The cross-section of tested beams was 100 mm x 220 mm, while the overall length was 4000 mm. Each beam was composed of seven 32 mm thick laminations, glued together with phenol-resorcinol adhesive. The beams were a product of company "Piramida" from Sremska Mitrovica. At the supports, on both sides, the beams were notched so that the height was reduced to 110 mm (by half) and the length of notches was 250 mm. Before the tests were performed, the beams without reinforcement were conditioned at a temperature of $T = 20 \pm 2^{o}C$ and a relative humidity of $RH = 65 \pm 5\%$. After testing, moisture content was measured in each beam using a digital hygrometer at different locations. The moisture content was measured using Gann Hydromette HTR 300 in four different points for each tested beam and it varied between 11.0% and 11.9%.

The reinforcement selected for the repair of cracked beams was GFRP bars with a diameter of 10 mm and length equal to the beams height of 220 mm, produced by manufacturer “Kompozit Armatura” from Kragujevac. Two bars were installed perpendicular to beam axis near the both notched ends of the cracked beams. The reinforcement was positioned as close as possible to the notch corners, while satisfying the requirements for minimal edge distances and spacing. Both sides were repaired, even though beams cracked only on one side, in order to achieve failure in bending and avoid fracture caused by crack opening on the opposite side of the existing crack.

When considering the specimens that were going to be repaired, special attention was put into inserting the GFRP bars. Clamps were used to pull together separated parts of the beams, after which the holes for bars were drilled very carefully to a diameter of 14 mm, with a drilling length of 220 mm, throughout the beams height. The dust from drilling was removed by air blowing. Firstly, the epoxy based SikaDur 30 adhesive was poured into the prepared holes. After that, bars were carefully inserted by twisting, so that the excess glue was squeezed out. Before the tests were performed, the beams were conditioned at a temperature of T = 20 ± 2°C and a relative humidity of RH = 65 ± 5% for seven days, in order for adhesive to achieve its full strength.

All beams were tested in bending in accordance with EN 408 (2010). The beams were tested to failure 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 indentations at the load application and support positions were minimized by placing the steel plates.

A schematic illustration of the bending test configuration for both series U and series S-f90 is shown in Fig. 3.

The load was applied until failure using a hydraulic jack and recorded with a compression load cell (HBM C6A). The load was transformed from one point to two points with a steel beam. Monotonic static load was applied at a stroke-controlled rate of 4 kN per minute so as to cause the failure of the original beams in approximately 5 minutes. The repaired beams were tested with the same load rate in order to ensure a fair comparison of test results. The failure of the repaired beams was achieved in about 10 minutes.

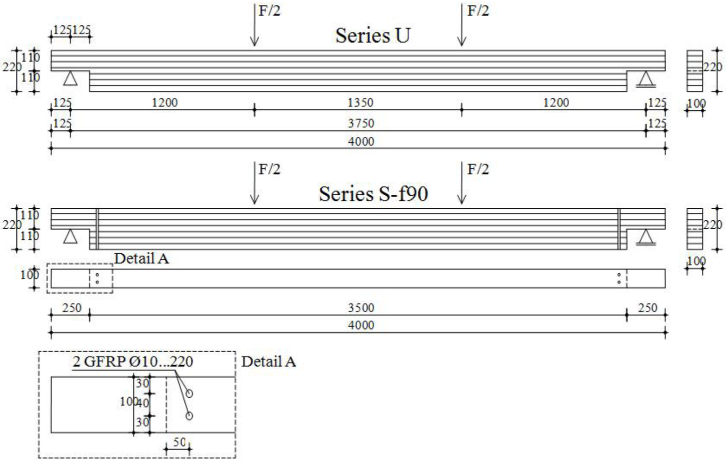


Fig. 3: Geometry and loading of the beams.

Linear variable differential transducers (LVDTs) were used for the measurement of mid-span deflection of the beams (HBM 1-WA/200mm-L) as well as the measurement of crack opening in notch details (HBM 1-WA/20mm-L). The deformation data from LVDTs and corresponding load data from a loading cell were recorded by a computerized data acquisition system (HBM MGC). Self-weight of hydraulic jack and steel beam were added to the recorded load. This additional load was 1.3 kN.

RESULTS AND DISCUSSION

Load-deflection behaviour and failure modes

The load-deflection behaviour to failure for the two series of beams is shown in Fig. 4.

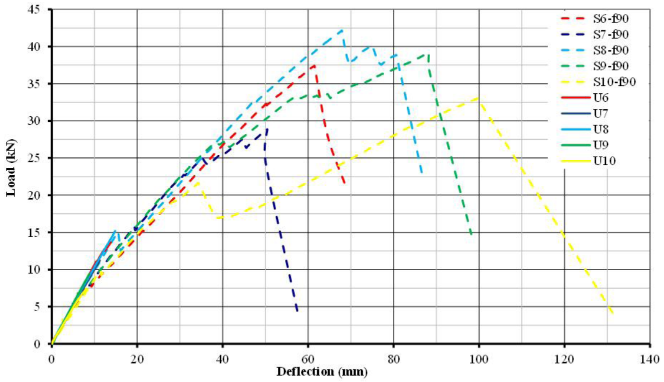


Fig. 4: Load-deflection curves for tested beams.

The notches have significant effects on the mechanical properties of glulam beams. All tested beams with unstrengthened notches (series U) exhibited linear load-deflection behaviour until the point of failure. Excessive tensile stress perpendicular to grain at the notch details was a cause of failure of series U beams, as it is shown in Fig. 5.

Fig. 5: Typical failure mechanism of series U beams.

Crack opening (Mode I fracture) at the notch corner was the obvious failure mechanism of notched beams without reinforcement. However, crack shearing (Mode II fracture) also had a considerable influence. Due to brittle nature of wood behaviour in tension and in shear, failure of unstrengthened notched beam was sudden and 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.

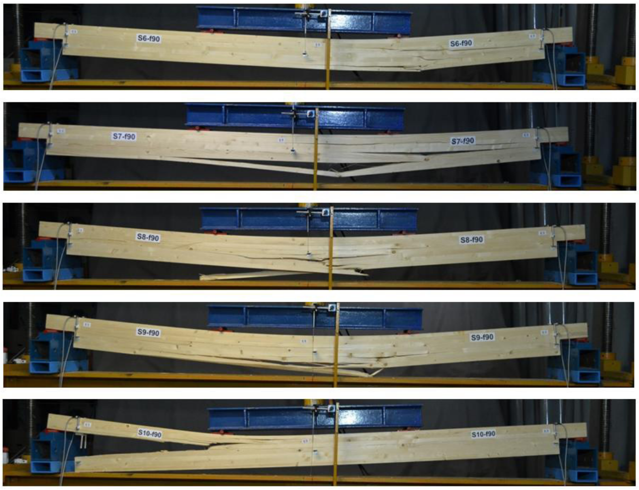
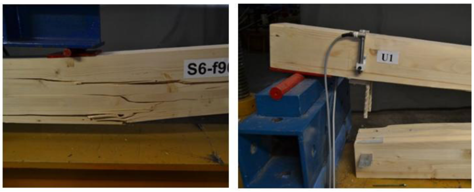


Fig. 6: Failure of repaired beams – series S-f90.

As previously mentioned cracked beams from series U were repaired with GFRP bars and tested again (series S-f90). Repaired notched beams experienced behaviour that is much more ductile when compared to original notched beams. Fig. 6 shows all five repaired beams after they had failed.

Four out of five repaired beams exhibited bending failure brought about by excessive tensile stresses in bottom laminations. This failure was generally initiated at defects or discontinuities (e.g. knots), which were located in the zone of maximum bending moment between load application points (Fig. 7a). The GFRP bars helped the cracked beams in resisting the horizontal shear force and prevented the possible shear failure. It was observed that despite the application of reinforcement, initial cracking occurred at relatively low loads within the notch detail that did not fail originally. This can be explained by the very small deformation capacity of wood before the tensile strength perpendicular to grain is exceeded. With further load increase, the crack growth was stable until failure in bending. The reinforcement showed sufficient strength for preventing excessive crack opening and lower beam part falling off.

One of the repaired beams failed due to unstable crack growth from the notch corner (Fig. 7b). It can be assumed that shear failure was a dominant failure mechanism (Mode II fracture). The failure happened on the same side as it did for the original unstrengthened beam. Failure of the notch was accompanied by bars withdrawal. No failure of the reinforcement itself was observed.



a) Bending failure. *b) Shear failure.*

Fig. 7: Typical failure modes.

Load carrying capacity, deformability and stiffness

The results of experimental tests in terms of load carrying capacity, deflections and stiffness for the two series of beams are given in Tab. 1.

Tab. 1: Experimental results.

Beam designation	**Ultimate load F (kN)**		**Mid-span deflection for ultimate load w (mm)**		**Bending stiffness EI ($kNmm^2 x 10^8$)**	
	Series U	**Series S-f90**	**Series U**	**Series S-f90**	**Series U**	**Series S-f90**
6	15.0	38.7	13.8	61.5	9.04	5.98
7	12.7	30.2	12.1	50.4	8.85	7.56
8	16.7	43.5	15.1	67.9	9.55	6.18
9	10.7	40.4	8.8	88.3	9.91	6.94
10	8.7	34.3	8.0	99.7	8.60	6.59
Average	12.8	37.4	11.5	73.5	9.19	6.65
SD	3.2	5.2	3.1	20.1	0.53	0.63
CV	25.2	14.0	26.6	27.3	5.8	9.5

Comparisons in relation to ultimate load, mid-span deflection and bending stiffness for the repaired beams (series S-f90) and original beams (series U) are reported in Tab. 2.

Tab. 2: Comparison between series S-f90 and series U experimental results.

Beam designation	**Difference in *F* (%)**	**Difference in *w* (%)**	**Difference in *EI* (%)**
6	158.6	345.6	-33.8
7	138.1	317.9	-14.6
8	160.0	351.0	-35.3
9	278.3	905.4	-29.9
10	294.1	1141.7	-23.4
Global Avg.	193.5	537.0	-27.6

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:

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

where: E - modulus of elasticity ($kN \cdot mm^{-2}$),
I - moment of inertia (mm^4),
$\Delta F/\Delta w$ - slope of load-deflection curve between 10% and 40% of ultimate load,
l - beam span (mm),
c - distance between support and load application point (mm).

The original notched beams (series U) had average ultimate load of 12.8 kN. The load carrying capacity of the beams was considerably reduced due to presence of notches. Introduction of reinforcement at the notched ends of the cracked beams resulted in improvement of the ultimate load. The repaired beams (series S-f90) had average ultimate load of 37.4 kN. It is observed that for all five tested beams, application of GFRP bars completely repaired the damage in regard to load carrying capacity. Moreover, all repaired beams showed an increase in ultimate load when compared to the loads recorded for the same beams during the first test. This increase ranged from 138% to 294%. The original notched beams completely lost their load carrying capacities after the first crack has developed. On the other hand, repaired beams continued to carry the load after initial cracking. This indicates that bars prevented shear failure in cracked beams and tied up the crack-separated parts to work together. Also, it can be noted that in the case of repaired beams, reinforcement in the form of glued-in GFRP bars tends to reduce the scattering of experimental results, in a sense that it makes the beams bending behaviour less sensitive to notches.

The repaired beams underwent large deformations before the failure when compared to the original ones. Average measured mid-span deflection at ultimate load was 73.5 and 11.5 mm for beams of series S-f90 and series U, respectively. At failure, the repaired beams exhibited in average 6 times larger mid-span deflections. The repaired beams showed a high residual deformation after initial cracking. Hence, bars helped improve the ductility of cracked beams.

The notched beams repaired with GFRP bars (series S-f90) achieved an average bending stiffness of 6.65 x 108 kN·mm^2. It can be observed from experimental results that these beams had very different mechanical properties particularly in terms of bending stiffness. This is due to high variability of material properties and pre-existing cracks of tested notched beams. The notched beams without reinforcement (series U) had an average bending stiffness of 9.19 x 108 kN·mm^2. The stiffness of the repaired beams was considerably lower than the flexural stiffness recorded for the same beams during the first tests (average decrease of 27.6 %). The brittle failure mechanism of unstrengthened notches resulted in the separation of the beam in two parts of reduced height. In spite of the notches being repaired, the two beam parts generally acted separately as individual members, which in turn led to a decrease of section moment of inertia and therefore decrease in stiffness of these beams.

Consequently, the repaired beams experienced higher mid-span deflections compared to the original ones at the same load level. Large deflections are not desirable from serviceability limit state point of view.

CONCLUSIONS

The experimental procedure performed in this research included bending tests of five end-notched glulam beams to the point of failure. After that, the damaged beams were repaired at the notched ends and tested again. GFRP bars were selected as reinforcement. The effects of repairing intervention were evaluated in terms of load-deflection behaviour, failure mode, ultimate load carrying capacity and stiffness of repaired beams, which were compared to the original notched beams. Following conclusions were drawn:

- End-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 unstrengthened notched beams.
- Using the reinforcement, full separation of the two beam parts due to fracture initiated at the notch corner can be prevented and full bending capacity of the beam can be reached.
- Repairing intervention of cracked notched glulam beams with GFRP bars completely restores and even increases the load carrying capacity (average increase in ultimate load of 194%) and deformability (average increase in mid-span deflection of 537%).

- In spite of the beams being repaired, there was no improvement of bending stiffness. Bending stiffness is highly influenced by pre-existing cracks; therefore, bars application only at the notched ends cannot recover the original stiffness.
- At the notch corners, bars used as reinforcement are subjected to combined parallel and perpendicular to the crack loading. Hence, reinforcement with high strength and stiffness in both directions like glued-in GFRP bars can achieve the best repairing effects.

This research gives an insight in strengthening and repairing possibilities of existing timber members using advanced materials like GFRP bars. It can be a good basis for further investigation of the effectiveness of other types of reinforcement. In addition, results obtained from tests can be useful in developing appropriate analytical design models for reinforced and repaired notched timber members.

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