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REDUCING THE IMPACT OF KNOTS ON THE STATIC WORK OF BENT WOODEN BEAMS BY LOCAL REINFORCEMENT WITH CFRP STRIP

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ABSTRACT

The basic criteria of visual grading of timber are knots. This is one of the most common defects in timber. The adverse effect of knots is manifested in. al. in the reduction of bending strength in the tension zone of the beam. It is assumed that the effect of the knot is comparable to the knothole.
However, studies showed that knothole and loose knot cause a much more disadvantageous stress distribution, which further weakens the beam. It is related to the local concentration of stresses caused by section discontinuity.
Analysis of constructional wooden elements shows that as a result of the increase in the load of the construction, as well as its degradation caused by biological factors, there is often a need of strengthening it. Hence, knots and knotholes pose a high risk as the most likely place of the damage propagation. Therefore it is necessary to strengthen the weakened elements. This reinforcement of the economic and aesthetic reasons should only be used in the weakened place.
In the paper as a local reinforcement carbon strip was used. Bending strength test of weakened by a hole timber beams, strengthen with CFRP strip was carried out, as well as measurement of deflections, which were used to analyze the static work.

Keywords: *Knots, Timber beam, Reinforcement, CFRP strips, Bending*

1. GENESIS OF THE WORK

Structural lumber is especially inhomogeneous material. Its technical and utilitarian value is tightly connected with its anatomical structure. Because of common structural anomalies and impact of biological factors, these values could be easily lowered.

1.1. Knots

Knots are most common wood defect, especially in construction works. Their influence on strength properties depends on their size and condition. Even small, healthy knots cause faults in wood structure, which manifests in grain direction disturbance in neighboring area and in the knot itself. Additionally, in case of resin knots, hardness and density of the knot and surrounding area are highly increased. Negative influence of the knots manifests mainly thru lowered tensile strength, bending strength, and to lesser degree in compression strength (Table 1).
Additionally, in case of partially or fully rotten knot, showing signs of advanced biological corrosion, strength parameters ale also lowered. Preventive actions should be undertaken, in aim to stop rot propagation into surrounding sound wood and remove infected parts of the section.

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Table 1 Knot influence on wood strength [1]

Pine wood	Density	Tension parallel to grain	Compression	Static bending in the radial direction	Static bending in the tangential direction
	kg/m^3	N/mm^2	N/mm^2	N/mm^2	N/mm^2
Clear	500	78	40.3	50.2	55.2
Few, small knots	530	38.4	36.1	47.1	50.8
Many, larger knots	570	11	31.4	42	35.6

1.2. Reinforcement

Reinforcement problem is especially important, because of its direct connection with safety, both in new and historical constructions. In the scope of increased historical consciousness, repair engineering undergoes significant development [2]. Reinforcement technology in contemporary structural works is tightly connected with raw material quality. It is estimated that only 15% of the average log could be refabricated in highest quality knotless material, which causes problems in acquisition of such material on the market, especially with continuously increasing wood prices. It is purposeful then, to develop solutions, making possible utilization of lower quality material, which after reinforcing will conform to higher construction safety standards.

In the latest times, composite materials are especially valued by designers and conservators, being real alternative to natural materials, because of its special properties. They are characterized by low density with very good physical and strength parameters. For example carbon fiber, being reinforcement in CFRP tapes, with density of 1.7-1.9 g/cm^3, has tensile strength of up to 6 GPa.

Until now, CFRP tapes were used as a reinforcement material of variable placement regarding the section, glued onto stretched fibers or placed inside the material, in various amounts and positions. In most cases, tape is glued onto element on whole length. In case of local section weakening (such as knot), full length reinforcement is not economically justified. Because of that, article proposes local reinforcement, strengthening only weak point area.

2. EXPERIMENT

Testing was performed in testing laboratory of Faculty of Wood Technology, Warsaw University of Life Sciences.

Simple pine beams were subjected to testing. Beams were weakened by 18mm hole, with center placed at 12 mm from lower edge of the beam. Hole was simulating most common natural wood defect, knot. Research proves, that influence of the hole of loose or rotten knot is similar to sound knot effect [3]. Later works describe knotholes as even more adverse, causing disturbances in stress distribution around notch area [4].

According to that, reinforcing of such elements is purposeful. Research program assumed application of CFRP tape as a reinforcement, glued to the bottom of the element. Basin on the numerical test results, it was determined [5], that optimal length of local reinforcement equals 6 diameters of weakening, so in the tests CFRP tape of 108mm length was used. This assumption conforms to de Saint Venant rule [6]. According to the rule, disturbance of uniform stress field and increase of normal stresses connected to discontinuity of the section, including weakening, is also local. At the distance of multiple hole diameters, is negligible.

Test material, in natural, technical size of 50 × 100 mm section and 2200 mm length was placed in Tira Test 2300 machine, on the free support pins (Fig. 1).

At the first stage, beams weakened with hole were tested, for the future comparison reasons. Non-destructive testing is aimed at determination of global modulus of elasticity, and was made In accordance to the standard [7]. Four point flexural test was used, testing was stopped at the level of 40% of assumed destruction force.

At the next stage, half of the beams were reinforced. As a reinforcing material CFRP S&P Lamelle CFK 150/2000 tape was used (Table 2). Tape was glued locally to the bottom of tested element with regular epoxy glue and clamped. After hardening of the bond and stress conditioning, samples were four-point bend loaded, at this time until destruction.

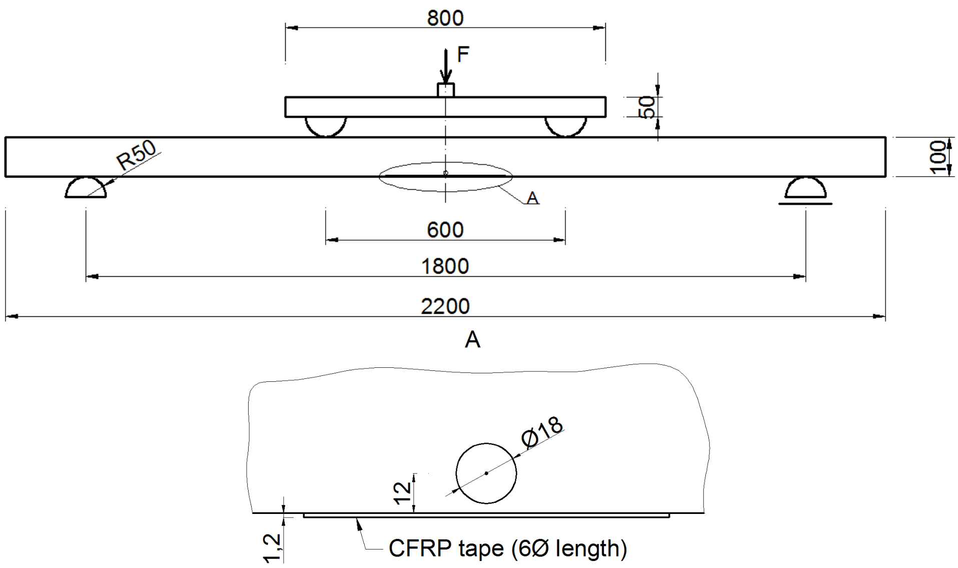


Fig. 1 Load scheme, weakening and strengthening methods of tested material

Table 2 CFRP S&P Lamelle CFK 150/2000 tape details

Technical details		
tape width	[mm]	50
tape thickness	[mm]	1.2
Young's modulus	[GPa]	>165
tensile strength	[MPa]	>2800
rupture strain	[%]	> 1.5

Data acquisition system was used during testing.

3. RESULTS

Two series of the beams were set for testing: A series (weakened not-reinforced beam), B series (weakened, reinforced beam). During the testing procedure, load and deflection values were recorded. Within A series, part of the beams was selected for reinforcing, in aim to compare modulus of elasticity (Fig. 2).

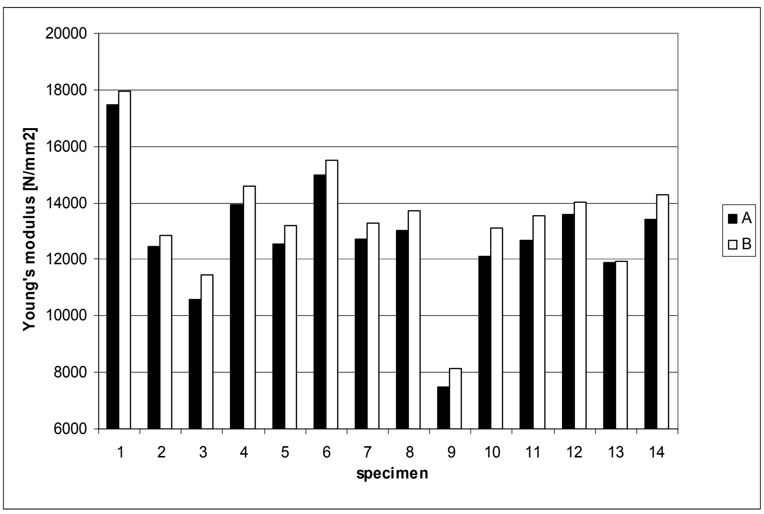


Fig. 2 Modulus of elasticity of A and B series beams

Average modulus of elasticity gain for B-series beams in comparison to A-series ones reached 5.1%. In aim to determine statistical significance of the data, "t" Student test was performed.
Average error of difference of statistical averages was calculated (1).

$$m_d = \pm\sqrt{\frac{\sum_{i=1}^{n}(x_1 - x_2)^2 - N\cdot(x_{1s} - x_{2s})^2}{N\cdot(N-1)}} \qquad (1)$$

where: x1 = A-series modulus of elasticity for n-th sample, x2 = B-series modulus of elasticity for n-th sample, N = sample count, x1s = A-series average modulus of elasticity, x2s = B-series average modulus of elasticity.
Average error of statistical averages difference reached ±985. On this basis random variable of the test (2) was calculated, equaling 4.417.

$$t = \frac{x_{1s} - x_{2s}}{m_d} \qquad (2)$$

For 95% confidence level and degrees of freedom at 26, theoretical random variable equals 2.056, for confidence level 99% again 2.779. This stands for statistical importance of differences between average moduli of elasticity between A and B series.
CFRP reinforced beams B-series reached load capacity 34.7% higher than non-reinforced A-series, and similarly 33.7% higher strength. Deflection reduction for reinforced beams 4.9% (Table 3).

Table 3 Strength testing results of A and B series

	Average value of destructive force [N]	Standard deviation	Coefficient of variation	Bending strength [N/mm²]	Deflection at 3000 N load
A-series	5795.4	1454.1	25.09	20.8	7.24
B-series	7808.1	1614.8	20.68	27.8	6.88
Increase [%]	34.7			33.7	4.9

Absolute strain and strain increase of pine beams of A-series caused by local CFRP reinforcement dropped. Highest deflection was reached by beam number 9 (Fig. 3). Before reinforcement, deflection equalled 11.95 mm at 3000 N load, reinforcement caused deflection drop by 5.4%, at the same load. Additionally, this beam showed lowest modulus of elasticity (Fig. 2). Lowest deflection was shown by beam number 1, which reached 4.9 mm before reinforcement, after CFRP tape application deflection dropped by 2.8%. Effectiveness of reinforcement was highest for beam number 8, causing deflection drop by 8.3%.

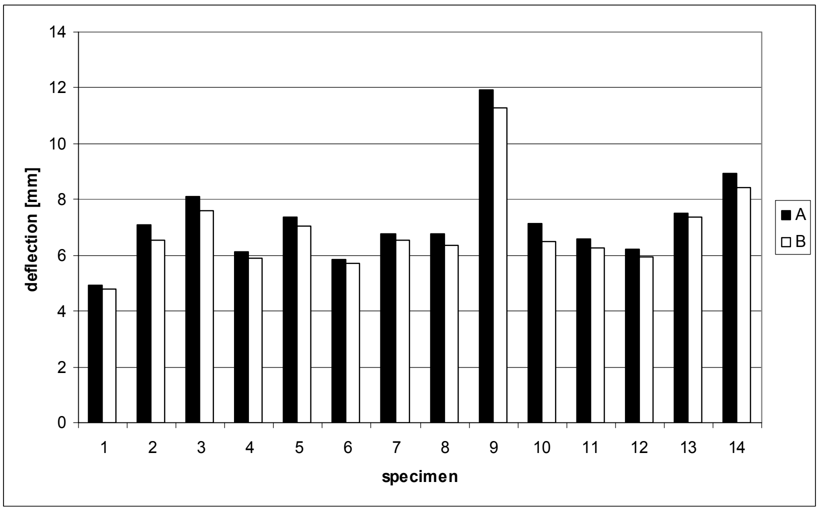


Fig. 3 Absolute strain of beams before and after reinforcement, at 3000 N load

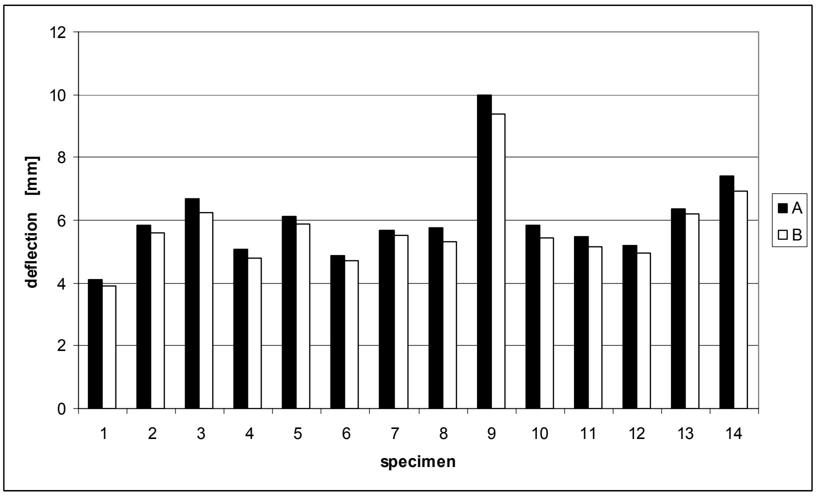
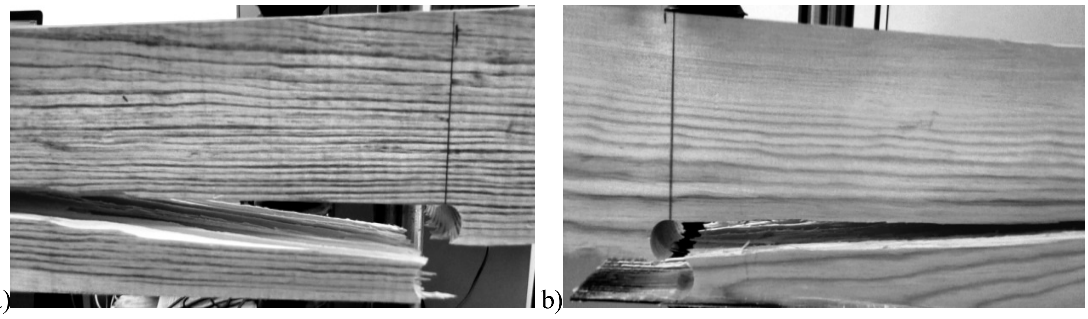


Fig. 4 Strain gain at 500-3000 N load for A and B series beams

For A-series beams, typical crack type was wood delamination in tensile area, which in all cases was initiated by crack of the fiber layer below the hole (Fig. 5a). B-series beams cracked by delamination at the wood-tape contact area, crack occurred in the wood (Fig. 5b). Crack initiation occurred in the area of tape end; further delamination proceeded along the grain.



a) b)

Fig. 5 Typical crack for A-series (a) and B-series (b) beams

4. CONCLUSIONS

Test results confirmed, that local CFRP tape reinforcement is purposeful in structural lumber. This type of reinforcement may become serious alternative for whole-length strengthening, because of lower cost of reinforcing materials, and lower intervention into historical structures, which is valuable in the scope of conservational thesis.

Strengthening by glued reinforcement from the tensile side, limited significantly influence of the knots, simulated by hole made in most unfavorable place, closest to the tensile area, with least possible material layer below the opening. One may conclude that CFRP tape limited influence of the inclusion and structure disturbance, as well as significantly changed fracture type. Before reinforcement, fracture occurred in the wood area, initiated by rupture of the wood grain below the opening. After reinforcement, crack occurred in the bond area, being weakest point of the composite. It is necessary then to perform additional research, aiming at the development of the bond and strengthening contact between wood and used composite. Modification of wood surface, for example by impregnation [8], as well as development of proper glue, should provide additional load capacity gain.

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