Local Reinforcement of Timber with Composite and Lignocellulosic Materials

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This work compares the effectiveness of local reinforcements of pine beams. Test beams were reinforced with carbon fiber reinforced polymer (CFRP) tape and layered laminate bamboo composite (LLBC) plates. The effective length of local reinforcement reached 5% of the entire beam length. Beams were tested to determine static bending strength in accordance with the EN-408 (2012) standard. On the basis of testing and calculations, it was concluded that local reinforcement with both reinforcing materials caused a significant ($p < 0.05$) gain in load capacity and modulus of elasticity. The LLBC, which has a tensile strength 25 times lower and a modulus of elasticity 17 times lower than CFRP, resulted in the highest load capacity. This phenomenon is related to the more uniform stress distribution on the composite with LLBC plate - glue bond - wood layers and lower strain within the bond in comparison to the CFRP reinforcement. Therefore, critical stresses within the bond were not exceeded, which often happens in reinforcement with materials of high modulus of elasticity (such as CFRP tape).

Keywords: CFRP tape; LLBC plate; Reinforcement; Knots; Bending strength

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INTRODUCTION

The building industry is one of the most conservative of all industrial branches. Cherishing such a tradition leads to application of well-checked methods and an unwillingness to modify existing production technologies. Because of this, new technologies utilizing advanced materials and innovative techniques often meet resistance in practical applications (German 2000).

In the wood building industry, providing high safety enforcement and using high-quality materials, as well as the availability of stock conforming to standard requirements, are important issues. It is estimated that in a typical pine log, only 15% of the volume can be sawn into high-quality, knotless lumber. The remaining 85% of the volume is loaded with various structural defects, which decrease the strength of the lumber.

Knots are the primary and most frequent defect of structural wood, and lumber grading is usually based on their presence. Single knots with diameters less than 5 mm are neglected during wood grading. Knots with adverse placement and significant size can prevent some lumber pieces from being used in structural applications. Amongst possible knot locations, the most adverse placement is in the middle of the span and in the tensile area of bent wood (Burawska *et al*. 2011b).

Pine wood with knots present in the tensile area, independent of the knot type (sound or loose), loses its ability to withstand stress (Baño 2009). In this case, stress distribution around the knot is similar to distribution around a round hole, a theory confirmed by numerous simulations.

Amongst various numerical knot models, one with a simulated hole was found to be the most adequate (Baño *et al.* 2011). Other simulation methods, utilizing material of higher density, or adhering or partially adhering to wood with variable major and minor wood axes, are less precise and show higher total estimation errors.

When modelling knots, distortion of the grain surrounding the knot is often taken into account. This distortion is often simulated by shifting major and minor material axes (Baño *et al.* 2011), as well as based on the laminar flow of liquid (Guindos and Guaita 2013). Neglecting this factor in modelling (Oscarsson *et al.* 2012) generates similar errors in the estimation of the load capacity of structural members.

The necessity of reinforcing wooden structural members may apply for both new structures, at the stage of material preparation, as well as existing ones requiring some repair. Many strengthening techniques have been developed. Usually, reinforcement is applied to the whole length of the strengthened member, which solves problems related to depth of anchorage, sufficient to withstand the assumed load. However, techniques involving local reinforcement, placed at limited parts of the member, are gradually becoming more common (de Jesus *et al.* 2012). Such techniques can significantly reduce the total cost of reinforcement as well as interference with the original structures, which is important from a conservational point of view (especially in historical structures).

Every structural anomaly of wood, usually caused by defects, disturbs the stress field created under load. According to the Saint-Venant's Principle (Orłoś 1977), such disturbances only occur locally. In the case of a centric knot, at a distance of a few knot diameters, stress rises and the field distortion is negligible. Thus, application of reinforcement to the whole length of the member is not justified. Numerical tests aimed at determining the optimal length of reinforcement (Burawska *et al.* 2011a) agreed with the Saint-Venant's Principle. The length of local reinforcement should be 5 to 6 times longer than the diameter of the weakening (*i.e.,* hole or knot), concentrating stresses. This length can be extended to limit the influence of shear stress in wood-bond-reinforcement joints. Application of local reinforcement increases the continuity of the weakened section and improves its strength parameters.

The building industry often utilizes reinforcements based on high-strength synthetic materials such as metal composite rods or flat or shaped bars; since the 1970s, fiber reinforced polymer (FRP) composites have been used. However, strengthening may also utilize natural, usually lignocellulosic, materials. This concept evolved from their high strength properties, including tensile and compressive strengths. Another advantage of such materials is a relatively short renewability period (in the case of bamboo, 1 to 3 years). More generally, usage of renewable materials helps to provide independence from the traditional resource base. It is therefore reasonable to consider the possibility of replacing synthetic reinforcing materials with natural, lignocellulosic materials.

This work aims to compare the effectiveness of reinforcements made using lignocellulosic (layered laminate bamboo composites) and composite (carbon fiber reinforced polymer) materials.

EXPERIMENTAL

Materials

Test material

The test materials were pine beams (*Pinus sylvestris* L.) of technical size (50 mm x 100 mm x 2200 mm). The pine wood was grown in northeastern Poland. The density of test samples averaged 589.9 kg/m^3, with 11.5% moisture content. Samples were weakened with a borehole 18 mm in diameter, simulating a centric knot (Burawska *et. al* 2013). The bore was placed in the most adverse location – in the middle of the beam's span, in the tensile zone. Below the hole, a thin 3-mm layer of wood was secured (Fig. 4). The experimental program assumed testing in bending of 53 solid wood samples.

Reinforcing material

As reinforcement, two materials were used: (1) a synthetic, highly processed composite, CFRP tape (CFRP S&P Lamelle CFK 150/2000; S&P Polska Sp. z o.o., Malbork, Poland) (Fig. 1a) and (2) a natural, renewable, lignocellulosic material, LLBC plate (DLH Linea Series, Bambus Karmel; DLH Poland Sp. z o.o., Warsaw, Poland) (Fig. 2a). Figures 1b and 2b present the microscopic image of structure for the CFRP and LLBC surfaces.

Fig. 1a. CFRP tape

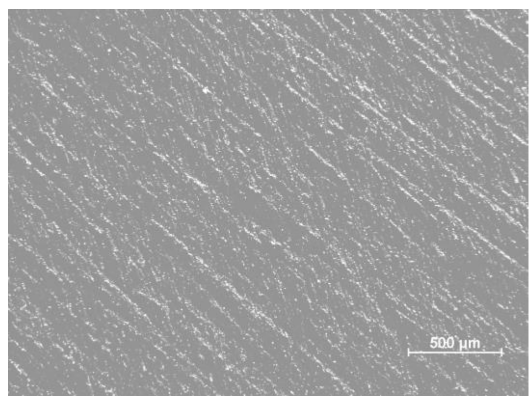

Fig. 1b. Optical micrograph of CFRP tape

Fig. 2a. LLBC plate

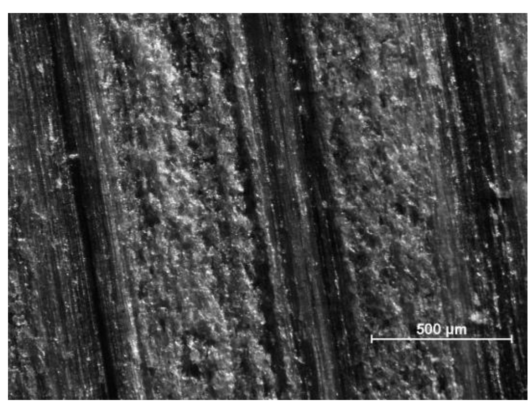

Fig. 2b. Optical micrograph of LLBC plate

The CFRP was selected for testing because of its wide application in the building industry and its high strength parameters (Table 1). However, composite materials, especially those based on carbon fiber, are highly priced. Therefore, along with increasing ecological consciousness, it is reasonable to research alternatives to such materials, which require high energy expenditure. Therefore, the effectiveness of reinforcement with CFRP tape was compared to that of an LLBC plate, as a representative natural material, fulfilling the requirements of sustainable building engineering. Selected strength parameters of CFRP and LLBC are presented in Table 1 (Kozakiewicz 2010; Verma *et. al* 2012).

Table 1. Properties of CFRP Tape and Layered LLBC

Property	CFRP	LLBC
Density (kg/m^3)	1500	900
Young's modulus (GPa)	> 165	9.5
Tensile strength (MPa)	> 2800	110

Methods

Determination of surface wettability

The local reinforcement technique employed in this work entails strengthening by gluing the reinforcing material (CFRP tape or LLBC plate) to the pine beam with a two-component epoxy glue (Havel G60, Havel Composites Poland Sp. z o.o., Cieszyn, Poland). Gluing characteristics were determined with respect to surface wettability and surface energy for all materials used (pine wood, CFRP tape, and LLBC plate). Testing was performed with a Phoenix 300 goniometer (Surface Electro Optics Co. Ltd., Suwon City Gyeonggi-Do, Korea (Figs. 3a and 3b). The wettability of a solid body by low-molecular weight liquid (*e.g.*, distilled water) is generally determined using the wetting angle, which is measured tangential to the liquid contact point with the surface and the surface itself.

Measurement of the wetting angle was performed using the static method, based on the geometry of a stabilized drop of distilled water. In this experiment, measurement was conducted after 15 s, counting from the moment the drop was set on the tested surface. For each material, five measurements were performed, and the results were averaged.

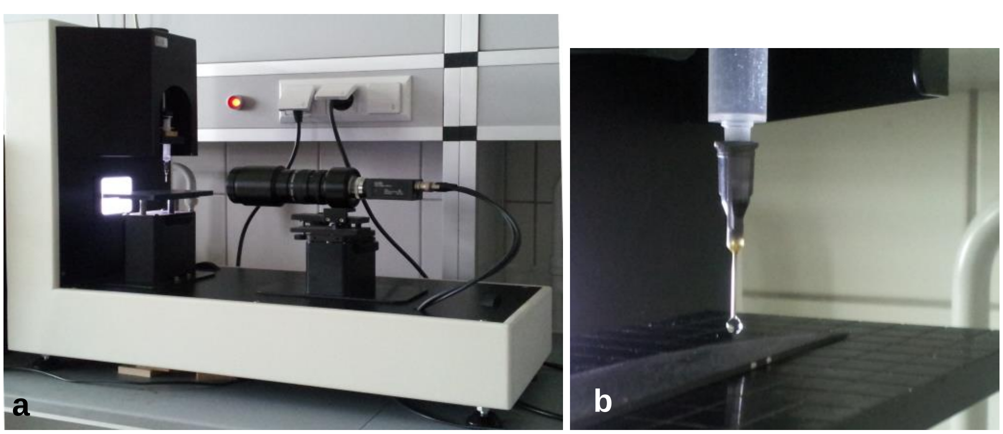

Fig. 3. (a) Phoenix 300 goniometer device; (b) setting the drop for wetting angle measurement

Next, testing of materials against surface energy was conducted. The Owens-Wendt method (Owens and Wendt 1969) was used, consisting in determination of two component energies, *i.e.*, polar and dispersive. Both energies were determined based on wetting angle measurements obtained for two liquids (apolar- distilled water and bipolar- diiodomethane). Used liquids were characterized by a known surface free energy values. As before, results were averaged from five measurements.

Testing of reinforced beams

Test materials were divided into four groups: A - pine beam, weakened with an 18-mm hole (15 samples); B – weakened pine beam, locally reinforced by 1.2-mm CFRP tape (15 samples); C - weakened pine beam, locally reinforced by 1.2-mm LLBC plate (11 samples); and D - weakened pine beam, locally reinforced by 4.2-mm LLBC plate (12 samples). The length of reinforcement in groups B, C, and D was determined in accordance with previously published literature describing numerical testing (Burawska *et al.* 2011a), at a value six times longer than the diameter of weakening. The reinforcement length in groups B, C, and D was thus 108 mm. In group C, the thickness of reinforcement was set to be equal to that of the CFRP tape. In group D, the thickness of LLBC reinforcement was set at a value providing a reinforcement mass exactly equal to that of group B, which utilized CFRP tape.

Wooden structural beams were strengthened by gluing the reinforcing material using epoxy glue. The reinforcement was placed under the reinforced beam, in the middle of its span (Fig. 6). Glue was spread by brush at a density of approximately 200 g/m^2. After gluing, members were clamped and left under pressure until the glue fully cured. An average thickness of the adhesive equal to 0.5 mm was measured after the adhesive curing.

After seasoning, samples were tested to determine bending strength in accordance with the EN 408 (2012) standard. Testing was performed on a Tira Test 2300 universal testing machine (TIRA GmbH, Schalkau, Germany). The test setup is presented in Figs. 4 and 5.

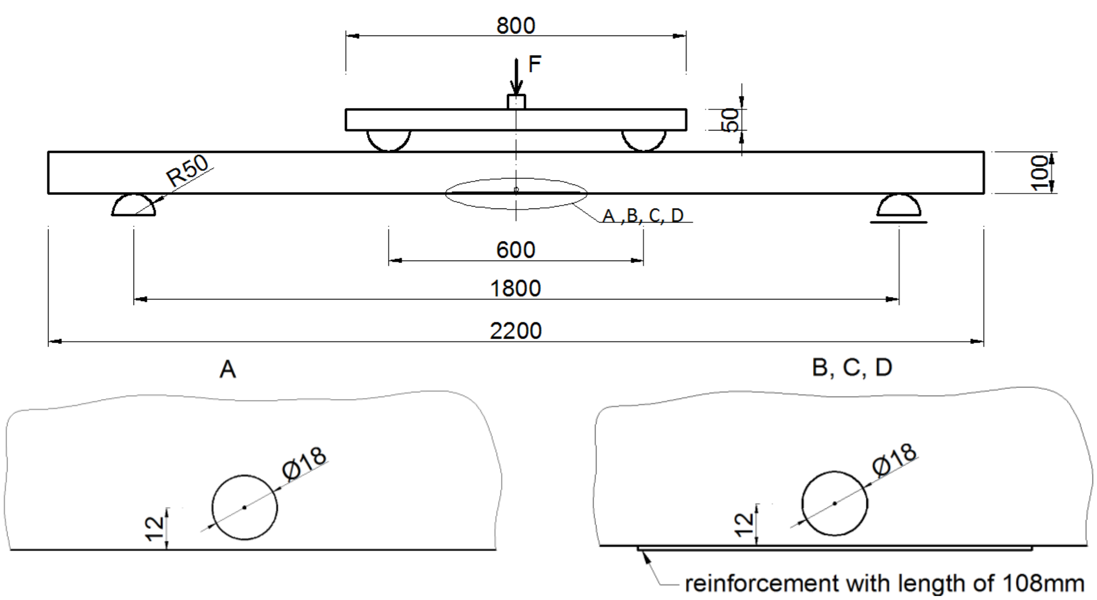

Fig. 4. Load scheme and weakening and strengthening methods of tested material

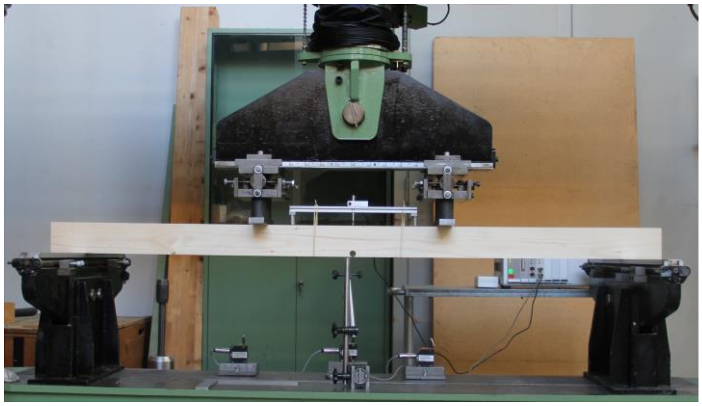

Fig. 5. Four point bending test arrangement

Tests were conducted in displacement control mode with a speed rate equal 3.0 mm/min. During testing, force and displacement values were recorded. Based on these data, the bending strength and modulus of elasticity were calculated, assuming the hypothesis of a uniform equivalent pine beam. Additionally, force-displacement characteristics were compared along with a description of the fracture.

Statistical analysis

Statistical analysis of test results was carried out in Statistica v.10 software (StatSoft, Inc., Tulsa, USA). Data were analyzed and provided as the mean ± standard deviation, the median, scatterplot of results around the median, and minimum and maximum values. Additionally, Student's T test was performed, with confidence level of 95% to determine the significant differences between the mean values of the tested parameters in each analyzed group.

RESULTS AND DISCUSSION

Surface Wettability

Figure 6 presents images of distilled water drops set on tested surfaces, and the obtained contact angle values are presented in Fig. 7. The highest wetting angles were observed with CFRP, and the lowest values were found with LLBC. A high wetting angle suggests the presence of surface hydrophobicity, and a low wetting angle suggests a hydrophilic surface. Materials with high contact angles are thus resistant to gluing with polar liquids.

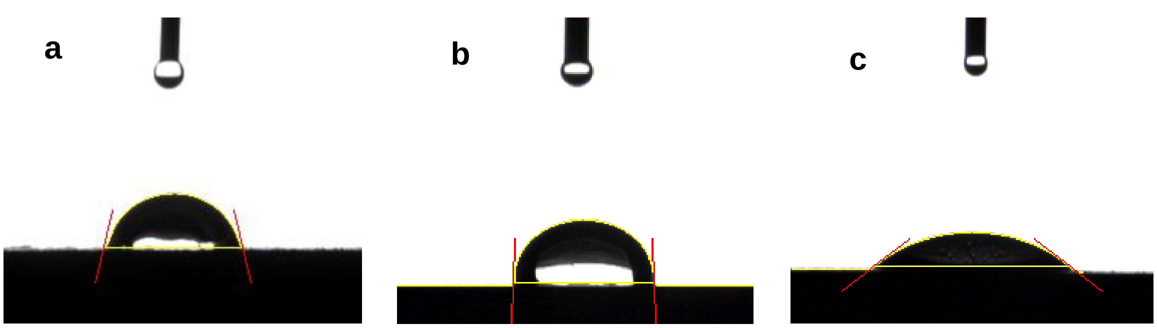

Fig. 6. Determination of contact angle for (a) pine wood, (b) CFRP, and (c) LLBC

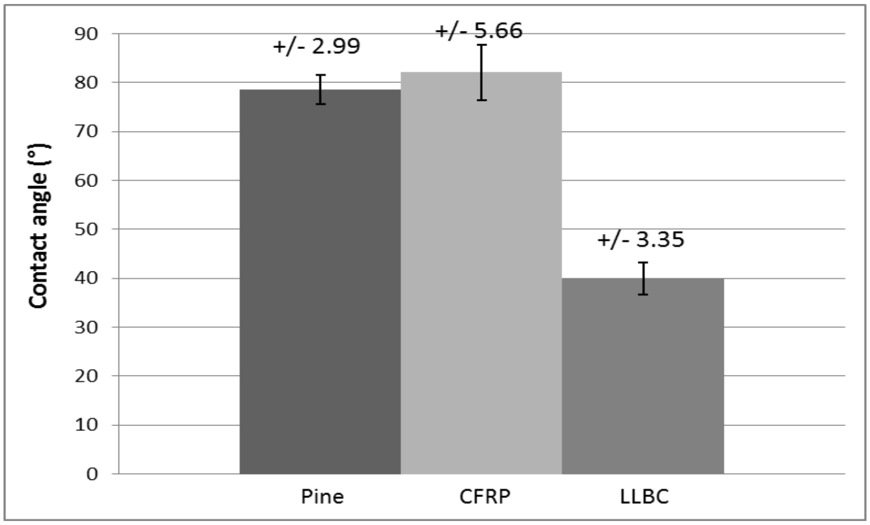

Fig. 7. Contact angle values for tested materials. Data provided as the mean ± SD

Figure 8 shows the measured surface energy values of the tested materials. Surface energy, along with contact angle, determines the gluability of materials. Surface polarity, and by extension gluability, increases as surface energy increases. The LLBC had the highest surface energy amongst the materials tested; CFRP had the lowest.

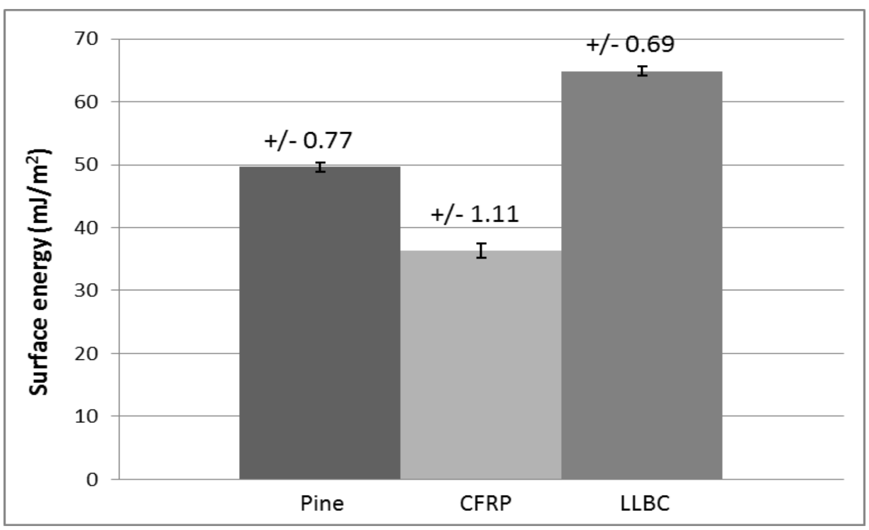

Fig. 8. Surface energy values for tested materials. Data provided as the mean ± SD

Strengthening Effectiveness

Strengthening effectiveness was determined by the modulus of rupture (MOR) and Young's modulus (MOE) values. Figure 9 presents MOR values measured for groups A, B, C, and D. The lowest average bending strength was measured in group A samples. Statistical analysis (95% confidence level), showed that all reinforcing materials caused a statistically significant increase in MOR. Strengthening with CFRP tape increased the MOR by 40% in comparison to the control (group A) samples. In the case of groups C and D, the increase in MOR in comparison to group A reached 71% and 99%, respectively. Reinforcement with LLBC plate (groups C and D) was more effective than that with CFRP tape with the same length, shape, and placement of reinforcing patches. Differences between average MOR results obtained for groups B and C and groups B and D were also statistically significant ($p < 0.05$).

Differences in MOR caused by varying the thickness of LLBC reinforcement (group C – 1.2 mm; group D – 4.2 mm) were not statistically significant.

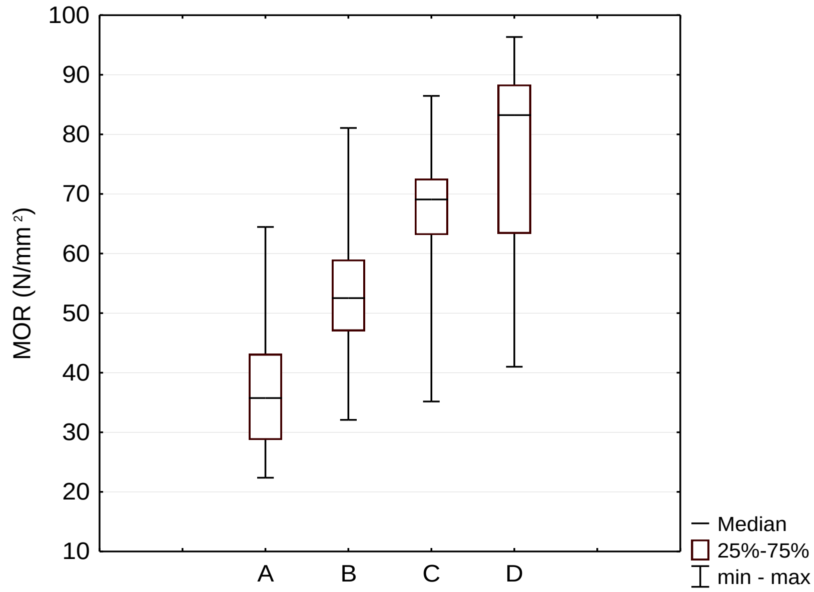

Fig. 9. MOR median values, with the minimum and maximum values

Based on the tests performed, MOE values were calculated for weakened (group A) and strengthened (groups B, C, and D) samples. Figure 10 presents the results.

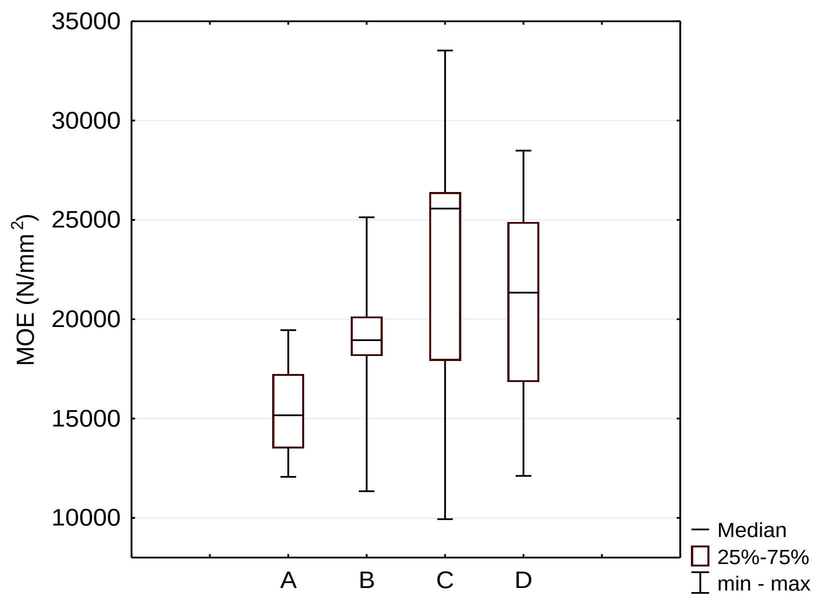

Fig. 10. MOE median values, with the minimum and maximum values

Application of reinforcement in all cases caused statistically significant ($p < 0.05$) MOE gain in comparison to group A beams. Reinforcement with CFRP tape increased the average MOE by 14.6%, while LLBC boosted the MOE by 49.3% for group C and 33.8% for group D. Reinforcement of structural beams with 1.2-mm-thick LLBC caused the highest MOE gain, but results of group D were characterized by the highest variability. Independent of reinforcement method, differences between MOE averages for B, C, and D series were not statistically significant. This can be explained by the relatively short reinforcement area; 108 mm is only 5% of the length of the test samples. Most likely, increasing the length of reinforcement, especially with high MOE CFRP, should significantly improve MOE values.

Figure 11 shows load–displacement characteristics for beams in groups A, B, C, and D. Analysis of load – displacement dependencies shows the unique characteristics of beams reinforced with CFRP tape (group B). The CFRP tape undergoes a delamination process, with cracks initiated usually in the glue bond-wood contact area. This is caused by high shear stresses in the glueline and surrounding wood. After destruction of the bond and shearing off the CFRP tape, the secondary failure can be observed. Increased load force destroys the wood itself. Other groups of samples (group A, C, and D) do not show sharp load drop characteristic. This is attributed to a more uniform stiffness distribution along the wood-glueline-reinforcement setup. After destruction of LLBC plate wood itself is not able to withstand the loading what leads to further crack propagation.

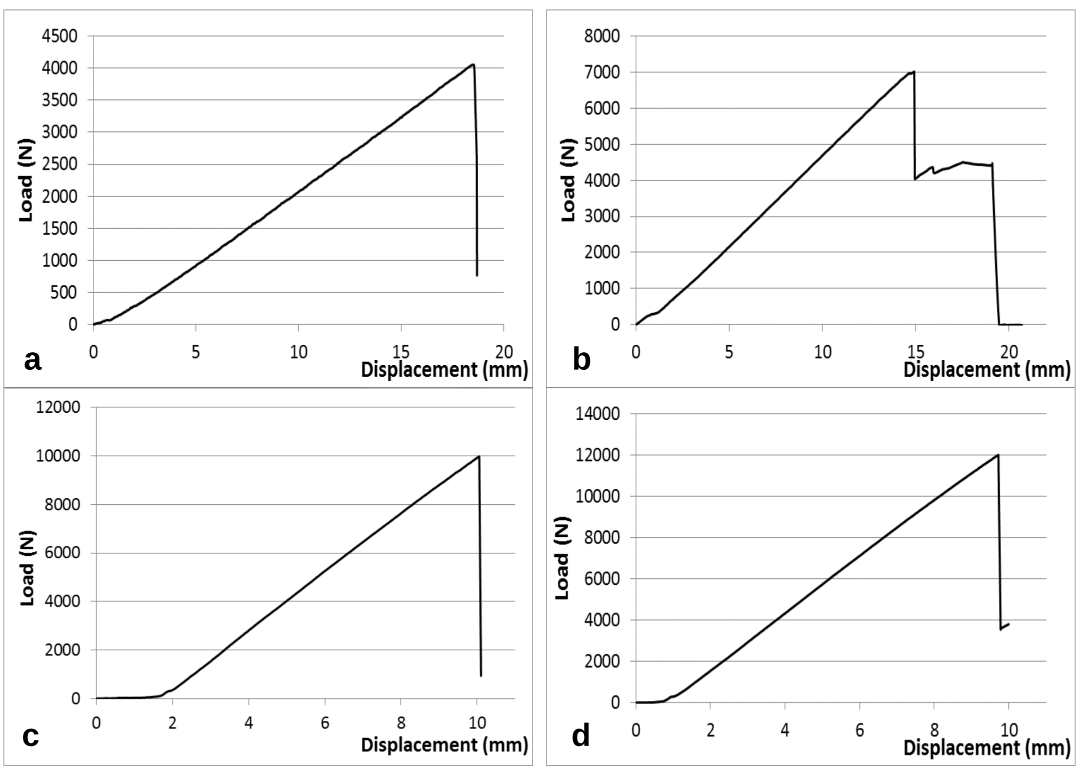

Fig. 11. Load – displacement dependencies for beams from (a) group A, (b) group B, (c) group C, and (d) group D

Fig. 12. Failure modes observed in (a) group A, (b) group B, (c) group C, and (d) group D

In group A beams, the crack was initiated just below the weakening hole (Fig. 12a), in the spot of maximal tangential and normal stresses. For group B, the crack was caused by concentration of normal and tangential stresses in the glueline, on the edge of the CFRP tape, leading to its delamination (Fig. 12b). Delamination of the tape and destruction of the bond occurred in most cases; the glue bond joining elastic and stiff material (wood and CFRP) did not withstand the stresses. In groups C and D, with different stress distribution, the fracture characteristics also differed (Figs. 12c and 12d). Fracture was caused when LLBC was exposed to critical tensile forces. The glue bond withstood the stresses; strain within the bond was lower thanks to bonding of two relatively similar elastic materials (LLBC and wood). Schemes of glue bond strain for all configurations are presented in Fig. 13. The presented scheme is based on the analysis of the stiffness difference of each layer of the wood-glueline-reinforcement setup and observation of the failure modes.

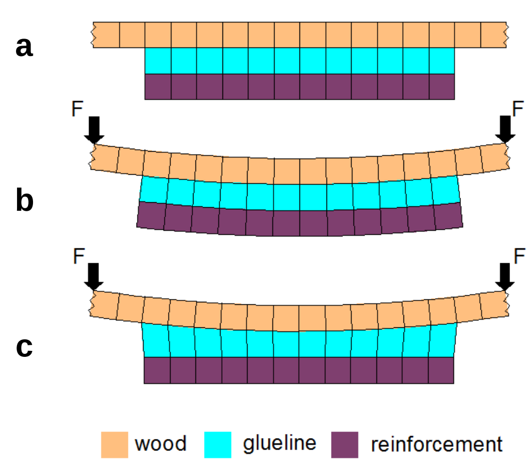

Fig. 13. Strain of glue bond (a) without load, (b) loaded, wood-glue-LLBC setup, and (c) loaded, wood-glue-CFRP setup

CONCLUSIONS

1. Local reinforcement is reasonable in structural timber. Application of both CFRP tape and LLBC plates resulted in a significant ($p < 0.05$) increase in MOR and MOE.
2. Reinforcing with materials of comparable MOE (where the elasticity of the reinforcement material is similar to elasticity of reinforced material) provides more desirable, uniform stress distribution within the bond. Stress within the glue bond does not exceed critical values; therefore effectiveness of the reinforcement increases.
3. The LLBC, because of its rough surface, low contact angle, and high surface energy, is more appropriate for gluing than CFRP tape. The bond itself and wood-bond-LLBC contact area are not prone to cracking, which can lead to destruction of the joint.
4. The LLBC, as a natural and renewable material, is an interesting alternative to synthetic, highly processed materials (including CFRP). Local reinforcement with LLBC enables significant material and economical savings.

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