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PREFABRICATED SYSTEM FOR STRENGTHENING FULL-SIZE WOODEN GIRDERS USING PRE-STRESSED FIBER-REINFORCED POLYMERS AND STEEL – BENDING SHEAR TESTS

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Abstract: *This paper describes a study of four-point bending with shear of full-size KG and KS grade glulam beams using glued-in pre-stressed basalt BFRP, glass GFRP and steel rods. From the tests, it was found that the composite bars as well as the glass bars perfectly compensated for the heterogeneous structure of the timber, showing significant ductility in contrast to the brittle fracture of unreinforced beams, the same applies to the shear area in the support zones and on the supports. Using pre-stressed composite bars and pre-stressed steel bars in tension and compression, the following results were obtained: an increase in load capacity and stiffness, respectively steel bars - 39.2 %, 20.2 %; basalt bars - 35.4 %, 19.4 %; glass bars - 32.7 %, 17.2 % compared to unreinforced beams, also influenced by the distance from the neutral axis. The use of composite and steel bars is an effective, economical, environmentally friendly, ecological and natural technology for the repair of elements, as well as the possibility of increasing the span of the girders and reducing their cross-sections, which gives an increase in the possibility of using wood-based products with other materials, including natural materials - fibre-reinforced polymers - for structural elements.*

Keywords: Glued Laminated Timber, FRP and steel bars, pre-stressed, bending with shear test, load capacity, local and global stiffness.

1. Introduction

Wood is the few natural renewable raw materials that can be used as structural elements in construction. And, in addition, wood provides an attractive natural appearance and a high strength-to-weight ratio compared to traditional building materials such as concrete or structural steel (Corradi et al., 2021; Jian et al., 2022). Thus, by enhancing the natural limitations of wood, engineered timber products offer a sustainable alternative to traditional building materials. These products include: solid beams, I-beams, Glued Laminated Timber or Cross Laminated Timber (CLT) - e.g. beams, slabs, and Laminated Veener Lumber (LVL), as well as other materials made of glued veneers or other wood-based materials, e.g. plywood, Parallel Strand Lumber, Laminated Strand Lumber, construction beech wood (BauBuche) - experimental, theoretical and numerical research carried out by the author on these products under static, dynamic, ad hoc, repeatedly variable, cyclic, long-term loads reinforced by various artificial and natural fibers, fiber composites, Fiber Reinforced Polymer, polyester, hybrid, steel, in various shapes and forms, under pressure and pre-stressed, in addition fire, temperature and humidity resistance, among others bars, pipes, different profiles, angles, C-sections, I-sections, T-sections, T-bars, fasteners, shapes, sheets, fabrics, tapes, mats, sandwich structures - bending, shear, bending with shear, tension, compression. Therefore, the recent growth of mass timber construction is mainly due to the popularity of CLT applications or advanced manufacturing technologies for large-scale glulam structural elements. In contrast, the use of timber

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reinforcement is often used to increase the structural strength of major elements, e.g. beams, columns. The use of FRP reinforcement is a convenient, economical method of improving the static performance of a structure (Jian et al., 2022; Bi et al., 2021 and Sun, 2022). This application can improve the load-bearing capacity, just as it improves the operational safety of the structure and meets higher performance requirements. Considering fibre-reinforced polymers is a component formed by mixing a fibre material and a matrix material (resin) in a specific proportion. The benefits of such materials include lightness, non-conductivity, high mechanical strength, recyclability and improved corrosion resistance. Therefore, over time FRP can partially replace steel bars for the reinforcement of timber beams. Using FRP reinforcement can increase the ultimate load-bearing capacity and flexural stiffness of timber beams. There are different types of FRP on the market, such as CFRP (carbon fibre reinforced polymer), GFRP (glass fibre reinforced polymer), AFRP (aramid fibre reinforced polymer), BFRP (basalt fibre reinforced polymer), etc. The use of FRP reinforcing bars prevents the risk of possible corrosion, as with steel bars. In the same way, they can improve the stiffness, load-bearing capacity and ductility of timber beams. Based on studies (Wdowiak-Postulak, 2019; Wdowiak-Postulak, 2021; Wdowiak-Postulak, 2023; Wdowiak-Postulak et al., 2023a; Wdowiak-Postulak et al., 2023b; Wdowiak-Postulak et al., 2023c and Wdowiak-Postulak et al., 2024), it was found that the decisive factors affecting the effectiveness of FRP-reinforced timber beams are the degree of reinforcement, the type of FRP, the length of the beams, the grain direction or the bonding surface (Jian et al., 2022). Liu et al. (Liu et al., 2020) performed an experimental study of BFRP-reinforced poplar beams with different lengths. Based on the study, they found that timber beams reinforced with BFRP bars of 1900 × 50 mm showed the highest load capacity and maximum deflection, which increased by 77.8 % and 110.1 %, respectively, compared to unreinforced beams. Kramár et al. (2020) investigated the effect of using corrugated surfaces on improving adhesion between FRP and wood. Based on the experimental study, they found that beams with CFRP corrugated surfaces had the highest flexural strength, here the adhesion between FRP and the corrugated wood surface helped.

2. Methods

Wood of pine, spruce and fir was used in the study. Specifically, the timber used in the study was from the same sawmill, with the designation of origin coming from the Małopolska Region Nature and Forest of Poland and from the beginning and end of the growing season, at the full moon, thus reducing variability. The glued laminated beams had a GL20c grade, tensile strength of 15 MPa, modulus of elasticity of 10 400 MPa (outer laths T13 and inner laths T8) according to PN-EN 14080:2013-07. The structural lumber was previously dried artificially in a drying kiln, then classified according to PN-D-94021:2013-10 into KG grades - inferior quality grade and KS grades - medium quality grade. In the laboratory, the resulting glued laminated beams, pieces of 20 with dimensions 82 x 162 x 3650 mm, were stored with a relative humidity of 65 ± 5 % and a temperature of 20 ± 2 °C. The moisture content was tested in accordance with EN 13183-1:2004 and an average moisture content of 10.7 % with a standard deviation of 0.89 % was obtained, the average density was 359.5 kg/m^3 with a standard deviation of 25.4 kg/m^3. The influence of humidity and temperature was constantly determined and their parameters were determined. An epoxy resin-based adhesive layer was obtained by mixing LG 815 epoxy resin with HG 353 hardener. After mixing the resin and hardener, the adhesive achieved a flexural strength of 110–120 MPa and an elastic modulus of 2 700 ÷ 3 300 MPa. For the reinforcement, first 14 mm by 14 mm holes were cut in the beams, then the wood and bars were cleaned. Similarly, to obtain the straightness of the rod in the cut holes and milling cutters, thin steel nails and steel wires were inserted every 40 centimeters. And at the ends of the beam to properly anchor and fasten the bars, pre-stressed, by threading the rods at the ends, then applied appropriate anchoring plates, nuts, steel and aluminum profiles, steel sheets, plexiglass, pads, connectors were introduced, the nuts were screwed in, obtaining the reverse arrow, to obtain an initial stress of 15 MPa - measured by extensometer. Moreover to prevent shearing occurring along the beam at supports and in support zones – applied appropriate vertical FRP and steel rods for the entire height of the beam, anchors. Then pre-stressed basalt BFRP, glass GFRP, and steel rods with a diameter of 10 mm were used for reinforcement. Material data were obtained from in-house, experimental studies: BFRP - elastic modulus 79.2 MPa, GFRP - elastic modulus 60.1 MPa, steel - ribbed, B500SP. The experimental investigations included the effects of reinforcement on the load-carrying capacity and static working stiffness of reinforced glued beams compared to unreinforced beams. The beam configurations are shown in Fig. 1 and the test scheme is shown in Fig. 2. Five repetitions were tested for each configuration for better statistics of the results. Reinforcement included a tensile zone as well as a compressive zone with identical degrees of reinforcement. Experimental tests of glued beams were carried out in four-point bending with shear according to EN 408+A1:2012. First, all unreinforced beams were tested by determining the global and local stiffness, using two actuators with a piston area of 50 cm^2 and a maximum exerted pressure of 10 MPa from VEB Werkstoffprufmaschinen Leipzig. The local stiffness measurement is suspended from the neutral axis over a length of five times the beam height. Local indentations were minimised by placing 80 mm × 80 mm × 5 mm steel plates at the support and actuator locations. Load did not exceed the elastic limit or exceed 40 % of the ultimate load - only to local rigidity. The modulus of formability was also determined. On the basis of the shear zone - strains, shear stresses, the modulus of shear deformation was also determined.

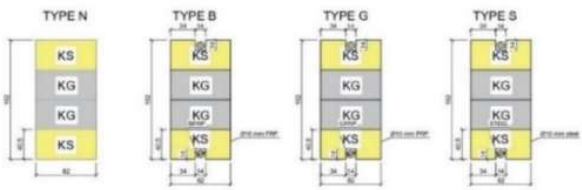

Fig. 1: Beam reinforcement diagrams.

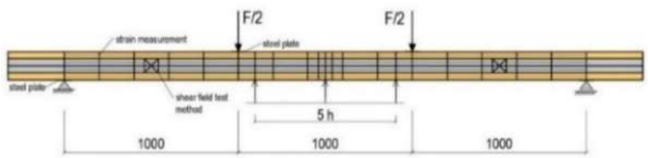

Fig. 2: Four-point bending with shear test stand.

3. Results

The load-deflection ratio as noted in the figure for the failure of unreinforced beams showed in a linearly elastic manner up to the point of failure (Fig. 3). The beams mostly failed in the lower layers in the tension zone due to timber defects. The compression and tension reinforcement resulted in the neutral axis being placed approximately mid-height due to the balanced reinforcement layout adopted. Longitudinal shear cracks of the fibers often appeared in the zones adjacent to the actuator and on the supports. Pre-stressed basalt, glass, steel bars placed in the tensile and compression zones reduced the knot area ratio in the top and bottom layers and thus reduces the likelihood of ductility. Therefore, it can be seen that the ultimate tensile strength of the wood is usually reached in the lower layer, as long as the ultimate compressive strength occurs in the upper layer. A mean global stiffness of 3.95×10^{11} N.mm^2 with a standard deviation of 0.23×10^{11} N.mm^2 and a mean local stiffness of 4.34×10^{11} N.mm^2 with a standard deviation of 0.35×10^{11} N.mm^2 were obtained.

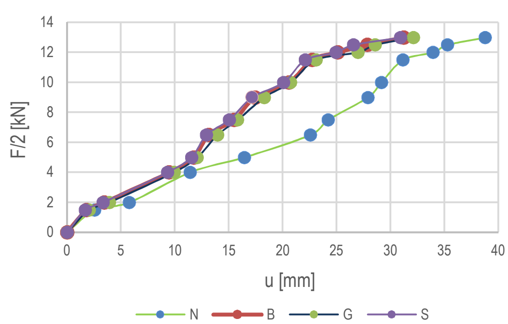

Fig. 3: Load-deflection diagram for all beams at mid-span.

4. Conclusions

On the basis of experimental investigations of the bending reinforcement of low-quality laminated glulam using pre-stressed basalt, glass and steel glued-in rods, the following conclusions were obtained:

- Unreinforced glued laminated beams tended to fail in the tension zone and worked in the linear-elastic range, brittle fracture occurred. Compared to reinforced beams, where in the tension and compression zones, the neutral axis was usually at mid-height of the height of the beams and shear also occurred. Shear was most common along the beam, shear in the support zones outside the loads and at the supports, especially with pre-stressed steel reinforcement, pre-stressed basalt reinforcement, less so in pre-stressed glass reinforcement. Pre-stressed bars increased shear strength through compressive stresses developed in the beam.

- Noticeable non-linear work is exhibited by beams consisting of lamellas of lower quality classes of structural lumber.
- The use of reinforcement equally distributed in the tension and compression zones resulted in an increase in load capacity and stiffness, respectively: pre-stressed steel bars - 39.2 %, 20.2 %; pre-stressed basalt bars - 35.4 %, 19.4 %; pre-stressed glass bars - 32.7 %, 17.2 % compared to unreinforced beams.

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