Behavior of glulam beams strengthened with BFRP bars

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Abstract. Currently, FRP fiber composites are increasingly used in construction. They can be used in the form of: tapes, mats and bars. Composite rods are already widely used in reinforced concrete structures as replacements for steel rods. They are also used as elements for repairing various types of structures: reinforced concrete, timber, steel and masonry. It is much less popular to use composite rods as reinforcement elements for laminated timber beams at the production stage. The paper presents the results of experimental and numerical analysis of glued laminated timber beams, reinforced with BFRP basalt-epoxy rods to determine the effect of the distribution of composite reinforcement on the load-bearing capacity of reinforced joists. The tested elements were reinforced with bars of various diameters, arranged differently at the cross-section. The beams were made of GL24h wood, while basalt-epoxy bars with a diameter of 7 and 9 mm were used to strengthen the beams. During the experimental investigations, the deflection of beams, the value of the destructive force and the form of destruction, were investigated. Computer calculations based on the Finite Element Method (FEA) were also obtained, achieving good consistency of displacement results. In numerical studies, wood and composite rods have been modeled as an orthotropic material. The numerical analysis was carried out in the elastic range. In experimental studies, significant differences in the values of deflections and destructive forces in the scope of one research series were observed, which may be due to the inaccuracy of execution. Values of destructive forces in experimental studies were not directly related to the value of reinforcement percentage of different series of beams.

1. Introduction

Because of favorable properties of the composites (low weight, high tensile strength, resistance to chemical and biological corrosion), there is a great interest in this material in the building and construction industry. The most popular and the most widely used are the fiber composites FRP (Fiber Reinforced Polymer), in which the epoxy resin, also called continuous phase, or a matrix, is reinforced by the fibers, i.e. fiberglass, carbon fiber, or aramid cords. Strength and durability of the composites reinforced by the fibers to great extent are dependent on the way of manufacturing and compaction of the fibers. There is analyzed the use of the natural fibers (such as cotton [1]) in a reinforcing process, because of the more natural character of the fibers of this type. One of the first large-scale appliances of wooden beams reinforced with the fiber composites is the method invented and patented in the USA by Dan Tingley called FIRP. This method is based on pasting the composite tape between the last and the last but one wood slats. Such reinforcement allows to save from 25-40% of the wood usage [2]. In Poland analyses of such type of the beams were conducted by the researchers from Silesian University of Technology in cooperation with the Austrian company Buchacher [3]. The subject for analyses included 15 glulam beams, 6200 mm long, with spacing of the pillars 5760 mm reinforced with the glass-aramid reinforced polymers (GARP) placed between the last and the last but one slats and at the
bottom of the beam. On the basis of the research it was stated that the bearing capacity increased respectively, for 54% in case of reinforcement attached at the bottom of the beam, and 68% for reinforcement attached between the slots. An increase in stiffness was equal 15%. The method described above became the basis for further analyses concerning the subject of adhesive bonds between the FRP and wood [4] and analyses of the costs of the constructions of this type, which are so far quite high [5]. The new solution with the use of fiber composites proposed by the author [6, 7] suggests the use of the aramid cords between the wood slots in order to strengthen the glulam beams. The above mentioned method of reinforcing wooden constructions is still in a phase of experimental and numerical studies. After the initial numerical studies it was concluded that the influence of this type of reinforcement on the character of static work is positive. Solid wooden beams are also reinforced with the use of the fiber composites. Nowak [8] is an author of the extensive studies concerning this type of beams combined with the composite material -Carbon Fiber Reinforced Polymer CFRP. There were analyzed the beams with reinforcement put in the cross-section, by means of which the conditions of reinforcing historical elements were simulated. The increase in bearing capacity of the analyzed beams was in a scale from 21 % (series F) to 69 % (series D) [9]. The way of reinforcing beams with significant damages was suggested by the researchers from the Szczecin University of Technology [10], in which reinforcement with the carbon tape goes through the whole length of the beam, including the most strenuous places (in the middle of the span and over the pillars). There are also functioning the reinforcing methods with the use of composite bars used in a similar way like steel bars [11], and mixed methods, using both bars as well as composite tapes for beams with significant loads [12]. An element worth considering in the following paper is [13] an epoxy-basalt bar which may be an alternative for steel bars. A favorable phenomenon in case of the elements reinforced with composites is an increase in their fire resistance [14, 15], but the subject is not fully understood and there is still some research conducted in this field.

2. Experimental tests

2.1. Materials

2.1.1. Timber. To make the beams, PCAB spruce (Picea abies) was used. Spruce wood is relatively easy to process. They can easily be cut, grinded, milled and drilled. During drying, it has a slight tendency to cracking and warping. The T14 (C24) fins have been used for the production of finished elements, whose strength properties are respectively: characteristic tensile strength of planks along fibers $f_{t, 0, 1, k} = 14$ N / mm$^2$, average elastic modulus of longitudinal boards $E_{l, 0, 1, mean} = 11,000$ N / mm$^2$, board density $\rho_{l, k} = 350$ kg / m$^3$. The boards used had no knots with a diameter of more than 6 mm. The moisture content of the boards ranged from 6 to 15%, while for two boards connected with each other, the humidity difference was no more than 5%. The exact segregation of the boards was made according to the standard [16] in the factory that produced the beams. The material for making finished beams was GL24h layered wood (Table 1).

2.1.2. Epoxy-basalt bars. BFRP basalt-epoxy rods were used to reinforce the beams, which are made in such a way that the fiber bundles are arranged in one direction along the axis of the bar and are embedded in the matrix. The rods were purchased at POLPREK Polskie Pręty Kompozytowe with diameters $\varphi 7$ and $\varphi 9$, because the company has only rod diameters available. At POLPREK, rods are manufactured using the pultrusion method, which means pulling in the machine polymerized fibers that are embedded in an epoxy resin. Strength features of POLPREK rods can be found in reports from research conducted by the Department of Concrete Construction of the Lodz University of Technology [17-19]. The list of strength characteristics of BFRP basalt rods is presented in Table 2.
Table 1. Characteristic values of strength and elasticity in N/mm² and density in kg/m³ for a homogeneous laminated wood [16]

| Property               | Symbol       | Value |
|------------------------|--------------|-------|
| Bending strength       | $f_{m,g,k}$  | 24    |
| Tensile strength       | $f_{t,0,g,k}$| 19.2  |
|                        | $f_{t,90,g,k}$| 0.5   |
| Compressive strength   | $f_{c,0,g,k}$| 24    |
|                        | $f_{c,90,g}$ | 2.5   |
| Cutting resistance     | $f_{v,g,k}$  | 3.5   |
| Elasticity modulus     | $E_{0,g,mean}$| 11 500|
|                        | $E_{0,g,05}$  | 9 600 |
| Form deformation modulus| $G_{g,mean}$  | 650   |
|                        | $G_{g,05}$    | 540   |
| Density                | $\rho_{g,k}$ | 405   |
|                        | $\rho_{g,mean}$| 445   |

Table 2. Characteristic values of strength and elasticity for basalt-epoxy BFRP rods [17-19]

| Property                              | Symbol       | Value, MPa |
|---------------------------------------|--------------|------------|
| Medium tensile strength for φ7 bars   | $f_{fu}$     | 1 184.97   |
| Tensile strength characteristic for φ7 bars| $f_{fu}$ | 1 474.90   |
| Medium tensile strength for rods φ9   | $f_{fuk}$    | 817        |
| Tensile strength for rods φ9          | $f_{fuk}$    | 1038       |
| Modulus of elasticity for rods φ7     | $E_{f,kr}$   | 56 300     |
| Modulus of elasticity for rods φ9     | $E_{f,kr}$   | 56 300     |

2.2. Samples preparation

For laboratory tests, the beams were prepared by ANDREWEX sp. z o. o., specialized in the production of structural elements made of glued laminated timber. After consultations with the company due to limitations of the testing machine (maximum length of samples is 1.20 m), lateral dimensions of the beams were determined so that they were the smallest possible (cross-section 6 cm x 17 cm). The accepted wood class was also forced by the need to obtain the lowest possible strength, also due to the limitations of the machine on which the beams were tested.

The purchased rods were sent to ANDREWEX sp. z o. o. Structural elements at ANDREWEX sp. z o. o. are made in accordance with PN-EN 14080: 2013 [16], which defines the parameters when making beams. Execution of reinforced beams began with proper segregation and milling of lamellas so as to place basalt-epoxy bars of appropriate diameters. The lamels used had a thickness of 40 mm, while the lengths were connected to wedge connectors. A single-component PU polyurethane adhesive type IFJ70 was used for making wedge joints. From the wedge joint, the knot with the permissible diameter was at least 3 times the diameter of the knot. The load capacity of the wedge coupling of the lamelle is $f_{m,j,k} = 30$ N/mm². Due to the fact that they are prototype beams, initial compression of reinforced beams without glue was carried out to determine the behavior of the executed structures during gluing. During the preparatory work the temperature in the room was around 15 °C, while during the squeezing of boards about 18 °C. The humidity in the room during the beams was about 50%. Then, the lamellas and rods were glued together and joined together in ready-made structural elements and placed in the press. A phenol-aminoplastic MUF adhesive type IGP90S was used to
bond together the lamellas. The thickness of the adhesive applied to the lamellas was about 0.6 mm. The lamellas were combined at 1.0 N / mm² pressure. The formaldehyde emission declared by the company is less than 0.124 mg HCHO / m³ of air, which allows to classify beams up to E1 class. Due to machine restrictions, the company made beams of 2.5 m in length, while they were cut in the laboratory to a test length of 1.2 m.

A total of 12 beams, 1.2 m in length, with a cross-section of 7 x 16 cm made of laminated wood have been planned. As reinforcement, two diameters of bars were used: 7 mm and 9 mm (figure 1).

2.3. Test settings
Beams during laboratory tests were subjected to four-point bending in a testing machine allowing a four-point bending test to a load of 100 kN. The static scheme of the tested beams is shown in Figure 2, while the test stand is shown in Figure 3. The span of the tested beams was 1.02 m, while the spacing between the applied forces was 0.18 m. Forks were used over the supports to protect the beams against buckling. The tested beams were freely supported. In order to protect the beams against local dents, 10 mm thick metal plates were used, both above the supports and under the concentrated forces. The load speed was 0.200 kN/s. The average time to destruction was about 300 seconds. During the tests, the value of loading and destructive force was recorded, the displacement value in the middle of the span using a dial indicator and in the middle span of the beam a 1 cm x 1 cm grid was applied and the deformation of the net with the camera at 24 frames per second was recorded.

3. Numerical analysis
3.1. Characteristics of the modeled constructs
Theoretical models corresponding to experimental models were used for the analysis. The static scheme was adopted in such a way as to reliably represent the scheme for experimental research.

Wood is an anisotropic material – its properties depend on the direction we apply the tests. Due to the possibility of identifying three perpendicular to each other directions in a small sample of the
material, it is assumed that wood is an orthotropic material. For this model we distinguish directions adhering to the following patterns: along the fibers, across the fibers but radial to grain and across the fibers but tangential to grain. Since wood properties vary depending on the direction assumed for measuring, it is important to properly model this material when preparing numerical calculations.

3.2. Numerical models
The numerical models of beams reinforced with BFRP basalt-epoxy rods (Figure 4) were created from two parts: a wooden one (in which holes for rods were made) and BFRP bars with a diameter of 7 and 9 mm led along the whole length of the beam.

![Numerical model of the beam](image)

**Figure 4.** Numerical model of the beam

Due to the often overlooked modeling of epoxy glue and individual lamellas in the literature [20-22], these elements were not included in the numerical calculations.

Materials have been declared as orthotropic, homogeneous in the case of both wood and basalt-epoxy rods. Data for calculations, which are presented in Table 3, were adopted on the basis of material tests [17-19], standard [16] and available literature [23]. Connections between parts of the structure have been created by means of a function that connects the individual parts rigidly with each other and equates the displacement values at the contact limits.

The finite element grid was applied to each part separately (Figure 5).

![Finite element mesh of the structure](image)

**Figure 5.** The finite element mesh of the structure
Table 3. Material’s data assumed for the calculations [16-19, 23, 24]

| Parameter               | Unit | Timber | BFRP |
|-------------------------|------|--------|------|
| Coefficient of direct elasticity |       |        |      |
| $E_x$                   | [MPa]| 897    | 56300|
| $E_y$                   | [MPa]| 494.5  | 9383 |
| $E_z$                   | [MPa]| 11500  | 9383 |
| Modulus of rigidity     |      |        |      |
| $G_{xy}$                | [MPa]| 34.5   | 1968 |
| $G_{xz}$                | [MPa]| 736    | 1968 |
| $G_{yz}$                | [MPa]| 701.5  | 1968 |
| Poisson’s ratio         |      |        |      |
| $\nu_{xy}$              | [-]  | 0.435  | 0.35 |
| $\nu_{xz}$              | [-]  | 0.372  | 0.35 |
| $\nu_{yz}$              | [-]  | 0.467  | 0.35 |

4. Results and discussion

Displacement-load diagrams from experimental and numerical calculations for all series are shown in Figures 6-9. Figure 10 shows the nature of the deflection of the A series numerical model.

There is a good correlation between the experimental and numerical results until the beam enters the plastic range, but in all series the values of deflections from the numerical calculations are noticeably smaller.

The addition of reinforcement in all tested beams shows the nature of work with plastic entry. The most advantageous character of the work is shown in series C and D (figure 8, figure 9), because they achieved the highest values of destructive forces at the lowest value of deflections. The operating characteristics for series A and B are similar (figure 6, figure 7), however, the values of the breaking forces are higher for the B series samples.

Figures 6 and 9 show large discrepancies in the results of experimental studies for individual samples.

![Figure 6. Deflection / force diagram for A series beams](image1)

![Figure 7. Deflection / force diagram for B series beams](image2)
5. Conclusions
Numerical analysis correctly reflects the nature of the work of reinforced beams, however, only in the initial working range of the beam. This is due to the fact that the beam, implying that the nature of the beam's work itself, changes to plastic. Minor discrepancies may result from the fact that material data for BFRP bars are partially determined analytically. Therefore further analysis of the work of this type of construction are necessary, however, using non-linear numerical analysis in relation to the materials used and development of exact values of strength characteristics are needed.

The best static work was characterized by series C and D, reaching the lowest values of deflection forces at the highest values, which is associated with the highest percentage of reinforcement in these samples. In series A, B, D there are significant discrepancies in the test results, which is most probably caused by the low accuracy of the beams. These are an innovative solution and manufacturing technology should be further developed.

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