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Parametric analysis of the reinforcement of glued laminated timber beams with composite bars containing basalt fiber

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Abstract: Due to the greater importance put on the environment in the construction industry, wood, being a natural building material, has become more popular. It is of particular importance in the case of making elements with high aesthetic value and resistant to chemical corrosion. Due to high strength and, at the same time low weight, composite materials, especially fibrous composites, are also increasingly used. Among the fibrous composites, basalt fiber materials that are of natural origin and are ecological deserve attention. Therefore, the possible benefits resulting from the combination of two ecological materials was considered. In Ansys 16.1, a numerical model was created for parametric tests, assuming various construction configurations. In the ANSYS program, beams made of glued laminated timber, reinforced with BFRP bars, were modeled in various configurations of beam height, bar length, and bar distance from the lower and upper edge of the cross-section. The best results were obtained for the highest-height reinforced beams.

Keywords: glulam, fibrous composites, BFRP, basalt-epoxy rods, numerical analysis

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Introduction

Due to the environmental situation of the planet, great importance is attached to sustainable development that does not cause excessive carbon dioxide emissions and the production of waste. Accordingly, the aim is to use natural materials in a sustainable way. Construction is a sector that has a significant impact on waste management. The production of wooden elements is less harmful to the environment compared to the production of concrete or steel elements, therefore wood has been experiencing a renaissance in recent years. Wood is a natural material, which also

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has many advantages, the most important being: its aesthetic appearance and a favorable strength-to-weight ratio.

In order to increase the load-bearing capacity or reduce the wood consumption, it is possible, but still not common, to add the reinforcement at the production stage especially in elements made of glued laminated timber. One of the greener materials used to strengthen structures is BFRP basalt epoxy.

Currently, the use of reinforcement in the form of composite elements is more and more common and there are many studies dealing with the subject.

The work (Vahedian et al., 2019) presents extensive experimental studies and analytical calculations of glued laminated beams reinforced with carbon tapes. The tapes used were of various thickness, width and length. The reinforced beams showed an increase in stiffness by 31-64%. Furthermore, the research results presented in (Glisovic et al., 2016) show the beneficial effect of composite reinforcement, however, the increase in stiffness is smaller, amounting to 11-19%, compared to the results presented in the paper (Vahedian et al., 2019).

Extensive experimental studies and analytical calculations are presented in (Yang et al., 2016). Glued laminated timber beams reinforced in various configurations in the tension zone and the tension and compression zone were tested. The following were used as reinforcement: steel bars, GFRP and CFRP strips and GFRP bars. The bars were placed in square holes, filling the free space with glue.

In order to increase the adhesion of the reinforcement, it was proposed to lay several thinner bars in one hole. However, this solution did not increase the adhesion of the bars. The bars were placed in square and round holes. Beams with circular openings showed better properties.

Relatively few studies can be found in which the BFRP composite reinforcement is made of glued laminated timber. In studies (O'Ceallaigh et al., 2018; Raftery & Kelly, 2015), the beams were reinforced with bars glued into previously prepared larger holes, filling the free space with glue. The bars were placed in holes cut on the outer surfaces of the beams from the bottom and on the side surfaces. In both works, the influence of FRP reinforcement turned out to be beneficial for static work by increasing the load-bearing capacity and stiffness.

In the work (Fosetti et al., 2015), the beams were reinforced with BFRP bars glued between the lamellas, into previously cut square holes. The remaining space between the bars and the wood was filled with resin. The stiffness of the beams with BFRP bars did not turn out to be higher than that of non-reinforced beams. The authors explain the results with too much of the resin being used, which lowered the value of the longitudinal modulus of elasticity of the beams.

The aim of the article is to determine the influence of basic construction parameters on the stiffness of wooden beams reinforced with the use of BFRP bars.

1. Materials

For numerical calculations in the commercial program Ansys Workbench 16.1, wood was declared as an orthotropic material, taking into account the constitutive models discussed. During the analyzes it was assumed that the mechanical properties in relation to the axes defining the tangent and radial directions are the same. This assumption is commonly used in the literature due to the geometrical characteristics, especially the dimensions of the cross-section of the lamellas (Azinovic et al., 2019; Khelifa et al., 2015; Khelifa et al., 2016; Sandhaas et al., 2020; Sirumbal--Zapata et al., 2018; Tran et al., 2018; Xu et al., 2019; Zhang et al., 2018). The yield point was determined on the basis of the Hill strength criterion, taking into account the data presented in Table 1. The mechanical characteristics of wood used for numerical calculations are presented in Table 1. An elastic-perfectly plastic model was assumed, adopted for both compression and tensile, and no differentiation was made of the yield strengths for the above-mentioned stress states. The resistance and plastic mechanical characteristics of wood were implemented via the command line.

Table 1. Material data adopted in the numerical model (Del Coz Diaz et al., 2013; Kamińska et al., 2012a; 2012b; 2013; PN-EN 14080:2013-07; PN-EN 338:2016-06; Xu et al., 2019)

Characteristic	Unit	Timber	BFRP
Young's modulus	MPa	$E_L = 9600$	$E_{\phi 7} = 52\,800$
		$E_R = E_T = 250$	$E_{\phi 9} = 56\,300$
Kirchhoff modulus	MPa	$G_{LR} = G_{LT} = G_{RT} = 540$	
Poisson's ratio	–	$\nu_{LR} = \nu_{LT} = \nu_{RT} = 0.41$	$\nu = 0.3$
Yield point	MPa	$\sigma_y = 38.15$	
		$\sigma_0 = 19.2$	
		$\sigma_{11y} = 19.2$	
		$\sigma_{22y} = \sigma_{33y} = 0.5$	
		$\sigma_{12y} = \sigma_{13y} = \sigma_{23y} = 3.5$	

The values of the modulus of longitudinal elasticity and transverse elasticity were taken from the standards (PN-EN 14080: 2013-07; PN-EN 338: 2016-06) for wood of the GL24h class. The values of the Poisson coefficients were determined on the basis of (Del Coz Diaz et al., 2013; Xu et al., 2019) for glued laminated timber. The literature studies indicate that the use of standard data for numerical calculations gives correct results in comparison to the values obtained in experimental studies and can be successfully used for numerical analyzes (Azinovic et al., 2019; Bedon & Fragiacomo, 2019; Tran et al., 2018; Xu et al., 2019).

Material data for BFRP basalt-epoxy bars, whose work model was adopted as isotropic linear-elastic, was adopted on the basis of information taken from laboratory tests carried out at the Lodz University of Technology, which were presented in the studies (Kamińska et al., 2012a; 2012b; 2013). The values of the mechanical characteristics for the BFRP bars are also presented in Table 1.

2. Methods

The boundary conditions were established with the use of steel washers used in the experimental research. The hinged supports were modeled using the Remote Displacement function, and the loads were modeled using the Force function. Both functions were set linearly so as to map the cylindrical supports.

In the parametric analysis, the tangent diagram of a four-point bending was used and a beam length of 3.04 m was assumed. The spacing between the supports was 2.88 m. The spacing between concentrated forces was assumed as 0.96 m, it was equal to 1/3 of the beam span between supports (Fig. 1). Due to the large size of the calculation files, the symmetry of the system was used in order to limit the number of finite elements and the associated reduction of the calculation time (Fig. 1). The Symmetry Region command was used for the calculations on two faces of the analyzed beams. Finally, 1/4 of the entire beam was used for the analysis. The size of the finite element was assumed as 1 cm (Fig. 2). The finite element SOLID186 was used for the calculations.

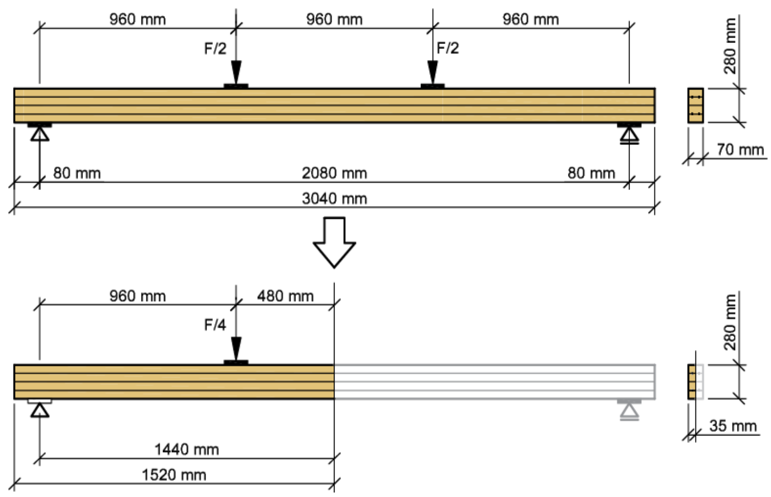

Fig. 1. Static diagram adopted for parametric analysis and dimensions of the adopted numerical model (*own study*)

An unreinforced comparison beam was also calculated for each parameter. The parametric analysis was carried out for specific models reinforced with BFRP bars with a diameter of 9 mm, for three main variables, for which four different values of the variables were assumed:

- beam height (160, 200, 240, 280 mm),
- distance between the reinforcement bars and the edge of the beam (40, 35, 20, 18 mm),
- longitudinal length of the reinforcing bars (3040, 2240, 1600, 960 mm).

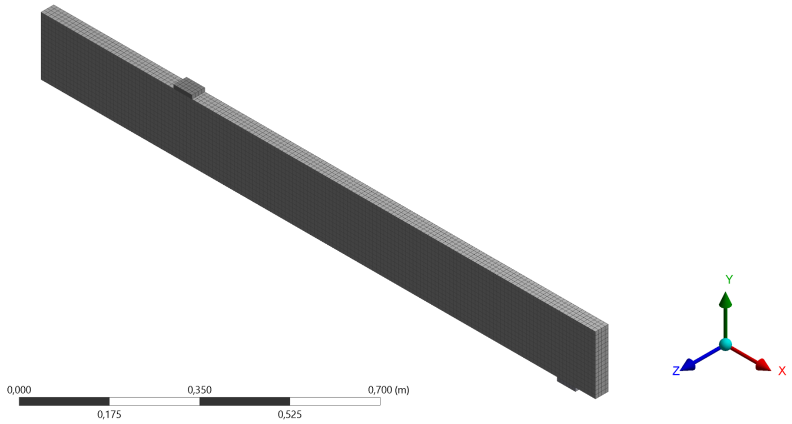

Fig. 2. Model finite element mesh for parametric analysis (*own study*)

3. Results and discussion

3.1. The height of the beams

The first analyzed variable was the height of the beams (unreinforced, single and double reinforced with 9 mm diameter bars). Figure 3 shows the equilibrium paths (deflection-force relationships) for beams reinforced with two basalt-epoxy bars $\phi 9$ and unreinforced beams with heights: 160, 200, 240, 280 mm. The height jump is assumed to be 40 mm, it is the most common thickness of the lamellas used to make glued laminated timber beams. Figure 4 shows the equilibrium paths for beams double-reinforced with BFRP $\phi 9$ bars. The heights of the analyzed beams were also: 160, 200, 240 and 280 mm. For comparison, the values for unreinforced beams of the same heights are also presented. As the height of the beam increases, the influence of the reinforcement used is more favorable, which is associated with a marked increase in stiffness (Figs. 3 and 4). For reinforced beams, the increase is doubled. Increasing the height of the beams has an impact on the more effective use of the reinforcement, which reduces the normal stresses in the wood.

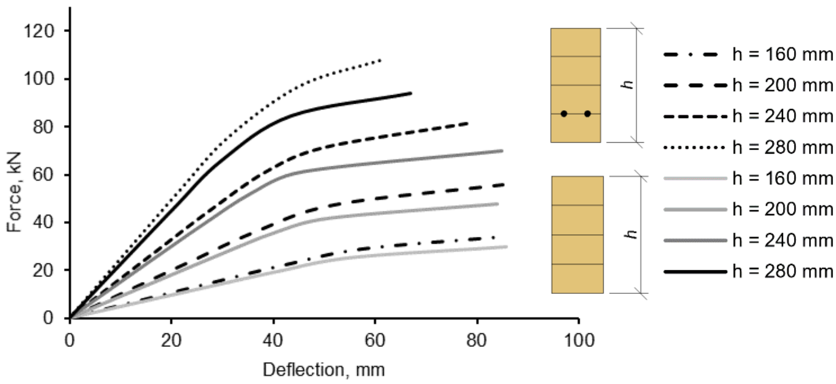

Fig. 3. Force-deflection diagram for beams (not reinforced and reinforced with two BFRP bars) of different heights (*own study*)

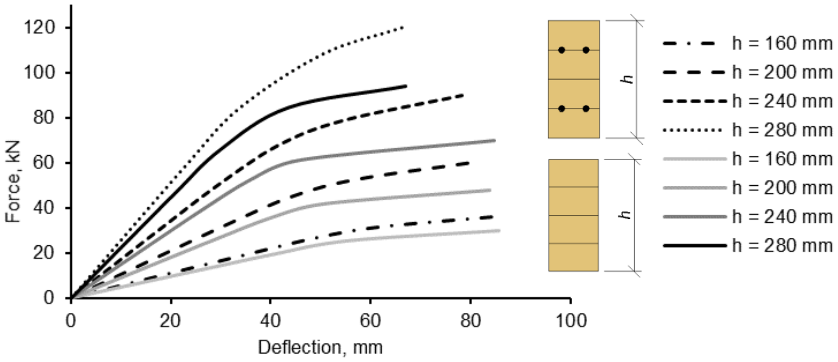

Fig. 4. Force-deflection diagram for beams (not reinforced and reinforced with four BFRP bars) of different heights (*own study*)

3.2. The distance of the bars from the lower and upper edges of the cross-section

Another analyzed factor was the distance of the BFRP rebars from the bottom and top edge of the cross-section. Figures 5 and 6 show the equilibrium paths for 160 mm high beams with different distances of the BFRP bars from the bottom and top edge of the beams. Moreover, the values for the unreinforced beam, also 160 mm high, are presented for comparison. The following bar distances were adopted: 40, 35, 20, 18 mm. These distances are dictated by the thickness of the lamellas, which are given by the manufacturers as possible to be made on a special request. Reducing the distance of reinforcing bars from the edge does not significantly affect the stiffness of the elements. The stiffness increases slightly, which, however, becomes visible only after changing the scale of the graphs (Figs. 5 and 6). The increase in stiffness is greater with double-reinforced beams.

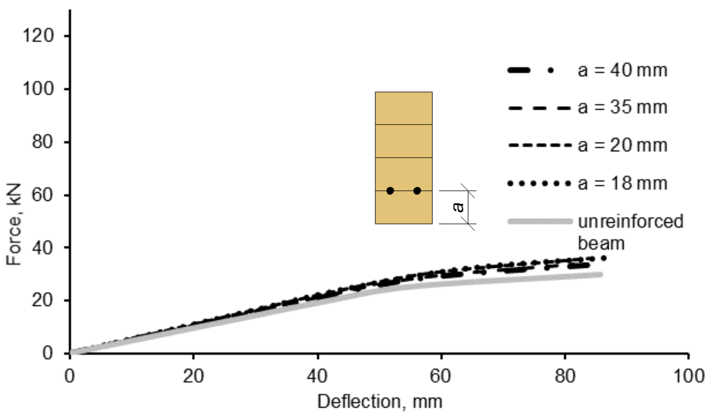

Fig. 5. Force-deflection diagram for beams reinforced with two BFRP bars with different bar distances from the bottom edge (*own study*)

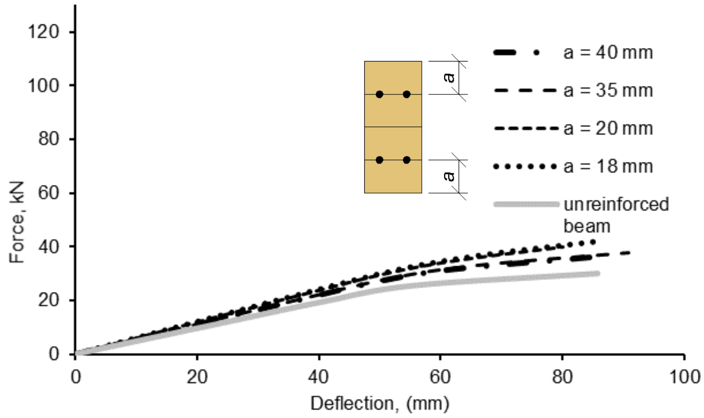

Fig. 6. Force-deflection diagram for beams reinforced with four BFRP bars with different bar distances from the bottom and top edge (*own study*)

3.3. Length of the BFRP reinforcement bars

The last analyzed parameter was the length of the reinforcing bars. Four lengths of bars were adopted for the analyzes: 3040, 2240, 1600 and 960 mm. Figures 7 and 8 show the equilibrium paths for 160 mm high beams for which different lengths of reinforcing bars were assumed. The reduction of the bar length beyond the area of the maximum value of the bending moment does not significantly reduce the stiffness of the beams. On closer inspection, a slight reduction in stiffness is visible when 960 mm long bars are used, which is the value of the spacing between the applied concentrated forces.

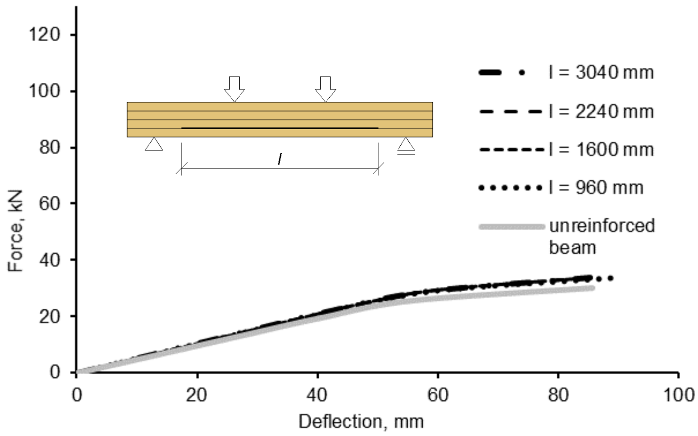

Fig. 7. Force-deflection diagram for beams reinforced with two BFRP bars of different lengths (*own study*)

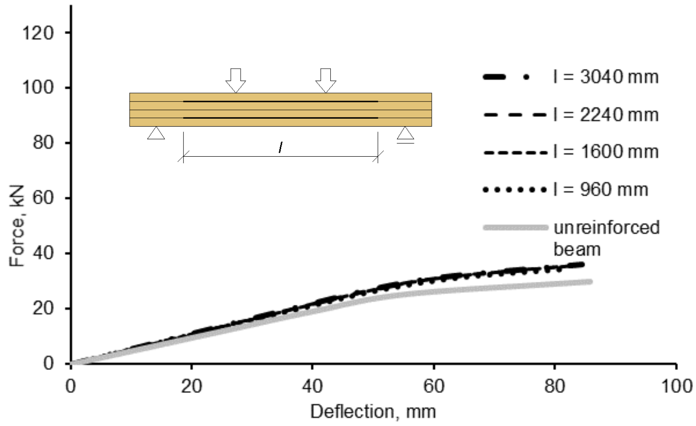

Fig. 8. Force-deflection diagram for beams reinforced with four BFRP bars of different lengths (*own study*)

Conclusions

The article presents a parametric analysis of the reinforcement of glued laminated timber beams, reinforced with BFRP bars. Based on the numerical analyzes performed, the following conclusions can be presented.

- Increasing the height of reinforced beams had a positive effect on the effectiveness of the reinforcement use, resulting in a greater increase in stiffness and a more favorable distribution of normal stresses in the wood.
- Moving the reinforcing bars away from the center of gravity of the cross-section did not significantly increase the stiffness of the beams.
- The shortening of the bars did not reduce the stiffness of the beams, assuming the use of bars in the place of the maximum bending moment and assuming a certain allowance in the length of the bar, related to with the anchorage length.

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