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APPLICATION OF CARBON FIBERS ON WOOD BEAMS

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ABSTRACT

The paper deals with one of the possibilities of wood beam reinforcing, namely with the aid of carbon fibers, particularly the SikaWrap 300C carbon fabric. To determine suitability and possibility of application of this reinforcement, laboratory tests with a load in four-point bending needed to be performed using the EN 408. Two (2) - component epoxy resin was chosen as an adhesive agent. After the evaluation of experimental measurements increased strength of reinforced beams by 17 % for bonded-on carbon fabric and by 34 % for pre-strained carbon fabric was detected. Flexure increase approved significantly as well - for reinforced beams average value by 23 % and for pre-strained beams by 24 %.

Keywords: wood beam, carbon fibers, reinforcing.

INTRODUCTION

The subject of this paper is the evaluation of suitability rates for application of carbon-based fibers – fabrics in composites and for applications of grown wood-based structural elements. Wood structural elements are reinforced with other materials in order to increase strength and carrying capacity. Wood beams are suitable structural elements for use in constructions with a large width of span. The advantages of their use include low energy consumption during production, ecological sustainability of the used material, and maintaining wood characteristics while also being fire resistant (KUKLÍK 2001, ČSN EN 384).

These days research is oriented on solving the demand to achieve a large width of span without a support for wood-based structures (KUKLÍK *et al*. 2006). At the present time, further new processes are tested and applied to increase toughness and strength of wood-based structural elements. For example, reinforcing wood structural beams with composites which are created by fibers (particularly carbon-based fibers), then fiberglass or aramid fibers in combination with an appropriate binder. The main task of the binder in a composite is to protect fibers against the impact of an aggressive ambient atmosphere and from fast degradation and structural impairment.

THEORETICAL ANALYSIS OF THE PROBLEMS

The main factors which are generally considered when designing reinforcement of carrying structures with high-strength fibers are tensile strength, density, weight, modulus of elasticity, corrosion resistance and many others. A no less important factor is the technology of bonding the reinforcement to the reinforced material. Bonding of these elements is most often carried out with the help of adhesives. This further depends on the character and type of a fiber and also on the type of the strengthened material (ROHANOVÁ 2003). Type of adhesive used has an impact not only on the mechanical properties of the final composite but also affects other physical and functional characteristics such as the effect of resistance to humidity or the amount of formaldehyde release (BÖHM *et al.* 2012). As these high-tech materials are rather new products, their production costs are high. Although the price of high-strength fibers has been reduced since the start of commercial production, prices are still higher in comparison with other structural materials (MINSTER 2006).

Fibers which were used for tests of reinforced wood beams had been selected on the basis of stress type. Given that the most of beam elements are stressed flexurally and reinforcement was performed on the bottom side of the beam where are the greatest bending tensions, fibers with high tensile strength needed to be considered (HLUŠÍ *et al.* 2007).

The paper is a follow-up to earlier research focused on observing strength of a reinforced massive wood with carbon fibers in a form of a fabric (OZEL *et al.* 2000, ROMANI *et al.* 2001), but also even lamellae (MELZEROVÁ 2009, VÍDEŇSKÝ 2005), for which a design and numerical model of bonded lamella beams was determined (KUKLÍK *et al.* 2007). To some extent, these models can be applied even to observations of reinforced massive wood.

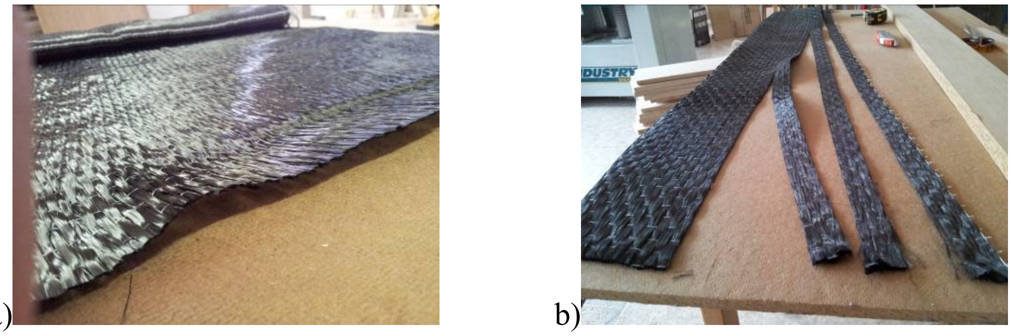
METHODICS, MATERIAL AND MEASUREMENT PROCEDURE

The following groups of beams were used for the experiment:

- Non-reinforced wood beams;
- Wood beams reinforced with bonded SikaWrap 300C fabric; and
- Wood beams reinforced with pre-strained SikaWrap 300C fabric with subsequent onding.

In each group, there are ten beams of a unified dimension 30 × 66 × 1 200 mm. All the elements were planed to the accurate dimension according to ČSN EN 408 standard requirements. The dimensions of the beams have come out from the breaking machine dimension which has a maximal span of fixtures of 400 mm.

The used carbon fibers (Fig. 1a) were delivered by SIKA CZ s.r.o., a Swiss based company with representation in the Czech Republic. These fibers outclass other materials in a number of parameters. Advantages of these carbon fibers are high strength, low density and high modulus of elasticity (KRŇANSKÝ 2009). Tensile modulus of elasticity is up to 600 GPa, tensile strength is up to 4 000 MPa and fiber density is about 1.9 $kg \cdot m^{-3}$. Another unquestionable advantage is high chemical resistance and stability of properties up to a temperature of 2 000 °C. They also feature low thermal and electrical conductivity and have a low coefficient of thermal expansion. The only disadvantage of these fibers is their high brittleness. The fibers were divided to individual strips (Fig. 1b) according to the beam dimensions so that they fully covered the tension stressed part (BRUNNER 2001).



a) b)

Fig. 1 SikaWrap 300 carbon fabric used for reinforcing a) delivered condition b) created individual strips according to the beam dimension.

For one group of beams, pre-straining on a specially developed device was used (Fig. 2). This enabled pre-straining of the given SikaWrap fabric up to 100 kg, which is 980 N. For fabric pre-strained this way, the device allowed up to 5 beams to be bonded at once.

Fig. 2 Attaching the pre-strained carbon fabrics to the wood beams.

The total number of the reinforced beams was 20 pieces. Ten pieces had the same type of adhesive and the rest were non-reinforced. Sawn wood for the manufacture of beams was made of spruce wood and classified as S10 according to ČSN 73 2824-1 requirements, or C22 class according to ČSN EN 338 intended for structural beam production. The beams had been left in a proper atmosphere of an air conditioned chamber. This meant a relative air humidity of w_r = 65 % and temperature of 20 °C, until their mass decreased over 6 hours to less than 0,1 %. In these conditions for bonding the reinforcing fabric were met. The subsequent measurement of wood humidity was performed by a weighing method according to ČSN EN 13183-1 and ČSN EN 384. The measured humidity value before bonding as well as before performing the experiment was 12 %.

Sikadur 330 adhesive was delivered by the company SIKA CZ. This is a two-component adhesive which consists of an epoxy resin and a hardener. This two-component epoxy-based thixotrophic laminating resin was intended by the manufacturer for bonding SikaWrap carbon fabric to strengthen flexurally stressed or shear loaded structural elements and structural wood. Advantages of this adhesive are high strength, long duration of workability (30 minutes at 20 °C) and quite low viscosity. Mixing ratio of A component (epoxy resin) and B component (hardener) is of a mass ratio 4:1. The adhesive was laid on by a special laminating roller for applying a recommended amount of the adhesive and creating an adhesive gap of approximately 0,5 mm in thickness. According to the technical data sheet, Sikadur 330 adhesive has a 5 day curing time (observing the proper conditions for bonding). Therefore the beams were left in an air conditioned atmosphere for this period. They were then ready for four-point bending testing.

The breaking machine which was used for performing the tests is situated in a laboratory of the Faculty of Forestry and Wood Sciences at the Czech University of Agriculture in Prague. This is UTS 50 TESTSYSTEM GMBH & CO type with distribution of compression points as shown in [Fig. 3]. Loading rate was constant and loading head movement speed must not be higher than 0,003 h - meaning that it must not be higher than $0.003 \times 66 = 0{,}198\ \mathrm{mm \cdot s^{-1}}$.

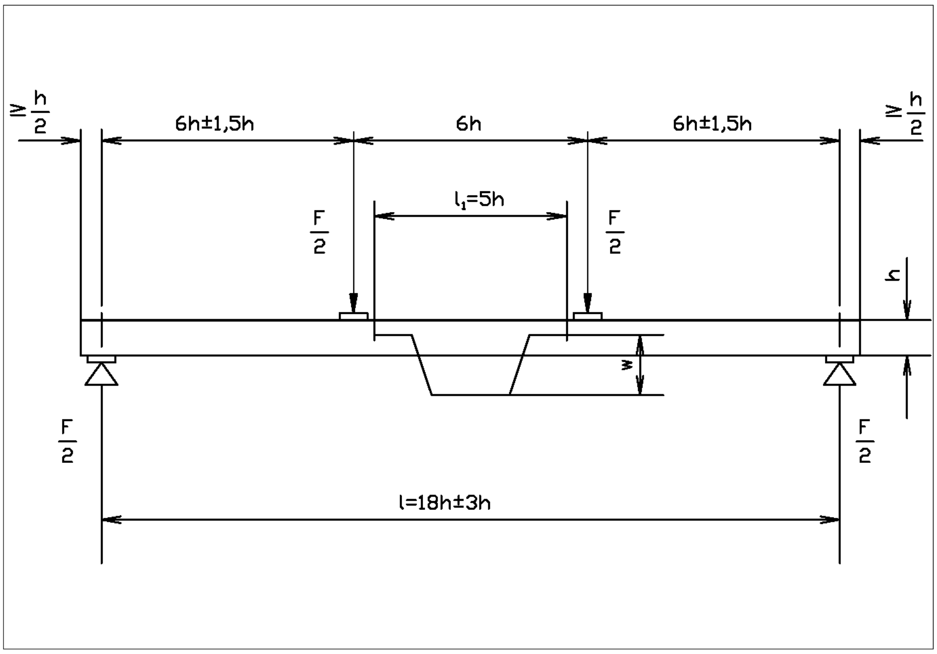


Fig. 3 Four-point bending test arrangement (ČSN EN 408).

Distribution of supports and loading jigs were arranged according to ČSN EN 408 requirements for all three sets of the beams. For all the beams the distances between the loads and supports were used as shown in Fig. 3. While loading, the beam flexure was measured with the aid of a dial gauge with 0.01 mm accuracy.

RESULTS AND DISCUSSION

By evaluation of the measured data of:

- 10 beams reinforced by bonding-on the carbon fabric;
- 10 beams reinforced by bonding-on the pre-strained carbon fabric; and
- 10 non-reinforced beams.

A set of values had been acquired which was then assessed. On the basis of one-factor analysis of variance of the reinforced, pre-strained and non-reinforced beams it was possible to find a correlation between these groups for a force needed to break the beam and for the beam flexure.

The following table (Tab. 1) shows the results of the loading force and flexure for the respective beams. This was always with an average value, a decisive variation and a variation coefficient. The table is divided according to the beam types.

Tab. 1 Measured values of force and flexure for non-reinforced beams, the beams reinforced with the carbon fabric and the beams reinforced with the pre-strained carbon fabric.

non-reinforced beams				
	m [g]	**ρ [kg/m^3]**	**F [N]**	**w [mm]**
Average value	971.67	470.75	6 024.05	31.64
Decisive variation	50.15	31.83	841.24	6.08
Variation coefficient	5.16 %	6.76 %	13.96 %	19.20 %
beams reinforced with the carbon fabric				
Average value	956.91	423.38	7 299.19	40.88
Decisive variation	65.68	27.23	654.54	7.07
Variation coefficient	6.86 %	6.43 %	13.08 %	17.30 %
beams reinforced with the pre-strained carbon fabric				
Average value	1 078.18	463.18	9 124.75	41.92
Decisive variation	64.35	41.87	1 025.36	5.67
Variation coefficient	5.97 %	9.04 %	11.24 %	13.62 %

Individual data was compared by two averages conformity hypothesis testing, and tests considered on a five-percent level of significance. The significance of the observed factors is shown in the following diagrams.

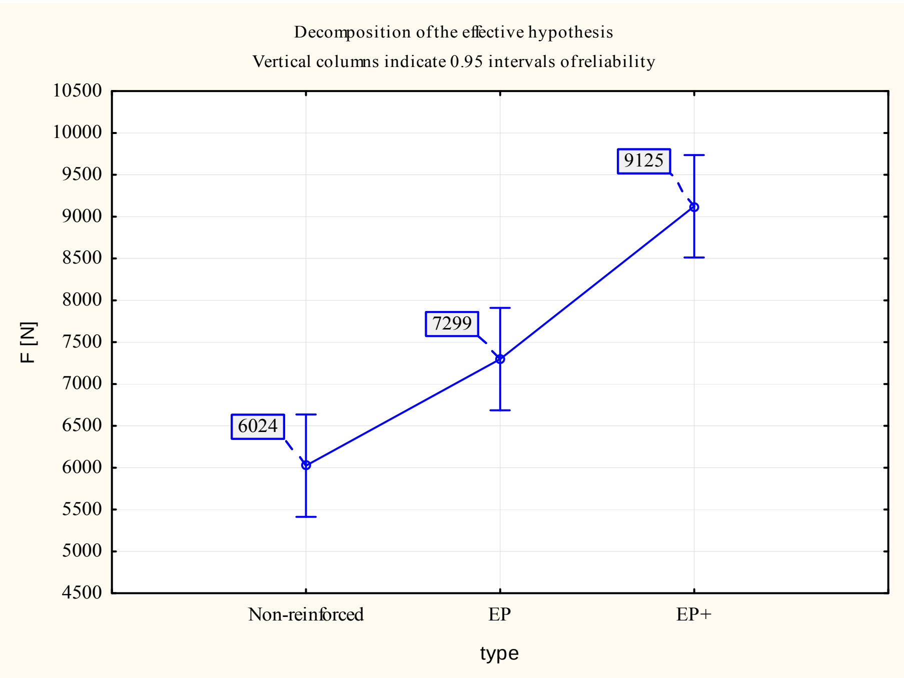


Fig. 4 Dependence of the loading force according to the beam types.

The achieved results imply the apparent difference between the values for the non-reinforced beams and the beams reinforced with the carbon fabric (and, in some cases, with the pre-strained carbon fabric).

This effect results from the carbon fibers which partly eliminate wood anisotropy and cumulate a larger part of strength values of the reinforced beams into the sets with a lower variance. In the case of the force needed for breaking the beam, the statistical calculation of two averages conformity proves that the average values between the groups differ statistically. It implies that the reinforced beams have higher strength at an average than the non-reinforced ones. Still, the greater significant difference is between the group of the non-reinforced beams and the beams with the pre-strained fabric (Fig. 4). These results are shown in the following table (Tab. 2).

Tab. 2 Tukey's HSD test with a variable F [N].

	type	(1) 6024.1	(2) 7299.2	(3) 9124.7
1	**Non-reinforced**		*0.014653*	*0.000127*
2	**EP**	*0.014653*		*0.000633*
3	**EP+**	*0.000127*	*0.000633*	

In the case of flexure at breaking the beam the statistical calculation of two averages conformity proves that the average values between the groups differ statistically, and this between the groups of the reinforced beams and the non-reinforced ones [Fig. 5].

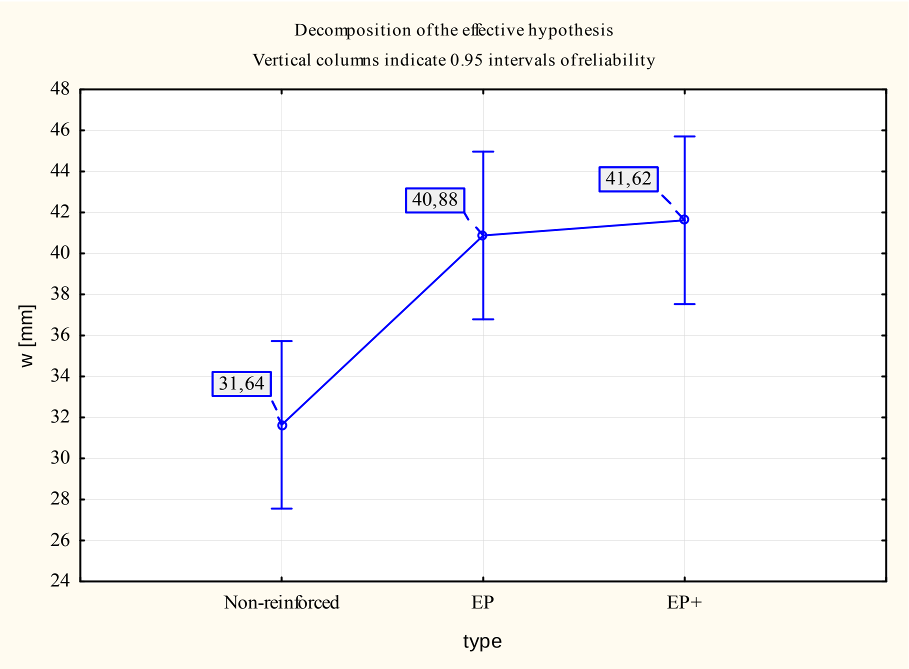


Fig. 5 Flexure dependence according to the beam types.

For the reinforced beams and the beams with the pre-strained fabric the result is statistically insignificant in this case (Tab. 3). It implies that the reinforced beams, (including the pre-strained ones), have greater flexure, on average, than the non-reinforced ones.

Tab. 3 Tukey's HSD test with a variable w [mm].

	type	(1) 6024.1	(2) 7299.2	(3) 9124.7
1	**Non-reinforced**		*0.007920*	*0.004145*
2	**EP**	*0.007920*		0.962668
3	**EP+**	*0.004145*	0.962668	

In this case the statistical calculation of two averages conformity proves that the flexure average values do not differ statistically only between the reinforced beams. It implies that the reinforced beams have greater flexure, on average, than the non-reinforced ones.

On the basis of the performed measurement and the achieved results of the compared parameters, we may state that a change in behaviour of the reinforced beams and the reinforced ones with the pre-strained fabric occurred while being loaded. Statistically, the force needed for breaking the beam differs significantly between all three categories and the flexure differs significantly between the reinforced beams and the non-reinforced ones. Sikadur 330 epoxy resin has been developed for application to carbon fibers in a form of a fabric and it has been proved that this method of reinforcement is advisable.

The following tables summarise the foregoing results. From these results, it was possible to determine an increase (expressed as a percentage) of strengthening with the carbon fabric and the pre-strained carbon fabric on the basis of the average values. The increases always relate to the initial average value of the non-reinforced beams - whether in the case of the average value of the force needed for breaking the beams (Tab. 4) or the recorded average value of the flexure when breaking the beams (Tab. 5).

Tab. 4 Summary of the resulting data of the force needed for breaking the beam and the percentage increase for the given groups.

Force F [N]						
	$\bar{x}$ **[N]**	**s**	**v [%]**	F_{min}	F_{max}	**Increase %**
Non-reinforced	6 024.05	841.24	13.96	4 386.24	6 885.10	0
EP	7 299.19	954.54	13.08	5 660.99	9 259.34	17
EP+	9 124.75	1 025.36	11.24	7 453.28	10 496.09	34

Tab. 5 Summary of the resulting data of the flexure when breaking the beam and the percentage increase for the given groups.

flexure w [mm]						
	$\bar{x}$ **[mm]**	**s**	**v [%]**	w_{min}	w_{max}	**increase %**
Non-reinforced	31.64	6.08	19.20	25.18	41.03	0
EP	40.88	7.07	17.30	28.30	49.29	23
EP+	41.62	5.67	13.62	32.03	50.48	24

The results imply that for breaking the wood beams in the case of such reinforced beams the force has to be increased by 17 % for bonded-on carbon fabric and by 34 % for pre-strained carbon fabric up to 980 N in the tensioned part of the beam. The flexure increase was significant as well. For the reinforced beams 23 % and for the pre-strained beams 24 %.

The results from other authors show that it is important to determine the bonding procedure beforehand and the dimensions of the beams and other parameters arising from laboratory conditions (ROHANOVÁ *et al.* 2003). There is a relatively high concentration of tension on the beams in the place where carbon fibers are stuck. And because of the higher strength in skid of the glue itself than the wood fibers, it happens to breaking the beams when the carbon fibers are torn out. This can be explained by too a high modulus of elasticity of carbon fibers in cases when used together with wood.

Because high-strength fibers are not stuck using the simpler gluing method fully in the bottom part of the beam where tension is utilized, the idea was fulfilled to pre-stress these fibers. Then their strength is better utilized. The application of a high force is a problem because the transfer of pressure from the fibers in the ends of the beam to the main part of the beam can cause delamination – branching out. The problem of delamination is notable, according to research (BRUNNER 2001), from the pre-tension values higher 30 kN. According to (STEIGER 2004) documented tests on small samples in tension showed that the joint strength of the carbon fibers and wood is quite high, and it can bear loads of up to nearly 250 kN.

The force needed for breaking and the appropriate flexures of the wood beams are always the input parameters on the basis of which it is possible to assess the conclusions of these tests (BLANKENHORN 2001). The established strength and values of deflection from evidence tests are used to determine the physical and mechanical properties, especially the bending strength and modulus of elasticity in bending with the principles according to ČSN EN 408. Modulus of elasticity in static bending is then given by:

$$E_{stat} = \frac{a l_1^2 (F_2 - F_1)}{16 I (w_2 - w_1)}, \quad (1)$$

where: E_{stat} is the static modulus of elasticity;
$F_1 - F_2$ is the increment of forces in linear deformation;
$w_1 – w_2$ is the corresponding increment of deflection;
I is the moment of inertia of the cross section of the beam;
a is the distance of the load from the move proximate support;
l_1 is the length of the sensor for determining the modulus of elasticity.

From the calculated values of the modulus of elasticity for each non-reinforced beam is the average value E_m = 12 689 MPa, for reinforced beams by bonding-on the carbon fabric E_m = 12 923 MPa and for reinforced beams by bonding-on the pre-tensioned carbon fabric E_m = 16 050 MPa. The average growth of values from the modulus of elasticity in static bending for reinforced beams are determined by increasing the load force and the growth of increment of deflection. Values are higher overall than the standard.

Flexural strength is measured in the same configuration of the load device as in the case of the static modulus of elasticity in bending. Flexural strength f_m is given by:

$$f_m = \frac{a F_{max}}{2W}, \quad (2)$$

where: F_{max} is the maximum of the fracture force;
a is the distance of the load from move proximate support;
W is the section modulus.

The value of the flexural strength for non-reinforced beams is determined by division into quality class according to C22, therefore f_m = 22 MPa. Compressive strength in flexural cannot be directly compared with the flexural strength because non-reinforced beams is tensile strength in flexure. For high-quality wood is the compressive strength in flexure lower, but without knowing the strength of the wood in simple tension and pressure this value cannot be calculated. The values of compressive strength for flexure are, as for non-reinforced so for reinforced beams, similar and the wood therefore does not have exceptional strength. In this case, the increased modulus of elasticity can be attributed to the method employed by bending tests only.

The summary of the results of the mechanical and physical properties are comparable with the results of the authors (HLUŠÍ *et al*. 2007). HLUŠÍ (2007) mentions that carbon fiber reinforced beams feature higher parameters than standard ones, and thus the resulting conclusions are confirmed. Further recommended possibilities observing similar characteristics are carbon lamellae reinforcements for bonded laminated wood (MELZEROVÁ 2009).

CONCLUSION

The bending test evaluation is divided into two groups which compare the selected sets of samples with each other. This allows an increase in strength and flexures of the beams to be defined as a percentage. The strength increase is substantial for the pre-strained textile carbon-based fibers (by more than 34 % in comparison with the non-reinforced beams). The flexure, which is generally around 23 % and 24 % for carbon fabric reinforcement, showed itself to be a noticeable factor, too.

The beams reinforced with carbon fibers in the form of textiles feature higher strength. Therefore, a higher force is needed for failure in a bend, and they also feature greater flexures in these points. This fact applies for the beams reinforced with the use of Sikadur 330 epoxy resin and particularly for reinforcement with the carbon textile which is pre-strained to 980 N, with the use of the same adhesive.

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