Determination of Strength Characteristics of Construction Timber Strengthened with Carbon and Glass Fibre Composite Using a Destructive Method

Přemysl Šedivka,* Jan Bomba, Martin Böhm, and Aleš Zeidler

Beams strengthened with a composite material consisting of carbon and glass fibre stabilised with two types of adhesives were evaluated. The primary objective was to determine the technical attributes of joints, the maximum bending strength capacity, deflection, and modulus of elasticity. The reinforcement fibres tested were based on carbon and glass fibre. Epoxy and polyurethane adhesives were used for stabilising the fibres on a spruce timber beam. Composite beams glued in both a prestressed and non-prestressed condition were tested and then compared with non-reinforced control beams. A four-point deflection pursuant to EN 408 (1995) was used in the determination of the strength of the load-bearing construction beams based on composites, consisting of a fibre type, adhesive type, and spruce timber. This approach was applied to define the size of the construction beams and process the measurement results. Reinforcing construction beams with fibres applied in a prestressed condition resulted in an increase in the bending strength capacity by 31.6 to 44.4% compared with a non-reinforced solid timber construction beam. These construction elements, strengthened with carbon and glass fibre composites glued with epoxy and polyurethane adhesives, are suitable for applications that require bending resistance perpendiculary to the glued joint direction.

Keywords: Composite material; Reinforced wood; Carbon fibres; Glass fibres

*Contact information: Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Kamýcká 1176, 165 21 Prague 6 – Suchdol, Czech Republic; *Corresponding author: sedivka@fld.czu.cz*

INTRODUCTION

The changing sociological needs of consumers, increasing demand for the use of renewable structural and building materials, constantly growing aesthetics requirements, and the good mechanical and physical properties of construction timber have recently led to the development of new types of construction elements based on timber that is reinforced with composites (Ferrier *et al.* 2012). According to Fridley (2002), it is important to "develop hybrid systems that capitalise on the economy and flexibility of wood and the unique characteristics of other materials to create economy and efficiency in the final product." To make use of the new types of materials, their properties must be determined to allow for the widest possible application. Solutions for the broader application of timber as a construction material are being developed that aim at reducing the anisotropic nature and imperfections of wood and improving its mechanical properties, especially increasing its strength (Yusof and Saleh 2010; Gaff and Gáborik 2014). In general, wood has a very low level of plasticity. Improper loading results in linear deflection up to the point of damage to the element due to fibres being damaged by fraying or breaking. The element loses its strength capacity at this point. This type of defect in the form of a sudden loss of strength occurs without any preceding warning and for this reason is typically disastrous (Gardner 1989). Research focused on studying and developing techniques for strengthening timber structures has been done, and is ongoing.

Previous research has contributed significantly to encouraging the use of FRP and serves as a reference for future research (Wangaard 1964; Biblis 1965; Spaun 1981; Triantafillou 1997; Gilfillan *et al.* 2001; Gilfillan *et al.* 2003; Borri *et al.* 2005; Dempsey and Scott 2006). Plevris and Triantafillou (1992) tested the rate of absorbed stress in a wooden beam reinforced with a thin carbon slat. They determined that even a very small number of fibres – up to 1% of the cross-sectional area of the FRP joints of the thin carbon slats and wood beams – may be decisive in increasing the strength on the order of 60% initially, and even higher when wood compressive yield occurs. Dolan *et al.* (1997) presented research focusing on prestressed beams of laminated wood. The research demonstrated that both strength and rigidity increase when a small quantity of prestressed Kevlar yarns are used. Gentile *et al.* (2002) undertook a study to determine the flexural behaviour of creosote-treated sawn Douglas fir timber beams strengthened with glass fibre-reinforced polymer (GFRP) bars. The study indicated that the tensile strain and bending strength increased by 64% and 46%, respectively, through the use of GFRP. A project done by Buell and Saadatmanesh (2005) determined whether the application of an FRP composite, in the form of either a fabric or laminate, to timber beams increases the load capacity of a given beam. The results showed that the application of a fibre fabric to the timber beams provides a significant increase in the bending and shear capacity. The bending strength of all the reinforced beams increased by 40 to 53%. Properties of wooden beams reinforced with GFRP slats were studied by Gomez and Svecova (2008). The beams were reinforced for shear and bending. This reinforcement increased the element's rigidity by 5.5 to 52.8%. Another project, carried out by Alam *et al.* (2009), focused on reinforcing a wooden beam using steel and FRP. The results indicated that this reinforcement is highly effective and increases the bending strength. Li *et al.* (2009) reported that the flexural strength in retrofitted wood beams with 1, 2, and 3 layers of CFRP composite sheets increased from 39 to 61%. Ferrier *et al.* (2010) developed an innovative beam composed of glued laminated timber and short fibre-reinforced concrete planks, with and without internal reinforcement consisting of steel and FRP bars. The results showed that a beam reinforced in this way increased the flexural rigidity and final load capacity compared to glued laminated timber of the same dimensions. Li *et al.* (2014) focused on an examination of four-point bending of wood beams strengthened by GFRP sheets. By comparing the bending moments of the reinforced and unreinforced specimen group of beams, the average strength of the GFRP was found to be 4.3% greater than that of the control group of non-reinforced beams. Togay and Ergin (2014) dealt with the determination of the bending resistance and compressive strength of wooden construction elements strengthened with woven wire fibreglass using polyvinyl acetate (PVAc) adhesives. In the wooden beams reinforced with PVAc, the average bending strength tested through four-point bending between laminated beams strengthened with woven wire fibreglass and solid beams increased by 73.0%.

This research focused on defining the bending strength limit in a solid timber beam strengthened with the carbon fibre-reinforced polymer (CFRP) and the glass fibre-reinforced polymer (GFRP). Experiments were conducted with and without prestressing the beam and were compared with a non-strengthened beam (control beam). Moreover, two types of composite adhesives – Epoxy (EP) and Polyurethane (PU) – were tested for each beam. All beams were tested under four-point loading according to EN 408 (1995).

EXPERIMENTAL

Measurement Methodology

The experimental programme consisted of testing nine types of construction elements with two different composites. The first two types were composites made of a combination of spruce wood, the carbon fibre, and the epoxy adhesive (EP). Two other types were composites of spruce wood, the carbon fibre, and the polyurethane adhesive (PUR). The next two types were composites made of a combination of spruce wood, glass fibre, and epoxy adhesive (EP). The last two types of elements were composites of spruce wood, the glass fibre, and the polyurethane adhesive. In each pair of elements, one group was bonded without prestressing, and the other was produced with prestressing. For a comparison of the measurement results, the ninth group was a non-reinforced beam of solid timber of the prescribed quality according to DIN 4074-1 (2012).

The measurement, preparation of test objects, and evaluation of results were made pursuant to the standard EN 408 (1995).

The test specimens were made of spruce wood (*Picea abies*) with a nominal density of (450 ± 50) kg/m^3, classified in quality class S13 (DIN 4074-1, 2012) with regard to the quality of laminated construction timber. Wood imperfections such as rot, insect damage, reaction wood, and dropping or ingrown knots of excessive size were not permissible. The timber was left in an appropriate environment (relative air humidity of 65 ± 5% and temperature of 20 ± 2 °C) for 1 month; the timber moisture content was 12 ± 1% after the stabilisation. The dimensions of the test objects were calculated based on the dimension requirements specified by the standard EN 408 (1995). The dimensions were calculated based on the calculation of critical bending strain, relative slenderness, and coefficients of transverse and torsional stability (Kuklík 2005), with a requirement to provide for deflection of the test object while being loaded. The object dimensions were set to 30 x 66 x 1500 mm, and were machine tooled precisely to these dimensions. The shape of tested objects is shown in Fig. 1.

Before the actual adhesion and application of fibres with high strength, according to the manufacturer's recommendations, the contact surface of the tested beam has always been machined *via* grinding to degree of accuracy 8 (roughness 0.4 μm) (ČSN 49 0231) in order to achieve a mechanically-open surface structure. Furthermore, the surface was cleared of solid dust particles via compressed air, and the surface to be bonded was checked in order to remove potential impurities and grease. Subsequently, the fibres were pre-stressed in preparations with a force of 1000 N in the longitudinal axis of the bonding in order to utilize their high strength when bending (Fig. 1). A fixing adhesive was applied on the contacting surfaces of the beam and the fibres without using a primary coating, which was spread in order to ensure proper penetration of the fibres. After application of the fibres on the surface of the beam, polyethylene (PE) foil was applied as the top layer. Preparations were then applied for pressing the surface of the beam. The samples were subsequently air-conditioned for 7 days at +20 °C ± 2 °C and 65 ± 5% relative humidity, up to the absolute hardening of the adhesive. After this phase the composite was relieved and the samples were prepared for laboratory testing.

The test objects were prestressed with a force of 1000 N, and a type of adhesive was applied to the bottom surface, thus applying the carbon fibre fabric. The specimens were then left in an air-conditioned environment for 7 days and then made ready for the bending strength testing. The main objective was to determine whether the adhesives used are suitable for bonding wood/carbon fibre and wood/glass fibre composites while conforming to strength requirements.

Fig. 1. Method of pre-stressing timber beams

Table 1. Properties of Tested Adhesives (Technical Data Sheets)

Adhesive	**Epoxy***	**Polyurethane***
Type	Epoxy (EP)	Polyurethane (PUR)
Bond quality	D4	D4
Application quantity [kg/m^2]	0.70 – 1.20	1.50 – 2.20
Minimal processing temperature [°C]	+ 10	+ 15
Open time [min]	0 – 90	0 – 90
Time to harden [days]	5	1
Minimal wood moisture [%]	4	8
Pressure [MPa]	0.30	0.6 – 0.8
Density [g/cm^3]	1.31	1.10
Elastic Modulus (after 7 day and temperature 23 °C) [MPa]	3 800	–

* The trade names of the adhesives are replaced with their constituents.

Table 2. Properties of Tested Carbon and Glass Fibres (Technical Data Sheets)

Fibre	Carbon fibre**	Glass fibre**
Type of the Fibre Matrix	Carbon (CF)	Glass (GF)
Density [g.cm^{-3}]	1.81	2.56
Elastic Modulus [GPa]	242	76
Tensile Strength [GPa]	3.80	3.40
Specific Tensile Strength [kN.m.kg^{-1}]	2 400	1 300
Elongation at Break [%]	max. 0.60	max. 0.60

** The trade names of the fibres are replaced with their constituents.

Test principle

The bottom surface of each construction timber beam with a rectified surface and set dimensions was reinforced by applying the given type of adhesive and fabric to produce a compact composite. One specimen from each group of objects was prestressed by force. The test objects were then left in an air-conditioned environment for 7 days and then made ready for bending strength testing. The four-point bending test defined by EN 408 (1995) was employed to determine the modulus of elasticity.

Test device

The test device used was a testing machine UTS Testsysteme 50 kN with sensors for deflection measurement ESDA (type SM50.61-5,0-0) with a constant feed rate described in ISO 5893 (2002).

Number of test objects

The total number of 108 test objects were divided into nine groups. Each group contained 12 test objects, with a sufficient number of test specimens to permit the achievement of at least 10 valid readings for each measurement type. The samples that did not perform the standards EN 408 (1995) demands were excluded from the evaluation as invalid readings.

Bending resistance

The test method was four-point bending and the modulus of elasticity testing was done according to standard EN 408 (1995). The force was applied from two symmetric points around the centre of the object being measured, perpendicular to the longitudinal axis of the object and perpendicular to the glue line (Fig. 2). This method provided a break opportunity for the weakest part between the points having the acting force without forming shearing tension between the points. The capacity range of the testing machine was 0 to 5000 kN, and the load rate of the shearing machine was set to 0.18 mm/sec and remained constant (EN 408 (1995)). The load was applied symmetrically such that the greatest load with two-point loading was achieved between 3 and 7 min. The measurements performed using the measuring device were done in such a way that the load exerted on the specimens could be measured with an accuracy of 1%.

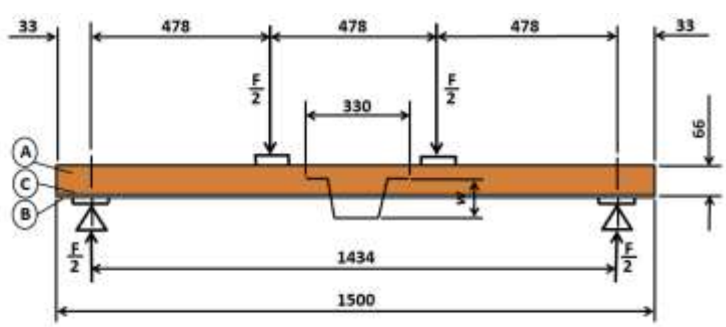

Fig. 2. Test layout for measuring local modulus of bending elasticity pursuant to EN 408 (1995) Annotation: A – Beam; B – Carbon or Glass Fibres; C – Glued Joint

Expression of results

The modulus of elasticity of the composite test construction element (E) is expressed in MPa and calculated according Eq. 1.

$$E = \frac{a \,.\, l_1^2 \, (F_2 - F_1)}{16 \,.\, I \, (w_2 - w_1)} \tag{1}$$

where $(F_2 - F_1)$ is the load increment in Newtons (N) on a regression straight line with a coefficient of correlation of 0.99 or better; $(w_2 - w_1)$ is the deformation increment in millimetres (mm) corresponding to $(F_2 - F_1)$; a is the width of the composite test construction element in millimetres (mm); l_1 is the distance at the centre of the measurement base, equalling five times the cross-sectional height h of the composite test construction element in millimetres (mm); and l is the distance between the two supports of the composite test construction element in millimetres (mm) (EN 408 (1995)).

RESULTS AND DISCUSSION

The measurements are characterised by values of maximum bending strength (Fig. 3), maximum deflection (Fig. 4), and modulus of elasticity (Fig. 5) while achieving the maximum bending strength of the composite element. The measured values are specified in Tables 3 and 4.

Table 3. Overview of Measured Values for Epoxy adhesive (EP)

Type of Beam	Non-reinforced control	CFRP	GFRP	CFRP+	GFRP+
F [MPa]	6059.40	7201.04	6717.20	9796.42	8993.52
Max. [MPa]	7001.74	8221.85	7622.66	10233.47	9420.88
Min. [MPa]	5122.77	6563.52	6152.67	9215.55	8322.04
SD	586.89	488.08	532.06	348.12	398.52
v [%]	9.69	6.78	7.92	3.55	4.43
w [mm]	34.75	40.88	40.29	40.05	39.67
Max. [mm]	48.42	43,55	42,13	42,97	41,11
Min. [mm]	23.78	39,32	38,52	38,03	37,45
SD	8.86	1.41	1.11	1.57	1.24
v [%]	25.48	3.45	2.76	3.92	3.12
E [MPa]	14878.60	16734.33	16192.28	21291.28	19605.99
Max. [MPa]	20721.67	21580.61	27550.29	26267.56	25383.09
Min. [MPa]	9955.05	13124.69	9620.56	17557.28	17003.62
SD	3600.05	3100.41	5960.69	2790.63	2760.83
v [%]	24.20	18.53	23.82	13.11	14.18

Annotation: CFRP – carbon fibre-reinforced polymer; GFRP – glass fibre-reinforced polymer; F – average value of strength; w – average value of deflection; E – average value of modulus of elasticity; Max. – maximum measured value; Min. – minimum measured value; SD – standard deviation; v – coefficient of variation; + nomenclature – preloaded elements

Table 4. Overview of Measured Values for Polyurethane adhesive (PUR)

Type of Beam	Non-reinforced control	CFRP	GFRP	CFRP+	GFRP+
F [MPa]	6059.40	7781.41	6888.78	8865.32	8777.98
Max. [MPa]	7001.74	8354.52	8511.79	10332.21	10110.78
Min. [MPa]	5122.77	6989.84	5715.12	7111.67	7222.23
SD	586.89	393.08	908.82	1252.64	933.07
v [%]	11.69	5.15	13.19	9.13	10.63
w [mm]	34.75	47.41	45.34	36.42	34.75
Max. [mm]	48.42	61.48	59.14	47.78	48.42
Min. [mm]	23.78	36.84	37.35	26.88	23.78
SD	8.86	8.19	8.23	6.70	8.86
v [%]	25.49	17.27	18.15	18.39	25.48
E [MPa]	14878.60	17470.73	17991.78	18982.53	18672.01
Max. [MPa]	20721.67	23975.56	24299.96	27683.60	23307.97
Min. [MPa]	9955.05	11180.54	11212.59	13349.12	13305.10
SD	3600.05	4332.15	4432.65	4737.87	4004.54
v [%]	24.20	23.80	22.64	21.96	21.45

Annotation: CFRP – carbon fibre-reinforced polymer; GFRP – glass fibre-reinforced polymer; F – average value of strength; w – average value of deflection; E – average value of modulus of elasticity; Max. – maximum measured value; Min. – minimum measured value; SD – standard deviation; v – coefficient of variation; + nomenclature – preloaded elements

The results were evaluated at a significance level of α = 95% using an analysis of variance (ANOVA), and the difference of individual groups was determined using a post-hoc test (Tukey HSD test). The results of the analysis of variance are shown in Figs. 3, 4, and 5.

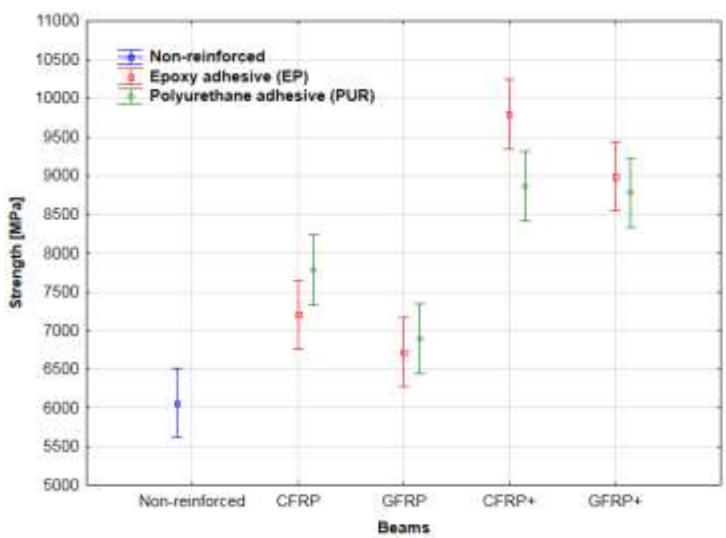

Fig. 3. Bending strength according to beam type

The highest bending strength was achieved in the prestressed wood beams strengthened with the carbon fibre composite CFRP+ glued with epoxy adhesive, in which the average bending strength tested by four-point bending increased by 31.6 to 44.4% (3231 to 4093 MPa) ($p = 0.000132$) compared to the non-reinforced control beams. This matches the results of Buell and Saadatmanesh (2005), who determined that timber beams reinforced with carbon fibre composites showed a significant 46% increase in the average bending strength.

In the prestressed wood beams strengthened with the glass fibre composite GFRP+ glued with Epoxy adhesive, the average bending strength tested by four-point bending increased by 25.7 to 38.4% (2419 to 3199 MPa) ($p = 0.008058$) compared to the non-reinforced control beams. Gentile *et al.* (2002) indicated that the bending strength of sawn Douglas fir timber beams strengthened with glass fibre-reinforced polymer (GFRP) increased by 28%.

The bending strength capacity of the prestressed and non-prestressed beams reinforced with the carbon fibre composites CFRP and CFRP+ glued with epoxy adhesive increased by 26.5% (2595 MPa) on average; CFRP and CFRP+ glued with polyurethane adhesive increased by 12.2% (1084 MPa).

The bending strength capacity of the prestressed and non-prestressed beams reinforced with the glass fibre composites GFRP and GFRP+ glued with epoxy adhesive increased by 25.3% (2276 MPa) on average; GFRP and GFRP+ glued with polyurethane adhesive increased by 21.5% (1889 MPa).

The standard deviations for the values of the bending strength in the beams strengthened with the fibre composites GFRP, CFRP+, and GFRP+ glued with the polyurethane adhesive were higher than those for the beams glued with epoxy adhesive (Tables 3 and 4). The reason for this is that the epoxy adhesive is stiffer than the polyurethane adhesive, resulting from its chemical composition and content of softeners (Eisner *et al.* 1983).

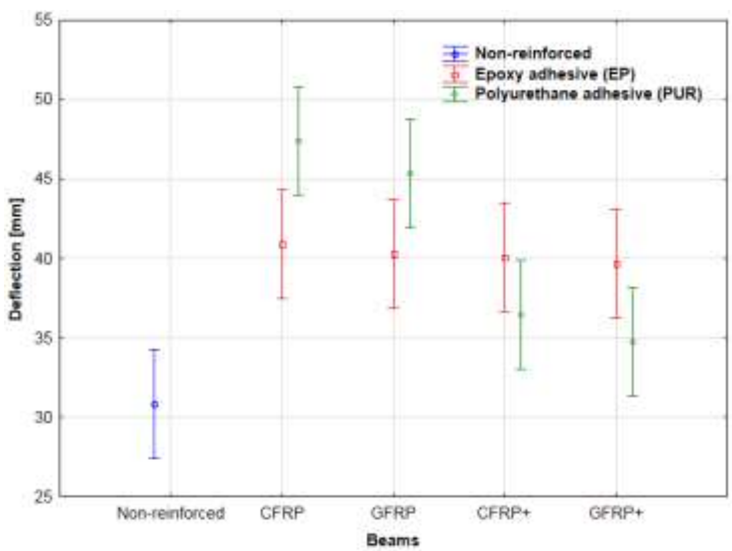

Fig. 4. Size of deflection according to beam type

The gross deflection values were always lower for the prestressed beams than for the non-prestressed ones (Fig. 4). The values of gross deflection for the beams reinforced with composites glued with epoxy adhesive did not have a statistically significant difference between all 4 types of composites (Tables 3 and 4). A statistically significant difference in the deflection values was shown for the beams reinforced with the CFRP and GFRP using polyurethane adhesive, both non-prestressed and prestressed.

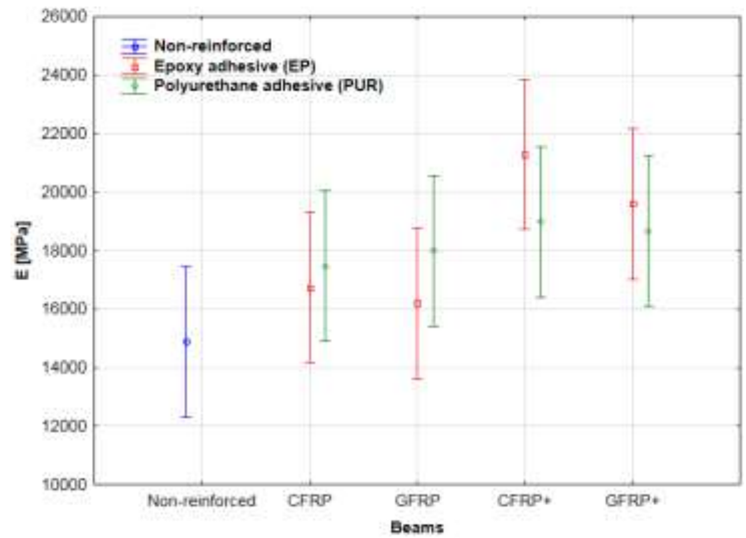

Fig. 5. Modulus of elasticity according to beam type

The highest modulus of elasticity was achieved in the wood beams strengthened with the carbon fibre composite CFRP+ glued with epoxy adhesive in a prestressed condition. The reason for this is the relatively higher elasticity of the epoxy adhesive used with the composites (Eisner *et al.* 1983). The values modulus of elasticity for the beams reinforced with composites glued with polyurethane adhesive did not have a statistically significant difference between all 4 types of composites (Tables 3 and 4). The variation coefficients for all the prestressed and non-prestressed beams reinforced with the carbon and glass fibre composites were lower than those for the non-reinforced control beams. The reason here is the lower spread of values due to the beam reinforcement.

Failures at knots in the tension-side occurred in the reinforced and non-reinforced beams, which almost destroyed the whole cross section. The beams reinforced with carbon (CFRP) and glass (GFRP) composites showed good stiffness increase. The failures were initiated at a knots in wood out from the matrix. There was debonding of 11 reinforced beams observed during the tests that were excluded from the measurement. In other tests there was no sign of de-lamination in the glue line. The adhesive transferred the load to the reinforcement. The strain distribution across the cross section was linear in most cases and the neutral axis remains only moves slightly as the load increases, in spite of compressive plastification.

CONCLUSIONS

1. Beams reinforced with a carbon composite showed higher strength, higher modulus of elasticity, and lower deflection than beams reinforced with a glass fibre composite.

For all reinforced and non-reinforced beams, failures were initiated at knots in the tension-side. Eleven of the reinforced beams were observed to have delaminated during the tests. These samples were excluded from the measurement. In the majority of specimens, there was no sign of delamination in the glue line. The adhesive acted well in transferring the load to the reinforcement.

2. All the reinforced beams glued in a prestressed condition showed a higher bending strength than the non-prestressed beams, namely by 31.6 to 44.4% compared to the non-reinforced control beams.
3. Beams reinforced with composites in a non-prestressed and prestressed condition showed statistically significant differences in strength. The measurement values did not show statistically significant differences between the strength of composites using the epoxy and polyurethane types of adhesives.
4. The values of deflection for beams reinforced with composites glued with the epoxy adhesive in both a non-prestressed and prestressed condition did not show a statistically significant difference. The reason for the relative constant value of deflection for beams reinforced with glass and carbon composites glued with epoxy adhesive (Fig. 4) is that the epoxy adhesive was stiffer than polyurethane, and the joints achieved lower values of deflection.
5. By the reinforcement of beams with composites, the variability of strength was reduced in comparison to unreinforced beams. The reason could be the elimination of defects by wood reinforced by composites, leading to improvement of mechanical and physical properties and enhancement of stiffness of composites. But the reduction of wood defects (cracks, knots, radial wood, *etc*.) was not a main topic of the research, and this finding was not conclusive.

ACKNOWLEDGMENTS

The authors are grateful for the support of the Internal Grant Agency of Faculty of Forestry and Wood Sciences, CULS, Project No. 20134353 Estimation of time dependence by increase strength bonded joints.

REFERENCES CITED

Alam, P., Ansell, M. P., and Smedley, D. (2009). "Mechanical repair of timber beams fractured in flexure using bonded-in reinforcements," *Journal of Composites:* Part B. 40, 95-106. DOI: 10.1016/j.compositesb.2008.11.010

Biblis, E. J. (1965). "Analysis of wood–fiberglass composite beams within and beyond the elastic region," *Forest Products Journal* 15(2), 81-88. DOI: 10.3968/j.ans.1715787020110402.137

Borri, A., Corradi, M., and Grazini A. (2005). "A method for flexural reinforcement of old wood beams with CFRP materials," *Composites Part B: Engineering* 36, 143-153. DOI: 10.1016/j.compositesb.2004.04.013

Buell, T. W., and Saadatmanesh, H. (2005). "Strengthening timber bridge beams using carbon fibre," *Journal of Structural Engineering* 131(1), 173-187. DOI: 10.1061/(ASCE)0733-9445(2005)131:1(173)

ČSN 49 0231. (1993). "Allowance for machining of sawn timber and dimensions timber. Surface roughness of wooden and wood-based products," Federal Office for Standardisation and Measurement, Czech Repulic, 1-8

EN 408. (1995). "Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties," British Standard Institution, Chiswick High Road, London, United Kingdom, 1-18.

DIN 4074-1. (2012). "Strength grading of wood - Part 1: Coniferous sawn," Deutsches Institut für Normung E. V., Berlin, Germany, 1-23.

Dempsey, D. D., and Scott, D. W. (2006). "Wood members strengthened with mechanically fastened FRP strips," *Journal of Composites for Construction* 10(5), 392-398. DOI: 10.1061/(ASCE)1090-0268(2006)10:5(392)

Dolan, C. W., Galloway, T. L., and Tsunemori, A. (1997). "Prestressed glued-laminated timber beam – Pilot study," *Journal of Composites for Construction* 1, 1-38. DOI: 10.1061/(ASCE)1090-0268(1997)1:1(10)

Eisner, K., Havlíček, V., and Osten, M. (1983). *Dřevo a Plasty*, SNTL-Nakladatelství Technické Literatury, Praha.

Ferrier, E., Labossiere, P., and Neale, K. W. (2010). "Mechanical behavior of an inovative hybrid beam made of glulam and ultrahigh-performance concrete reinforced with FRP or steel," *Journal of Composites for Construction* 14, 217-223. DOI: 10.1061/(ASCE)CC.1943-5614.0000063

Ferrier, E., Labossière, P., and Neale, K. V. (2012). "Modelling the bending behaviour of a new hybrid glulam beam reinforced with FRP and ultra-high-performance concrete," *Applied Mathematical Modelling* 36, 3883-3902. DOI: 10.1016/j.apm.2011.11.062

Fridley, K. J. (2002). "Wood and wood-based materials: Current status and future of a structural material," *Journal of Materials in Civil Engineering* 14, 531-539. DOI: 10.1061/(ASCE)0899-1561(2002)14:2(91)

Gaff, M., and Gáborik, J. (2014). "Effect of cycling loading on the elasticity of beech solid and laminated wood," *BioResources* 9(3), 4288-4296. DOI: 10.15376/biores.9.3.4288-4296

Gardner, G. P. (1989). "A reinforced glued laminated timber system," 2nd Pacific Timber Engineering Conference (2).

Gentile, C., Svecova, D., and Rizkalla, S. H. (2002). "Timber beams strengthened with GFRP bars: development and application," *Journal of Composites for Construction* 6(1), 11-20. DOI: 10.1061/(ASCE)1090-0268(2002)6:1(11)

Gilfillan, J. R., Gilbert, S. G., and Russell, D. P. (2001). "Enhancement of the structural performance of home-grown Sitka spruce using carbon fibre reinforced polymer," *Journal of Structural Engineering* 79(8), 23-28.

Gilfillan, J. R., Gilbert, S. G., and Patrick, G. R. H. (2003). "The use of FRP composites in enhancing the structural behavior of timber beams," *Journal of Reinforced Plastics and Composites* 22(15), 1373-1388. DOI: 10.1177/073168403035583

Gomez, S., and Svecova, D. (2008). "Behavior of split timber stringers reinforced with external GFRP sheets," *Journal of Composites for Construction* 12, 202-211. DOI: 10.1061/(ASCE)1090-0268(2008)12:2(202)

ISO 5893:2002. (2002). "Rubber and plastics test equipment – Tensile, flexural and compression types (constant rate of traverse) – Specification," International Organization for Standardization, Geneva, Switzerland, 1-14.
Kuklík, P. (2005). *Dřevěné Konstrukce*, ČVUT v Praze, Praha.
Li, Y. -F., Tsai M. -J., Wei, T. F., and Wang, W. -Ch. (2014). "A study on wood beams strengthened by FRP composite materials," *Construction and Building Materials* 62, 118-125. DOI: 10.1016/j.conbuildmat.2014.03.036
Li, Y. -F., Xiao, Y. M., and Tsai, M. J. (2009). "Enhancement of the flexural performance of retrofitted wood beams using CFRP composite sheets," *Construction and Building Materials* 23(1), 411-422. DOI: 10.1016/j.conbuildmat.2007.11.005
Plevris, N., and Triantafillou, T. (1992). "FRP-reinforced wood as structural material," *Journal of Materials in Civil Engineering* 4(3), 300-317. DOI: 10.1061/(ASCE)0899-1561(1992)4:3(300)
Purbond HB 110 (2006). *Technical Data Sheets*, Purbond AG.
Sikadur 330 (2006). *Technical Data Sheets*, Sika CZ s.r.o.
SikaWrap-430G/25. *Technical Data Sheets*, Sika CZ s.r.o.
SikaWrap-450C/90. *Technical Data Sheets*, Sika CZ s.r.o.
Spaun, F. D. (1981). "Reinforcement of wood with fiberglass," *Forest Products Journal* 31(4), 26-33.
Togay, A., and Ergin, E. (2014)."Determination of some physical attributes for wooden construction elements strengthened with woven wire fibreglass," *BioResources* 9(3), 3883-3900. DOI: 10.15376/biores.9.3.3883-3900
Wangaard, F. F. (1964). "Elastic deflection of wood–fiberglass composite beams," *Forest Products Journal* 14(6), 256-260. DOI: 10.1016/j.conbuildmat.2014.03.036
Yusof, A., and Saleh, A. L. (2010). "Flexural strengthening of timber beams using glass fibre reinforced polymer," *Electronic Journal of Structural Engineering* 10, 45-56. DOI: 10.1061/(ASCE)1090-0268(2002)6:1(11)

Article submitted: September 15, 2014; Peer review completed: November 29, 2015; Revised version received and accepted: May 29, 2015; Published: June 11, 2015.
DOI: 10.15376/biores.10.3.4674-4685