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Local reinforcement of timber beams using D-shape CFRP strip

Izabela Burawska[1,2], Amir Hossein Mohammadi[2,3], Robert Widmann[2], and Masoud Motavalli[2,3]

[1] Faculty of Wood Technology, Warsaw University of Life Sciences-SGGW, Warsaw, Poland
[2] Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland
[3] School of Civil Engineering, University of Tehran, Tehran, Iran

ABSTRACT: Carbon fibre reinforced polymer strip (CFRP) is an effective material for the strengthening of structural members and therefore often used in practice. Such systems (surface or near-surface mounted CFRP strips) can be further optimised by shaping the reinforcement material as well as by reducing its length. These solutions could be particularly advantageous in the case of strengthening timber which is defected by knots.

In this paper an innovative method of reinforcing timber structural elements is being discussed. The low quality of timber beams as a result of e.g. the presence of large knots can be upgraded by introduction of a D-shaped CFRP strip of a distinct length into the tension zone of the beam. The effectiveness of the reinforcement technique was evaluated by bending tests in accordance with the EN-408 (2012) standard on timber structures.

Described reinforcement system was optimized by development of a numerical model, which incorporates orthotropic material modelling to predict the load – deflection behaviour, stiffness and strain distribution of reinforced beam.

1 INTRODUCTION

The limited amount of high-quality raw material, virtual trend to protect the forests, need to keep low production costs, demand an efficient utilization of wood in structural applications. In this context, the reinforcement of timber beams using CFRP strip (Carbon Fibre Reinforced Polymer) has been gaining a great interest.

Application of FRP materials reduces the need of the use of high grade wood and may limit its volume in timber structures [Brol 2005]. Moreover, reinforced beams are characterized by lower variability of mechanical properties [Borri et al. 2005, Issa et al. 2005]. Despite the great benefits of using CFRP strip, its application is limited due to economic reasons. It is related to quite high price of CFRP strip running meter, in spite of rapid development of materials science.

Structural defects of wood are known of having negative impact on its material properties. The most common wood defect of timber are knots. Their adverse effect is manifested mainly by lowered bending strength, tensile strength and compression strength. Studies of Baňo et al. (2011) and Burawska et al. (2011) show that the knot situated in the tension zone of bent beam can be simulated by a simple hole. Laboratory tests and analytical investigations have shown that the disturbances in uniform stress field around the knot have only local effect. That is why it is not economical justified to apply the reinforcement to the entire length of the strengthened beam.

The objective of this study was to investigate the possibility of compensation the knot influence through the introduction of reinforcement material, in term of elastic properties and bending strength. Innovative method of local strengthening was developed, which aimed at lower material costs while maintaining high reinforcement efficiency. Further evaluation of these technique was performed by Mohammadi et al. (2015).

2 EXPERIMENTAL DETAILS

2.1 *Materials*

The test materials were spruce beams of technical size (50 mm x 100 mm of section and 2000 mm of length). The density of test samples averaged 417 $kg/m^3 \pm 14 kg/m^3$, with 13.8%±0,5% moisture content. The total number of 20 beams were subjected to the study.

The reinforcement material was CFRP strip (CFRP S&P Lamelle CFK 150/2000). The CFRP was selected as a reinforcement because of its high strength parameters (Table 1), easy availability and widespread use in the building industry.

Table 1. Properties of CFRP strip - data obtained from the manufacturer

Property	CFRP strip
Density (kg/m^3)	1500
Young’s modulus (N/mm^2)	>165
Tensile strength (N/mm^2)	>2800

2.2 *Methods*

All beams, before being reinforced, were tested in elastic range in four point bending according to the EN 408 (2012) standard (Figures 1, 2). During the testing procedure, force and displacement values were recorded. It enables to determine the elastic properties of timber beams and to use the bending stiffness as a characterization of its initial quality. The experimental program assumed testing in bending of 20 solid wood samples.

Then the samples were divided evenly into four groups- weakened with a borehole 20 mm in diameter (group A), 30 mm (group B), 40 mm (group C) and 50 mm (group D), simulating a centric knot in aim to investigate the effect of size of knots in timber beams. The hole of 20mm in diameter constituted 20% weakening of cross section height, 30 mm, 40 mm and 50 mm – 30%, 40% and 50% respectively. The borehole was placed in the middle of the beam’s span, in the tensile zone. Additionally, the borehole was situated in such way that below it there was no layer of wood (Figure 3). Then beams were subjected to bending tests in the elastic range. Based on obtained data, bending stiffness of weakened samples was determined. Then the weakening of beams group A, B and C was increased by broaching the holes until the 50 mm in diameter.

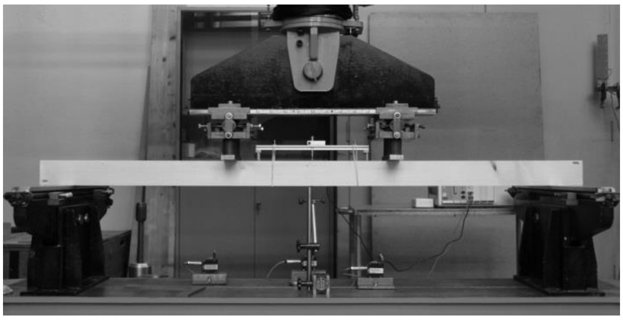

Figure 1. Four point bending test set up

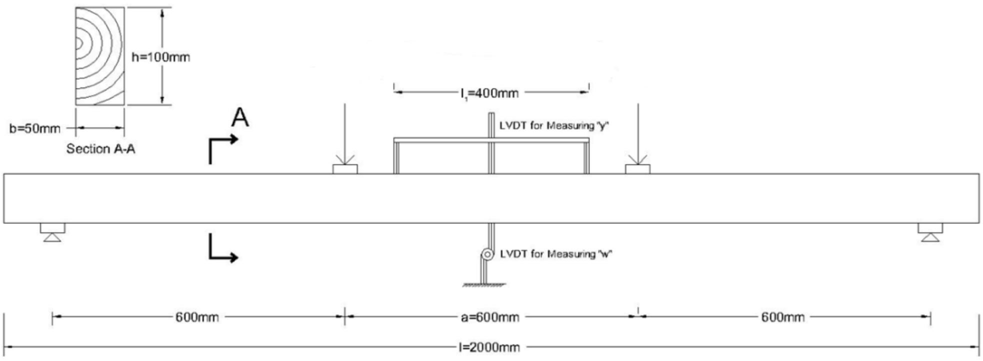

Figure 2. Loading and measuring system in four point bending

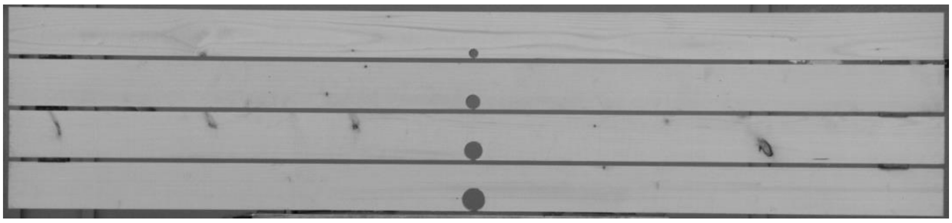

Figure 3. Position and size of borehole simulating knot

The last and crucial stage of the testing program was the local reinforcement of samples weakened with 50 mm in diameter bores. The new, innovative reinforcement technique was developed, consisting in streamlining the shape of reinforcement in aim to avoid the stress concentration as a result of notches (Figure 4). Strengthening method involves inserting the D-shape CFRP strip into the previously made using hand held circular saw disc grooves. After that the CFRP strip is bonded with the wooden cross section using two component epoxy adhesive. After seasoning, samples were tested again in four point bending, until destruction. Tests were conducted displacement control with a speed rate equals 3.0 mm/min. During testing, force and displacement values were recorded. Based on the obtained data, the bending stiffness and strength were calculated, assuming the hypothesis of a uniform equivalent spruce beam.

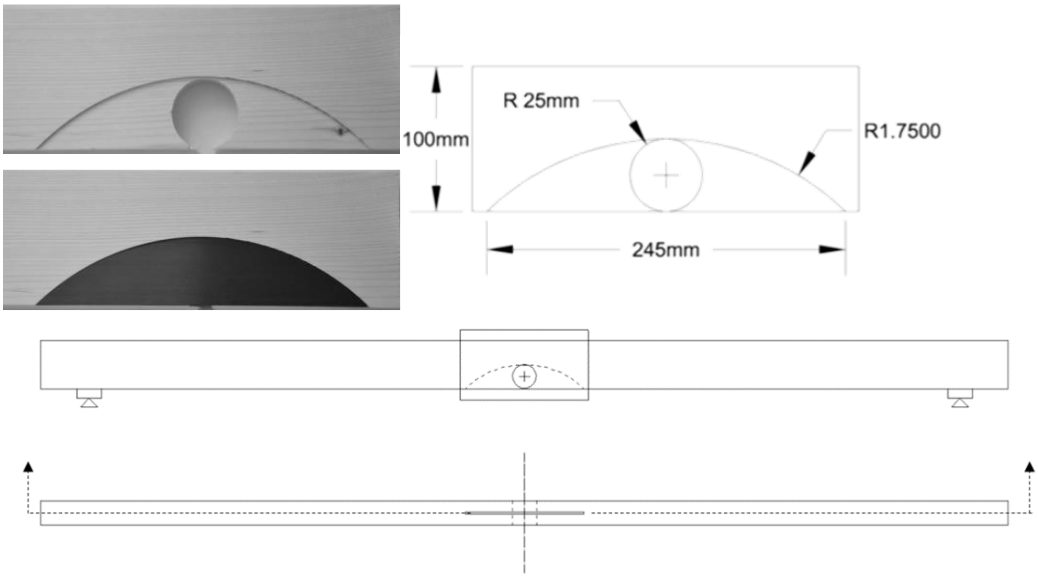

Figure 4. Four point bending test arrangement, strengthening method of tested beams

3 RESULTS AND DISCUSSION

Figure 5 presents reduction in bending stiffness for groups A, B, C and D, weakened with bores of 20 mm, 30 mm, 40 mm and 50 mm diameter. It is noticeable that the reduction in bending stiffness is not proportionally dependent on the weakening percentage of the cross section. With increasing ratio of knot diameter to height of the beam, decrease in flexural stiffness is getting smaller. Figure 6 shows the average value of bending stiffness in dependence on the type of tested beam (control, weakened, reinforced). The borehole of 50 mm diameter caused 83% drop of bending stiffness. Local reinforcement in form of D-shape CFRP strip, with the length covering only around 12% of the total beams length, significantly increased the bending stiffness five times in comparison to the weakened samples. The possibility to increase the bending stiffness by application of reinforcement material of limited length is related to specific parameters of CFRP (over 16-times higher value of Young's modulus in comparison to spruce wood).

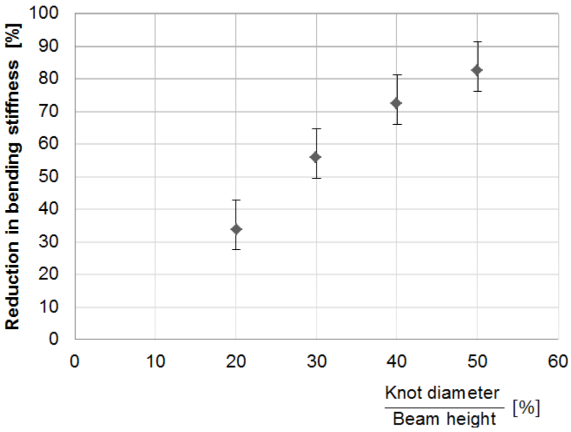

Figure 5. Reduction in bending stiffness depending on the ratio of knot diameter to height of the beam

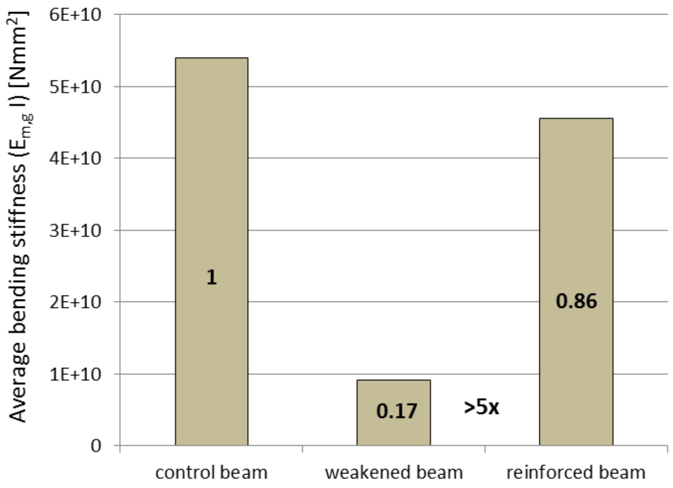

Figure 6. Average bending stiffness values obtained during testing

Strengthening effectiveness was characterized as well by the bending strength of reinforced beams. For assessing the reinforcement technic it was possible to refer to the predetermined stiffness parameters of control beams and to standard C24 grade spruce beams (parameters taken from EN 338:2011). Figure 7 presents the dependence of ratios between bending stiffness/bending stiffness of sound beam and bending strength/bending strength of C24. As can be seen on the mentioned figure, stiffness of the beams does not depend on the forthcoming (consequent) crack propagation, strength of the beams however, shows greater dependence. During testing, two main types of failure modes were observed (figure 8). Type A corresponds to perfect and partial failure in timber's fibers, whereas type B refers to failure in timber and glue interaction or in glue and CFRP interaction. It can be observed a direct relation between the types of failure mode and bending strength of reinforced beams, in contrast to the bending stiffness which does not show this tendency. High values of bending strength were obtained, when the type A of failure occurred.

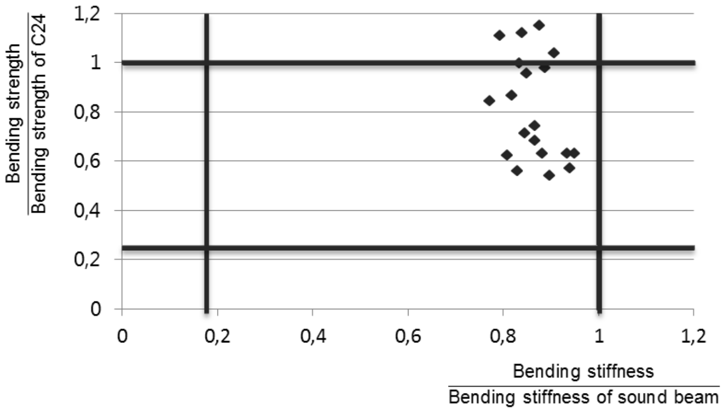

Figure 7. Dependence between bending stiffness and bending strength regarding to sound beam

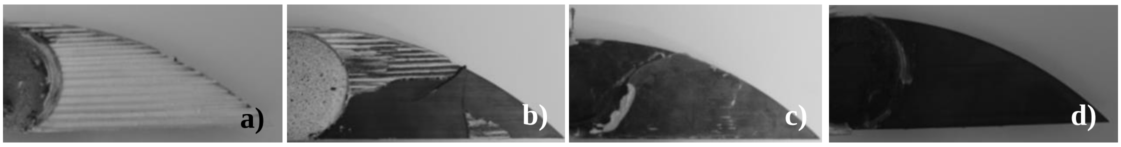

Figure 8. Types of failure modes observed during testing; Type A: failure in wood (a), partial failure in wood (b), Type B: failure in timber and glue interaction (c), failure in glue and CFRP interaction (d)

In most of the samples the failure occurs as follows:

a) A combined shear and tension crack through the interface of glue and FRP in one side of the beam,

b) A shear failure in timber in another side of the beam,

c) Horizontal crack perpendicular to timber fibers.

4 NUMERICAL ANALYSIS

A three dimensional (3D) numerical simulation of the four point bending test of an actual timber beam was developed using a commercial software ABAQUS (Figure 9). The geometry of spruce beam was created by 8-node elements (C3D8R), while CFRP strip by a shell element (S8R) from the ABAQUS library. In the computations the symmetry of the beams was taken into account in order to reduce the number of finite elements. The removed parts were replaced with a lock of an adequate displacement and angles of rotation. During testing no noticeable plasticity has been seen until failure, thus no plasticity rules were accounted for in the analytical study. As a failure criteria a simple rule was adopted from the experimental study (1). The strain in the CFRP strip reaches higher values than the maximum strain causing the crack propagation and finally the failure of reinforced element.

$$\varepsilon_{CFRP} \geq \varepsilon_{max} \quad (1)$$

Where:

ε_{CFRP} – Strain in the CFRP strip [‰],

ε_{max} – Maximum strain in the reinforced beam [‰].

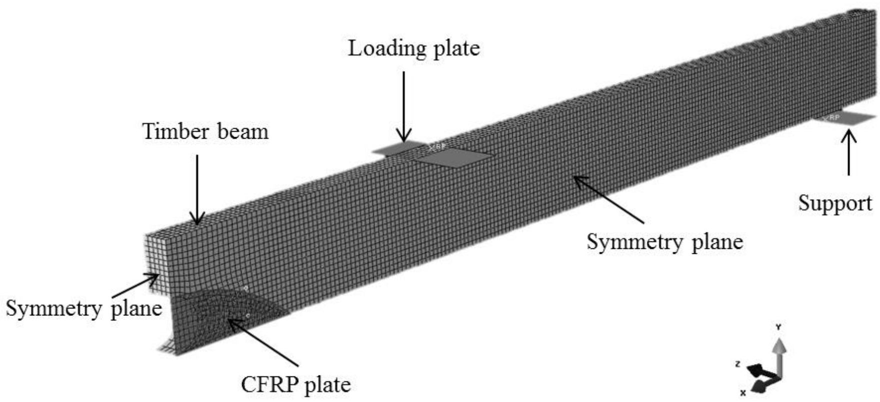

Figure 9. FEM model of reinforced beam

The timber beam was modelled as an orthotropic material. Its mechanical parameters used in the simulations are presented in table 2. The Young's modulus in x direction is adopted from the experiments. Other values of modules are based on the relations given in the literature [Bodig et al. 1982]. The values of Poisson's coefficients were adopted from the literature as well [Kollmann i Cote 1968]. The CFRP was modeled as an isotropic material, with the mechanical parameters as shown in table 3.

Table 2. Properties of spruce beams

E_x	E_y	E_z	μ_{xy}	μ_{xz}	μ_{yz}	G_{xy}	G_{xz}	G_{yz}
N/mm^2	N/mm^2	N/mm^2	-	-	-	N/mm^2	N/mm^2	N/mm^2
12600	1010	630	0.37	0.47	0.25	900	846	90

Table 3. Properties of CFRP strip

E	μ_{xy}
N/mm^2	-
165000	0.3

Simultaneously with the FEM analysis, the strain distribution through the height of the cross section was determined analytically (Figure 10) according to the gamma method (EN 1995-1-1:2004). Strain was calculated based on the formula (2), using mechanical parameters related to the actual beam.

$$\varepsilon = \frac{M \cdot z}{EI} \tag{2}$$

Where:

ε – Strain [‰],

M – Bending moment [Nmm],

z – Distance from the neutral axis of the section to the point for which the stain is calculated [mm],

EI – Bending stiffness [Nmm^2].

A finite element model showed the strain distribution through the height of the beam, assuming the elastic behaviour of the material. It also presented the upward shift of the neutral axis as the compressed part of the beam becomes less plastic.

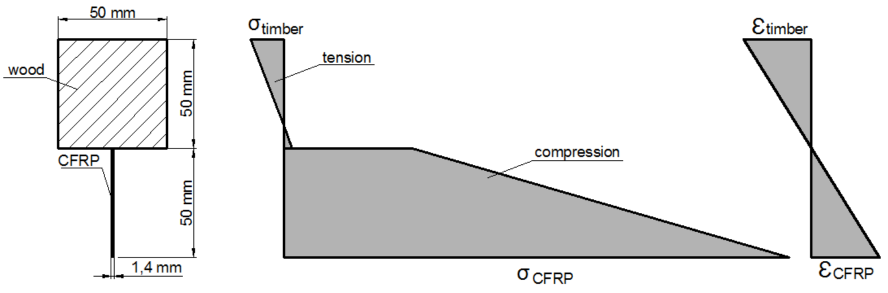

Figure 10. Stress and strain distribution through the height of the beam

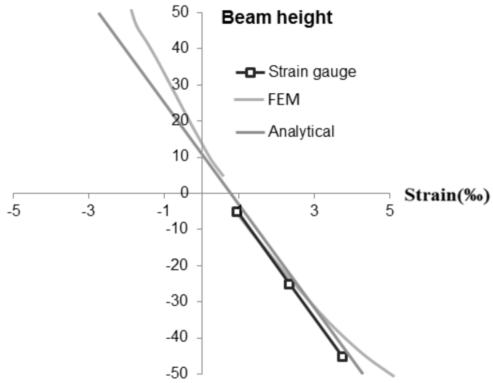

Figure 11. Strain distribution obtained by analytical calculations, FEM analysis and experimentally, load 6.88 kN

5 CONCLUSIONS

Reduction in bending stiffness due to presence of defects is not proportionally dependent on the weakening percentage of the cross section. Increasing ratio of knot diameter to the height of the beam cause smaller decrease in flexural stiffness.

Application of local reinforcement in form of D-shaped CFRP strip caused significant increase in stiffness and bending strength of timber beams. The reinforcement efficiency is directly related to the type of failure under destructive force. If timber failure (Type A) is guaranteed in the beam, the D-shape local reinforcement method is a sufficient option for reinforcing a defected beam. Improper failure modes (Type B) need to be studied more in detail. Studying the strength of interface between the glue and FRP should help to understand the problem more deeply.

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