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Research Paper

Weakened Zones in Wood – Based Composite Beams and Their Strengthening by CFRP: Experimental, Theoretical, and Numerical Analysis

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This paper looks at the mechanical behaviour of wood-based beams. Laboratory tests of an I-beam show a considerable decrease of capacity in the weakened zones, e.g., at the connection between two pieces of pine wood used as a flange. We propose strengthening of the zones using fibre composite tapes based on CFRP. This article demonstrates the way for protection of the I-beam with defects in the bottom flange against the loss of load-carrying capacity. The required anchor length is determined by an analytical method formulated in the paper. The numerical results are presented. The full adhesion between CRFP and wood is assumed in the numerical simulations.

Key words: wood-based composite beam; strengthening; CFRP; FEM; laboratory tests.

1. Introduction

This paper concerns the analysis of deflections and stresses in I-beams made with wood and wood-based materials reinforced by carbon fibre reinforced polymer (CFRP) [5, 11]. The laboratory tests of I-beam show a considerable decrease of capacity in the weakened zones such as at the connection between two pieces of pine wood used as a flange. We propose strengthening of these areas by using fibre composite tapes based on CFRP.

The different approaches to reinforce wood beams can be found in the literature, and the most popular is strengthening along the entire beam, but the segmental strengthening is also proposed by some researchers [1, 6, 7, 10]. The partial reinforcement efficiently increases the bearing capacity and limits the influence of defects (e.g., loose knots, connectors, finger-joints, cracks) as well as usually leads to the decrease of costs in comparison to continuous reinforcement (e.g. in the tensile or shear zone). The possibility of the finger-joints strengthening with short CFRP segments was analysed and presented in [8]. The choice of strengthening material and glue as well as the estimation of anchor length are the fundamental tasks in such approach.

The considered I-beams very often have the finger-joints in the flanges, and also in the bottom tensile flange zone. This is especially dangerous for the structure and decreases its load-carrying capacity. We have observed such a case in our experiments, and the details are presented in the next part of the paper.

The main goal of this research is to estimate the influence of the reinforcement on the behaviour of the structure. The numerical analysis is performed and compared with our laboratory results. The presented numerical results are made with the assumption of full adhesion [4, 9] between CFRP and wood. The glue strength is not considered.

2. Laboratory tests

Experimental investigations of I-beams made with wood and wood-based materials were conducted in the laboratory of the Institute of Building Engineering at the University of Zielona Góra. Three I-beams of natural dimensions made of pine wood and OSB board were examined in the four-point bending test (Figs 1–4). The test equipment used enabled testing in accordance with the principles given in EOTA TR 002 [3]. Load-carrying capacity and flexural rigidity were measured during the tests. All tests were carried out in temperature of 20°C and relative air humidity of 50%. The beams were stored in the laboratory hall for three months under constant thermal and humid conditions.

Measurements of flexural rigidity were made using the test machine INSTRON 8804. The load was applied in the following order:

- loading to displacement of hydraulic actuator equal to 10.0 mm during 100.0 s (velocity 0.1 mm/s);

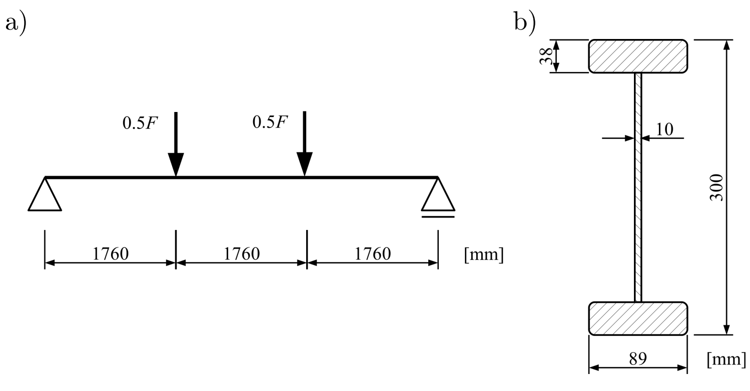

Fig. 1. Static schema and cross-section of I-beam.

- unloading to displacement of hydraulic actuator equal to 2.0 mm during 80.0 s (velocity 0.1 mm/s);
- loading from displacement 2.0 mm to 10.0 mm during 80.0 s (velocity 0.1 mm/s); measurements of beam deflection and force.

The flexural rigidity $(EI)_{\text{beam}}$ is given by the formula [3]:

$$(EI)_{\text{beam}} = \frac{\Delta F \cdot l \cdot l_k^2}{48 \cdot \Delta w_4}, \tag{2.1}$$

where ΔF – force increment during loading from displacement 2.0 mm to 10.0 mm; l – beam span (5280 mm); l_k – span of deflection measurement setup (1500 mm, Fig. 2); Δw_4 – local deflection along the span of beam l_k.

$$\Delta w_4 = \Delta w_3 - \frac{\Delta w_1 + \Delta w_2}{2}. \tag{2.2}$$

The deflections measured in the pure bending zone are used to calculate the stiffness in accordance with Fig. 2 and formulas (2.1) and (2.2).

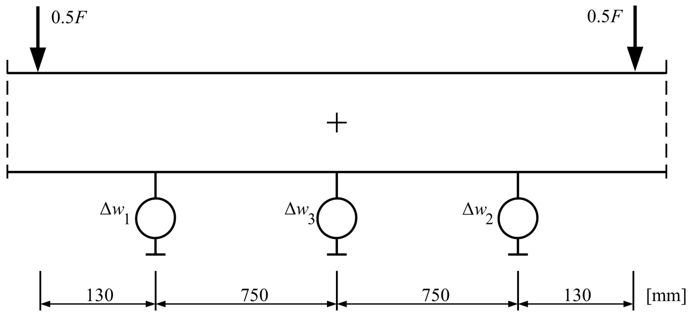

FIG. 2. Deflection measurement setup.

The I-beam was unloaded after calculating the flexural rigidity. Next, the specimen was loaded to failure (velocity 0.1 mm/s, time to failure about 10 min).

The moment capacity M_u is given by the formula [3]:

$$M_u = \frac{F_u \cdot l}{6}, \tag{2.3}$$

where F_u – total ultimate force; l – beam span (5280 mm).

The obtained experimental results demonstrate that the quality of tensile wooden flange turned out to be decisive for the load-carrying capacity of the I-beams (Figs 3–6).

Fig. 3. I-beam in the laboratory.

Fig. 4. Destroyed connection in tensile wooden flange.

Fig. 5. Close-up of the damage area of the beam from Fig. 4.

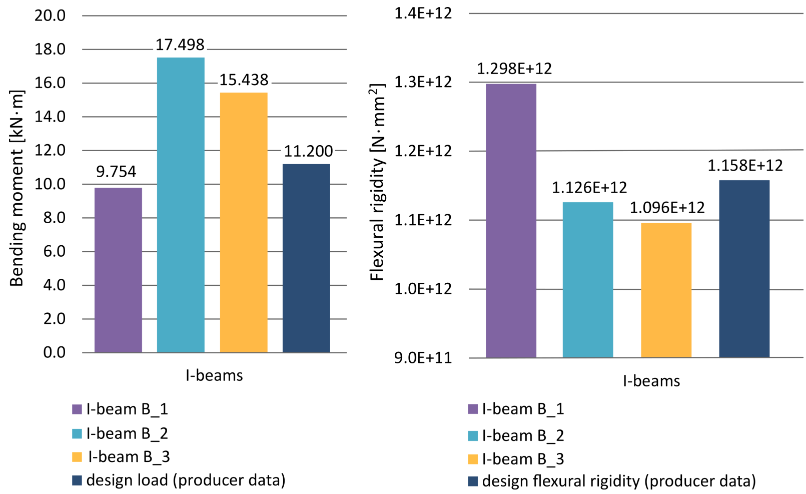

Fig. 6. Load-carrying capacity and flexural rigidity of I-beams.

The decrease in load-carrying capacity of the I-beams when the poor quality connections are at the central point of the span is shown in Fig. 6 (about 17%). Quality of connections does not influence the flexural rigidity of the tested I-beams (Fig. 6). The bearing capacity of B_1 beam is equal to 9.754 kN · m and it is lower than the manufacturer declared value. The finger-joint in bottom flange appeared as the weakest place in the beam. The connection was localised in the middle zone of the beam span. After the ultimate failure of the bottom flange the crack appeared in the web, then the crack went through the web to the top flange and the beam collapsed.

The load-carrying capacity of the B_2 beam is higher than the declared capacity, and its value amounts to 17.498 kN · m. The failure of the beam was relatively complex. Firstly, some cracks appeared in the surrounding of the support, nevertheless the beam was able to carry the load up to reaching the bending momentum of 17.498 kN · m. The upper flange collapsed in the middle zone, in the vicinity of the knot. It led to the beam damage. The reason for a much higher load- carrying capacity of the beam B_2 then B_1 is the quality of a bottom flange without any joints and knots in the tensile zone. The third beam B_3 behaved similarly to B_2, the load-carrying capacity was equal to 15.438 kN · m. The force-displacement dependence obtained in our experiments is shown inn diagrams in Fig. 9.

3. Strengthening layer

CFRP strips are widely used in civil engineering to optimise the ratio between the weight of a structure and its load capacity [5, 11]. By using CFRP as an additional layer, the capacity of the new composite structure could be increased without a change of cross section. In this work, two cases are considered, one with the CFRP tape glued along the whole bottom surface of the beam and the second where the tape is used to strengthen the sections to which the bottom flange is connected (the weakened zone).

The anchor length must be determined for the segment reinforcement [10].

The calculations are made with the following assumptions:

- The shear strength of the glue layer between the wood and CFRP is higher than the wood shear strength along the fibres.
- Only the linear-elastic behaviour of the component materials is considered.
- The compression, tensile, and bending strength of the beam are equal.
- The experimental tests did not show the influence of a weakened zone (connection in the wood bottom flange) on beam stiffness.
- The extreme case is considered – the stress in the bottom layer of the girder is carried by the CFRP tape.

The concept of a transformed field was implemented whereby the cross-section field of CFRP tape A_{CFRP} and the OSB cross-section field A_{OSB} are suited to the wood layer field $A_{\mathrm{CFRP}}(E_{\mathrm{CFRP}}/E_D)$ and $A_{\mathrm{OSB}}(E_{\mathrm{OSB}}/E_D)$. The transformed cross section is assumed and presented in Fig. 7.

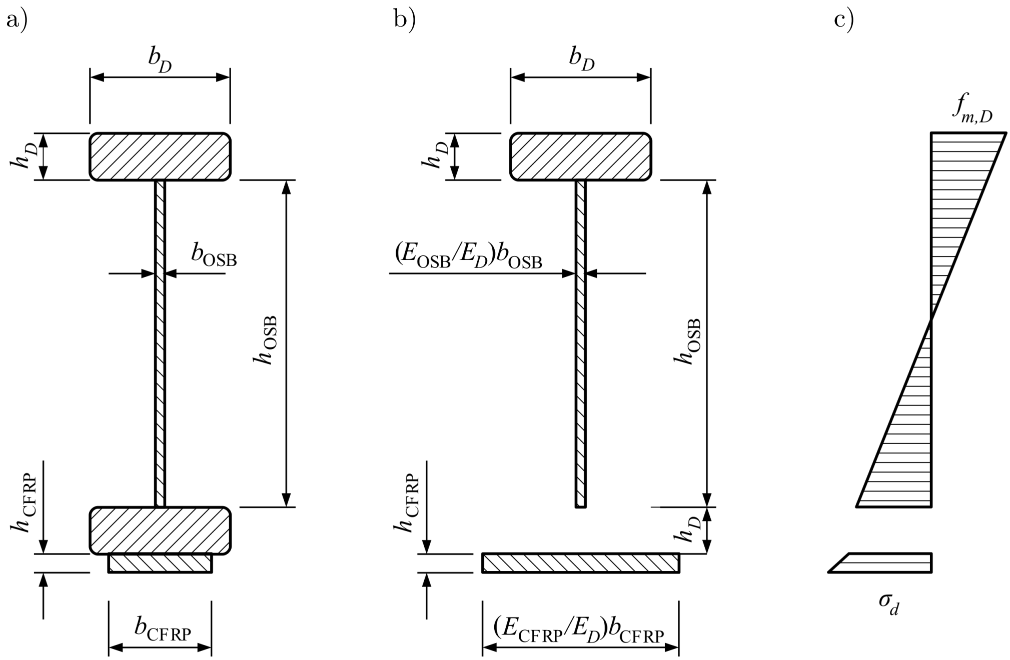

Fig. 7. Actual cross section (a), transformed cross section accepted for calculation (b), distribution of stresses (c).

The strength of CRFP tape is many times greater than the strength of wood. Considering the work of beam in the elastic range it is assumed that the stresses in the top fibres of the wood are equal to the bending strength of wood $f_{m,D}$

$$\sigma_g = f_{m,D} = \frac{M}{W_g}, \tag{3.1}$$

where

$$M = W_g f_{m,D}. \tag{3.2}$$

The maximum stresses in the bottom layer of the beam are

$$\sigma_d = \frac{M}{W_d}, \tag{3.3}$$

thus

$$\sigma_d = \frac{f_{m,D} W_g}{W_d}. \tag{3.4}$$

The anchor length l_{CFRP} is determined with the condition that average shear stresses between the glue layer and the wood do not reach the shear strength value of the wood along the fibres $f_{v,D}$. The maximum tensile stress in the CFRP tape can be calculated from the formula

$$\sigma_{\mathrm{CFRP}}\, b_{\mathrm{CFRP}}\, h_{\mathrm{CFRP}} = \sigma_d \frac{E_{\mathrm{CFRP}}}{E_D}\, b_{\mathrm{CFRP}}\, h_{\mathrm{CFRP}}. \tag{3.5}$$

The resultant force of normal stresses in CFRP is

$$F_d = \sigma_d \frac{E_{\mathrm{CFRP}}}{E_D}\, b_{\mathrm{CFRP}}\, h_{\mathrm{CFRP}}, \tag{3.6}$$

thus

$$\sigma_{\mathrm{CFRP}} = \sigma_d \frac{E_{\mathrm{CFRP}}}{E_D}. \tag{3.7}$$

The formula (3.7) results from the equal-strain assumption in the cohesion zone between the CFRP tape and the wood.

The average stress between the tape and the wood is

$$\tau = \frac{F_d}{b_{\mathrm{CFRP}}\, l_{\mathrm{CFRP}}} \le f_{v,D}. \tag{3.8}$$

Taking into account (3.4), (3.6) and (3.8) the anchor length could be calculated from the formula

$$l_{\mathrm{CFRP}} \ge \frac{W_g}{W_d} \frac{f_{m,D}}{f_{v,D}} \frac{E_{\mathrm{CFRP}}}{E_D}\, h_{\mathrm{CFRP}}, \tag{3.9}$$

where E_{CFRP} – CFRP Young modulus along fibres, E_D – wood Young modulus along fibres, E_{OSB} – OSB/3 Young modulus, W_d – bottom transformed section modulus of the beam, W_g – top transformed section modulus of the beam.

Material and geometric parameters of the considered beam (see Fig. 1):

OSB/3:

$$E_{\mathrm{OSB}} = 4.93 \text{ GPa}, \; v_{\mathrm{OSB}} = 0.2;$$

Solid wood:

$$E_D = 11 \text{ GPa}, \; v_D = 0.2, \; f_{mD} = 24 \text{ N/mm}^2, \; f_{vD} = 2.5 \text{ N/mm}^2;$$

Beam:

$$\text{height} = 300 \text{ mm}, \; \text{length} = 5280 \text{ mm}, \; W_g = 778\,221 \text{ mm}^3, \\ W_d = 455\,167 \text{ mm}^3;$$

CFRP:

$$\text{thickness} = 1.2 \text{ mm}, \; \text{width} = 80 \text{ mm}, \; E_{\mathrm{CFRP}} = 165 \text{ GPa}, \\ f_{\mathrm{CFRP}} = 2900 \text{ MPa}, \; v_{\mathrm{CFRP}} = 0.2.$$

Using the data and derived formulas the anchor length is calculated as $l_{\mathrm{CFRP}} = 295.5$ mm. The stress in CFRP is equal to $\sigma_{\mathrm{CFRP}} = 615.5$ MPa and is much lower than the tensile strength of the tape $f_{\mathrm{CFRP}} = 2900$ MPa.

4. Numerical model

A numerical model of a simply supported beam was developed in ABAQUS 6.14-5 (Fig. 8). A finite element C3D20R (20-node quadratic brick, reduced in-

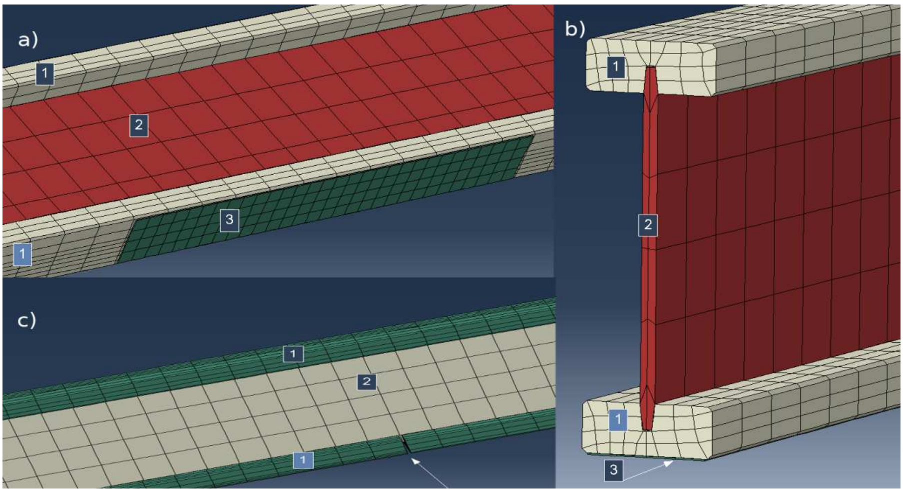

Fig. 8. Numerical model of beam (1 – flanges made of solid wood, 2 – OSB/3 board, 3 – CFRP): a) beam reinforced in the middle zone of bottom flange B_CFRP_60, b) beam reinforced along bottom flange B_CFRP, c) notched beam NM_N.

tegration) is used in the model. The full adhesion is assumed between flanges and OSB board as well as between CFRP and the bottom flange (contact type Tie [2]). The static diagram of the analysed beam is presented in Fig. 1a.

The numerical analyses are performed for the cases:

- NM – I-beam researched in the laboratory (Fig. 1 and Fig. 3);
- NM_N – I-beam with a notch in the middle of the bottom flange (failure);
- B_CFRP – I-beam strengthened along the bottom flange by CFRP;
- B_CFRP_60 – I-beam strengthened in the middle zone of the bottom flange by CFRP, the length of the zone $2 \cdot l_{\mathrm{CFRP}} = 591$ mm;
- B_N_CFRP – notched I-beam strengthened along the bottom flange by CFRP;
- B_N_CFRP_60 – notched I-beam strengthened in the middle zone of the bottom flange by CFRP, the length of the zone $2 \cdot l_{\mathrm{CFRP}} = 591$ mm.

All component materials are modelled as an ideal elastic-plastic with parameters presented in Sec. 3. The plastic yield is assumed for all used materials: for OSB/3 it is 18 MPa, solid wood – 24 MPa, and CFRP – 2900 MPa.

The experimental results are verified (Fig. 9) by a FEM analysis as the first step of numerical research. The model NM (without failure) is in good agreement with actual beams. The notched beam NM_N is a simplification of a real problem, and our numerical simulations are not able to cover the whole complex

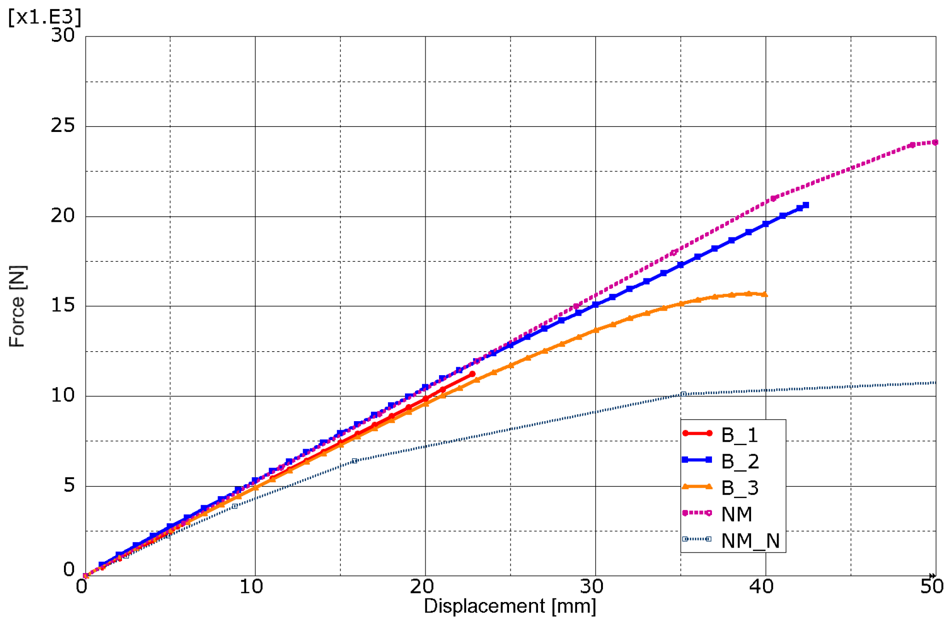

Fig. 9. Comparison of force-displacement curves for beams tested in the laboratory and numerically.

problem of the crack onset on growth. In a real structure, the crack appears and grows under the load. The model assumed the initial crack (notch), and this assumption simplified the model. The safety of the approach is related to the specificity of solid wood and the possibility of an existing initial discontinuity, e.g., loose knots.

Figure 10 shows the relation force-displacement for all numerical and experimental tests. The curves B_1, B_2, and B_3 are the experimental results.

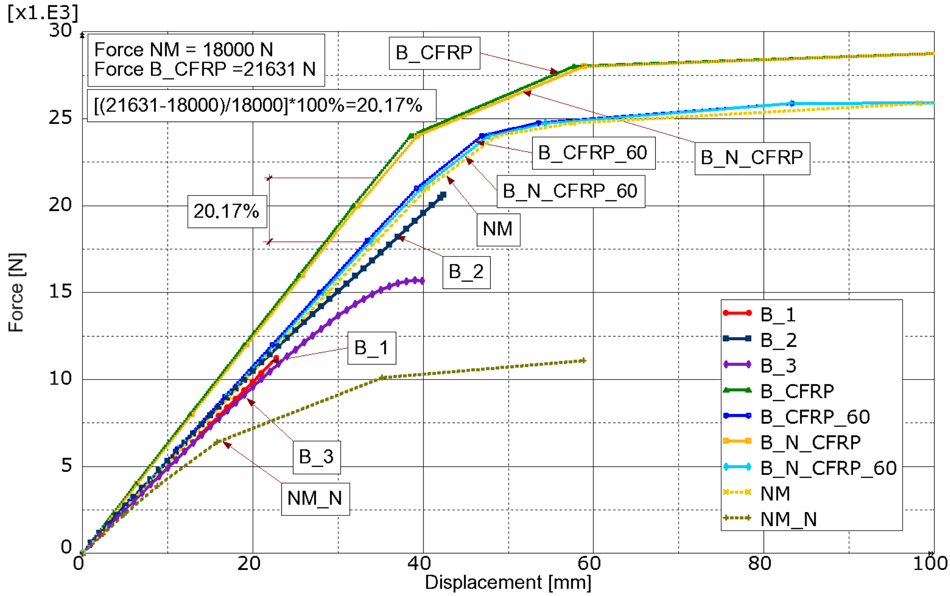

FIG. 10. The relation force-displacement for all numerical and experimental tests.

The numerical results lead to some conclusions:

- The CFRP reinforcement in the middle zone with the length calculated with the formula (3.9) does not cause the significant rise of load capacity.
- The CFRP reinforcement in the middle zone protects the beam against the loss of the bearing capacity if the failure occurs in the bottom flange.
- The partial reinforcement with the 60 cm length decreases the middle deflection by 2.86% (Fig. 10) in comparison to the beam without the reinforcement (NM).
- The CFRP glued along the whole bottom flange increases the load capacity by 20.17% and decreases the maximum deflection by 16.14% relative to NM (Fig. 11).

The Mises stresses distribution is presented in Fig. 12. The shown beam stresses are related to the first plastic strains. The detection of the plastic strains

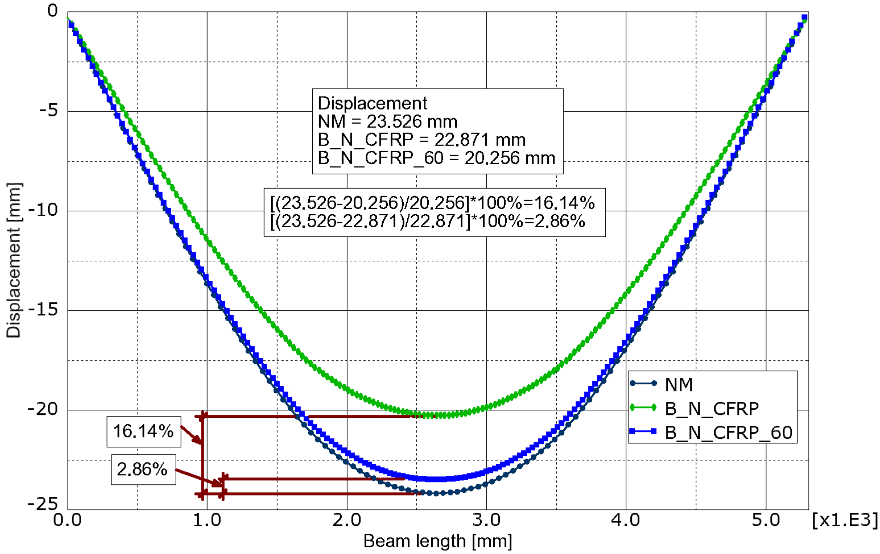

Fig. 11. Distribution of displacements along the beam length, where NM – numerical model of the beam, B_N_CFRP the beam strengthened along the whole bottom layer, B_N_CFRP_60 – the beam strengthened by 600 mm long CFRP tape in the weakened zone.

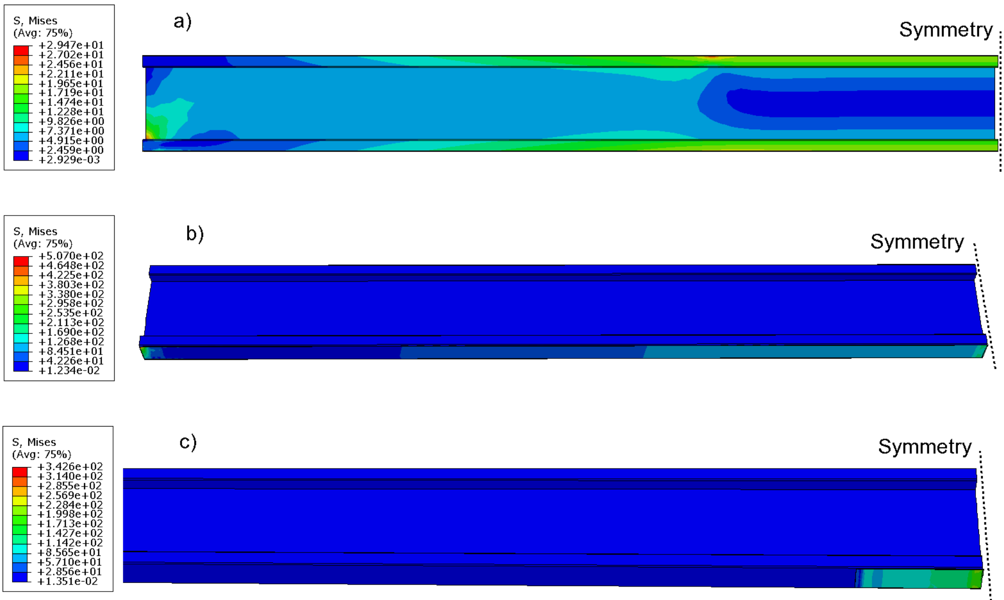

Fig. 12. Mises stresses: a) NM, b) B_N_CFRP, c) B_N_CFRP_60.

is realized by the distribution of the variable AC YIELD. It is a scalar quantity and its value, greater than zero, indicates plastic deformation [2].

The normal stresses distribution along the height of the beam cross section is shown in Fig. 13. The considered cross section is in the mid-span of the beam. The beam is loaded by concentrated force $F = 11.084$ kN, and this value corresponds to destructive force from our experiments. The load affects the elastic behaviour of the beam without any defects in the bottom flange. The curve marked NM_N_10%F shows the normal stress distribution in the notched beam (the same cross section as in the 'pure' beam). The notched beam works in the elastic range under the force $F = 1.108$ kN (10% of the elastic force in the beam without defects).

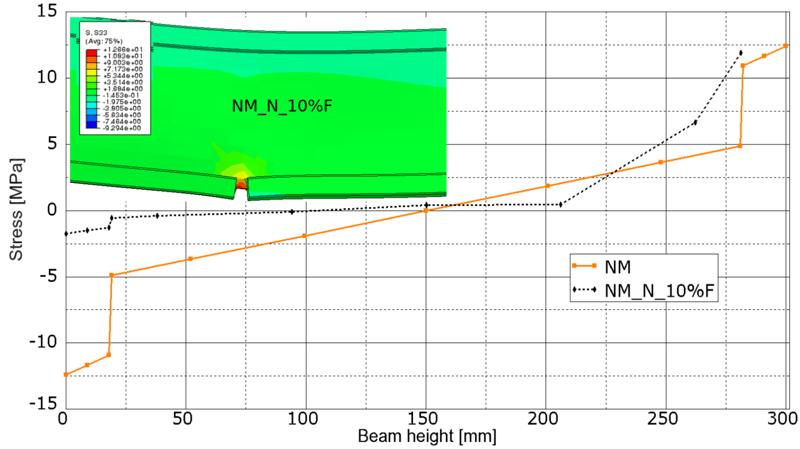

FIG. 13. Distribution of normal stresses in the mid-span along the height of the beam.

Figure 14 presents the distribution of normal stresses in the notched beams with the CFRP reinforcement (B_N_CFRP_60 and B_N_CFRP). The full

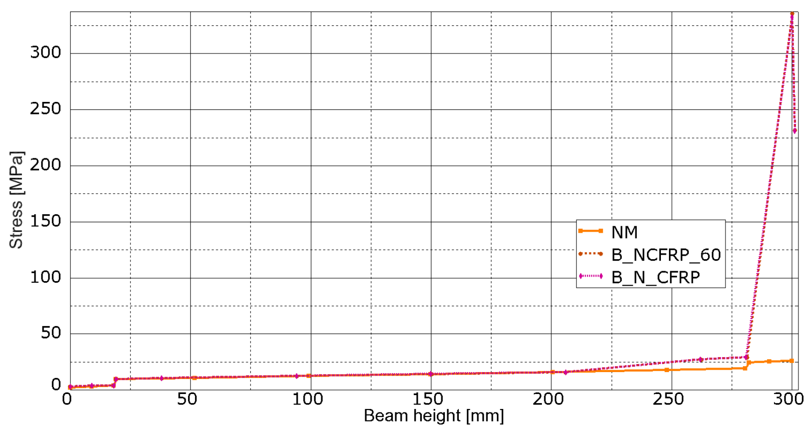

FIG. 14. Distribution of normal stresses in the mid-span along the height of the beam.

adhesion between CRFP and the wood is assumed and the strength of glue is omitted. The reinforced notched beam works in the elastic range under the force $F = 11.084\text{kN}$.

5. Conclusions

The numerical results of the test without a CFRP layer are in good agreement with the laboratory test. The CFRP influence on a load-bearing capacity is depended on the length of the tape, e.g., the increase is 20.16% for the tape glued along the whole beam. The maximum deflection of the strengthened beam is reduced by 2.86% for the partial reinforcement and 16.14% when the whole bottom flange is reinforced. The numerical tests confirmed the advantage of using CFRP tape to increase tensile strength in the weakened zone. The section reinforcement is sufficient when the anchor length is estimated. Therefore this is an economical approach as well.

The non-linear behaviour of the materials is taken into account in numerical simulation, the plastic yields of OSB, the solid wood and CFRP are provided for analysis. However, in our approach, the CFRP influence on beam behaviour is researched in the elastic range. The reason for this simplification is associated with the analytical calculation of the anchor length for CFRP, formulated for the linear-elastic problem.

In future work, the complex behaviour of a glue layer must be taken into account. Such a layer is quite sensitive, and some unexpected failure could appear in it, especially in the surrounding knots and the flange connections (stress concentration). This could lead to a loss of connectivity referred to as delamination [9].

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