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EXPERIMENTAL INVESTIGATION OF CLT PANELS REINFORCED WITH GFRP BARS

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ABSTRACT: When it comes to designing timber structures the limiting factors are usually stiffness properties of the engineered wood products. Stiffness requirements within the serviceability limit state (deformations and vibrations) are often the most relevant criterion for the design of timber elements subjected to bending. This paper shows an experimental study undertaken to investigate the effectiveness of glass fiber reinforced polymers (GFRP) as flexural reinforcement of cross laminated timber (CLT) panels. Five panels reinforced with GFRP bars and five unreinforced (control) panels were tested up to failure in a four-point bending configuration. Identical reinforcement arrangement in both tension and compression zones was considered in order to achieve the maximum increase in stiffness. The mechanical properties of reinforced panels are compared to those of unreinforced panels with regard to the load-deflection behaviour, failure mode, load-carrying capacity, deformability, bending stiffness values, as well as strain distribution along the panels' depth. The experimental results demonstrated the beneficial effect of the proposed reinforcing solution in terms of strength, stiffness and ductility. No issues were evident regarding the integrity of the bond between CLT panels and GFRP bars.

KEYWORDS: CLT panels, glass fibres, reinforcement, bending tests

1 – INTRODUCTION

Nowadays, timber as a building material is often combined with different materials in order to improve mechanical performance of timber structures. High mechanical properties of composite materials can significantly increase load-carrying capacity and stiffness of the reinforced elements, while also making timber structures more reliable. In addition, the composite effect leads to better utilization of wood resources [1]. Therefore, it is possible to reduce dimensions of timber elements or to use lower grades of wood. Furthermore, lifespan and durability of timber structures can be extended [2].

Fibre reinforced polymers are a group of advanced composite materials consisting of fibres with high mechanical properties (as micro-reinforcements) connected by an extremely strong, chemically resistant and durable synthetic resin (as a matrix). In structural engineering, the most common types of fibres are glass, carbon, aramid and basalt. Outstanding characteristics such as high stiffness and tensile strength, low weight, easy installation, high durability (no corrosion), electromagnetic neutrality and wide variety of available sizes and shapes, make these composite materials suitable for many structural applications [3]. The successful application of composite materials in combination with timber is feasible thanks to the compatibility and complementarity of their characteristics [4]. For example, the low weight of timber, which is one of its most important characteristics, is not threatened by the application of composite reinforcements. In addition, the most obvious disadvantage of timber, which is mechanical heterogeneity due to the presence of numerous defects, can be reduced by addition of another material such as FRP composite. In the past, FRP composite materials have been combined with solid and glulam timber elements and their effectiveness was confirmed through various experimental, analytical and numerical studies [5-10]. However, investigations on the mechanical performance of FRP reinforced cross laminated timber (CLT) members are limited [11-13].

Cross laminated timber is one of the most promising engineered wood products that can replace concrete and steel in modern construction industry. Orthogonally oriented layer configuration gives CLT excellent in-plane and out-of-plane resistance and thus allows the use of CLT panels for both floors and walls. However, the excessive deflection is often recorded in CLT panels under the out-

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of-plane loading, which results in the design being controlled by the stiffness properties, limiting CLT's structural application and wasting a large amount of strength capacity. This paper describes experimental research which examines the flexural reinforcement of CLT panels with glass fibre reinforced polymer (GFRP) bars. Reinforcement strategy included reinforcement of both tension and compression zones in order to achieve the maximum increase in stiffness. Bending behaviour of reinforced CLT panels was compared to unreinforced ones to determine effects of reinforcing solution.

2 – BACKGROUND

The mechanical properties of CLT panels are determined by the properties of the constituent boards, but also by the system effect. The composition of CLT, with its cross-wise layered boards, evens out the wood's properties variability [14]. The layering of the panel's cross-section is very important in terms of achieving desired strength and stiffness. In special configurations, consecutive layers may be placed in the same direction, thus creating a double layer, to obtain specific structural capacities [15]. Alternatively, performance of structures can be optimised by combining CLT with other materials.

FRP reinforcements are available as factory products in the form of plates, sheets or bars. Implementation of reinforcement is usually done by adhesive bonding. Hence, FRP reinforcing technique can be easily and effectively integrated into manufacturing procedure of engineered wood products. Unlike plates and sheets, which are most often placed externally, bars are placed along the grooves or slots cut into the structural elements. Since the reinforcement is hidden, mechanical and fire protection is provided by the surrounding wood. In addition, the probability of premature delamination is significantly reduced when the reinforcement is placed internally, due to a larger bond surface area.

The arrangement of the reinforcement in cross-section makes it possible to control the bending behaviour of timber elements with regard to strength, stiffness and ductility [16]. For enhanced strength performance, 25% and 75% of the reinforcement should be at the top and bottom of the beam section, respectively. The maximum stiffness enhancement can be achieved when the reinforcement is equally distributed between top and bottom sides. To achieve maximum ductility, all of the reinforcement should be placed on the bottom.

3 – EXPERIMENTAL TESTING

The experimental program included bending tests of CLT panels reinforced with composite reinforcement (GFRP bars) and unreinforced (control) CLT panels. A total of 10 panels were tested – 5 reinforced panels (Series C) and 5 unreinforced panels (Series A). All panels had a conventional orientation of the laminations of transverse layers at an angle of 90° in relation to the laminations of longitudinal layers. CLT panels of Series C were reinforced with near surface mounted GFRP bars positioned along the length of the panels. The configuration of reinforced test series is shown in Fig. 1. The adopted reinforcement scheme included application of a relatively small amount of composite material, with a reinforcement percentage of 0.87% (distributed equally in tension and compression zones). The reinforcement percentage is calculated as a percentage of the cross-section area.

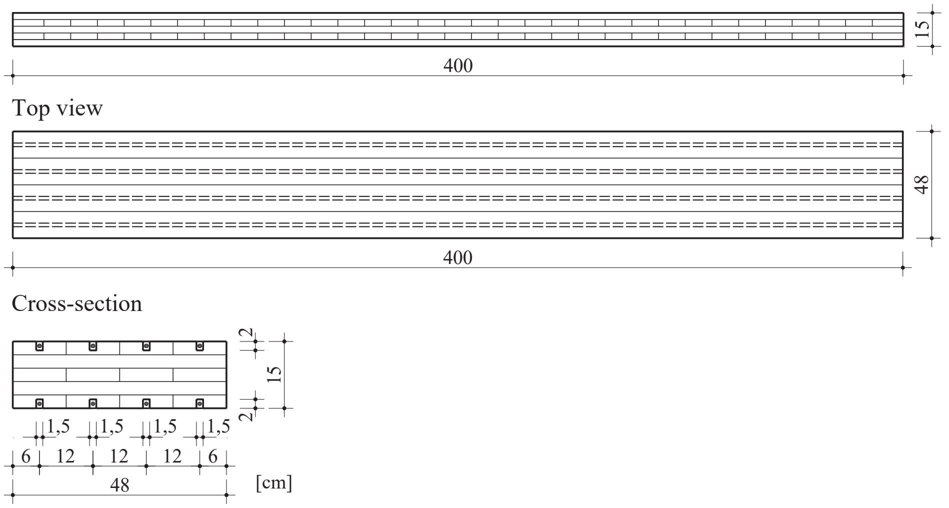

Figure 1. Configuration of reinforced CLT panels

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All CLT panels were made of softwood (spruce) classified in the strength class C22 according to EN 338 [17]. Dimensions of tested panels were 48 cm width × 400 cm length × 15 cm thickness. The panels consisted of five layers made of laminations 12 cm wide and 3 cm thick. Longitudinal laminations were formed by joining the boards with finger joints. Arrangement of finger joints within the laminations was completely arbitrary. Transverse laminations did not contain joints, but were all from one piece. Polyurethane adhesive (PUR) was used for finger joints and bonding of longitudinal and transverse layers. Adjacent laminations within the layers had no edge bonding. In the case of reinforced panels, the grooves for GFRP bars were machine-cut after the panels were made. Grooves were made in the lower and upper zones, within the laminations of the outer (longitudinal) layers, along the entire length of the panel. Size of the grooves (15 mm wide and 20 mm deep) was adopted to enable installation of the bars with the minimal required thickness of the adhesive layer and with the minimal weakening of laminations.

GFRP bars used in this experimental test program were comprised of glass fibres in an epoxy matrix. External surface of the GFRP bars was spirally wound with a glass fibre tow. GFRP bars were chosen due to their availability and favourable mechanical properties, as well as their low cost. The implemented GFRP bars had a nominal diameter of 10 mm and a length of 4000 mm. The mechanical properties of used GFRP bars are given in Table 1.

Table 1: Mechanical properties of GFRP bars from manufacturer data

Property	**Value**
Tensile strength	> 1200 MPa
Tensile modulus of elasticity	> 50 GPa
Elongation at break	2.3 %

The adhesive applied in the near surface mounted technique is a groove filler and acts as the medium through which shear stresses are transferred between the host timber and GFRP bars. In this research, epoxy adhesive Sikadur-31+ produced by Sika Group [18] was used. Sikadur-31+ is a two-part, low-VOC (volatile organic compounds), moisture-tolerant structural adhesive which bonds to many building materials. It is also used for structural repairs, joint filling and crack sealing. This adhesive was chosen for its compatibility with GFRP bars, as well as for its good physical and mechanical properties.

The experimental investigation was carried out at the Laboratory of Structures, Faculty of Civil Engineering, University of Belgrade. The bending tests were performed in the main bearing direction of CLT panels. All panels were tested in bending as simply supported beams with a span of 380 cm (approximately 25 times the panel thickness) symmetrically loaded with two concentrated forces at a distance of 90 cm (6 times the panel thickness), in accordance with EN 16351 [19]. A schematic illustration of the test layout is given in Fig. 2.

Testing of CLT panels was performed using servo-hydraulic actuator. In the experimental procedure the load was transformed from one concentrated force to two forces distributed along the panels' width using a steel box with welded steel sheets at the points of force input. Steel roller bearings were used at the supports. Also, roller bearings were used at the load application points to ensure that the load acts vertically. Steel plates were placed under the load application points and at the supports to minimize local indentations.

Load application was measured using the actuator loading cell. Deflection of the panels was measured using linear variable differential transducers (LVDTs). The mid-span deflection was measured on both sides using two LVDTs. In addition to deflections, in the mid-span, strains were measured around the cross-section using strain gauges. Strain data from strain gauges and deflection data from LVDTs were collected using the acquisition system.

Testing was performed in accordance with EN 408 [20] with a constant loading-head movement of 12 mm/min in order to achieve maximum load in 300 ± 120 s. Both series of CLT panels were tested using the same loading procedure, thus ensuring a valid comparison of the results. Immediately after each test was completed, the moisture content of timber was measured using a digital hygrometer at various points on the panel. The recorded moisture content in all specimens ranged from 10.4 to 12.2%.

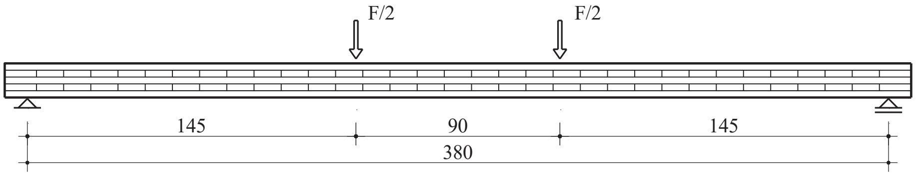

Figure 2. Panel testing layout (dimensions in cm)

4 – RESULTS

4.1 LOAD-DEFLECTION CURVES AND FAILURE MODES

Load-deflection curves for all tested CLT panels of Series A and C are given in Fig. 3. Displayed values of deflection at failure of each specimen represent average values of measurements of two LVDTs placed in the mid-span on both sides of the panel.

The unreinforced CLT panels (Series A) showed linear-elastic behaviour until failure. A certain degree of nonlinear behaviour was noticed in two tested panels (specimen A2 and A3). Failure of all specimens occurred due to tensile failure of the outer longitudinal layer laminations. Failure in tension zone was accompanied by pronounced shear cracks that extended along the glue-line between outer longitudinal layer and adjacent transverse layer and/or through transverse layer. In all cases, the unreinforced panels exhibited catastrophic failures. A typical failure mode of the Series A panels is shown in Fig. 4. Failure was initiated at wood defects (knots) or finger joints of longitudinal laminations in maximum bending moment area, between the load application points. None of the panels showed signs of plastification in compression zone.

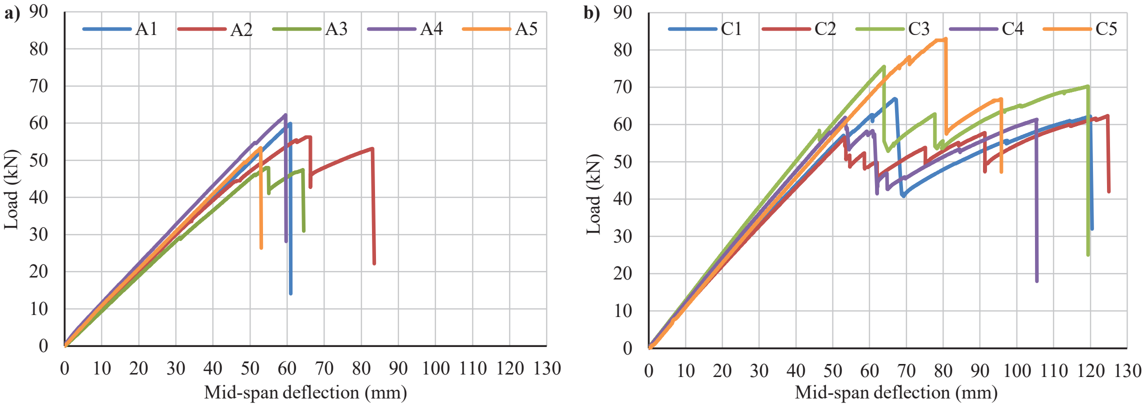

Figure 3. Load-deflection curves for: a) Series A panels; b) Series C panels

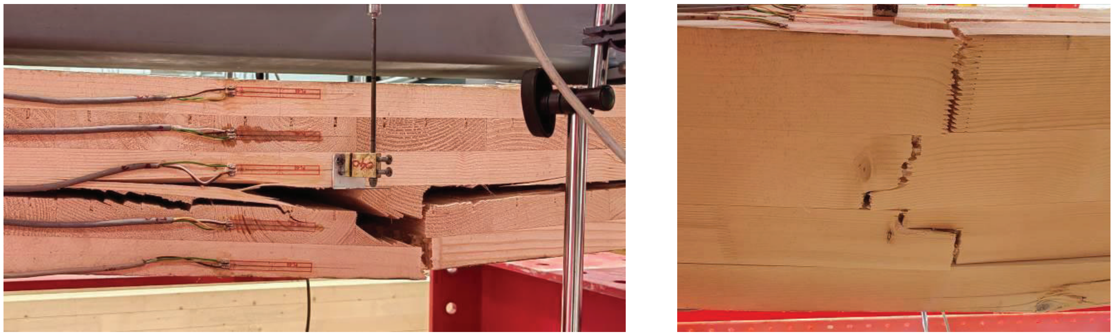

Figure 4. Typical failure mode of the Series A unreinforced panels (Specimen A2)

Figure 5. Typical failure mode of the Series C reinforced panels (Specimen C3)

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Reinforcing with GFRP bars has a significant influence on bending performance of CLT panels subjected to out-of-plane loading. Behaviour of the reinforced panels (Series C) is linear-elastic until the appearance of local damages caused by wood defects and discontinuities in the tension zone. Afterwards, activation of the bars causes a pronounced nonlinear behaviour that ends in the loss of load-carrying capacity due to tensile failure of timber, within the middle part of the panels. A typical failure mode of the Series C panels is shown in Fig. 5. The abrupt changes recorded on the load-deflection curves correspond to the intensive cracking process in the bottom timber laminations, which resulted in a gradual reduction of cross-sectional rigidity. The initial crack opening cannot be prevented by reinforcement, but it is possible to limit further crack development and propagation. Consequently, the reinforced panels have a higher load-carrying capacity and exhibit less brittle failure mode than the unreinforced panels. The degree of ductility of the reinforced panels largely depends on the quality of the longitudinal laminations in the tension zone. No traces of plastification in the compression zone were recorded in any of the reinforced panels. GFRP bars placed in the compression zone significantly reduce the possibility of plastic yielding occurring in the timber. The epoxy adhesive did not show signs of premature failure, and cracked only after the significant cracks in timber had developed. Fracture caused by reaching the timber ultimate tensile strength in bending did not cause bond failure or detachment of the tensioned GFRP bars. Buckling of the compressed GFRP bars was not observed in any of the tested panels and there was no problem with the bond between the reinforcement and wood.

4.2 LOAD-CARRYING CAPACITY AND DEFORMABILITY

The experimental results in terms of maximum load and mid-span deflection at maximum load, as well as mid-span deflection at failure for tested panels are given in Table 2. Corresponding values for loads and deflections were read from experimentally obtained curves.

The mean value of maximum load for the unreinforced CLT panels (Series A) was 56.1 kN, with a coefficient of variation of 9.9%. The load-carrying capacity of CLT panels is largely determined by the presence of wood defects and finger joints of the laminations in the critical tension zone.

Test carried out on CLT panels reinforced with GFRP bars (Series C) showed the mean value of maximum load of 69.9 kN, with a coefficient of variation of 13.1%. When compared to unreinforced panels, failure of reinforced panels occurred at considerably higher loads. The increase in load-carrying capacity of the Series C panels compared to the corresponding Series A panels was 24.8%.

Reinforcement of CLT panels did not reduce the variation of the ultimate load results, because the collapse of reinforced panels, like unreinforced panels, is caused by

Table 2: Experimental test results of Series A and C panels

Specimen	Maximum load F_{max} (kN)	Deflection at maximum load w_{corr} (mm)	Deflection at failure w_{max} (mm)	Bending stiffness EI_{global} (kNmm^2)
A1	59.9	60.9	60.9	10.666×10^8
A2	56.3	66.2	83.0	10.569×10^8
A3	48.0	55.0	64.3	10.041×10^8
A4	62.2	59.6	59.6	11.127×10^8
A5	53.8	52.9	52.9	10.748×10^8
Mean	56.1	58.9	64.1	10.630×10^8
STDEV	5.6	5.2	11.3	0.391×10^8
CV (%)	9.9	8.9	17.7	3.7
C1	66.9	66.8	120.0	11.668×10^8
C2	62.3	124.7	124.7	11.455×10^8
C3	75.5	63.9	119.3	13.334×10^8
C4	61.9	53.4	105.3	12.743×10^8
C5	83.1	80.8	95.8	12.377×10^8
Mean	69.9	77.9	113.0	12.318×10^8
STDEV	9.1	27.9	12.1	0.775×10^8
CV (%)	13.1	35.8	10.7	6.3
Increase C/A (%)	24.8	32.2	76.2	15.9

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tensile failure. Tensile failure of timber is brittle, random and difficult to predict. Failure mode can be changed from brittle to ductile by different reinforcement distribution between tension and compression zones (higher percentage in the tension zone), causing the reduction in the variability of the reinforced panels' ultimate load.

The CLT panels reinforced with GFRP bars (Series C) reached significantly higher deformations at failure compared to the corresponding unreinforced CLT panels (Series A). The increase in the mean value of mid-span deflection at failure was 76.2% (from 64.1 mm to 113.0 mm). Also, there is a noticeable decrease in the variation of deflection at failure for the Series C panels (CV = 10.7%) compared to the Series A panels (CV = 17.7%), which can be explained by the pronounced nonlinear behaviour of the reinforced panels. GFRP bars are capable of limiting crack opening and bridging timber defects.

4.3 BENDING STIFFNESS

Experimental results of bending stiffness for tested series of CLT panels are also given in Table 2. It is the out-of-plane bending stiffness of the panels, which was determined based on the measurement of global deflection of the panels. More specifically, bending stiffness of tested panels was calculated based on the slope of load-deflection curves (Fig. 3) for the linear-elastic region between $0.1 \cdot F_{\max}$ and $0.4 \cdot F_{\max}$ ($F_{\max}$ – maximum load).

The mean bending stiffness of the unreinforced CLT panels (Series A) was 10.630×10^8 kNmm^2, with a coefficient of variation of 3.7%. The recorded coefficient of variation is very low. This can be explained by the relatively small number of tested samples, but also by the fact that wood defects are evenly distributed in CLT panels and influence of each individual defect on the global properties of a CLT panel is significantly reduced.

Test carried out on the reinforced CLT panels (Series C) showed the mean bending stiffness of 12.318×10^8 kNmm^2, with a coefficient of variation of 6.3%. The strengthening effect when incorporating the GFRP bars is evident. The increase in stiffness compared to the unreinforced panels was 15.9%. Regardless of the relatively small percentage of reinforcement (0.87%), the optimal position of GFRP bars in relation to the neutral axis achieved the maximum utilization of the composite material. Contrary to expectations, by reinforcing the panels, variability of the stiffness results increased compared to the unreinforced panels. The reason can be a certain deviation in the position of the bars within the grooves filled with the epoxy adhesive.

The GFRP reinforcement of the CLT panels effectively reduced deflections in the elastic region compared to the panels without reinforcement. This effect is very significant from the SLS point of view as it can ensure occupant comfort requirements for CLT structures.

4.4 STRAIN DISTRIBUTION

Strains along the height of cross-section in the mid-span were measured for each specimen continuously from the beginning to the end of tests. Due to tensile cracking, some strain gauges were not in operation after a certain load level, therefore the analysis for reinforced panels was carried out to the maximum load before the initial failure.

The strain distribution along the height in the mid-span of the panels was determined based on the values read from the load-strain diagrams and the position of strain gauges. Examples of typical strain distributions for tested CLT panels at different load levels are given in Fig. 6. These profiles show compressive and tensile strains on x-axis as negative and positive values, respectively, and the position of strain gauges along the height on y-axis, measured from the lower edge of the cross-section. The given strain values represent the mean values of the corresponding measurements on both sides of the panel.

The strain distribution along the height of the unreinforced CLT panels (Series A) is completely linear until the ultimate load is reached, thus confirming the assumption of bending theory that plane sections remain plane during deformation. Measured strains on longitudinal and transverse layers of the CLT panels indicate that there is no sliding between the layers. Although minor variations are noticeable immediately before reaching the load-carrying capacity (when load is redistributed due to initial fracture), it can be stated that strain values in tension and compression zones were approximately the same at all load levels. This indicates the uniform quality of the boards used for the CLT production.

The linear strain distribution along the height is also visible in the case of reinforced CLT panels (Series C). The plane section assumption is generally satisfied during loading, providing the basis for subsequent analyses. The neutral axis of the double-reinforced cross-section is approximately in the middle of the panel's height. With an increase in load, a minimal shift of the neutral axis towards the compression zone was recorded. This phenomenon is caused by cracking initiated at defects in the bottom tension laminations, resulting in reduction of second moment of area and rigidity of the cross-section. Absence of the nonlinear behaviour in the compression zone confirms that plastfication did not occur in the top

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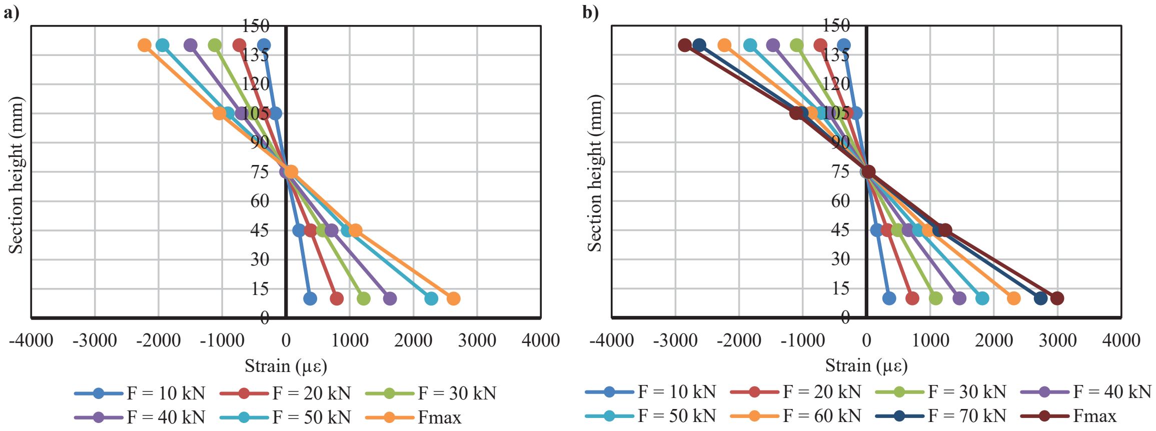

Figure 6. Strain distribution along the height of cross-section for: a) Series A panels (Specimen A2); b) Series C panels (Specimen C3)

laminations. The adopted configuration of reinforcement with GFRP bars in both tension and compression zones does not allow efficient use of nonlinear compressive characteristics of timber.

The reinforced panels showed some improvement in strain values. It can be seen from the presented strain profiles that tensile strain in the reinforced panels is lower than in the unreinforced panels at the same load level. On the other hand, the presence of GFRP bars reduced the influence of wood discontinuities and allowed for an increase in the maximum tensile strain of timber. The average increase in tensile strains at the ultimate load of the reinforced panels compared to the unreinforced panels was about 10%. Larger strains indicate higher stresses in CLT at ultimate loads. Therefore, presence of GFRP bars increases the bending strength of the CLT.

5 – CONCLUSION

Based on the conducted experimental tests of five-layer CLT panels reinforced with GFRP bars, with identical distribution of reinforcement in the tension and compression zones, subjected to out-of-plane bending, the following conclusions, significant from a theoretical and practical point of view, can be drawn:

- The considered reinforcement technique is very simple to apply. Reinforcement can be easily carried out in factory or construction site within a short period of time. It is possible to achieve an adequate quality of bond between CLT and composite reinforcement using epoxy adhesive.
- GFRP reinforcement has a great influence on the global behaviour of CLT panels. Strengthening primarily in the tension zone introduces nonlinearity into global behaviour of the panels and enables less brittle failure compared to the unreinforced panels. However, reinforcement in the compression zone significantly reduces the possibility of plastic yielding in timber.
- The reinforced CLT panels failed in the tension zone. The fracture was initiated at wood defects (knots) or at finger joints of longitudinal laminations in the area of maximum bending moment. It is not possible to prevent the initial opening of cracks with GFRP bars, but it is possible to limit their further development and propagation until the global failure is reached.
- Reinforcement can significantly improve the load-carrying capacity and stiffness of CLT panels. An increase in ultimate load by 24.8% and an increase in stiffness by 15.9% was observed for the considered reinforcement arrangement and reinforcement percentage of 0.87%.
- The strain distribution along the height of the reinforced CLT panels is quite linear for different load levels until the maximum load is reached. The assumption of plane sections is acceptable for CLT panels reinforced with GFRP bars.
- The presence of GFRP bars improved the ultimate timber tensile strain. The average increase in tensile strains at the ultimate load of the reinforced CLT panels compared to the unreinforced panels was about 10%. This indicates the ability of reinforcement to reduce the influence of wood discontinuities.

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