

*This study reports the results of experiments comparing the effect of structural reinforcement for timber beams strengthened with different carbon composite materials. Samples of one series were strengthened by gluing a carbon fiber plate from the outside to the face of the beam. The samples of the other series were strengthened by laterally gluing two carbon fiber rods inside the beam.*

*According to the bending research program, the ultimate loads and deflections were determined for both series. As a result of the analysis of the results and comparison with unreinforced samples from the control series, the effect of beam reinforcement and the model of their destruction were determined. Studies have shown that the effect of external reinforcement with a plate was 86.7 % according to the criterion of full failure load, 20.5 % according to the criterion of ultimate load, 13.4 % according to the criterion of ultimate deflection. The effect of rod reinforcement was 48.6 %, 18.6 %, and 4.1 %, respectively. The theoretical analysis of the results showed a convergence of up to 8.2 % with the experimental results.*

*External reinforcement with a plate compared to lateral gluing of rods showed better results due to the placement of the plate in the zone of maximum tensile stresses. This arrangement more effectively limited the spread of ultimate stresses and the development of cracks.*

*The reinforcement parameters of the samples (materials, placement, percentage of reinforcement) were selected under the condition of the same theoretically predicted bearing capacity after reinforcement. However, comparative experimental studies have revealed differences in the processes of deformation and destruction of reinforced beams.*

*The results will contribute to making rational project decisions and for choosing a relevant technique of strengthening timber beams with carbon composite materials*

*Keywords: carbon composite materials, flexural strength, stiffness, reinforcement efficiency, timber beams*

UDC 624.07

DOI: 10.15587/1729-4061.2023.287673

# COMPARING THE EFFICIENCY OF STRENGTHENING TIMBER BEAMS REINFORCED WITH CARBON COMPOSITE RODS AND PLATES

**Serhiy Bula**

Corresponding author

PhD, Associate Professor\*

E-mail: serhii.s.bula@lpnu.ua

**Andriy Pelekh**

PhD, Senior Lecturer\*

\*Department of Building Constructions and Bridges

Institute of Civil Engineering

and Building Systems

Lviv Polytechnic National University

S. Bandery str., 12, Lviv, Ukraine, 79013

Received date 11.07.2023

Accepted date 18.09.2023

Published date 30.10.2023

**How to Cite:** Bula, S., Pelekh, A. (2023). Comparing the efficiency of strengthening timber beams reinforced with carbon composite rods and plates. *Eastern-European Journal of Enterprise Technologies*, 5 (7 (125)), 14–22. doi: <https://doi.org/10.15587/1729-4061.2023.287673>

## 1. Introduction

The use of carbon fiber reinforced polymer materials (CFRP) is more and more common in strengthening building structures, in particular timber ones. This is a relatively new material that is gradually replacing steel elements, which were traditionally used to strengthen bent timber elements. In most cases, CFRP strengthening of timber structures takes place during the reconstruction of buildings-architectural monuments, where the complete replacement of elements is impossible due to the preservation of historical heritage [1]. However, the increase in the price of wood in Europe in 2016–2022 makes the use of composite materials even more economically justified [2], specifically when designing new reinforced timber structures in construction.

The advantages of using CFRP materials include lightness, high strength, corrosion resistance, ease of installation, aesthetics, seismic resistance, and the possibility of reinforcement in hard-to-reach places. On the other hand, the influence of such factors as the variability of wood characteristics, the presence of damage, the reliability of the adhesive bond, and the accuracy of calculation models are not yet sufficiently studied.

That is why an experimental study into the work of timber beams reinforced with CFRP plates and rods is relevant

and will allow obtaining new data on the actual effect of reinforcement and compliance with calculation models. The results could also be useful in the selection of reinforcement procedure and materials.

## 2. Literature review and problem statement

Research on CFRP in the strengthening of timber elements began in earnest [3] in the 1990s, following an increase in research on the performance of glass fiber reinforced polymers (GFRP) materials earlier in the 1980s [4, 5]. In more than 30 years of research, there have been quite a lot of studies on the joint performance of CFRP and wood bent elements. In their works, scientists pay attention to increasing the bending capacity and stiffness of reinforced beams and refine the calculation models of structures taking into account the presence of damage, the length of anchoring, and the technique of reinforcement.

External reinforcement by gluing to the faces of beams (EBR) is the most popular and convenient reinforcement technique from the point of view of installation.

Work [6] describes the results of research on small-sized models of 25×50×500 mm, which indicate an increase in the

stiffness of beams by (20–30) % after reinforcement with a carbon plate 1.5 mm thick on the lower and upper faces of the beams. Also, tests on small samples of 20×20×360 mm reinforced with a carbon lamella with a thickness of 0.16 mm in article [7] confirmed an increase in bending strength by 34 %. The results were confirmed by analytical calculations with good convergence of results. The authors of [6, 7] studied small-sized models, which may impose certain limitations in applying the results to full-sized elements.

In [8], the authors confirm an increase in stiffness by 13 % to 30 % for timber beams (45×45×1000 mm) reinforced with fabric-type carbon fibers on the lower face of the beam with a percentage of reinforcement of 0.268 % and 0.307 %, respectively. The increase in bearing capacity was recorded at the level of 27 %. Numerical modeling using the finite element method was also carried out. Paper [9] describes the influence of the number of layers of carbon fiber fabric reinforcement for beams (750×80×38 mm). Research results showed an increase in the bearing capacity of reinforced beams from 28 % to 41 %. Works [8, 9] focused on the research of fabric-type CFRP, which is rarely used in beams with a significant cross-section.

A comprehensive study [10] of beams the size of 3000×120×60 mm reinforced with fabric-type carbon tape with 0.4 % percent reinforcement showed an increase in stiffness by 1.15–1.3 times compared to non-reinforced beams. The purpose of the study was to compare the effectiveness of reinforcement with carbon and glass fiber materials. Despite the interesting experimental results for medium-sized beams, the stress distribution over the entire height of the beam section was not covered.

In study [11], 221 beams of different sizes (20×20×380 mm, 100×100×1950 mm, and 200×200×4000 mm) were tested for hard (oak) and soft (fir) wood species. Reinforcement with fabric-type carbon fibers on the lower face with a reinforcement percentage of 0.165 % for fir samples increased the bending strength by 65.6 % and the stiffness of the beams by 11.2 %. Load-deflection diagrams with mostly linear dependence were also built. The authors note that the strength of CFRP plates is not even half used, which prompts a more careful selection of reinforcing elements. The advantage of these studies is the testing of a large number of beams of different sizes and types of wood, but reinforcement with laminations and bars was unfortunately not part of the research program.

There are also a number of studies on timber beam structures that have already had a certain service life. In work [12], such beams with a cross-section (150..190)×(150..200) were tested. One series was reinforced with a carbon lamella (1.4×50 mm) along the lower stretched face of the beam. The other series was reinforced with two such lamellas by gluing on the side faces. The strengthening effect according to the stiffness criterion was 1.12 times. A comparative study of reinforcement techniques is the closest to the discussed topic, but it did not include reinforcement with rods.

Article [13] reports a study of beams from a historical building that were reinforced with CFRP plates with an increase in bearing capacity of ~60 %. The paper describes the comparative results of reinforcement with carbon, aramid, basalt, and glass fiber materials. But the theoretical calculation remained unexplained, which may be related to the variability of the wood characteristics of the historical building.

Studies [14] also confirm the increase in strength and stiffness of full-scale specimens reinforced with lamellas, however, it is noted that CFRP delamination occurred when only 27.2 %

of lamella strength was reached. The work did not use additional anchoring means, which are used in many cases with this technique of reinforcement and affect the work of the beams.

In addition to the externally bonded reinforcement (EBR), the near-surface mounted methods (NSM) in the cross section of the beam is widely used.

Research [15] included studies of beams (200×200×4000 mm) reinforced with CFRP rods with a diameter of 7.5 mm, which were glued into the grooves of the lower face. Beams reinforced with CFRP sheets glued in 3 layers on the bottom of the beam were also studied. Reinforcement with sheets showed an increase in bending capacity by 60.3 %. The effect of rod reinforcement was somewhat lower. The research program did not include reinforcement with rods on the side, and this issue remained unexamined.

Studies [16] were conducted on glued-laminated beams (3000×90×225 mm) to compare options for CFRP reinforcement with lamellas and rods. At the same time, variants with different locations of reinforcement were tested: along the lower face and at some distance from the lower face. According to the results of the experiments, an improvement in the bending strength of the beams was obtained in the range of (44–63) % and stiffness by 10 %. The analysis was carried out only for glued-laminated structures, and the strengthening features of solid timber beams were not investigated.

In [17], the influence of the technique and amount of reinforcement was investigated. The 1800×150×80 mm samples were reinforced with glued CFRP rods inside the lower face, textile material outside, and their combination in different proportions. Bending tests were performed for 21 beams. The results showed an increase of 25 % to 35 % in flexural strength, depending on the type of reinforcement. At the same time, the authors indicate the delamination of the reinforcing material and the need for additional research on its adhesion to wood. The studied reinforcement combinations did not include reinforcement with rods on the side and lamellas from below.

Another recent study [18] confirms the effectiveness of lateral gluing of rods in the stretched zone of the beam. Samples (3650×162×82 mm) with CFRP reinforcement with rods only and samples with combined reinforcement (rods and lamellae) were tested. The experiments showed an increase in the ultimate load by 30.51 % and 39.36 %, respectively. However, the experimental program did not include samples of solid wood beams.

Studies [6–18] show that the reinforcement with CFRP materials, in general, increases the strength and stiffness of timber beams. However, in the above studies, the strengthening of medium-sized timber elements made of solid wood reinforced with plates and rods is not fully disclosed, so conducting such a study is expedient.

---

### 3. The aim and objectives of the study

---

The purpose of this study is to experimentally determine the effect of strengthening timber beams that were reinforced with CFRP materials using the NSM (rods) and EBR (lamellas) techniques. The results will help in making rational project decisions and improving calculation models.

To achieve the goal, the following tasks should be solved:

- to determine the “deflection-load” dependences for the studied samples;

- to investigate the stress distribution along the height of the cross-section of the beams and the failure patterns of the samples;
- to investigate the elastic-plastic behavior of wood in terms of ultimate bending moments and evaluate the convergence with numerical calculation.

#### 4. The study materials and methods

##### 4.1. Materials

The object of our study is the effect of strengthening timber beams reinforced with CFRP materials. The main hypothesis of the research assumes that the reinforcement of timber beams leads to an increase in their rigidity and bearing capacity for bending. It is assumed that the characteristics of wood within one series are close in value.

For the manufacture of beams, soft wood was used – fir from the region of the Carpathian forests, which is often used as a structural material in Ukraine. The test samples were taken with dimensions of 2000×150×75 mm. A total of 2 series were studied. 3 samples for one series were made from one solid beam 6 m long. Thus, comparing the results of beams within the same series with different strengthening methods is more relevant. It also makes it possible to reduce deviations in the strength of the wood of the samples within one series. Wood moisture was measured using an electronic moisture meter Testo® 606-1 (PRC). Physical and mechanical characteristics of wood were determined in accordance with EN 408:2003 [19]. Experimentally obtained average values are given in Table 1.

Beams were reinforced with TM Mapei® materials (Italy). The characteristics of CFRP elements were taken according to the manufacturer’s technical maps.

CFRP plate Carboplate® E170 was used to reinforce samples with EBR method. Lamel Carboplate® [20] is a plate made of longitudinal carbon fiber pre-impregnated with epoxy resin, with a double protective polyethylene film. Characteristics: modulus of elasticity  $E_f=160,000$  MPa; ultimate tensile strength  $f_{f,uk}=2700$  MPa; ultimate elongation  $\epsilon_{f,uk}=1.6\%$ ; plate width  $l_{fpp}=50$  m; plate thickness  $t_{fpp}=1.4$  m; density  $t_{fpp}=1.61$  g/cm<sup>3</sup>. The percentage of sample reinforcement is 0.62 %.

Maperod C® CFRP rods were used to strengthen the samples with NSM method. Maperod C® rods [21] are pultrusion rods made of carbon fiber and epoxy resin for repairing and strengthening damaged elements. Characteristics: modulus of elasticity  $E_f=155,000$  MPa; ultimate tensile strength  $f_{f,uk}=2000$  MPa; ultimate elongation  $\epsilon_{f,uk}=1.5\%$ ; diameter of rods  $t_{fpp}=10$  mm. The percentage of sample reinforcement is 1.39 %.

##### 4.2. Sample preparation

###### 4.2.1. Reinforcement of prototypes with carbon lamellae

The procedure for strengthening the beam with a carbon plate is shown in Fig. 1, 2. Before installing the reinforcement, the base of the samples was prepared. The lower face of the beam was polished to a clean and smooth surface. In the places where the anchoring strips were glued, the sharp faces of the beams were rounded off. A layer of MapeWrap® Primer1 priming solution was applied to the prepared surface of the lower face of the beams (Fig. 1, a). The impregnated surface was dry, clean, and flat. While the solution was still “fresh”, an even layer of MapeWrap® 11 adhesive solution was applied (Fig. 1, b). The solution was applied in one layer with a thickness of 1–1.5 mm. After that, the protective film was removed from the carbon lamella Carboplate® E170 prepared in advance (according to the size of the beam) and a layer of the same solution was applied. Immediately, the lamella was pressed against the face of the beam (glue to glue) and the remaining air was removed by pressing with a roller (Fig. 1, c).

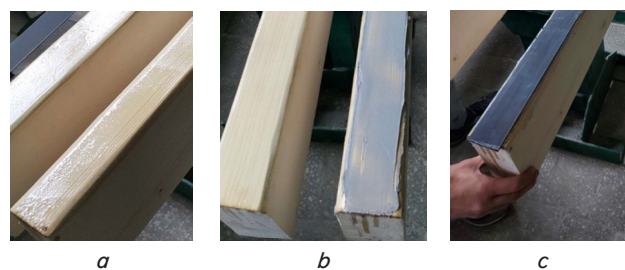


Fig. 1. Installation of CFRP lamella: a – application of MapeWrap Primer 1 primer; b – applying MapeWrap 11 glue;

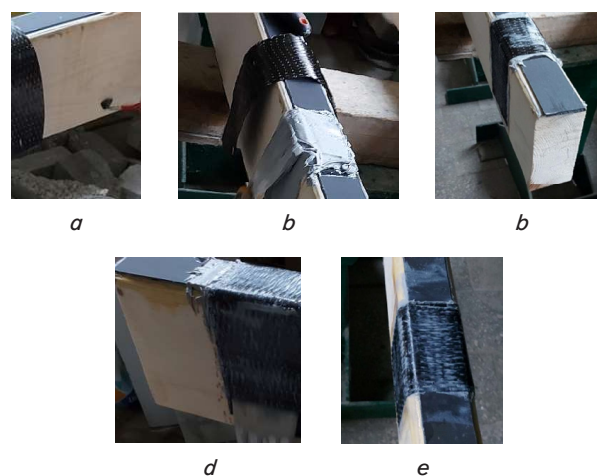


Fig. 2. Installation of anchoring strips for the carbon laminate Carboplate: a – application of MapeWrap Primer 1 primer; b – applying MapeWrap 11 glue; c – inserting a strip of MapeWrap®CUNI-AX fabric; d– fixation of the fabric strip; e – impregnation of the glued strip with MapeWrap® 31 solution

After the installation of the carbon lamella, anchor strips made of MapeWrap®CUNI-AX 300/10 fabric were mounted on the support sections of the beam in a regulated sequence (Fig. 2). After strengthening, the beams were kept for at least 7 days before testing for reliable adhesion of the adhesive materials.

Table 1

Properties of experimental timber beams

Label	Timber class	$f_{m,k}$ , MPa	$f_{t,w}$ , MPa	$f_{c,w}$ , MPa	$\rho_k$ , g/cm <sup>3</sup>	$E$ , MPa	Reinforcement type
1-Cn	C22	23.5	30	37	380	10,860	None
1-Rd							CFRP rods
1-Pl							CFRP plate
2-Cn	C22	22.1	27	35	350	9,520	None
2-Rd							CFRP rods
2-Pl							CFRP plate



### 4. 2. 2. Reinforcement of prototypes with carbon rods

The procedure for strengthening the beam with a carbon plate is shown in Fig. 3, *a–d*. Before installing the reinforcement in the beam, side slits measuring 15×15 mm were made along the entire length of both sides of the beam for the entire length of the beam. The distance from the slot axis to the lower face of the beam is 35 mm. As in the previous case, the faces of the beams were cleaned to a smooth state.

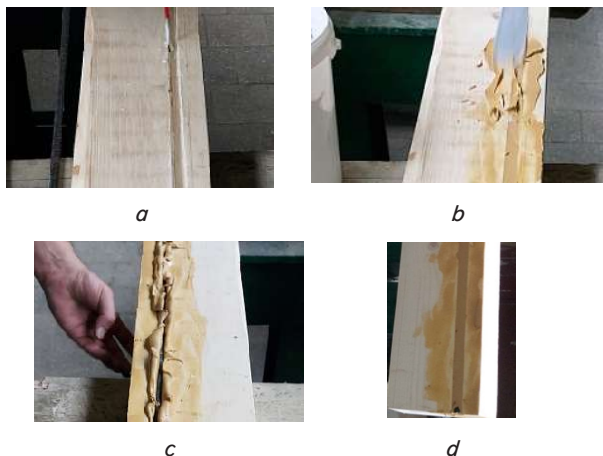


Fig. 3. Installation of Maperod C® CFRP rods: *a* – application of MapeWood®Primer 100 solution; *b* – application of MapeWood® glue; *c* – installation of Maperod C® carbon rod; *d* – removal of glue residues

A layer of two-component priming solution MapeWood®Primer 100 was applied to the inner surface of the slot (Fig. 3, *a*). After that, the two-component thixotropic

glue MapeWood® PASTE 140 was placed inside the slot with a spatula in such a way as to fill the entire volume of the slot (Fig. 3, *b*). A Maperod C® carbon rod with a diameter of 10 mm and a length of 2000 mm was sunk into the slot filled with glue (Fig. 3, *c*). Residues of glue were removed from the surface using a spatula (Fig. 3, *d*). This operation was performed on both sides of the beam.

### 4. 3. Research methods

Testing of test samples was carried out at Lviv Polytechnic National University according to the four-point bending scheme (Fig. 4, *a, 5*). The experiments were carried out in continuation of the research program on the strengthening of building structures with FRP materials [22, 23].

The tests were performed on a bench using a hydraulic jack (PRC) with a maximum possible load of 15 tons. Deformations on the surface of the beam of the experimental sample were measured using indicators (Ukraine). The scheme of their location along the cross-section of the sample is shown in Fig. 4, *b*.

The sample was loaded in steps of 3 kN with a duration of 10–15 minutes at each step. The design scheme of the beam was assumed to be freely supported on two supports. The span of the beam is 1800 mm, the load was applied by two concentrated forces at a distance of 600 mm in thirds of the span. The amount of load was monitored by a dynamometer using the divisions of the built-in indicator.

The indicators themselves were placed in the zone of pure bending between the applied forces in the middle of the beam. The deflection of the beam was measured in the middle of the span using a protractor. Indicators were installed on the supports to measure the settlement of the supports. During the tests, photo-video recording and visual observation were carried out.

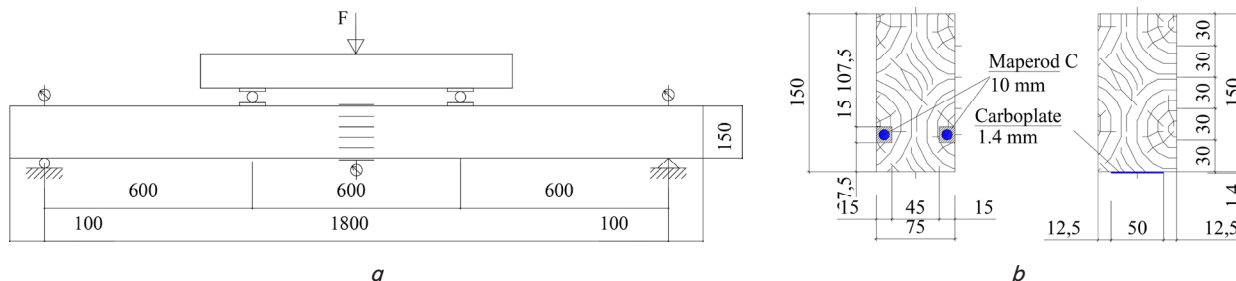


Fig. 4. Experimental scheme: *a* – bench for testing timber beams; *b* – placement of indicators along the cross-section of the sample



Fig. 5. General view of the timber beam test bench

### 5. Results of experimental studies of timber beams for bending

#### 5.1. Deflection-load dependences

According to our data on the deformations of the beams during the test, plots of the dependence of the beam deflections on the applied load were constructed for both studied series (Fig. 6).

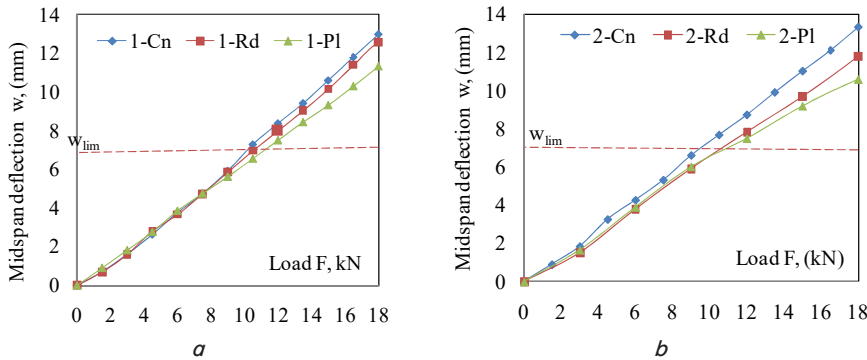


Fig. 6. Deflection-load dependence for beams: *a* – 1 series; *b* – 2 series

The dotted line on the plots shows the ultimate deflection (1/250 of the beam span) according to [24]. The “deflection-load” plots (Fig. 6, *a*, *b*) have a linear character in the initial stages, later the plot becomes distorted during the development of plastic deformations in the compressed zone.

#### 5.2. Stress distribution along the cross-section height of the beams and patterns of failure of the samples

The stress distribution along the cross-sectional height of the samples is shown in Fig. 7. Unreinforced structures (1-Cn, 2-Cn) collapsed suddenly with a characteristic loud sound, splitting of wood, and the formation of significant peeling and cracks in the stretched zone (Fig. 8).

The destruction of samples reinforced with rods (1-Rd, 2-Rd) began in the stretched zone. This was preceded by the achievement of minor plastic deformations in the compressed zone of the beam. After reaching the limit of the tensile stresses of the wood, cracks appeared on the lower face, which spread higher into the area where the rods are located and led to a violation of their adhesion to the wood (Fig. 9).

The technique of failure of beams (1-Pl, 2-Pl) reinforced with plates (Fig. 10) differed from the type of failure of samples (1-Rd, 2-Rd).

Exceeding the ultimate tensile stresses was restrained by the adhesion of the plate and wood along the lower part of the beam. Their appearance in the stretched zone was recorded only after the significant development of plastic deformations in the compressed zone (Fig. 7, *e*). Cracks appeared at the later stages of loading when the ultimate stresses spread in height to areas remote from the plate.

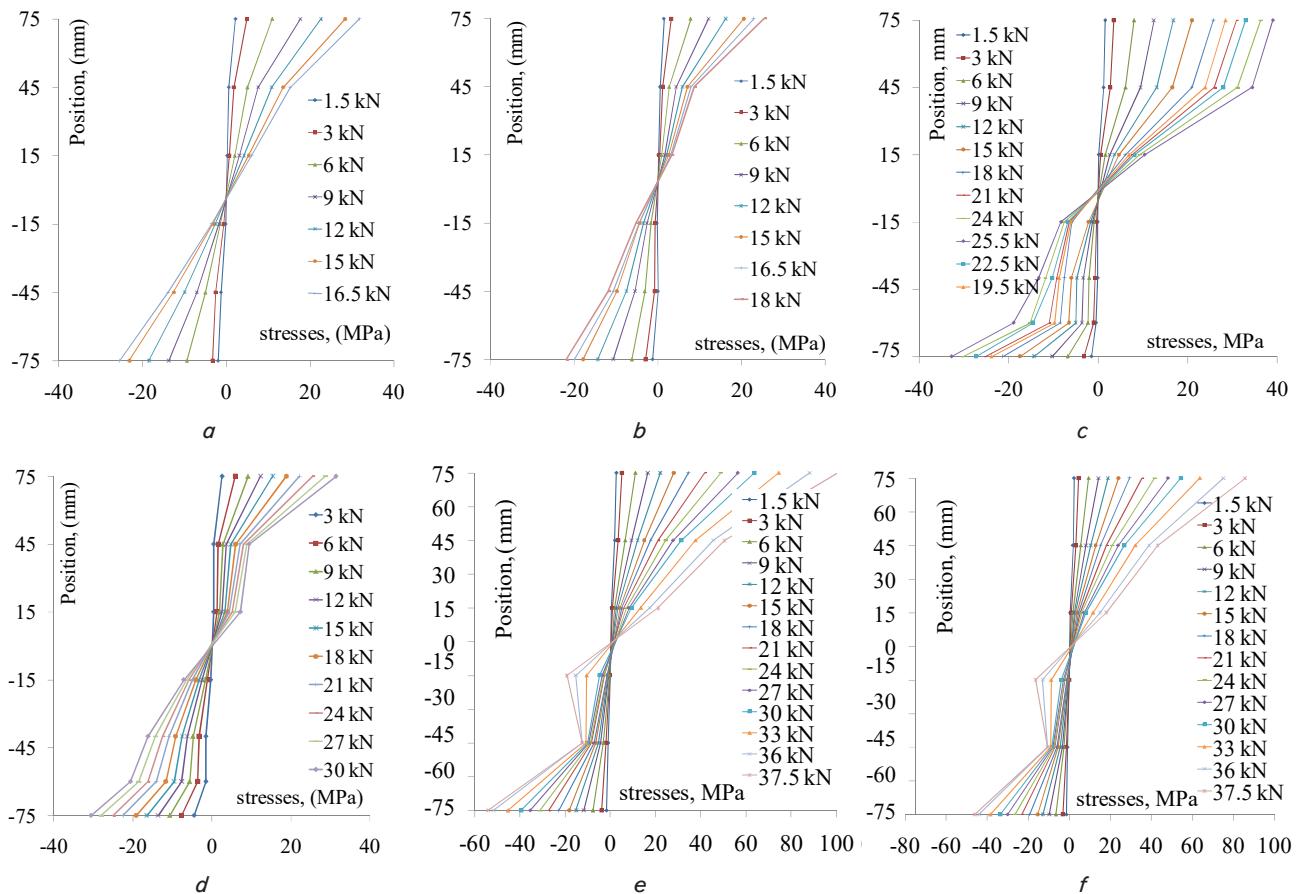


Fig. 7. Stress distribution along the cross-section height in the middle of the span: *a* – sample 1-Cn; *b* – 2-Cn sample; *c* – sample 1-Rd; *d* – sample 2-Rd; *e* – sample 1-Pl; *f* – sample 2-Pl



Fig. 8. Crack patterns of sample 1-Cn



Fig. 9. Crack patterns of sample 1-Rd



Fig. 10. Crack patterns of sample 1-PI

**5. 3. Studying the elastic-plastic work of wood by limiting bending moments and evaluation of convergence with numerical calculation**

For the theoretical calculation, the elastic-plastic model of wood deformation, which is implemented in the design standards [25], is adopted. These norms determine the criteria and conditions for the application of the most relevant techniques of FRP strengthening of existing building structures.

The analysis of different models of failure of timber elements subjected to bending reveals that the model of failure depends on the following parameters [25]:

- a) the ratio between the tensile and compressive strength of wood ( $\eta=f_{tu}/f_{cu}$ );
- b) nonlinearity of wood deformation during compression in the limit state;
- c) the cross-sectional area of wood in the tension zone (a parameter that is directly proportional to the presence of defects that can cause premature destruction).

When calculating elements reinforced with composite materials, the equation that applies to non-reinforced elements must be followed. The test should be performed at the limit states for strength and serviceability according to the relevant Eurocode standards [24].

Exhaustion of the carrying capacity is achieved when one of the criteria is exceeded [25]:

- 1) limit deformations of compressed fibers when the entire section is in the stretched zone;
- 2) limit deformations of stretched fibers when elastic deformations of wood develop in the compressed zone;

3) limit deformations of stretched fibers when plastic deformations of wood develop in the compressed zone;

4) ultimate deformations of compressed fibers when the FRP reinforcement is in the stretched zone;

5) ultimate deformations of compressed fibers when the FRP reinforcement is in the compressed zone.

Each of the criteria corresponds to its specific type of strain distribution, which in turn has its corresponding limiting value of the bending moment  $M_{Rd}$ . Analysis of the nature of the destruction of reinforced experimental samples indicates that criterion 3 is present in our case.

The value of the bending moment  $M_{Rd}^{theor}$  corresponds to the bearing capacity of the cross section and is found from the equation of the balance of moments (internal and external) relative to the center of gravity of the FRP reinforcement [25]:

$$M_{Rd} = M_3 \cdot B \cdot H^2 \cdot f_{cu}, \tag{1}$$

$$M_3(\xi) = \frac{1-\xi}{2 \cdot \eta} \cdot \left( \frac{1}{2} - \xi + \frac{2 \cdot (1-\xi)}{3 \cdot \eta} \right) + \frac{1}{2} \cdot \left( \xi - \frac{1-\xi}{\eta} \right) \cdot \left( 1 - \xi + \frac{1-\xi}{\eta} \right) + \eta \cdot \frac{1-\xi}{2} \cdot \left( \frac{1}{2} - \frac{1-\xi}{3} \right) + n \cdot \eta \cdot \left( \frac{p_{frp} - \xi}{1-\xi} \right) \cdot \rho_{frp} \cdot \left( \rho_{frp} - \frac{1}{2} \right). \tag{2}$$

By substituting the values of the actual characteristics of the materials (Table 1) into formulas (1), (2), the calculat-

ed value  $M_{Rd}^{theor}$  was determined. As the experimental value of the bending moment  $M_{Rd,ULS}^{exp}$  the load was taken, which corresponded to the achievement of the limit values of the wood's tensile stress (Fig. 7).

Table 2 gives the values of the ultimate bending moments that meet the criteria for complete destruction  $M_{ult}^{exp}$  and reaching the limit states ( $M_{Rd,ULS}^{exp}$  and  $M_{Rd,SLS}^{exp}$ ).

Experimental and theoretical values of ultimate bending moments of reinforced beams

Grade	Bending moment at the fracture stage $M_{ult}^{exp}$ , kN·cm	Bending moment for SLS (exp.) $M_{Rd,SLS}^{exp}$ , kN·cm	Bending moment at ULS (theoretical), $M_{Rd,ULS}^{theor}$ , kN·cm [25]	Bending moment for ULS (exp.), $M_{Rd,ULS}^{exp}$ , kN·cm	Reinforcement effect according to the criterion of strength ULS/fracture, %	Amplification effect according to the criterion of limit deflections at SLS, %	$\frac{M_{Rd,ULS}^{exp}}{M_{Rd,ULS}^{theor}}$
1-Cn	690	307	n/a	690	Control	Control	n/a
1-Rd	1050	318	720.5	780	13.1/52.1	3.6	1.08
1-Pl	1230	360	730.2	750	8.7/78.2	17.2	1.02
2-Cn	558	301	n/a	558	Control	Control	n/a
2-Rd	810	315	676.8	693	24.2/45.1	4.6	1.02
2-Pl	1089	330	705.3	738	32.2/95.1	9.6	1.04

The effect of reinforcement according to the criterion of limit deflections (SLS) of beams was determined by the percentage ratio  $M_{Rd,SLS}^{exp}$  of reinforced beams and control samples (1-Cn, 2-Cn). Similarly, the effect of reinforcement according to the criterion of destruction  $M_{ult}^{exp}$  and the achievement of ultimate stresses (ULS) in the wood  $M_{Rd,ULS}^{exp}$  of the beams was determined by the percentage ratio of these bending moments with the values in the control beams.

**6. Discussion of results of experimental studies to determine the effect of reinforcement of timber beams**

Analysis of stress distribution plots along the height of the beam (2-Rd) in Fig. 7, c revealed a displacement of the neutral axis by 5 mm higher at the late ( $F=19.5$  kN) stages of loading after the formation of cracks in the stretched zone. For samples (1-Pl, 2-Pl) Fig. 7, d, e, one sees the same displacement of the neutral axis upwards at significantly higher load levels ( $F=33$  kN). The development of significant plastic deformations (Fig. 7, e, f) corresponds to visually visible vertical zones of wood crumpling in the compressed zone (Fig. 10). The maximum depth of propagation of plastic deformations in the compressed zone of the beam is on average ~45 mm for samples 1-Pl, 2-Pl, and ~30 mm for samples 1-Rd, 2-Rd (Fig. 7, c-f, 9).

In the samples reinforced with rods, the failure of the reinforcement bond occurred faster in comparison with the beams reinforced with plates. However, complete destruction of the bond (delamination) did not occur in any of these test samples. The mechanism of destruction in the case of plate reinforcement is smoother. The probability of loss of adhesion of reinforcement to wood is greater for samples 1-Rd, 2-Rd due to the development of cracks that freely propagate from the lower face to the place of installation of reinforcement.

Compared to unreinforced beams, reinforced beams showed improved stiffness and flexural strength (Table 2).

Samples of the 1st series showed an increase in the destructive bending moment by 52.1 % when reinforced with rods, and by 78.2 % when reinforced with a plate. For beams of the 2nd series, these indicators were 45.1 % and 95.1 %, respectively. Such a significant increase in the destructive moment testifies to the significant potential of such structures in anti-seismic design.

Table 2

The stiffness of beams of the 1st series when reaching the limit deflections  $w_{lim}$  (SLS) was better than the indicators of the control samples by 3.6 % and 17.2 % for rods and plates, respectively. Series 2 elements showed the same trend (4.6 % and 9.6 %). From the point of view of beam stiffness, plate reinforcement proves to be somewhat more effective compared to rod reinforcement with increased load.

The significant deformability of the reinforcement elements does not allow them to be effectively included in the work at the early stages of loading.

However, for engineers, indicators of not only the destructive load but also the bending moments that correspond to the load-bearing capacity of the element, that is, the achievement of the ultimate stress of stretched fibers (ULS), are important for engineers. According to the results of our research, the strengthening effect was 13.1 % and 24.2 % (rods) and 8.7 % and 32.2 % (lamellas). Accordingly, plate reinforcement on the bottom face of the beam under the given research conditions has an advantage compared to rod reinforcement on the side faces.

Comparison of experimental results of ultimate bending moments (Table 2) showed that the actual effect of reinforcement is greater than theoretically calculated. The difference was no more than 8.2 % and confirms the conservative approach used in the CNR-DT-201 standards.

It should be noted that a certain limitation of such methods of strengthening is strict compliance with the work regulations and the formulation for the production of multi-component adhesive solutions. The slightest deviation can lead to a violation of the bond between reinforcement and wood already at the early stages of loading. From this point of view, rod reinforcement is simpler, has a smaller number of operations, and is less sensitive to operator errors. The use of simplified calculation models in the case of a complex stress-strain state and the variability of wood characteristics are also a limitation.

The disadvantage of these strengthening methods is the cost of CFRP materials and the need for economic justification when using them.

The development of the research may consist in expanded programs with a larger number of samples, other methods of reinforcement, and the use of FEM as a calculation model. Experiments were conducted on wood varieties and reinforcement elements that are widely represented in the Ukrainian market of construction and restoration materials. Reinforcement techniques



are widely used in project practice, and research results can be used during restoration works in Ukraine.

---

## 7. Conclusions

---

1. Deflections of beams reinforced with lamellae and rods decreased by 13.4 % and 4.1 %, respectively. These values correspond to the load at the stage of reaching the limit deflections of the beams  $M_{Rd,SLS}^{exp}$ .

2. In the studied cases of reinforcement, the plate better limits the propagation of cracks along the cross-section of the beam in comparison with rods. This allows more complete use of wood in the compressed zone of the beam. At the time of failure, when reinforced with a plate, ~40 % of the area of the compressed zone does not reach compressive strength, when reinforced with rods, ~60 %. The failure mode in both cases is smooth; no destruction of the bond between the reinforced elements and wood was recorded.

3. Reinforcement with a plate showed an increase in the failure bending moment  $M_{ult}^{exp}$  by 86.7 %, and reinforcement with rods by 48.6 %, which indicates significant anti-seismic properties of such types of reinforcement. If we analyze the bending moment, which corresponds to the achievement of the ultimate stresses in wood  $M_{Rd,ULS}^{exp}$ , the recorded strengthening effects are smaller –18.6 % (rods) and 20.5 % (plates).

The conclusions show the averaged values for two series. The analytical calculation showed a discrepancy between experimental and calculated values of up to 8.2 %.

---

## Conflicts of interest

---

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

---

## Funding

---

The study was conducted without financial support.

---

## Data availability

---

All data are available in the main text of the manuscript.

---

## Acknowledgments

---

All materials used to strengthen the samples were provided by Mapei-Ukraine.

---

## References

1. Meier, U. (2001). Strengthening and stiffening of historic wooden structures with CFRP. FRP composites in civil engineering: proceedings of the international conference.
2. Kawecki, B., Sumorek, A. (2022). Study on Profitability of Combining Wood and CFRP into Composite Based on Mechanical Performance of Bent Beams. *Applied Sciences*, 12 (20), 10304. doi: <https://doi.org/10.3390/app122010304>
3. Plevris, N., Triantafyllou, T. C. (1992). FRP-Reinforced Wood as Structural Material. *Journal of Materials in Civil Engineering*, 4 (3), 300–317. doi: [https://doi.org/10.1061/\(asce\)0899-1561\(1992\)4:3\(300\)](https://doi.org/10.1061/(asce)0899-1561(1992)4:3(300))
4. Saucier, J. R., Holman, J. A. (1975). Structural particleboard reinforced with glass fiber-Progress in its development. *Forest Prod. J.*, 25 (9), 69–72.
5. Bulleit, W. M. (1984). Reinforcement of wood materials: A review. *Wood and fiber Science*, 3, 391–397. Available at: <https://wfs.swst.org/index.php/wfs/article/view/832>
6. Ianasi, A. C. (2015). On the role of CFRP reinforcement for wood beams stiffness. *IOP Conference Series: Materials Science and Engineering*, 95, 012015. doi: <https://doi.org/10.1088/1757-899x/95/1/012015>
7. Karagöz İşleyen, Ü., Kesik, H. İ. (2021). Experimental and numerical analysis of compression and bending strength of old wood reinforced with CFRP strips. *Structures*, 33, 259–271. doi: <https://doi.org/10.1016/j.istruc.2021.04.070>
8. Saad, K., Lengyel, A. (2022). Experimental, Analytical, and Numerical Assessments for the Controversial Elastic Stiffness Enhancement of CFRP-Strengthened Timber Beams. *Polymers*, 14 (19), 4222. doi: <https://doi.org/10.3390/polym14194222>
9. Śliwa-Wieczorek, K., Ostrowski, K. A., Jaskowska-Lemańska, J., Karolak, A. (2021). The Influence of CFRP Sheets on the Load-Bearing Capacity of the Glued Laminated Timber Beams under Bending Test. *Materials*, 14 (14), 4019. doi: <https://doi.org/10.3390/ma14144019>
10. Fiorelli, J., Dias, A. A. (2003). Analysis of the strength and stiffness of timber beams reinforced with carbon fiber and glass fiber. *Materials Research*, 6 (2), 193–202. doi: <https://doi.org/10.1590/s1516-14392003000200014>
11. Corradi, M., Borri, A., Righetti, L., Speranzini, E. (2017). Uncertainty analysis of FRP reinforced timber beams. *Composites Part B: Engineering*, 113, 174–184. doi: <https://doi.org/10.1016/j.compositesb.2017.01.030>
12. Schober, K., Franke, S., Rautenstrauch, K. (2006). In-situ strengthening of timber structures with CFRP. CIB-W18/39-12-2. Florence. Available at: [https://www.researchgate.net/profile/Steffen-Franke-2/publication/306091279\\_In-situ\\_strengthening\\_of\\_timber\\_structures\\_with\\_CFRP/links/5848237508ae95e1d16651a6/In-situ-strengthening-of-timber-structures-with-CFRP.pdf](https://www.researchgate.net/profile/Steffen-Franke-2/publication/306091279_In-situ_strengthening_of_timber_structures_with_CFRP/links/5848237508ae95e1d16651a6/In-situ-strengthening-of-timber-structures-with-CFRP.pdf)
13. Brol, J., Wdowiak-Postulak, A. (2019). Old Timber Reinforcement with FRPs. *Materials*, 12 (24), 4197. doi: <https://doi.org/10.3390/ma12244197>



14. Biscaia, H. C., Chastre, C., Cruz, D., Franco, N. (2017). Flexural Strengthening of Old Timber Floors with Laminated Carbon Fiber-Reinforced Polymers. *Journal of Composites for Construction*, 21 (1). doi: [https://doi.org/10.1061/\(asce\)cc.1943-5614.0000731](https://doi.org/10.1061/(asce)cc.1943-5614.0000731)
15. Borri, A., Corradi, M., Grazini, A. (2005). A method for flexural reinforcement of old wood beams with CFRP materials. *Composites Part B: Engineering*, 36 (2), 143–153. doi: <https://doi.org/10.1016/j.compositesb.2004.04.013>
16. Johnsson, H., Blanksvärd, T., Carolin, A. (2006). Glulam members strengthened by carbon fibre reinforcement. *Materials and Structures*, 40 (1), 47–56. doi: <https://doi.org/10.1617/s11527-006-9119-7>
17. Nianqiang, Z., Weixing, S. (2017). Experimental investigations of timber beams strengthened by CFRP and Rebars under bending. *IOP Conference Series: Materials Science and Engineering*, 191, 012043. doi: <https://doi.org/10.1088/1757-899x/191/1/012043>
18. Wdowiak-Postulak, A. (2022). Strengthening of Structural Flexural Glued Laminated Beams of Ashlar with Cords and Carbon Laminates. *Materials*, 15 (23), 8303. doi: <https://doi.org/10.3390/ma15238303>
19. BS EN 408:2003. Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties. Available at: <https://knowledge.bsigroup.com/products/timber-structures-structural-timber-and-glued-laminated-timber-determination-of-some-physical-and-mechanical-properties-2/standard/details>
20. Carboplate. Available at: [https://cdnmedia.mapei.com/docs/librariesprovider58/products-documents/1001\\_carboplate\\_gb.pdf?sfvrsn=9e5f46ec\\_0](https://cdnmedia.mapei.com/docs/librariesprovider58/products-documents/1001_carboplate_gb.pdf?sfvrsn=9e5f46ec_0)
21. Maperod C. Maperod G. Available at: [https://cdnmedia.mapei.com/docs/librariesprovider12/products-documents/1\\_01015\\_maperod-c\\_en\\_cd885f927c8842beab063d7a02cba08f.pdf?sfvrsn=9c63b22d\\_0](https://cdnmedia.mapei.com/docs/librariesprovider12/products-documents/1_01015_maperod-c_en_cd885f927c8842beab063d7a02cba08f.pdf?sfvrsn=9c63b22d_0)
22. Bula, S., Kholod, M. (2020). Experimental Study of Compressed Ceramic Hollow Brick Masonry Structures Strengthened with GFRP Meshes. *Proceedings of EcoComfort 2020*, 71–78. doi: [https://doi.org/10.1007/978-3-030-57340-9\\_9](https://doi.org/10.1007/978-3-030-57340-9_9)
23. Bula, S., Kholod, M. (2022). Experimental Research of Damaged Clay Solid-Brick Masonry Strengthened with GFRP Wrapping. *Proceedings of EcoComfort 2022*, 48–55. doi: [https://doi.org/10.1007/978-3-031-14141-6\\_5](https://doi.org/10.1007/978-3-031-14141-6_5)
24. EN 1995-1-1 (2004) (English): Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings. Available at: <https://www.phd.eng.br/wp-content/uploads/2015/12/en.1995.1.1.2004.pdf>
25. CNR-DT 201/2005 (2007). Guidelines for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures. *Timber Structures*. Available at: <https://www.cnr.it/en/node/2637>