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Novel experimental method of pull-off strength with carbon fiber reinforced polymers composite made of wooden beams

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ABSTRACT

The main purpose of this paper is to analyze the results obtained during the conducted tests of the pull-off strength of a carbon fiber reinforced polymer (CFRP) composite glued to pine beams made of glued wood previously subjected to destructive tests. Three research methods were used in the tests to determine the CFRP composite's pull-off strength from the wooden beams' surface. In this research the Authors experimental method was used, PN-EN 1542 and ASTM C1583 standard. Pearson linear correlation analysis allowed to identify the relationship between the forces that destroyed the beams and their pull-off strength. The assumptions of the experimental method, description, and preparation of the samples for testing, the course of testing, the method of applying the pull-off force, and the types of substrate destruction were considered as well. The conducted tests showed that the most common causes were detachment of the composite layer from the wood, cohesive destruction in the substrate of the tested elements, and adhesive destruction between the adhesive layer and the disc, which were not determined in previous studies.

Keywords: pull-off, wooden structures, adhesion, epoxy resin, semi-destructive testing, CFRP composite.

INTRODUCTION

Wood has always been a basic construction material. This truly ecological, fully renewable, healthy and environmentally friendly material has been used by humans for thousands of years. Adequately protected and maintained, it can perform a structural role no worse than concrete or steel. As is known, mechanical properties are above all depended on the distribution of cellulose polymers occurring in the cell wall. For wood, this serves as a supporting skeleton. Furthermore, the mechanical properties also result from the amorphous lignin that fills the free spaces of the skeleton. Cellulose affects elastic properties, while lignin affects plastic properties. Together with capillary water filling the porous wood fibers, the complex structure of wood determines its mechanical and physical properties. The distribution of annual rings, divided into early and late growth, characterizes the mechanical properties of wood. Coniferous wood with dense rings is more suitable for construction than wood with wide rings. Wood is characterized by anisotropic properties as well. Its physical and mechanical ones can be changed depending on the direction recognized. From an engineering point of view you can see that the tensile, bending, and compressive strength depends on the direction of the forces acting about the direction of the fibers [1–2]. Wood is described by the exceptional mechanical parameters occurring along the grain, which, combined with its low density, allows for constructing light structures with large spans and heights. However, wooden structures, like other building materials, require repair or reinforcement, which may be a consequence of different factors, such as atmospheric, chemical or biological, as well as temperature changes, destructive effects of the environment, and design and construction errors [3]. It is also possible that the requirements that the user of the object originally set as their goal change, which consequently results in a change in the object's load-bearing capacity. Thereby, it becomes necessary to take actions that will increase the load-bearing capacity of the structure, e.g., by strengthening it with another material. As a result, before strengthening a particular structural element, detailed numerical and/or experimental analyses are carried out, which include the detection of damages occurring in similar structures [4] and the simulation of static [5] and dynamic loads [6-8] that may affect the materials durability [9].

In turn, dynamically developing materials engineering and the constantly growing needs and requirements of construction force the development of newer materials that would reduce production costs and, at the same time, be described by better strength, physical and chemical parameters than other traditional materials characterized by greater stiffness and possibly low density. This is how composites were created, becoming one of the most visible and original success of engineering materials [10].

Composite material side of at least two different components: a matrix and reinforcement, which were linked at the macroscopic level [11]. Composites were not, for example, metal alloys, which on a microscopic scale create a composition of many components. However, in the macroscopic image their behavior looks like typical homogeneous materials. Composites created based on synthetic polymers successfully replace methods that have been proven and widely used so far [12–21]. Undoubtedly, their advantage is more favorable strength and physical and chemical parameters than traditional materials. Additionally, they were characterized by many advantages, like greater strength and stiffness. It is also worth emphasizing such a feature as low density.

The first attempts to strengthen wooden beams with prestressed carbon tapes were carried out in 1992 by Triantafillou [22]. The tests included load-bearing capacity tests of beams with dimensions of 45 × 40 × 800 mm subjected to a three-point bending test. They were carried out on beams without reinforcement, reinforced with a composite tape without prestressing, and reinforced with a composite tape prestressed – 620 MPa. In [23], the results of tests on beams from a 32-year-old wooden quonset structure were presented. The beams were intentionally damaged and weakened by creating a notch in the middle of their span in the critical deflection area. Then they were reinforced with carbon fiber reinforced polymer (CFRP) composite. The tests showed that CFRP reinforcement improved the load-bearing capacity by up to 184% and the deflection ductility by up to 165% compared to the reference beams. Khelifa, Celzard, Oudjene, and Ruelle [24] carried out experimental bending tests on spruce wooden beams reinforced with CFRP material. Four-point bending tests were considered to determine the stiffness and strength of reinforced wooden beams. It turned out that the load-bearing capacity of the beams was increased by using CFRP reinforcement. Nowak [25], investigated the use of CFRP composite strips. The tests used 18 old, approximately 100-year-old pine beams, constituting series *A*-*F*. Beams from series A and G were not reinforced; they were a reference level for assessing changes about reinforced beams. The tests conducted were extensive and included, among other things, the loading force and the displacement of the beam in the middle as well as on the supports. Furthermore, deformations in the wood and the CFRP tape were also examined. The next aspect that was considered was to determine the destructive force and indicate the method of destruction. The tests showed an increase in load-bearing capacity for the *F* series beams by 21% and for the *D* series beams by, slightly over 79%. Paper [26] describes the bending strength of wooden beams strengthened using CFRP. First, a theoretical analysis of CFRP-equipped wooden beams was developed. Then, a four-point bending test was used to consider the load-displacement relationship of the wooden beams. During the tests, it was observed that the bending strength increased. Furthermore, the central vertical displacement decreased for the CFRP-equipped wooden beams compared to those without CFRP. An increased percentage of bending strength was observed in the range of 39 to 61%. An interesting example of CFRP reinforcement was the study of the behavior of an ancient wooden structure reinforced with a CFRP polymer sheet made on a 1:2 scale and subjected to earthquake simulation [27]. Three seismic excitations, El Centro, Tafta, and Lanzhou, were used in the study as excitation waves. During the study, the displacements of (i) the column base, (ii) the column head, (iii) the set of supports, (iv) the eaves beam, and (v) the entire structure due to the earthquake were recorded, monitored and analyzed. The studies showed that the strengthened ancient structure is characterized by appropriate seismic load-bearing capacity and complies with the requirements for a small earthquake.

Interesting studies on strengthening wooden structures with CFRP composite materials were also presented in [28–35]. In paper [28], the flexural behaviour of the glued beams reinforced by NSM-CFRP reinforcement was analysed. In this research, glued beams, reinforced beams and bending tests were carried out. The obtained results regarding load–deflection behaviour, failure modes, strengthening effects, and strain profile distribution were discussed. In [29] described similar research. In this paper, the Authors show the increase of the stiffness and flexural capacity of the composite beams when reinforced with CFRP through a few experiments, thus verifying the reinforcement efficiency. A statistical analysis was also carried out to quantify the tests' reliability and evaluate the results. Moreover, in [30], the experimental studies were described. The major aim was strengthen finger-jointed timber beams using CFRP material. These beams were subjected to a four-point bending test and restored their load-bearing capacity. In order to simulate the progressive failure of the finger-joint, a numerical procedure based on Cohesive Zone Models available in Abaqus software was shown. In study [31], a pre-tensioning system and prestressing methodology based on tensioning against the strengthened beam were proposed. Few critical aspects were investigated in the assessment process, including: (i) sustained load level, (ii) pre-tensioned strain level, and (iii) external composite reinforcement ratio. These parameters were assessed both experimentally and numerically. However, in paper [32], two types of externally bonded CFRP were applied on LVL beams. The efficiencies of such applications was analyzed in terms of maximum load-carrying capacity, ductility, and bending stiffness. These two types include covering a CFRP sheet on the soffit of the beam and as a U-wrap on the tension side of the beam. Fascinating results were shown in the paper [34]. The Authors presented tests carried out on old pine beams (over 200 years in service) extracted from the roof of the School of Law at the University of Granada (Spain). The research cover of the presentation of the method of this modification and the indication of much lower errors between analytical and experimental values for bending load capacity. In this paper, it was observed that a better mechanical behavior occurred in the reinforced specimens exhibit than in control beams (without reinforcement). In paper [34], an experimental research was conducted using full-scale timber beams strengthened with carbon fibre composite material. The authors focused on the bond between timber and FRP by testing its strength and behavior. Furthermore, several factors affecting FRP-to-timber beams were identified. To study the bonding performance of the interface between CFRPs and wood, the double shear test was analysed in [35]. Attention was also paid to how the length and width of the CFRP bond may be reflected in the properties of the interfacial bond. Moreover, the distribution of strains in the CFRP plates obtained throughout the entire loading process was presented. The CFRP–wood interfacial bonding bearing capacity model was presented. Additionally, the interfacial bonding shear stress–slip relationship model was evaluated. Ultimately, based on the conducted research, the authors demonstrated that the proposed models provide a theoretical basis and a practical reference for CFRP-aided strengthening of wood structures.

This article presents the results of testing the pull-off strength of a CFRP (carbon fiber reinforced polymers) composite glued to a pine beam made of glued wood. In this paper, a new method was presented that supplements current knowledge on the use of CFRP in wood beams. The wooden beams were previously subjected to destructive tests widely described in [36–37]. Based on these results, destructive tests with CFRP reinforcement were carried out to supplement the previously cited tests. To determine the most accurate detachment strength of CFRP from the surface of wooden beams, three research methods were used: (i) Authors experimental method, where the cut depth was 1.0 mm; (ii) PN-EN 1542 standard [38] with a cut depth of 5.0 mm in the composite and wood layers, and (iii) ASTM C1583 standard [39], in which the composite and wood layers were cut to a depth of 10 mm. It should be added that the standard methods presented: (i) PN-EN 1542 standard [38] and (ii) ASTM C1583 standard [39] ensure that the correct destruction occurs in the wood layer only at the depth of the cut.

In the conducted tests, the information on the pull-off strength was the detachment of the composite from the wood layer, so that the composite was glued only to the steel disc. Therefore, based on the earlier Authors experience, a cut (notch) in the composite layer thickness of 1 mm was sufficient, as was proved in this research. A linear Pearson correlation analysis was also performed, to determine the relationship between the detachment strength and the forces that destroyed the beams. Moreover, the results indicate that the Authors method is more optimal than previous studies because the wood layer is not destroyed.

DESCRIPTION OF EXPERIMENTAL MODELS

Carbon fibers determine the load-bearing capacity of the tensile zone of the wooden element. The interaction between the fiber and the resin matrix, which is responsible for absorbing the external load, should also be emphasized. The composite's cooperation mechanism with the wooden beam constitutes the essence of the reinforced structure. It is possible, among others, by the adhesion of the carbon fiber and the surrounding matrix. Three pine beams were used for the tests on this paper's subject. These beams were the basis for the previously conducted destructive tests, described in detail in papers [36-37].

In this paper, wooden beams were subjected to bending tests (Figure 1). The tests were carried out in the Material Strength Laboratory of the Kielce University of Technology. The research subject was full-size beams of laminated veneer reinforced with CFRP sheets. The study aimed to analyse the effectiveness of the reinforcement. The beams were strengthened with one layer of CFRP sheet bonded (reinforcement ratio, ρt = 1.11%). Properties of the CFRP: (i) Young modulus of 240 kN/mm², tensile strength of 4400 N/mm². In this research, the effect of wood moisture content and wood types on detachment strength has not been investigated. The reason for this lack of testing was that the moisture content difference was too small (1%), and only one type of glued wood (pine) was used. Furthermore, the studies examined glued laminated wood, which has approximately 80% higher strength than traditional structural timber. Bonding individual wood layers with glue increases dimensional stability, making glued laminated wood more resistant to deformation. This process provides high load-bearing capacity, similar to steel or concrete, so it was assumed that the detachment strength would be lower than the strength of the laminated wood layers. It should be noted that sanding and chemically treating CFRP composites can significantly weaken them, potentially leading to inaccurate results. Furthermore, sanding can damage (abrade) the composite due to the heat generated. This can result in a loss of adhesion due to resin vitrification. Furthermore, the pull-off tests performed involved a component that was actually researched in the structure, and the use of chemical and mechanical methods for surface preparation could have been detrimental to the research. Therefore, the study was limited to surface degreasing. In addition, in this research was used glue S & P Resin HP 55. The tested beams were previously reinforced with CFRP composite. Each beam was divided into two equal parts, i.e., (i) beam I: I-1, I-2, (ii) beam II: II-1, II-2, (iii) beam III: III-1, III-2. The beams were made of pine wood with dimensions of 43 × 200 × 1400 mm each (Figure 1).

During the destructive tests described later in this paper, the results for the destruction of bent pine beams were presented, in their central zone, i.e., in the places of the most incredible bending moment (between actuators). Then, the individual destroyed wood-composite layers were cut off. Finally, beams with dimensions as above, i.e., 43 × 200 × 1400 mm, were obtained for the pull-off tests after the cut-off destroyed fragments. It should be emphasized that beams I-1 and I-2, II-1, II-2, III-1, and III-2 were beams with damaged layers of wood and composite cut off. In the tests, the thickness of the CFRP layer was about 1 mm. In turn, the strength class of wood was determined as C27. Moisture content for the tested pine beams was: (i) I – 13.3%, (ii) II – 13.9%, and (iii) III – 14.2%. On the other hand, the density was equal to that of the wooden pine beams: (i) I – 0.59 g/cm^3, (ii) II – 0.60 g/cm^3, and (iii) III – 0.61 g/cm^3.

Each beam was glued with 18 pieces of steel discs with a diameter of 50 mm. A total of 108 samples (steel discs) were tested. The method of their arrangement on the tested beams was shown in Figure 2. The beams were reinforced with a CFRP composite. The process of strengthening the tested beams was presented in Figure 3.

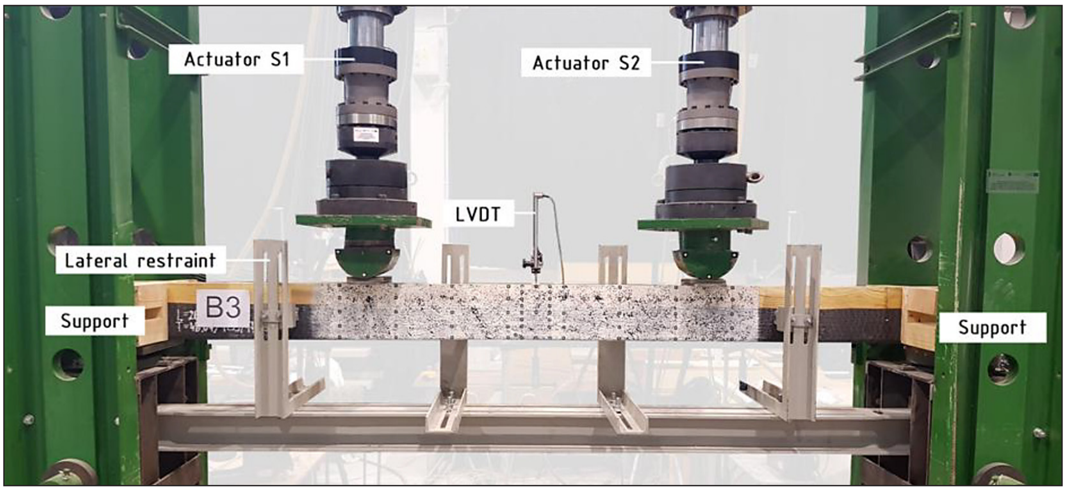


Figure 1. View on the static experimental test

EXPERIMENTAL TEST

General remarks

The tests were divided into four stages. In stage I, the CFRP composite pull-off strength from the wooden beam substrate was determined, assuming a composite cut depth of 1 mm. The test was performed based on Authors experimental method, specifying Authors assumptions and types of damage. The tested samples were marked in green (Figure 2).

In Stage II, the CFRP composite pull-off strength from the wooden beam substrate was determined, assuming a composite cut depth of 5 mm (notch) according to the assumptions of the PN-EN 1542 standard "Products and systems for the protection and repair of concrete structures – Test methods – Measurement of adhesion by pull-off" [38]. The samples were marked in black in Figure 3.

In stage III, the CFRP composite pull-off strength from the wooden beam substrate was determined according to the ASTM C1583 standard "Standard test method for tensile strength of concrete surfaces and the bond strength or tensile strength of concrete repair or overlay materials by direct tension (pull-off method)" [39], assuming, by the assumptions of this standard, a composite

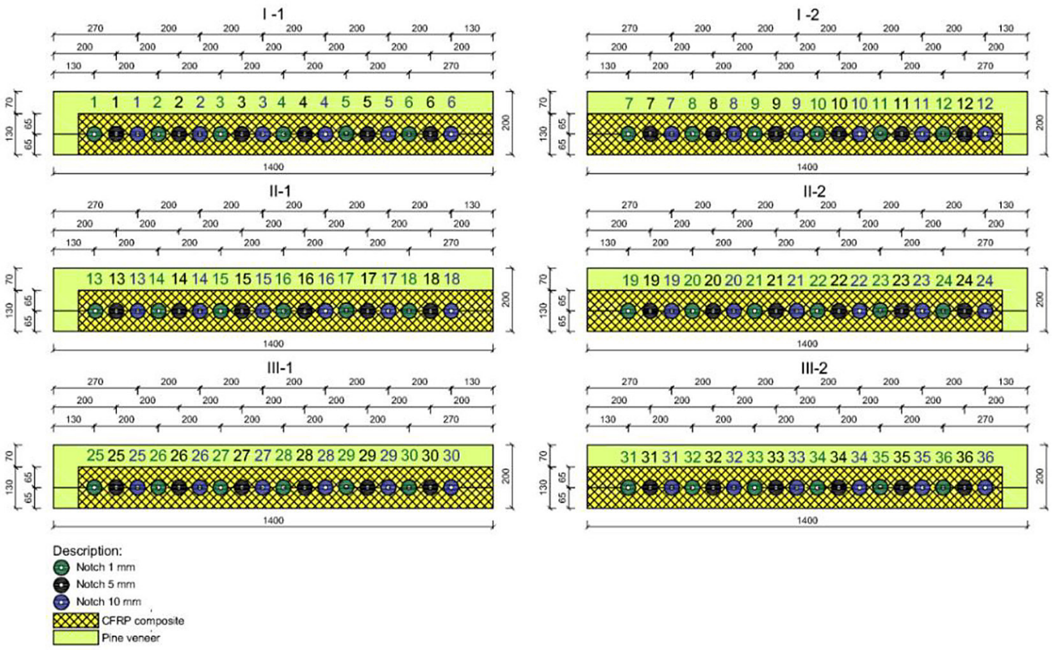


Figure 2. Arrangement of steel discs

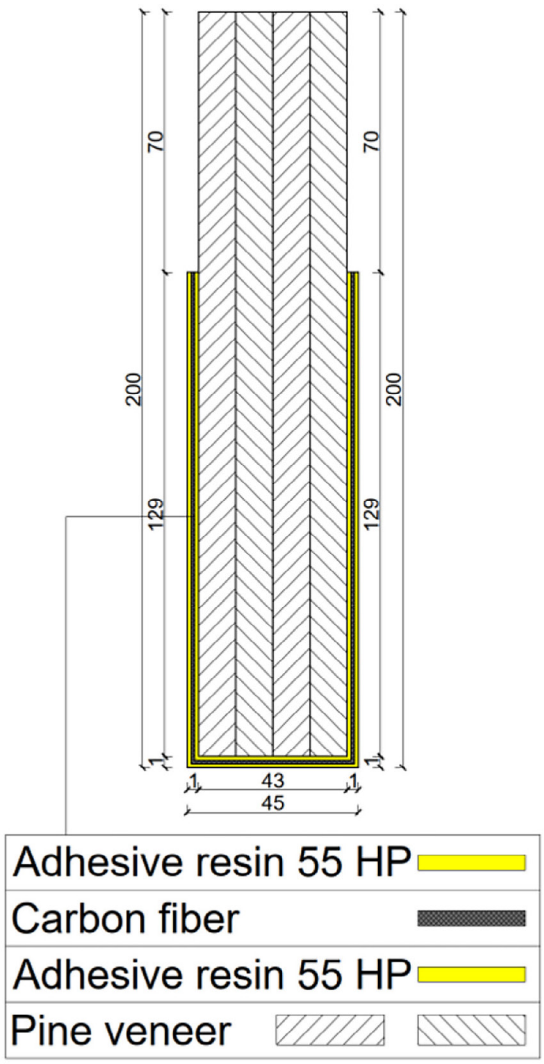


Figure 3. The strengthening of a veneer beam of research

cut depth of 10 mm. In this case, the samples were marked in blue.

In stage IV, Pearson linear correlation analysis was performed to determine the interdependence of the results obtained from stages I–III. The relationship between the CFRP composite pull-off strength from the wooden beam substrate and the forces that destroyed the beams was also determined.

The pull-off test is intended to indicate the tensile strength of the materials and the adhesion of the layers. It is performed on the composite surface.

The developed Authors experimental method determines five types of damage listed in Table 1. The result was correct when the composite was torn off from the substrate without destroying the wood layer. The measurement results were expressed in MPa.

According to the standard [38], the obtained test measurement result value was expressed in MPa. This value is the result of the force of separation of the layer of previously cut material (to which the cylindrical measuring pin breaking the sample was glued) relative to the surface of the cut layer. The standard [38] indicates 8 types of standard damages listed in Table 2 and cases when the measurement results should be rejected. The measurement result was considered entirely correct when the destruction, i.e., the pull-off of the disc with the tested material, occurs in the tested substrate.

According to the standard [39], the pull-off strength was calculated from the quotient of the tensile load to the sample surface. The value was expressed in MPa. The standard [39] defines 4 types of substrate destruction described in Table 3. Similarly, to the standard [38], the correct result was the pulling-off of the disc with the tested material in the tested substrate.

Description of stage I

In the first stage of the experimental study, the pull-off strength of the CFRP composite with a cut depth of 1 mm (notch) from a pine beam made of glued wood was determined according to Authors experimental method. This method consisted of cutting only the CFRP composite layer to a thickness of 1 mm without interfering with the wood surface. The main assumption of the method was to determine the pull-off strength of the “CFRP – wood” adhesive joint without damaging the wood. According to the authors, this test should most reliably reflect the CFRP composite pull-off strength from wood because only the composite itself will be pulled-off. This was the major aim of the experimental study. In addition, this test indicates that the force used was a real value defining the pull-off strength of the composite from the wood. The Authors experimental method defines 5 types of damages, which were listed in Table 1.

First, the surface of the CFRP composite was cut with a diamond core drill set at an angle of 90 ± 10 to the surface of the beams to a depth of 1 mm so that only the composite was cut. The goal of the next step was degreasing of the place where the discs and steel discs with a diameter of 50 mm were glued with technical acetone. Then, a two-component glue based on epoxy resin Dragon 5 min was evenly spread on the surface of the steel discs in such a way as to obtain a glue bond thickness of ± 1.0 mm.

Table 1. Types of failures according to the Authors experimental method (stage I of the conducted research)

No.	Type of failure	Description of failure
1	*α*	Pull – off the entire composite from the timber surface
2	*β*	Pull – off the fragment of the composite from the timber surface
3	*γ*	Pull – off the entire composite from the surface along with the whole timber substrate layer
4	*δ*	Pull – off the fragment composite from the surface, along with the fragment of the timber substrate layer
5	*ε*	Adhesion failure between the adhesive layer and the dolly

Table 2. Types of failures according to PN-EN 1542 [38] (stage II of the conducted research)

No.	Type of failure	Description of failure
1	*A*	Cohesion failure in the concrete substrate
2	*A/B*	Adhesion failure between the substrate and the first layer
3	*B*	Cohesion failure in the first layer
4	*B/C*	Adhesion failure between the first and second layer
5	*C*	Cohesion failure in the second layer
6	*–/Y*	Adhesion failure between the last layer and the adhesive layer
7	*Y*	Cohesion failure in the adhesive layer
8	*Y/Z*	Adhesion failure between the adhesive layer and the dolly

Table 3. Types of failures according to ASTM C1583 [39] (stage III of the conducted research)

No.	Type of failure	Description of failure
1	a	Failure in substrate
2	b	Bond failure at concrete/overlay interface
3	c	Failure in overlay or repair material
4	d	Bond failure at epoxy/overlay interface

Due to the lack of specialist equipment to determine the surface roughness of the tested samples, further tests were undoubtedly indicated. Therefore, the roughness of the wooden beam and the connection of the steel disc with the composite were assessed visually. The wood surface was evaluated as smooth, while the composite surface was uneven and slightly wrinkled in some places – hence, more two-component epoxy resin glue had to be applied in some areas.

By the glue manufacturer's assumptions, the test was started 24 hours after application. Finally, six samples were prepared for each tested beam – a total of 36 samples. The arrangement of the tested samples was shown in Figure 4.

The research was carried out using the PosiTest AT-M Adhesion Tester with software recording the pull-off force. The measuring device was set at an angle of 900 to the drilled surface, securing it so that they do not change position during the test. The load increased evenly and continuously at 0.05 MPa/s until destruction occurred. The pull-off test scheme was presented in Figure 5. The pull-off strength of the tested samples was calculated using the formula of the standard [38]:

$$f_h = \frac{4F_h}{\pi D^2} \tag{1}$$

where: f_h – pull-off strength of the tested sample [MPa], F_h – load at destruction [N], D – average sample size [mm].

Description of stage II

The second stage determined the CFRP composite's pull-off strength from a pine beam made of glued wood with a cut depth of 5 mm according to the PN-EN 1542 standard [38]. According to the standard [38], the test measurement result was a value expressed in MPa calculated from the force at which the layer of previously cut material (to which the cylindrical measuring pin breaking the sample was glued) was removed, in relation to the surface of the cut layer.

The standard lists 8 types of standard damages (Table 2) and presents cases when the measurement result should be rejected. The measurement result was considered fully correct when destruction occurs in the tested substrate, i.e., separation of the disc with the tested material. The measurement of the "CFRP - wood" adhesive joint resistance to pulling-off consisted of determining the actual tensile strength of the tested material, with minor damage to its layer (semi-destructive method). The PN-EN 1542 [38] standard determines the number and arrangement of samples. According to the standard, at least one product or repair system sample was required, on which five tests should be conducted. Six samples were used in the tests for each of the tested beams – 36 samples marked in black.

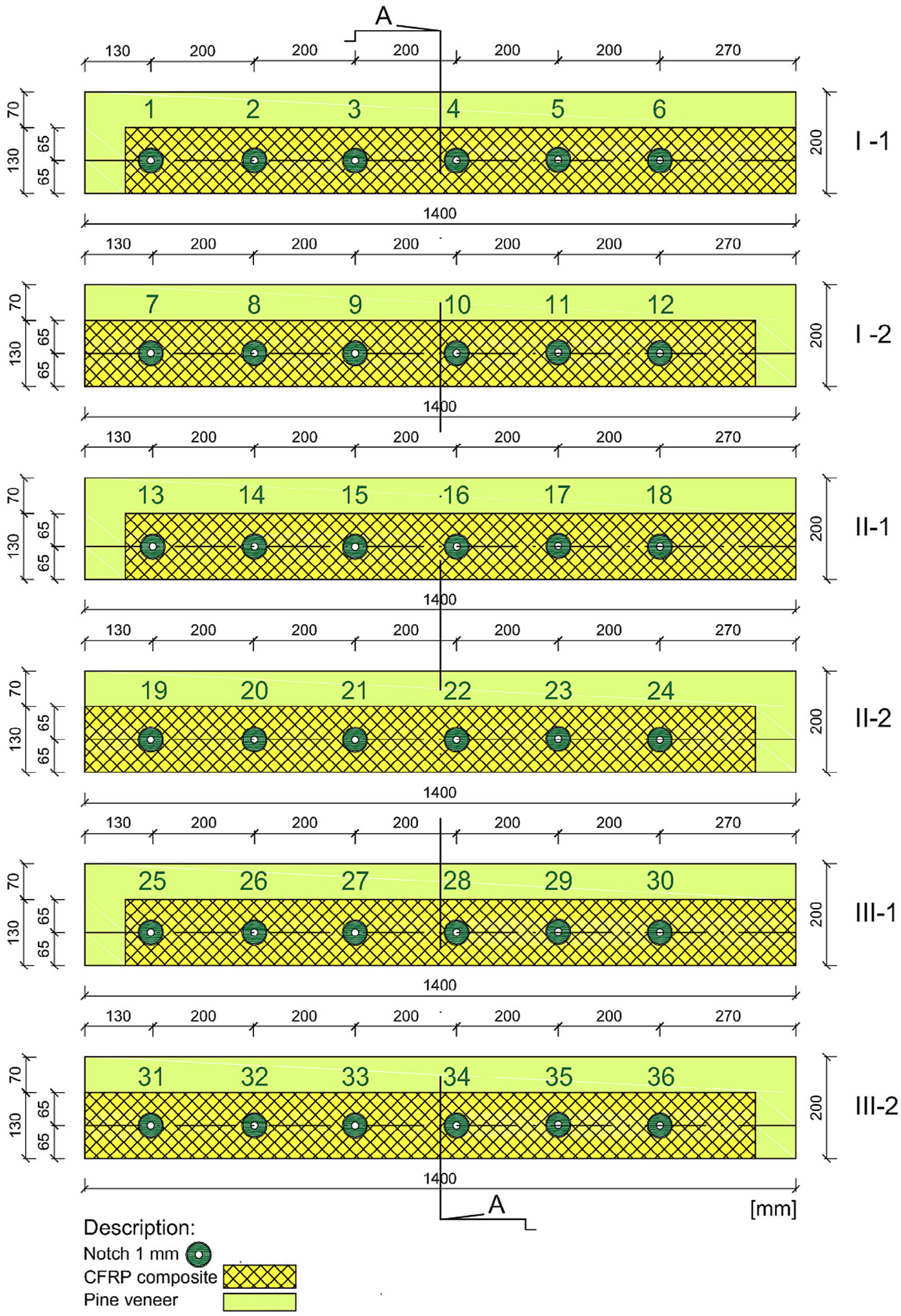


Figure 4. Distribution of tested samples

Similarly, to stage I of the experimental study, the CFRP composite surface was first cut using a diamond core drill set at an angle of 90 ± 10 to the beam surface. The depth of the cut at this stage of the study was 5 mm, so the composite and the wood layers were cut according to the assumptions resulting from the formula specified in the standard [38].

$$d_1 = d_d + (15 \pm 5) \quad (2)$$

where: d_1 – total drilling depth [mm], d_d – layer thickness [mm].

The subsequent steps of stage II were analogous to stage I, as described earlier in the text. The arrangement of the tested samples was shown in Figure 6. The scheme of the conducted test was

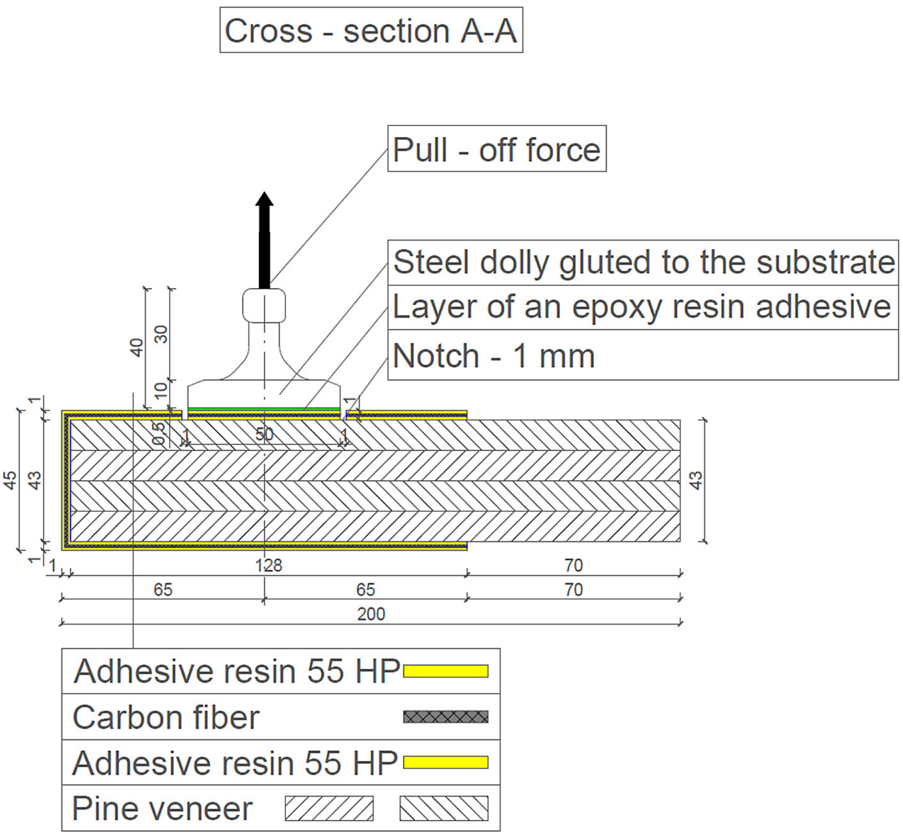


Figure 5. Pull–off test scheme for stage I

indoicated in Figure 7. The test samples' pull-off strength was calculated using the formula of the standard [38] (as described earlier in the text).

Description of stage III

In the third stage of the experimental study, the CFRP composite pull-off strength was determined from a pine beam made of glued wood with a cut depth of 10 mm according to the ASTM C1583 standard [39]. Six samples were used for each of the tested beams – 36 samples marked in blue. The individual steps of the third stage of the experimental tests were performed in the same way as in stages I and II (as described earlier in the text). The arrangement of the tested samples was shown in Figure 8.

The research was carried out using the PosiTest AT-M Adhesion Tester with software recording the pull-off force. The measuring device was set at an angle of 900 to the drilled surface, protecting it from changing position during the test. The standard [39] recommends that the tensile stress increase at 35 ± 15 kPa/s. Due to the use of a constant rate of 0.05 MPa/s in stages I and II according to the standard [38], it was decided to adopt a tensile stress rate of 0.05 MPa/s for the tests. The considered scheme was presented in Figure 9. Based on the obtained results, the pull-off strength of the tested samples was calculated using the formula included in the standard [39].

$$B_t = \frac{T_l}{A} \tag{3}$$

where: B_t – Bond or tensile strength [MPa], T_l – Tensile load [N], A – Area of the test specimen [mm^2].

RESULTS OF EXPERIMENTAL RESEARCH

Carbon fibers determine the load-bearing capacity of the tensile zone of the wooden element. Table 4 presents the pull-off strength values and the description of the destruction for the individual tested samples in each analyzed test stage (stages I – III). A statistical analysis was performed for each stage of the experimental study, the results of which were presented in Table 5.

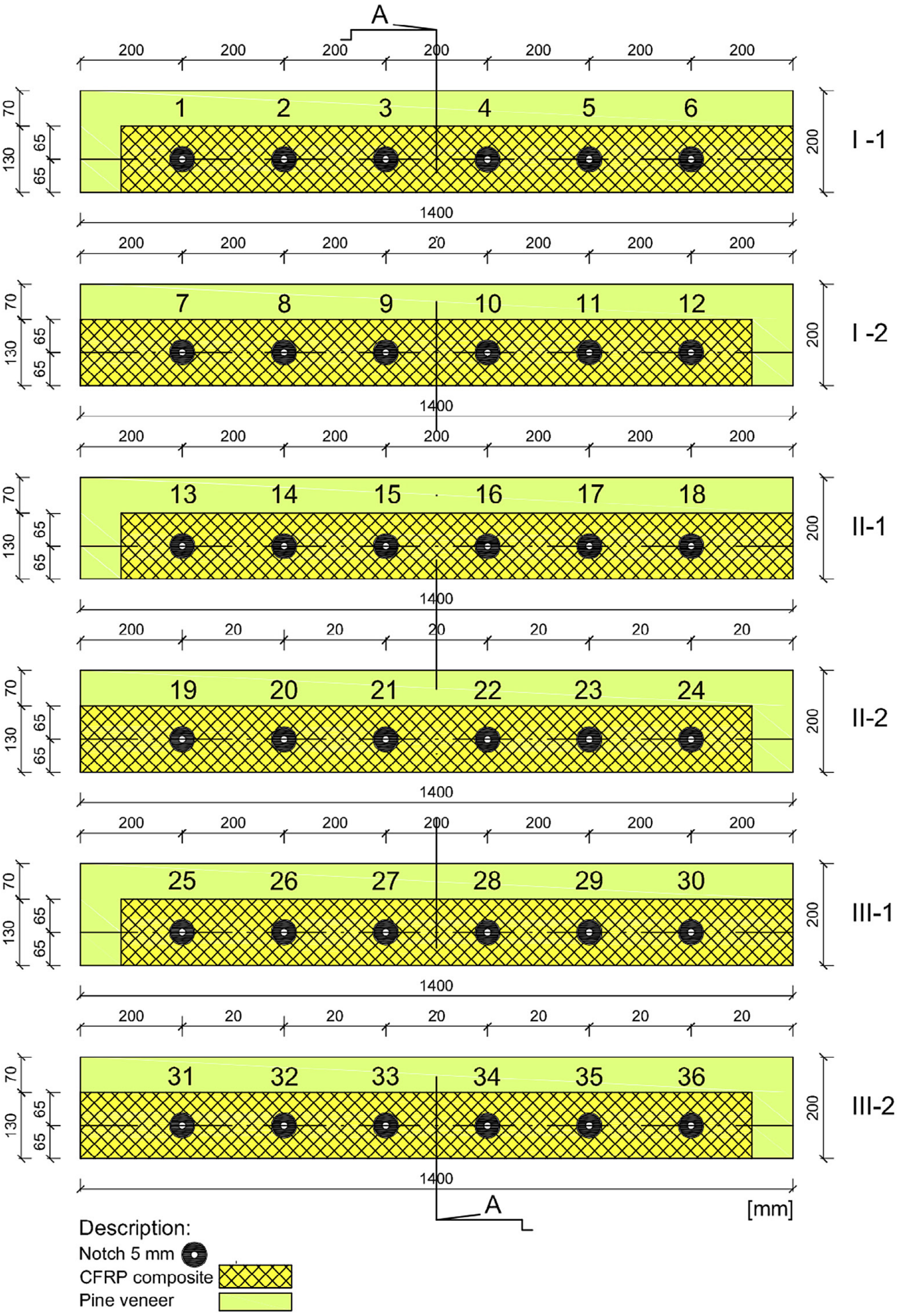


Figure 6. Distribution of tested samples for stage II. Samples marked in black colors

Results from stage I

In stage I, where the cut depth was 1 mm (notch), "*A*" type damage was observed in 23 cases. It consisted of detachment of the composite itself from the wood surface. In the remaining 13 cases, adhesive damage occurred between the adhesive layer and the "*Y/Z*" type disc (Table 4). Examples of samples with "*A*" and "*Y/Z*" type damages were shown in Figure 10.

The "*A*" type of damage was the most reliable way to determine the pull-off strength of the CFRP composite from the wood. The pull-off of the composite without the wood layers means that the applied force was the most reliable value for determining the pull-off strength because

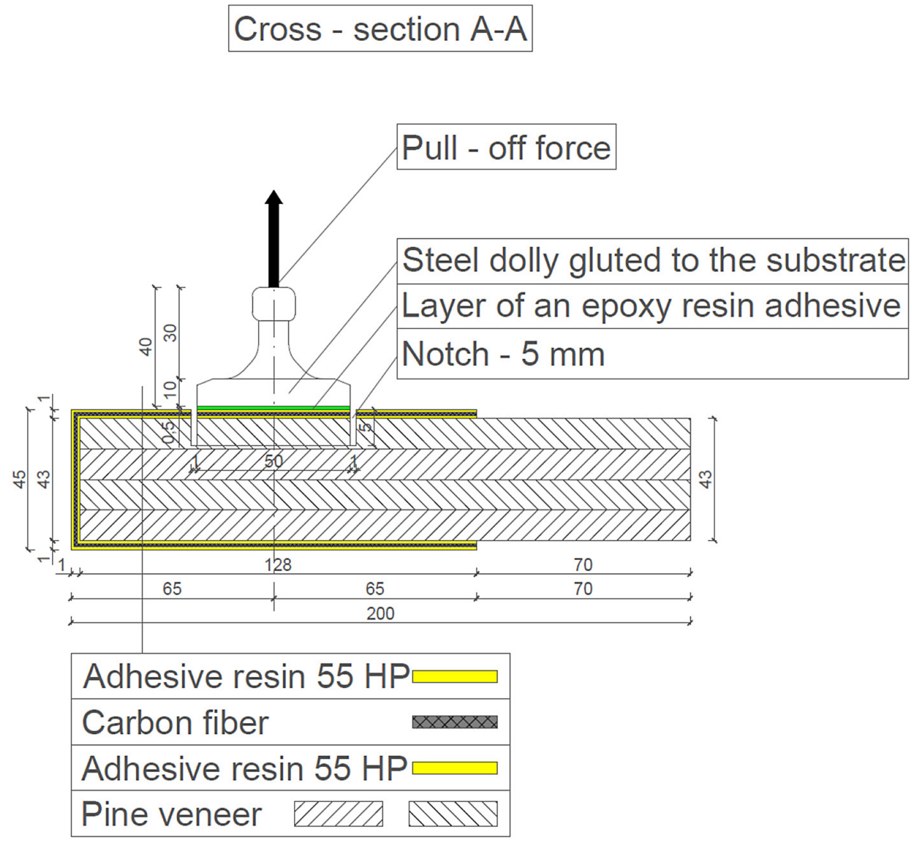


Figure 7. Pull–off test scheme for stage II

no wood material was pulled-off. The arithmetic average of the pull-off strength for "*A*" damages was of 1.76 MPa andwas close to the average strength for "*Y/Z*" damages, which was of 1.96 MPa. This means that in order to pull-off the metal disc together with the composite layer from the substrate without destroying it, the pull-off strength of each of the 23 samples was, on average of 1.76 MPa. The rejected results, the arithmetic mean of which was close to the correct values, also suggest good adhesion of the composite to wood. Still, in this case, the adhesion of the glue used to the metal disc turned out to be too low to detach the composite. However, despite rejecting the results, a greater pulling-off force was needed to detach the composite than the values obtained during the tests.

Based on the tests that were conducted, a statistical analysis was performed, the results of which were presented in Table 5.

Results from stage II

In 27 cases, cohesive failure of type "*A*" was observed in the substrate, while in 9 cases, adhesive failure between the adhesive layer and the disc of type "*Y/Z*" occurred, as shown in Figure 11.

The arithmetic mean strength of the samples for the "*A*" damage was 1.51 MPa and was not close to the mean value of 1.64 MPa for the "*Y/Z*" type of damage. This means that to pull-off the metal disc with the composite layer from the substrate together with the wood layer, the pull-off strength of each of the 27 samples was, on average of 1.64 MPa. Rejected results, the arithmetic means of which was not close to the correct ones, also indicate good adhesion of the composite to wood; however, in this case, too, the adhesion of the glue used to the metal disc turned out to be too low to detach the composite together with the wood layer.

Despite the rejection of the results, a higher pulling-off force was needed to detach the composite than the values obtained during the tests, indicating a good "CFRP - wood" connection. The summary of the statistical analysis of the test results was shown in Table 5.

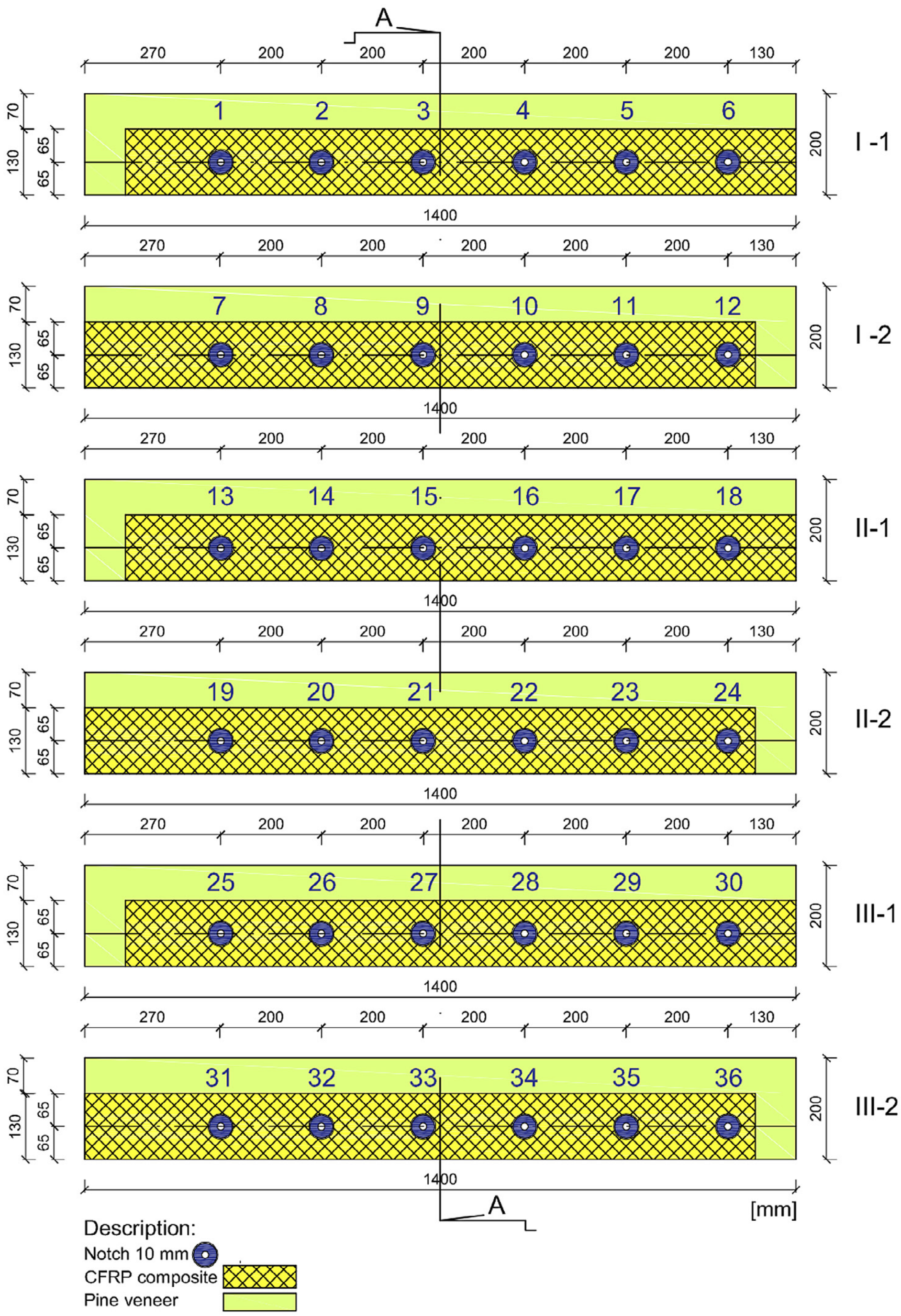


Figure 8. Distribution of tested samples for stage III. Samples marked in blue colors

Results from stage III

In stage III of the tests, in which the cut was made at 10 mm, in 29 cases, type "*a*" damage was observed in the substrate. In the remaining 7 cases, damage occurred between the adhesive layer and the type "*d*" disc. Examples of samples with observed damage were shown in Figure 12. The arithmetic mean strength for type "*a*" damage was 1.14 MPa. This value was not close to the mean value of 1.29 MPa for type "*d*" damage. This means that to pull, off the metal disc together with the composite layer from the substrate, the pull-off strength of each 27 samples was, on average of 1.14 MPa. Rejected results, the arithmetic means of, which was higher than the correct results, but was not close to them, also indicate good adhesion of the composite to the wood. However, in this case, the adhesive's adhesion to the metal disc was too low. Despite the rejection of the "*d*" type of destruction results, it can also be concluded that the "CFRP - wood" connection was good.

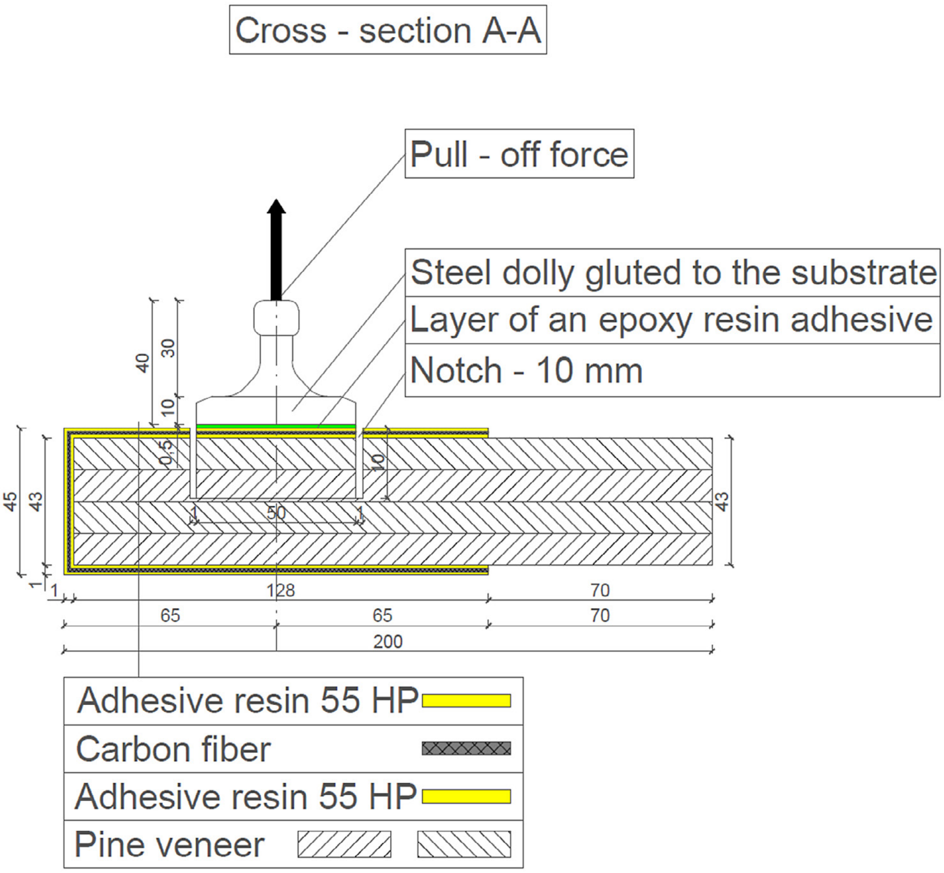


Figure 9. Pull–off test scheme for stage III

To detach the composite, an even greater pull-off force was needed than the values obtained during the tests. The results obtained from stage III of the tests were used to prepare a statistical analysis, which was presented in Table 5.

DETERMINATION OF PEARSON'S LINEAR CORRELATION COEFFICIENT

In the previous experimental studies, the analyzed beams were subjected to a destructive test described in more detail in [37]. The results obtained from conducted tests, as well as the arithmetic means of the pull-off strength for stages I, II, and III, were listed in Table 6.

The following types of damage were assumed for the calculations: "*α*", "*A*", and "*a*" while rejecting the types of damage: "*ε*", "*Y/Z*", and "*d*". Determining the correlation between the breaking force F_{max} and the value of the pull-off strength for stages I, II, and III was crucial in understanding the relationship between the breaking force and the pull-off force. The destructive force causes the destruction of the structural element and the separation of the composite from the substrate. Therefore, it was important to investigate whether there was a correlation between F_{max} and f_h and B_t, and if so, what kind?

The Pearson linear correlation coefficient was aimed at determining the correlation between the breaking force F_{max} and the value of the pull-off strength for stages I, II and III. For this purpose, the following formula was used [40]:

$$r_{xy} = \frac{\sum(X_i) - (\bar{X}) \times (Y_i) - (\bar{Y})}{\sqrt{\sum(X_i) - (\bar{X})^2 \times \sum(Y_i) - (\bar{Y})^2}} = \frac{\frac{1}{n}\sum X_i Y_i - \bar{X} - \bar{Y}}{\sigma X \, \sigma Y} = \frac{cov\, XY}{\sigma X \, \sigma Y} \quad (4)$$

where: X_i, Y_i – *i-th* observation values (X – stage I, Y – stage II); $\bar{X}$, $\bar{Y}$ – averages of populations X and Y; σ_X, σ_Y – standard deviation of population X and Y; $cov_{(x,y)}$ – covariance of variables X and Y, n – number of observations (the same for X and Y).

For the relationship between the destructive force and the pull-off strength for stages I, II,

Table 4. Pull–of strength with the type of failure for all research stages

Beam number		Sample number	Stage I		Stage II		Stage III	
			Pull – off strength [MPa]	Type of failure	Pull – off strength [MPa]	Type of failure	Pull – off strength [MPa]	Type of failure
I	I - 1	1	2.33	*Y/Z*	1.30	*A*	0.95	a
		2	1.69	*Y/Z*	1.19	*A*	1.34	d
		3	1.66	*Y/Z*	1.30	*A*	1.18	a
		4	0.89	*Y/Z*	1.05	*Y/Z*	1.15	a
		5	1.68	*A*	1.03	*A*	0.79	a
		6	1.71	*Y/Z*	0.88	*A*	1.2	d
	I - 2	7	2.11	*A*	1.35	*Y/Z*	1.03	a
		8	2.46	*A*	1.35	*A*	1.16	a
		9	2.45	*Y/Z*	1.27	*A*	0.9	a
		10	3.04	*Y/Z*	1.4	*A*	1.04	a
		11	2.31	*Y/Z*	1.22	*A*	0.93	a
		12	2.09	*Y/Z*	1.00	*Y/Z*	1.04	a
II	II - 1	13	1.67	*A*	1.93	*Y/Z*	1.43	a
		14	2.24	*A*	1.84	*Y/Z*	1.04	a
		15	1.38	*A*	2.32	*Y/Z*	1.43	a
		16	1.56	*A*	1.91	*A*	1.58	d
		17	1.94	*Y/Z*	1.34	*A*	1.44	a
		18	1.67	*A*	1.50	*A*	1.28	a
	II - 2	19	2.15	*A*	1.72	*Y/Z*	1.06	d
		20	2.46	*A*	1.96	*A*	1.48	a
		21	1.34	*A*	1.4	*Y/Z*	1.29	a
		22	2.17	*Y/Z*	2.16	*A*	1.38	a
		23	2.18	*A*	2.23	*Y/Z*	1.44	a
		24	2.25	*A*	1.68	*A*	1.67	a
III	III - 1	25	1.37	*A*	1.26	*A*	1.66	a
		26	1.50	*A*	1.77	*A*	1.16	a
		27	1.80	*A*	1.18	*A*	0.99	a
		28	1,86	*A*	1.47	*A*	1.28	d
		29	2.01	*A*	1.7	*A*	1.42	d
		30	2.00	*Y/Z*	1.94	*A*	1.18	d
	III - 2	31	1.78	*Y/Z*	1.95	*A*	1.00	a
		32	1.28	*A*	1.67	*A*	1.29	a
		33	1.34	*A*	1.49	*A*	0.91	a
		34	1.35	*A*	1.77	*A*	0.49	a
		35	1.33	*A*	1.60	*A*	0.66	a
		36	1.14	*A*	1.43	*A*	0,91	a

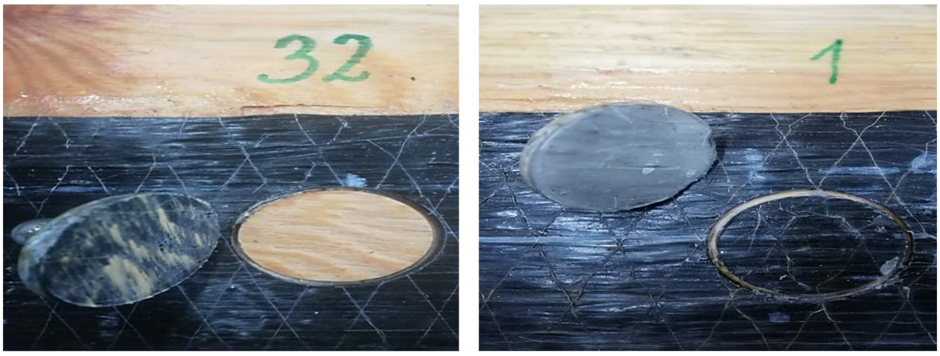
and III, the Pearson linear correlation coefficient "*r*" turned out to be positive and amounted to 0.988201, 0.820521, 0.984299, respectively. This means a very strong relationship between the tested features, i.e., with the increase or decrease of the destructive forces, the pull-off strength increases or decreases analogously.

The relationship between the breaking force and the pull-off strength for the Pearson linear correlation for stages I, II, and III was shown in Figures 13–15.

It should be noted that stages II and III yield slightly higher results because more samples had a valid failure than those that should have been rejected. Stage I yielded 23 valid results, Stage

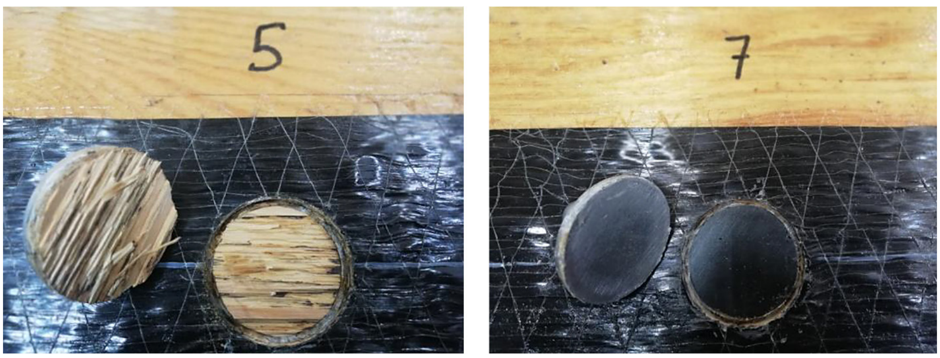
Table 5. Statistical data of the test results for all research stages

Statistical analysis	Type of failure					
	Stage I		Stage II		Stage III	
	A	*Y/Z*	*A*	*Y/Z*	*a*	*d*
Average pull – off strength [MPa]	1.76	1.96	1.51	1.64	1.14	1.29
Standard error	0.09	0.15	0.06	0.15	0.05	0.06
Median	1.66	1.97	1.47	1.72	1.15	1.28
Mode	2.46	-	1.3	-	1.04	-
Standard deviation [MPa]	0.30	0.17	0.31	0.47	0.28	0.17
Coefficient of variation	0.42	0.52	0.04	0.09	0.04	0.04
Sample variance	0.17	0.27	0.11	0.22	0.08	0.02
Kurtosis	-1.37	1.80	-0.56	-1.31	-0.17	0.08
Skewness	0.25	-0.02	0.194	-0.01	-0.08	0.47
Range	1.32	2.15	1.28	1.32	1.18	0.52
Minimum	1.14	0.89	0.88	1	0.49	1.06
Maximum	2.46	3.04	2.16	2.32	1.67	1.58
Sum	42.44	23.75	40.72	14.84	33.12	9.06
Counter	23.00	13.00	27.00	9.00	29.00	7.00



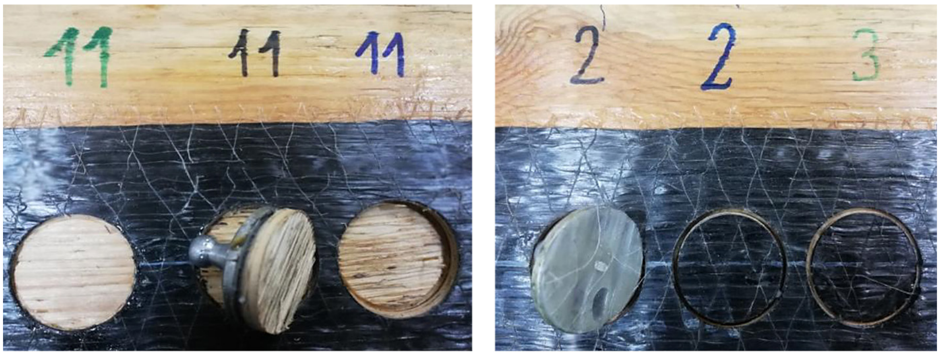
a) b)

Figure 10. Graphical presentation of the following type of damage: a) „*A*" – visible CFRP composite layer and traces of wood in the substrate, indicating very good adhesion of the disc to the substrate, b) "Y/Z" – visible 1 mm thick adhesive layer on the disc surface, indicating the lack of cooperation between the disc and the CFRP composite



a) b)

Figure 11. Graphical presentation of the following type of damage: a) „*A*" - visible layers of detached wood and damage to the wooden beam, b) „*Y/Z*" – a 1 mm thick layer of glue is visible on the disc surface, indicating a lack of cooperation between the disc and the CFRP composite



a) b)

Figure 12. Graphical presentation of the following type of damage: a) „*a*" - visible layers of detached wood and damage to the wooden beam, b) „*d*" - A 1 mm thick layer of glue is visible on the disc surface, indicating a lack of cooperation between the disc and the CFRP composite

Table 6. Summary of test results for the tested beams I, II, and III, along with the arithmetic means of the pull-off strength for stages I, II, and III

Beam number	Destructive force F_{max} [kN]	Arithmetic mean [MPa]		
		Stage I	Stage II	Stage III
I	53.39	0.97	1.21	1.02
II	62.21	1.37	1.75	1.39
III	54.86	1.10	1.60	1.01

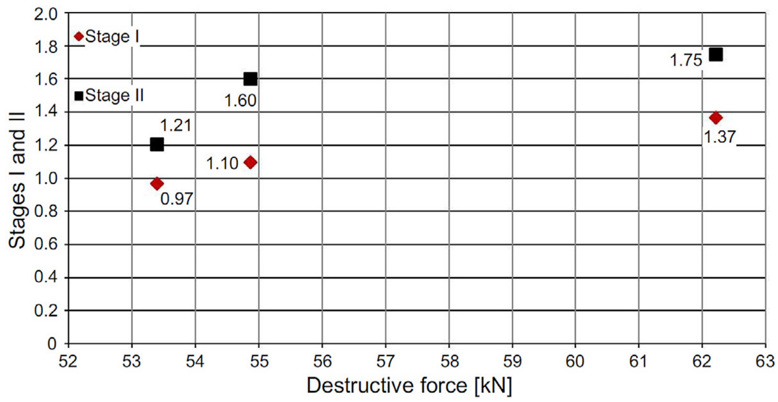


Figure 13. Pearson linear correlation for failure forces and pull-off strength for stages I and II

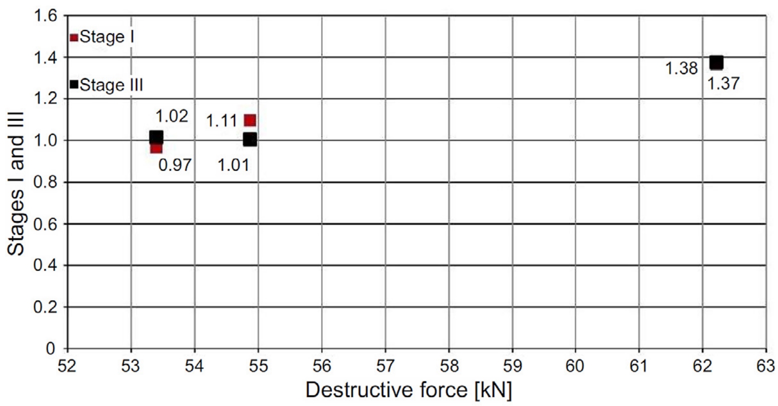


Figure 14. Pearson linear correlation for failure forces and pull-off strength for stages I and III

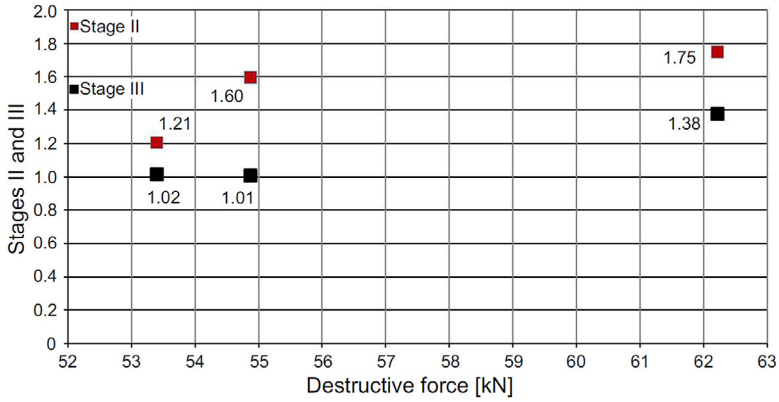


Figure 15. Pearson linear correlation for failure forces and pull-off strength for stages II and III

II yielded 27, and Stage III yielded 29 valid results. This explains the linear correlation in the tested samples. Confidence intervals or significance testing were not investigated in this paper. The goal of this paper was to determine the pull-off strength and compare the results with the beams failure force, which damaged the wood fibers and CFRP in a manner similar to pull-off. Therefore, the study utilized the Pearson linear correlation approach.

DISCUSSION

The paper presents the results of tests of the CFRP composite pull-off strength glued to pine beams made of glued wood previously subjected to destructive tests. To determine the pull-off strength of CFRP from the surface of wooden beams as accurately as possible, three research methods were used: Authors experimental method with a cut depth of 1.0 mm, method based on the PN-EN 1542 [38] standard "Products and systems for the protection and repair of concrete structures - Test methods - Measurement of adhesion by pull-off" for a cut depth (notch) of composite and wood layers of 5.0 mm and based on the ASTM C1583 [39] standard „Standard test method for tensile strength of concrete surfaces and the bond strength or tensile strength of concrete repair or overlay materials by direct tension (pull-off method)", in which the composite was cut together with the wood layers to a depth of 10 mm. Pearson linear correlation analysis was also performed, the main purpose of which was to determine the dependence of the pull-off strength on the forces that destroyed the beams. The assumptions of the experimental method and the standards used [38–39] were also characterized. The preparation of samples for testing, the testing procedure, the method of applying the pulling-off force, and the types of substrate destruction were described.

The obtained results suggest a good bond between the CFRP composite and the wood surface. The highest average value of the pull-off strength for correct damage was of 1.51 MPa for Stage II results with 27 correct samples, of 1.76 MPa for Stage I with 23 correct samples, and of 1.14 MPa for Stage III with 29 correct samples. The rejected results also suggest good adhesion of the composite to the substrate. Despite their rejection, their average was higher than the average of the correct results and was of 1.36 MPa compared to 1.28 MPa for the correct results. The average number of correct samples was higher than the number of rejected samples. It was of 26.67 pieces compared to 9.4 pieces, which also suggests that the values of the pull-off strength for the damage types: "ε", "Y/Z", "d" were higher than the values of the pull-off strength for correct samples. Therefore, it was reasonable to state that to detach the composite from the wood surface, an even greater pull-off force was needed than the values obtained during the tests. The statistical summary was presented in Table 7, with the average values of the results obtained for (i) pull-off strength, (ii) types of damage, and (iii) the number of samples.

The key fact that also affects adhesion was the surface roughness and the glue thickness, which in the cases studied was ± 1.0 mm. Unfortunately, it was impossible to examine and determine the surface roughness of the tested samples due to the lack of specialist equipment. Roughness analysis would largely contribute to a better understanding of the composite-wooden beam connection. Still,

Table 7. Average values of pull-off strength, types of failure, number of specimens

Counter	Average pull–off strength [MPa]	Type of failure	Counter	Average pull–off strength [MPa]	Type of failure
Stage I					
23	1.76	A	12	1.96	Y/Z
Stage II					
27	1.51	A	9	1.64	Y/Z
Stage III					
29	1.14	a	7	1.29	d
Total average [MPa]					
26.67	1.28	-	9.4	1.36	-

in the cases studied, it was possible to visually assess the surfaces of the wooden beam and the contact between the steel disc and the composite.

In the summary of this part, it can be concluded that the standard methods presented: (i) PN-EN 1542 standard [38] and (ii) ASTM C1583 standard [39] ensure that the correct destruction occurs in the wood layer only at the depth of the notch (from 5 to 10 mm). In the conducted tests, the information on the pull-off strength was the detachment of the composite from the wood layer, so that the composite was glued only to the steel disc. Therefore, based on the earlier author's experience [15–17 and 37], a cut in the composite layer thickness of 1 mm was sufficient, as was proved in this research. In addition, the results indicate that the method was more optimal than previous studies because the wood layer was not destroyed. This aspect has the most significant impact on practical research in engineering practice. It is worth noting that the additional aim of the research was to apply its findings in engineering practice. In the opinion of the Authors, this is not easy, as it depends on what is proposed for reinforcements and which boundary condition will work for a particular material. However, after conducting this research, it can be concluded that a sensible approach would be to utilize quality control based on the rules outlined in the standards. In addition, the long-term monitoring will be very helpful in the case of using these materials (wood with CFRP) in non-stable environmental conditions (the changing temperature and moisture).

It should also be added that the literature [41–43] provides information on various types of reinforcement using CFRP. However, this paper focuses on only one reinforcement method (Figure 1), which was analyzed, among others, in [44]. In [44] as in the experiment in this paper, the CFRP reinforcement was applied to the tension side of a wooden beam element. Overall, it can be concluded that CFRP reinforcement improves the mechanical load-bearing capacity compared to an unreinforced beam. The effect of CFRP was obvious, even in the case of the beams, which exhibited a large number of defects, knots, bark beetles, or a mixture of new and old wood in the same beam cross-section. It was observed that, at the same bending moment, the difference in strain absorbed by the epoxy resin was higher for the case studied in this study and in [44]. This translates into greater resistance to delamination. Other forms of reinforcement generated larger strains, and therefore, the effectiveness of CFRP reinforcement was lower. Therefore, it can be concluded that the tested form of strengthening wooden beams was valid, and the results provide a basis for further studies that take into account other forms of CFRP strengthening.

CONCLUSIONS

The paper presents the results of tests of the CFRP composite pull-off strength glued to pine beams made of glued wood previously subjected to destructive tests. To determine the pull-off strength of CFRP from the surface.

The statistical analysis showed the relationship between the beam's destructive force and the values of the pull-off strength. According to the authors, this analysis was crucial because the destructive force causes not only the destruction of the structural element but also the separation of the composite from the substrate, which to some extent determines the pull-off strength and allows determining the relationship between the tested features. Pearson's linear correlation coefficient "*r*" for the relationship between the breaking force and the pulling-off strength for stages I, II, and III turned out to be positive and amounted to 0.988201, 0.820521, and 0.984299, respectively. This means a very strong relationship between the tested features, i.e., with the increase or decrease of the braking forces, the pulling-off strength increases or decreases analogously. This conclusion was the most essential part of this research and supplements the previous knowledge in the literature. These results show an additional practical direction for other research. In addition, it can be stated that:

- The maximum force for the pulled-off samples in the Authors experimental method was identical to the process using the standard [39] (from stage III), where the maximum stress during pulling-off for both methods was 1.67 MPa. This means that the notch 1 mm (according to the Authors method) was enough to determine the correct pull-off strength of the wooden beam.
- In stage II of the tests based on the standard [38], the maximum stresses during detachment were higher than in the Authors method and using the standard [39] and amounted to 2.16 MPa. This means that the values were overvalued, and using this method can lead to unrealistic results.
- The lack of testing for the surface roughness of the tested samples due to the lack of specialist equipment limits the use of the method, but it can be used in experimental studies in a certain way.
- The test was carried out on pine beams using a CFRP sheet bonded reinforcement layer. In other wooden beams and with different numbers of layers of CFRP, the Authors method can show different relations in static and pull-off force.

It is worth noting that the additional aim of the research was to apply its findings in engineering practice. In the opinion of the Authors, this is not easy, as it depends on what was proposed for reinforcements and which boundary condition will work for a particular material. However, after conducting this research, it can be concluded that a sensible approach would be to utilize quality control based on the rules outlined in the standards (PN-EN 1542 and ASTM C1583). Based on the Standards, the safety margins and design guidelines describe composite beams made of wooden beams with composite CFRP (Carbon Fiber Reinforced Polymer). Furthermore, the long-term monitoring will be very helpful in the case of using these materials (wood with CFRP) in non-stable environmental conditions (the changing temperature and moisture). This is especially important in cases where these elements will be used in monumental buildings, and where the safety of people is of utmost importance.

The results obtained during the tests indicate a good connection and cooperation of the "CFRP – wood" mechanism. The lack of surface roughness testing for the tested samples creates additional research opportunities and improvement of our own research method.

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