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PULL-OFF ADHESION STRENGTH OF POLY-P-PHENYLENE BENZOBISOXAZOLE (PBO) – REINFORCED TIMBER

P. K. SOKOŁOWSKI[1], P. G. KOSSAKOWSKI[2]

The article discusses results of pull-off adhesion strength tests on poly-p- phenylene benzobisoxazole (PBO) mesh bonded to fir timber beams using epoxy resin. The tests were performed in accordance with the PN-EN 1542 standard. Timber elements reinforced with PBO fibres were subjected to pull-off tests to measure the adhesive strength of the mesh to the beams.The factors occurring during the test were also characterized, which may affect its results such as the method of application of the tearing force, selection of epoxy glue, surface preparation of the tested elements, occurrence of material defects in the wood and types of substrate destruction.The experimental data show that failure of the timber layer was not observed in all the specimens tested.

Keywords: *pull-off test, composite, timber, adhesion, epoxy resin, poly-p- phenylene benzobisoxazole (PBO)*

1. INTRODUCTION.

Timber is the oldest structural material used by man since the dawn of time. For many millennia, timber was the basic material used in construction. Also now, it is used to construct houses, buildings, bridges, etc. Natural internal structure of the timber makes it a material with good

[1]MSc., Eng., Kielce University of Technology, Faculty of Civil Engineering and Architecture, Al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland, e-mail: pso.sokol@wp.pl, orcid.org/0000-0002-5043-5876

[2]DSc., PhD., Eng., prof. PŚk, Kielce University of Technology, Faculty of Civil Engineering and Architecture, Al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland, e-mail: kossak@tu.kielce.pl, https://orcid.org/0000-0002-7827-4955

mechanical parameters, such as strength in the first place. Timber is an anisotropic material [1], where there are three basic directions of the anisotropy. The best mechanical parameters of timber are indicated along the fibres. At the same time, timber has a low density. As a result, structural elements made of timber are relatively light, which allows us to build buildings with large spans and heights.Timber structures, like others, need to be repaired during their use. Such situations occur when, for example, a structural component is damaged or overloaded. In the case of common structural materials used in construction, such as concrete and steel, it is possibly to analyze the deformation and damage process and predict material failure [2-7]. For timber structures it is very difficult and complex. Due to high sensitive of timber for structural failures in many cases it is better to replace the overloaded or damaged member. Of course observed damage not always determine the necessity of the removing a given element. It is often possible to repair such element and strengthen it. Currently, many methods and technologies are used to strengthen timber structures [8-12]. The decisive parameters in this regards is the type of damage and its effect. Another situation is when the load on a given element increases, which requires increasing its load-carrying capacity.

Nowadays there are many modern methods and materials used to strengthen structural elements. The composites are one of such materials. Composite material means a material that is made up of at least two different components that are combined at the macroscopic level. In this sense, e.g. metal alloys, which form a mixture of many components on a microscopic scale, are not composites. In the macroscopic image they behave as typical homogeneous materials. The use of plastic composites is not only due to their low bulk density, corrosion resistance and high fatigue strength, but also because of their high tensile strength and ease to assembly. Composite materials are used to repair and reinforce structures made of various materials, e.g. [13, 14], including wood [15-21]. Composites can be divided into those that use a resin matrix – FRP (Fiber Reinforced Polymer/Plastics) and a cement matrix – FRCM (Fiber Reinforced Cementitious Matrix). These two types are most often used for reinforcing structures. In FRP composites, an epoxy resin, called a continuous phase or matrix, is reinforced with fibers such as glass, carbon or aramid, while the FRCM system consists of meshes (e.g. Carbon, PBO) arranged vertically and embedded in a mineral mortar.

The paper presents the results of peel strength tests resulting from the combination of FRP and FRCM systems embedded in a PBO mesh made of epoxy resin adhered to wooden beams. Three wooden beams made of fir, subjected to an earlier destructive test aimed at estimating their load-carrying capacity, described in the literature [22], were used for the tests. The samples were placed in areas of material defects in wood (knots) and in places without the defects. The purpose of the study was to determine the PBO composite wood tearing strength, composite adhesion to the weakest places of beams, which are the places where natural material defects in wood (knots) occur, composite adhesion in places free of wood defects, and interpretation of results. This article defines the strength of a PBO composite - wood. Factors occurring during the test that may affect its results have been characterized. The most important of them are the preparation of the surface of the tested elements, the presence of material defects in wood and the types of faliure of the substrate as well as the method of applying the peeling force. The PBO mesh determines the load capacity of the tensile zone of the wooden structure. The cooperation of the mesh with the resin adhesive is very significant when it comes to transferring external load. The mechanism of this composite and wooden beam determines the strength of the reinforced structure. This cooperation is ensured, among others, by capturing the mesh and the surrounding glue.

Detachment is a test carried out on the composite surface to determine the tensile strength of the materials and the adhesion of the layers. Peel tests are described in PN-EN 1542: Products and systems for the protection and repair of concrete structures – Test methods – Measurement of bond strength by peeling [23]. According to this standard, the measurement result in the test is the value of strength expressed in MPa, calculated on the basis of the strength in relation to the surface of the cut layer.

The PN-EN 1542 [23] describes 8 types of standard failures (Table 1) and indicates cases in which the results of measurements should be rejected. The measurement is considered to be a completely correct result if the failure (detachment of the disc with the tested material) takes place in the tested substrate.

Table 1. Types of failures according to PN-EN 1542 [23].

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 (e.g. primer, bonding slurry or mortar)
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 adhesive layer (e.g. C/Y in a two-layer repair system)
7	Y	Cohesion failure in the adhesive layer
8	Y/Z	Adhesion failure between the adhesive layer and the dolly (which is Z)

In this article, the strength of the PBO – timber composite was determined. The factors occurring during the test, which may influence its results, were characterized. The main ones are the method of application of the pull-off force, selection of epoxy glue, preparations of the surfaces of the tested elements, occurrences of material defects in the timber and types of substrate destruction.

2. DESCRIPTION OF THE TESTS.

The first step is to cut the surface with a crown diamond drill set at an angle 90° ± 1° to the area according to the assumptions resulting from the following formula [23]:

$$d = d_d + (15 \pm 5) \tag{1}$$

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

The next stage is to degrease of the places of sticking the discs and to stick directly to the surface of the tested material of steel discs with a diameter of 50mm. Two-component epoxy adhesives are used to glue the discs.The measurement of the pull-off strength of the adhesive bonding “PBO–timber” is determined by the actual strength of the tested material for tension, with little damage to its layer (semi-destructive method).

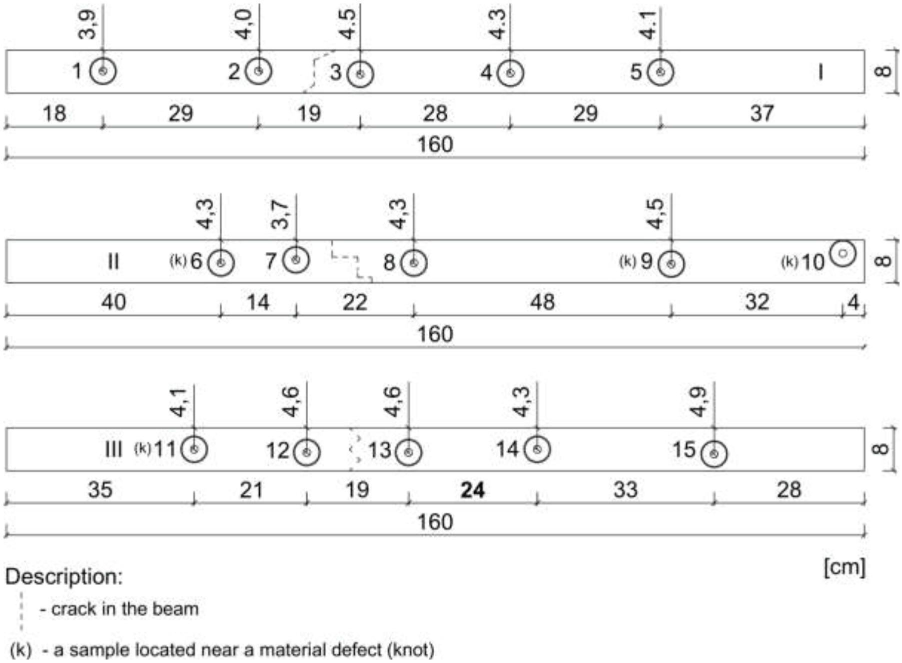

Fig. 1. Distribution scheme of the tested samples.

The PN-EN 1542 [23] standard specifies the number and placement of samples. According to the standard, at least one sample of the product or repair system is required, to be tested at least 5 times. Due to the fact that the timber beams had been subjected to a destructive test aimed at estimating their load capacity, it was decided to randomly arrange the samples for this test, as well as to deliberately distribute the samples in places of material defects and PBO mesh cracks (Figs. 1 and 2), located and described in Table 2.

Table 2. Description of the samples location.

Beam (mark)	Sample number	Description of sample location
I	1	The sample is located in a place without material defects
	2	The sample is located in a place without material defects
	3	The sample is located in a place without material defects
	4	The sample is located in a place without material defects
	5	The sample is located in a place without material defects
II	6	The sample is located directly on the material defect (knot)
	7	The sample is located in a place without material defects
	8	The sample is located in a place without material defects
	9	The sample is located directly on the material defect (knot)
	10	The sample is located directly on the material defect (knot)
III	11	The sample is located directly on the material defect (knot)
	12	The sample is located in a place without material defects
	13	The sample is located in a place without material defects
	14	The sample is located in a place without material defects
	15	The sample is located in a place without material defects

Fig. 2. View of the tested samples.

3. THE COURSE OF THE RESEARCH.

The study used three wooden beams made of solid fir wood with a strength class of wood K27, humidity 19-2% and density 4.527kg /m^3. Beams of dimensions 8 × 8 × 160 cm were reinforced with PBO mesh glued with Resin 55 resin adhesive. The composite layers were then cut to a depth of 5mm according to the assumptions of the formula resulting from [23]. After the degreasing process, a 50mm diameter steel disco were glued with Hysol Loctite 907 adhesive. Per each beam5 pieces of steel discs were applied (Fig. 3).

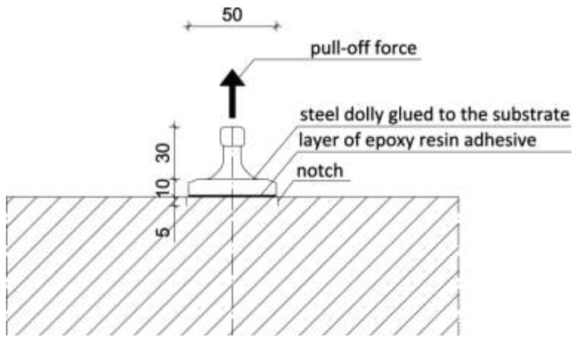

Fig. 3. Pull-off test scheme.

The test stand included the PosiTest AT-M Adhesion Tester with a software recording the tear strength. The measuring instrument was set at an angle of 90° to the pre-drilled surface, preventing any changes in position during the test. The load was increasing gradually and continuously at the speed of 0.05 MPa/s until the destruction occurred. Based on the obtained results, the adhesion pattern of the tested samples was calculated, as following:

$$f_h = 4\, F_h / \pi\, D^2 \tag{2}$$

where: f_h– adhesion strength of the test sample in [MPa], F_h – failure pull-off force in [N], D – average dimension of the sample in [mm].

4. Results and discussion.

In Table 3, pull-off strength values are presented along with a description of the failure for individual samples tested.

Table 3. Pull-off strength with description of sample failure

Beam (mark)	Sample number	Pull-off strength [MPa]	Description of sample failure
I	1	1.90	Y/Z – adhesive failure between the adhesive layer and the disc
	2	1.78	A – cohesion failure in the substrate
	3	1.01	Y/Z – adhesive failure between the adhesive layer and the disc 10%
	4	2.10	A – cohesion failure in the substrate
	5	2.39	A – cohesion failure in the substrate
II	6	2.09	Y/Z – adhesive failure between the adhesive layer and the disc 20%
	7	0.70	Y/Z – adhesive failure between the adhesive layer and the disc
	8	1.64	Y/Z – adhesive failure between the adhesive layer and the disc 10%
	9	2.88	Y/Z – adhesive failure between the adhesive layer and the disc 40%
	10	3.78	A – cohesion failure in the substrate
III	11	2.61	A – cohesion failure in the substrate
	12	1.09	A – cohesion failure in the substrate
	13	1.23	A – cohesion failure in the substrate
	14	1.00	Y/Z – adhesive failure between the adhesive layer and the disc 20%
	15	1.55	Y/Z – adhesive failure between the adhesive layer and the disc 30%

4.1. "Y/Z" failure – adhesive damage between the adhesive layer and the disc.

In two cases, for samples 1 and 7 located in places without material defects, the disc was detached from the ground, which caused no damage to the wood layer (Fig. 4). Table 4 presents the statistical analysis of the results for samples 1 and 7. The detachment of the samples occurred quickly after exceeding the maximum peeling force, which resulted in complete detachment of the disk from the tested substrate. According to PN-EN 1542 [23], the results of this type of damage should be rejected.

Table 4. Results of tests for samples 1 and 7 located in the area without material defects.

Sample number	1	7
Pull-off strength [MPa]	1.90	0.70
Average pull-off strength [MPa]	1.30	
Standard deviation [MPa]	0.84	
Coefficient of variation	0.65	

4.2. "Y/Z" Failure – adhesive damage between the adhesive layer and the shield from 10 to 40%.

For tests Nos. 3, 8, 14 and 15 located in areas without material defects, a non-standard - partial failure occurred in the wood layer, which caused the disc to be detached from the ground. In such cases, the percentage of the damaged area should be determined visually, and the results should not be included in the calculation (Fig. 5). A non-standard partial failure in the wood layer that caused the disc to break away from the ground also occurred for samples Nos. 6 and 9 located on material defects (knots). The average value of the peeling force was 2.48 MPa and is higher compared to the average value of the peeling force for samples located in places without material defects of 1.3 MPa. According to [23], the results should be rejected, but the results suggest good mesh adhesion to wooden substrates. Table 5 presents statistical analysis of results for samples Nos. 3, 6, 8, 9, 14, 15 located in places with and without material defects.

Table 5. Results of tests for samples 3, 6, 8, 9, 14, 15 located in the area with and without material defects.

Sample number	3	6	8	9	14	15
Pull-off strength [MPa]	1.01	2.09	1.64	2.88	1.00	1.55
Average pull-off strength [MPa]	1.69					
Standard deviation [MPa]	0.71					
Coefficient of variation	0.42					

The samples located in a place without material defects					The samples located directly on the material defect (knots)		
Sample number	3	8	14	15	Sample number	6	9
Pull-off strength [MPa]	1.01	1.64	1.00	1.55	Pull-off strength [MPa]	2.09	2.88
Average pull-off strength [MPa]	1.30				Average pull-off strength [MPa]	2.48	
Standard deviation [MPa]	0.34				Standard deviation [MPa]	0.55	
Coefficient of variation	0.26				Coefficient of variation	0.22	

4.3. "A" Failure – damage to consistency in the ground.

In other cases, for tests Nos. 2, 4, 5, 12, 13 located in places without material defects, there was complete destruction in the timber layer (Fig. 6). Detachment of samples was characterized by a sudden loud crack and damage to the timber layer. For samples Nos. 10 and 11, located at places of material defects, "A" type damage was also found. Table 6 presents statistical analysis of results for samples Nos. 2, 4, 5, 10, 11, 12, 13 located in locations without and with material defects.

Table 6. Results of tests for samples 2, 4, 5, 10, 11, 12, 13 located in the area with and without material defects.

<table>
<tr><td colspan="3">Sample number</td><td>2</td><td>4</td><td>5</td><td>10</td><td>11</td><td>12</td><td>13</td></tr>
<tr><td colspan="3">Pull-off strength [MPa]</td><td>1.78</td><td>2.10</td><td>2.39</td><td>3.78</td><td>2.61</td><td>1.09</td><td>1.23</td></tr>
<tr><td colspan="3">Average pull-off strength [MPa]</td><td colspan="7">2.14</td></tr>
<tr><td colspan="3">Standard deviation [MPa]</td><td colspan="7">0.91</td></tr>
<tr><td colspan="3">Coefficient of variation</td><td colspan="7">0.42</td></tr>
<tr><td colspan="6">The samples located in a place without material</td><td colspan="4">The samples located directly on the material defect (knots)</td></tr>
<tr><td>Sample number</td><td>2</td><td>4</td><td>5</td><td>12</td><td>13</td><td>Sample number</td><td>10</td><td colspan="2">11</td></tr>
<tr><td>Pull-off strength [MPa]</td><td>1.78</td><td>2.10</td><td>2.39</td><td>1.09</td><td>1.23</td><td>Pull-off strength [MPa]</td><td>3.78</td><td colspan="2">2.61</td></tr>
<tr><td>Average pull-off strength [MPa]</td><td colspan="5">1.71</td><td>Average pull-off strength [MPa]</td><td colspan="3">3.19</td></tr>
<tr><td>Standard deviation [MPa]</td><td colspan="5">0.55</td><td>Standard deviation [MPa]</td><td colspan="3">0.82</td></tr>
<tr><td>Coefficient of variation</td><td colspan="5">0.32</td><td>Coefficient of variation</td><td colspan="3">0.25</td></tr>
</table>

The presented results show that the average value of the peeling force for samples located in places of material defects is higher than the average value of samples located in places without their defects. It amounts to 3.19 MPa and 1.71 MPa respectively. Table 7 presents a comparison of test results for samples located in places where material defects occur and in other places.

Table 7. Results of tests for all samples located in places with and without material defects.

The samples located in a placewithout material defect											
Sample number	1	2	3	4	5	7	8	12	13	14	15
Pull-off strength [MPa]	1.90	1.78	1.01	2.10	2.39	0.70	1.64	1.09	1.23	1.00	1.55
Average pull-off strength [MPa]	1.49										
Standard deviation [MPa]	0.52										
Coefficient of variation	0.34										

The samples located directly on the material defect (knots)				
Sample number	6	9	10	11
Pull-off strength [MPa]	2.09	2.88	3.78	2.,61
Average pull-off strength [MPa]	2.84			
Standard deviation [MPa]	0.707			
Coefficient of variation	0.24			

Samples located in places of material defects were characterized by higher tear resistance compared to samples located in places without material defects. The tensile strength was 2.84 MPa and 1.49 MPa, respectively. After analyzing the results, it should be stated that the adhesion of the PBO mesh to the wooden beam surface depends on the roughness and unevenness of the reinforced surface. In these cases we are dealing with places of material defects such as knots. The roughness and unevenness of the surface on which the knots are located results in better absorption of the resin adhesive and thus a better connection of the reinforcing material, which results in good adhesion, which will certainly have a positive effect on strengthening the structural element. Table 8 shows the results of testing of samples located in places where material defects occur and in places without defects depending on the types of destruction "Y/Z" and "A". Table 9 presents statistical data for all fifteen endurance tests while Fig. 7 shows a graphical comparison of the pull-off strength for types of failure of the substrate "A" and "Y/Z".

Table 8. Results of tests for samples located in places where there are material defects and in places without defects, depending on the type of damage "Y/Z" and "A".

<table>
<tr><td colspan="7">Type of failure "Y/Z" samples located in places without material defects</td></tr>
<tr><td>Sample number</td><td>1</td><td>3</td><td>7</td><td>8</td><td>14</td><td>15</td></tr>
<tr><td>Pull-off strength [MPa]</td><td>1.90</td><td>1.01</td><td>0.70</td><td>1.64</td><td>1.00</td><td>1.55</td></tr>
<tr><td>Average pull-off strength [MPa]</td><td colspan="6">1.30</td></tr>
<tr><td>Standard deviation [MPa]</td><td colspan="6">0.46</td></tr>
<tr><td>Coefficient of variation</td><td colspan="6">0.35</td></tr>
<tr><td colspan="7">Type of failure "Y/Z" samples located directly on the material defect (knots)</td></tr>
<tr><td>Sample number</td><td colspan="3">6</td><td colspan="3">9</td></tr>
<tr><td>Pull-off strength [MPa]</td><td colspan="3">2.09</td><td colspan="3">2.88</td></tr>
<tr><td>Average pull-off strength [MPa]</td><td colspan="6">2.48</td></tr>
<tr><td>Standard deviation [MPa]</td><td colspan="6">0.55</td></tr>
<tr><td>Coefficient of variation</td><td colspan="6">0.22</td></tr>
<tr><td colspan="7">Type of failure "A" samples located in places without material defects</td></tr>
<tr><td>Sample number</td><td>4</td><td>5</td><td>12</td><td colspan="3">13</td></tr>
<tr><td>Pull-off strength [MPa]</td><td>2.10</td><td>2.39</td><td>1.09</td><td colspan="3">1.23</td></tr>
<tr><td>Average pull-off strength [MPa]</td><td colspan="6">1.7</td></tr>
<tr><td>Standard deviation [MPa]</td><td colspan="6">0.60</td></tr>
<tr><td>Coefficient of variation</td><td colspan="6">0.35</td></tr>
<tr><td colspan="7">Type of failure "A" samples located directly on the material defect (knots)</td></tr>
<tr><td>Sample number</td><td colspan="3">10</td><td colspan="3">11</td></tr>
<tr><td>Pull-off strength [MPa]</td><td colspan="3">1.00</td><td colspan="3">1.55</td></tr>
<tr><td>Average pull-off strength [MPa]</td><td colspan="6">1.27</td></tr>
<tr><td>Standard deviation [MPa]</td><td colspan="6">0.38</td></tr>
<tr><td>Coefficient of variation</td><td colspan="6">0.29</td></tr>
</table>

Table. 9. List of the statistical data of the test results.

Parameter	Type of failure	
	Y/Z	A
Average pull-off strength [MPa]	1.59	2.14
Standard deviation [MPa]	0.71	0.92
Coefficient of variation	0.44	0.43

Fig. 4. Adhesive failure between the adhesive layer and the disc

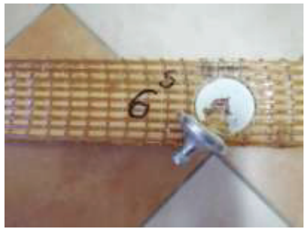

Fig. 5. Adhesive failure between the adhesive layer and the disc.

Fig. 6. Cohesive failure in the substrate.

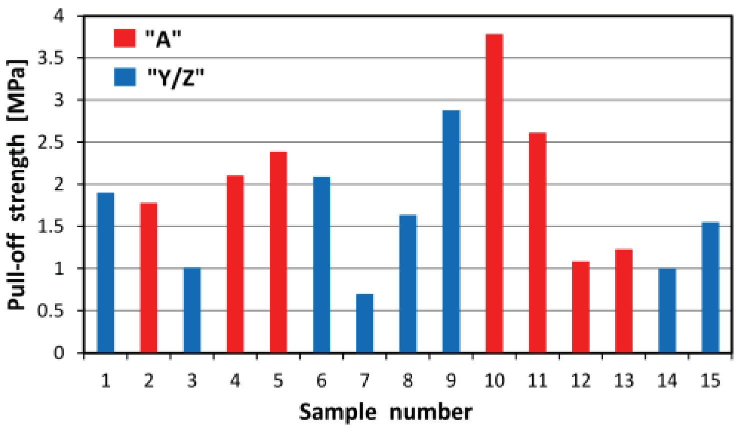

Fig 7. Comparison of the pull-off strength for types of failure of the substrate “A” and “Y/Z”.

5. CONCLUSIONS.

The paper presents the results of tests on measuring the adhesion for peeling of a PBO mesh adhered to wooden beams with epoxy resin based on the PN-EN 1542 standard. The samples were placed randomly and also in places where material defects (knots) and in places without defects. Test results were characterized depending on the types of damage and the place of occurrence of the samples. The tests show that the failure of the wood layer occurred in places of material defects and in places without material defects. It was also observed that the location of samples placed both in places of material defects is characterized by better adhesion of the PBO mesh to the wooden substrate than in places without material defects (2.84 MPa and 1.49 MPa). In this case, the adhesion is affected by surface roughness and its unevenness resulting in greater absorption of resin cladding and reinforced material. Depending on the type of failure, the strength was 2.14 MPa for the type of failure “A” and 1.59 MPa for the type of failure “Y/Z”. Comparing the obtained results to the results contained in the literature [17] where the tear strength of CFRP tape glued with resin adhesive was 2.64 MPa, it should be stated that these values are similar, which suggests good cooperation between the reinforcing material and the reinforced element. Compared to the results of the study [24], where the peel strength of the laminate with PUA coating adhered with a resin adhesive was 5.1 MPa and the peel strength of the laminate with PUA coating adhered with a matrix of styrene-butadienestyrene copolymer (SBS) was 1.5 MPa, it should be stated that this indicates good cooperation between the PBO mesh and the surface of the reinforced beam.

It was also observed that the detachment of the samples occurred quickly after exceeding the maximum peeling force, which was the case when the disc was completely detached from the tested substrate. In other cases, the detachment of samples was characterized by a sudden loud crack and damage to the wood layer. Although the test results for the “Y/Z” types should be rejected according to [23], their values suggest a good combination of the reinforcing material with the wooden beam surface. This is evidenced by the fact that to pull the disc away from the ground you will need an even greater value of force than the values obtained during the test. Other results for the type of failure“A” indicate a good connection of PBO mesh with wood, and thus durable and good reinforcement of the structural element.

The conducted tests clearly show that the adhesion of the mesh to the wooden beam mainly depends on the following factors:

- mutual chemical reaction of neighbouring layers, i.e. mesh and glue,
- mesh pressure against the adhesive layer,
- surface roughness.

It has also been observed that adhesion may depend on: the selection of the appropriate epoxy adhesive, the thickness of the epoxy adhesive layer and the method of applying the bursting force. However, additional research is needed to accurately determine the impact of these factors.

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LIST OF FIGURES AND TABLES:

Tab. 8. Wyniki badań próbek umieszczonych w miejscach, w których występują wady materiałowe oraz w miejscach bez wad, w zależności od rodzaju uszkodzenia typu „Y/Z" i „A".

Table. 9. List of the statistical data of the test results.

Tab. 9. Wykaz danych statystycznych wyników badań.

WYTRZYMAŁOŚĆ POŁĄCZENIA KOMPOZYTOWEGO POLY-P- PHENYLENE BENZOBISOXAZOLE (PBO) – DREWNO NA ODRYWANIE

Słowa kluczowe: wytrzymałość na odrywanie, kompozyt, drewno, przyczepność, żywica epoksydowa, poli-p- fenyleno benzobisoksazol (PBO)

STRESZCZENIE:

W artykule omówiono wyniki badań wytrzymałości na odrywanie siatki poli-p- fenyleno benzobisoksazolu (PBO) przyklejonej do belek drewnianych za pomocą żywicy epoksydowej. Badania przeprowadzono zgodnie z normą PN-EN 1542. Elementy drewniane wzmocnione siatką PBO i poddano próbie przyczepności, mając na celu określenie wytrzymałości na oderwanie siatki PBO przyklejonej do powierzchni belek w miejscach występowania wad materiałowych oraz w miejscach bez wad. Scharakteryzowano również czynniki występujące podczas badań, które mogą wpłynąć na ich wyniki, takie jak sposób przyłożenia siły odrywającej, dobór kleju epoksydowego, przygotowanie powierzchni badanych elementów, występowanie wad materiałowych w drewnie i rodzaje zniszczenia podłoża. Uzyskane wyniki wykazują, że nie we wszystkich badanych przypadkach nastąpiło zniszczenie w warstwie drewna.

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