The impact of the anchorage on the shear capacity of reinforced concrete beams

D Marcinczak¹ and T Trapko²
¹PhD student, Wroclaw University of Science and Technology, Faculty of Civil Engineering, Pl. Grunwaldzki 11, 50-377 Wroclaw, Poland.
²Associate Professor, Wroclaw University of Science and Technology, Faculty of Civil Engineering, Pl. Grunwaldzki 11, 50-377 Wroclaw, Poland.
Email: dorota.marcinczak@pwr.edu.pl

Abstract. This paper presents an experimental study on shear strengthening of reinforced concrete (RC) beams with PBO-FRCM composites. Key parameter of this study is the presence of composite anchorage. PBO-FRCM (Fabric-Reinforced Cementitious Matrix) composites consist of mineral mortar and PBO (p-Phenylene Benzobis oxazol) composite fibres. The most common failure mechanism of FRCM composites is debonding of the fibers from mineral mortar with no rupture of fibres, due to inappropriate coverage of all fibers by the mortar. To prevent premature debonding of the composite and increase the effectiveness of FRCM strengthening suitable anchorage should be used. In this case, experimental research was conducted on T-shaped RC beams strengthened in shear using PBO-FRCM with anchorages The study consisted of 5 beams, one of which was a control beam, one was strengthened without anchorage and the other three were strengthened with GFRP rebar anchorage. All beams were loaded until failure. Deformation, deflection and the width of cracks were recorded for each level of loading. The failure mechanisms of beams were analysed and described. The results obtained from research showed that the use of FRCM composites increased the shear capacity and had an impact on better use of the properties of the composite material.

1. Introduction
PBO fibers (p-Phenylene BenzobisOxazole) are new generation fibers, which in comparison to other fibers used for strengthening of reinforced concrete structures are characterized by the highest tensile. They are used as a component of the FRCM composite system, where the mineral mortar is used as a matrix, in case to improve its fire resistance. This material is increasingly the subject of research as evidenced by the constantly growing number of publications. The tests concern beams for bending, shearing, plates and columns [1-6]. However, the efficiency of the FRCM system is slightly smaller than that of FRP systems due to the low tensile strength of the mineral mortar and insufficient coverage of all fibers by the matrix. After exceeding this strength, the PBO mesh debonding from the surface of the element occurs, on the matrix-fiber layer [7-10]. All this leads to incomplete use of mechanical properties of PBO fibers in FRCM system.
To increase the efficiency of FRCM reinforcements, anchoring of PBO mesh should be used, which can prevent premature debonding of fibers and increase the utilization of the load capacity of the PBO mesh. Tests conducted on rectangular beams strengthened in bending [11] or shearing [12,13] with PBO-FRCM showed that the anchorage improves the bearing capacity of the element, and PBO fibers are more effectively used (have larger deformations) compared to beams without anchorage. Studies of T-beams with FRCM shear strengthening [14-17] showed that the anchorage has a large
contribution in the bearing capacity of the whole element. In fact, there is still a lack of tests on T-shaped RC beams strengthened with PBO-FRCM shear strengthening with anchoring. The subject of the presented research were T-shaped RC beams, strengthened in shear with PBO-FRCM composite with anchorage. The aim of the research was to study the effect of anchoring element on the load-bearing capacity and utilization of composite material.

2. Experimental research

Five reinforced concrete T-shaped beams were designed and tested. One of the beams was the reference beam, one was strengthened without anchorage and other three beams were strengthened with anchorage using PBO-FRCM materials with the same configuration and the same type of anchors.

2.1. Test specimens

The tests were carried out on T-shaped beams with cross-sectional dimensions of 350x400 mm, web width 150 mm and total length of 2300 mm. The main tensile reinforcement was designed to prevent destruction due to bending before exhausting shear capacity. The beams were reinforced at the bottom with 5 bars with a diameter of 20 mm and 2 bars with a diameter of 20 mm at the top. Stirrups with a diameter of 8 mm were made of the same type of steel. The spacing of stirrups was 250 mm (Fig. 1). The beams and specimens for determining the features of concrete were manufactured in a prefabrication plant during a single concreting and vibrating process. In order to determine the strength qualities of concrete the cylinder specimens were made with 150 mm in diameter and height of 300 mm. The average compressive strength of concrete obtained on day of testing was 42.25 MPa. Mean modulus of elasticity of the concrete was 33.69 GPa. The longitudinal reinforcements consisted B500Sp reinforcing steel bars with a yield strength of 526.6 MPa and modulus of elasticity 206.7 GPa were also obtained from test.

![Figure 1. The scheme of steel reinforcement and cross-section of beams.](image)

2.2. Beam preparation and test setup

The beams were shear reinforced with a PBO (p-Phenylene Benzobis Oxazole) Ruredil X Mesh Gold and mineral mortar Ruredil X Mesh M750 (Table 1). The PBO mesh is a bidirectionally woven sheet with four times more fibres in the main direction as in the lateral direction. Before the application of PBO-FRCM composites, the concrete surface was properly prepared by grinding, dusting and washing. To avoid stress concentration, the two bottom edges of each specimens were rounded (radius equal to 15 mm).

|                      | Tensile strength  | Young modulus | Ultimate tensile strain | Thickness of composite |
|----------------------|-------------------|---------------|-------------------------|------------------------|
| PBO fibre mesh       | 5800              | 270           | 2.15                    | 0.0455                 |
| PBO-FRCM system      | 1664              | 137           | 1.76                    |                        |
The same strengthening configuration with the same anchorage was used for each of the strengthened beams. The width of the PBO mesh strips for each beam was 100 mm and their spacing was 100 mm (Fig. 2). All strengthened beams have 20×20 mm cuts made under the slab. After shear strengthening, the ends of the PBO strips were wound on a GFRP bar and glued in a cut under the shelf. The bar had a length equal to the length of the beam and together with the PBO strips were covered with an outer layer of mortar.

![Figure 2. The scheme of shear strengthening with end-anchorage.](image)

The beams were tested under three-point bending monotonic load. The load was applied using material testing machine with a range of 0-6000 kN. An external LVDT was used to measure the vertical displacement at the load supplication position and in the places of support. Deformations of concrete, steel and composite were measured with strain gauges. Strain gauges on concrete were applied in the middle of the beams in the central cross section, at the top (compressed) surface. Strain gauges on the steel were applied before concreting, on stirrups at half height and on the longitudinal bar in the middle of the beam span. Strain gauges were adhered at the external stirrups made of PBO mesh in the middle of the beams in accordance with the direction of main fibres. Strain gauges were also applied at the places of composite anchorage.

3. Results

All tested beams failed in a shear with formation of main diagonal crack. Control beam B_0 reached an ultimate load of 453.67 kN (Fig. 3). Table 2 shows summary of the test results. The shear capacity increase is the ratio of capacity of strengthened beams to the capacity of the control beam. $P_{\text{max}}$ stands for the maximum force at the failure, and $\varepsilon$ stands for the maximum deformation of the composite. Shear capacity increase for strengthened beams was 1.05 for beam without anchorage and 1.10-1.12 for beams with anchorages. It means that effectiveness of the anchored composites in increasing the shear capacity of the T-beam was 1.05-1.06 times the effectiveness of the non-anchored composites. It follows that the use of the anchorage improves the shear capacity of RC beams.

The same failure mechanism was observed for all the strengthened beams with anchorages. It consisted in debonding of the PBO mesh from the mortar layer, without the participation of concrete cover (Fig. 4). The first inclined cracks were formed under a load of 80 kN for the control beam and 125 kN for anchored beams. It can therefore be seen that the use of the composite strengthening delayed the appearance of diagonal cracks. Prior to failure an inclined crack was formed in the slab. This crack was develop from the point of the force to the anchorage under the slab. Then the crack would run under the slab along the GFRP bar. This resulted in loosening the anchorage and PBO-FRCM stirrups, and thereby inclined cracks developed on the web of the beam (Fig. 4). Once the tensile strength of the cement mortar was exceeded, the PBO stirrups would debond and the inclined cracks would develop under them until the beam failure. Scratches caused by the slippage of the bundles of PBO fibres on the mortar layer were visible on its surface (Fig. 5). This phenomenon is often found in strengthening, where cement matrix is used as a matrix. This is due to the inaccurate coverage of all fibers in each bundle by the mortar.
Despite the presence of the anchorage no fibres were ruptured in any of the beams. Deformations in the anchorage would abruptly increase in the final stage of loading. This is evidence of the good performance of the anchorage which allowed the load to further.

| Beam     | $P_{\text{max}}$ [kN] | $\varepsilon$ [%] | shear capacity increase [-] |
|----------|------------------------|-------------------|----------------------------|
| B_0      | 453.67                 | -                 | -                          |
| B_P100_BZ| 477.34                 | 6.39              | 1.05                       |
| B_P100_1 | 508.10                 | 9.90              | 1.12                       |
| B_P100_2 | 499.35                 | 9.04              | 1.10                       |
| B_P100_3 | 499.17                 | 8.27              | 1.10                       |

Figure 3. Failure of control beam.

Table 2. Test results.

Figure 4. Failure of strengthened beam with anchorage, debonding of PBO mesh and cracking along GFRP bar.

Figure 5. Failure of strengthened beam with anchorage.
For beam B P100 BZ without anchorage failure mechanism was very similar to beams with anchorage. Debonding of PBO mesh in matrix/fibers layer was also observed. The first inclined cracks were formed under a load of 100 kN. It can therefore be seen that the diagonal crack was formed earlier in the beam without an anchorage than the anchored beam. The destruction occurred as a result of the loosening of the end of the PBO strip under the shelf (Fig. 6), because it was not held by the anchorage. Prior to failure an inclined crack was formed in the slab. This crack was develop from the point of the force to the PBO stirrups under the slab. Debonding of the ends of the PBO strips occurred only in places where the diagonal crack ran near the shelf.

The PBO-FRCM strengthening would begin to participate in carrying the shearing force while the first diagonal cracks appeared, which resulted in increase of deformations of the PBO fibres. This indicates that the PBO stirrups began to take part in carrying tensile stresses in the cracked cross section. The use of the anchorage has improved the efficiency of using the PBO-FRCM composite material. In the beam without anchorage, smaller deformations of the composite (6.39‰) were noted than in anchored beams (8.27-9.90‰). It means, that the maximum deformation of the composite in anchored beams was 30-55% greater than in the beam without anchorage. Comparing the maximum deformation values of the PBO-FRCM composite in the presented studies to the maximum deformation values of the PBO-FRCM material in the axial tensile test (which amounts to 1.76% according Table 1), it can be concluded that the PBO-FRCM material was used in 36% of the beam without anchoring and 47-56% in beams with anchorage.

4. Conclusion
The PBO-FRCM system as a shear strengthening of reinforced concrete beams is a promising solution. Thanks to the use of the PBO-FRCM system the shear strength of RC T-shaped beams increase by 5-12% in comparison with the un-strengthened reference beam. The relatively small increase in load capacity due to the strengthening of that research is associated with a low axial stiffness of the composite. In this research the PBO strips were 100 mm wide with a 100 mm spacing. With a larger amount of composite used, the load increase is greater [13]. For example, using PBO strips with a width of 150 mm, the load increase reaches up to 27%.

The use of the anchorage has a positive effect on shear strength of the beam and on the utilization of composite material. Shear capacity increase for strengthened beams was 1.05 for beam without anchorage and 1.10-1.12 for beams with anchorage. It means that shear capacity of the T-beam with anchorage was 5-6% greater than shear capacity of the beam without anchorage. For strengthened beams with anchorages the maximum strain in the composite reached 9.90‰, which amounts to 55% of the ultimate tensile strain of PBO-FRCM. For beam strengthened with the PBO-FRCM system without anchorage the maximum strain in the composite reached 6.39‰. This proves that the use of anchorage allows to better usage the properties of PBO-FRCM composite. Despite the use of the anchorage, the ultimate tensile strength of the PBO fibers was not reached. No PBO fibres ruptured in any of the beams.

Figure 6. Failure of strengthened beam without anchorage.
The same failure mechanism was observed in each of the strengthened beams. The mechanism consisted in the development of an inclined crack in the web and in the slab and in the propagation of a crack along the anchorage, resulting in the debonding of the latter and the outer stirrups from the surface of the member, in the layer between the fibres and the matrix. The destruction in beam without anchorage occurred as a result of the loosening of the end of the PBO strip under the shelf because it was not held by the anchorage. This proves that anchorages are needed.

The next stage of research should include the possibility of modifying the cement matrix so that premature debonding of the fibers does not occur and that the fibers are better covered with the matrix.

References
[1] Z.C. Tetta, L.N. Koutas, D.A. Bournas, Composites Part B, 77, 338-348 (2015)
[2] T. Blanksvärd, B. Täljsten, A. Carolin, ASCE J. Compos. Construct, 13, 25–34 (2009)
[3] TC Triantafillou, CG Papanicolaou, Mater Struct, 39, 93–103 (2006)
[4] A. D’Ambrisi, L. Feo, F. Focacci, ASCE J. Compos. Construct, 15, 707-720 (2009)
[5] L. Ombres, Compos. Struct., 94, 143-155 (2011)
[6] T. Trapko, Constr. Build. Mater., 73, 332-338 (2014)
[7] T. D’Antino, C. Carloni, L.H. Sneed, C. Pellegrino, Eng. Fract. Mech., 117, 94-111 (2014)
[8] L. Ombres, Composites Part B, 69, 418–426 (2015)
[9] A. D’Ambrisi, L. Feo, F. Focacci, Composites Part B, 43, 2938–2949 (2012)
[10] L. Ombres, Compos. Struct., 12, 316-329 (2015)
[11] T. Trapko, M. Musiał, Composites Part B, 118, 67-74 (2017)
[12] T. Trapko, D. Urbańska, M. Kamiński, Composites Part B, 80, 63-72 (2015)
[13] D. Marcinczak, T. Trapko, M. Musiał, Composites Part B, 158, 149-161 (2019)
[14] E. Tzoura, T.C. Triantafillou, Material and Structures, 49, 17-28 (2016)
[15] D. Baggio, K. Soudki, M. Noël, Constr. Build. Mater., 66, 634-644 (2014)
[16] Z.C. Tetta, L.N. Koutas, D.A. Bournas, Composites Part B, 95, 225-239 (2016)
[17] A. Brückner, R. Ortlepp, M. Curbach, Material and Structures, 41, 407-418 (2008)
[18] Ruredil, X Mesh Gold Data Sheet, Ruredil SPA, Italy,(2009)