

Challenges in Strengthening of Concrete Elements with PBO-FRCM Materials

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Abstract. In the paper a technology of reinforced concrete elements strengthening with PBO mesh bonded with a mineral mortar was presented. The possibilities of application of this system in shear strengthening of reinforced concrete beams and compressed elements are in the range of interests of the authors. In the paper authors experiences in strengthening of such type elements with PBO mesh bonded with mineral mortar were described. Research has shown that destruction of elements strengthened with PBO-FRCM system is caused by a debonding of the fibres from the matrix layer or delamination at the final overlap of PBO mesh. In order to obtain the most efficient use of PBO fibres and prevent premature loosening of composite appropriate anchorage should be used.

1. Introduction

The subject of reinforcing concrete structures using FRP (*Fiber Reinforced Polymers*) composite materials has been of interest for over two decades to many research centers in the world. For more than a decade, the subject has also been present in several Polish universities. It is evidenced by the growing number of publications, appearing in monographs, reputable scientific journals and at thematic conferences. The first laboratory work, engineering applications and computational models related mainly to bent beam elements. Materials used in them were based on *Carbon Fibre Reinforced Polymers* (CFRP), *Glass Fibre Reinforced Polymers* (GFRP) and *Aramid Fibre Reinforced Polymers* (AFRP).

Reliability and effectiveness of the FRP system depends on the epoxy resin, which connects composite and concrete. As has been shown in several studies parameter determining the efficiency of the strengthening is the temperature at which strengthened element is used [1]. Limit temperature for the FRP systems is glass transition temperature of epoxy resin, after which it loses its adhesive properties. The elimination of this problem is possible in two ways, through the use of thermal protection on strengthened elements or by eliminating resin as a binder combining composite with concrete.

In FRCM system (*Fiber Reinforced Cementitious Matrix*) resin was replaced with mineral mortar, which covers the reinforced element and which connects to the composite fiber grid, providing its adhesion to concrete. One of the reinforcement material used in this system is a mesh made from PBO fibers (*p-Phenylene BenzobisOxazole*), commonly called PBO mesh. This system is referred in the literature as PBO-FRCM. Table 1 compares the technical characteristics of the PBO mesh and the most popular composite carbon fiber sheet CFRP [2].



Table 1. Technical parameters of PBO mesh and CFRP sheet [2]

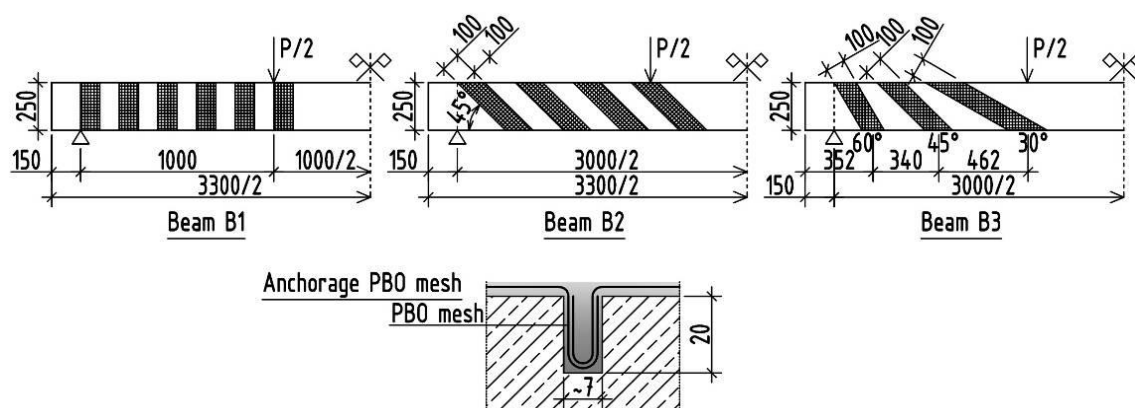
No.	Type of fibres	Tensile strength [MPa]	Modulus of elasticity [GPa]	Ultimate strain [%]	Density [g/cm ³]	Thickness of fibres [mm]
1	PBO	5270 ^(a) /5800 ^(b)	270	2,15	1,56	0,0455
2	CFRP	2670 ^(a, c) /4300 ^(b, d)	238	1,80	1,76	0,1310

(a) according to own tests; (b) according to the producers; (c) data for the laminate; (d) data for the fibres

2. Shear strengthening of reinforced concrete beams

The PBO-FRCM can be effectively used as shear strengthening of reinforced concrete beams as shown inter alia in own studies performed at the Faculty of Civil Engineering, at Wroclaw University of Science and Technology [3, 4].

Beams strengthened with PBO-FRCM system show more ductile nature of the work, than elements strengthened with FRP system. It is connected with the phenomenon of slip that occurs between mortar and fibres. This phenomenon does not appear in FRP systems. In most studies of shear strengthened beams with PBO-FRCM system the open U-shape grid [5-7], without an additional anchoring of the ends of the composite has been used. The mechanism of destruction was due to premature debonding of composite and the loss of the shear capacity, and thus incomplete and not very effective use of PBO mesh. For example, strain in the composite in studies [6, 7] only amount to approx. 2.5-3.5%. Better use of the PBO grid is possible with proper anchorage of composite stirrups, which was the subject of research performed by the authors [3, 4].

**Figure 1.** Scheme of strengthened beams – series 1

Reinforced concrete beams strengthened on a shear with external stirrup of PBO mesh with mortar mineral were constructed and tested. Research was conducted in two series. The first series consisted of three beams of a rectangular cross-section 150x250 mm (Fig. 1). The B1 beam was strengthened by wrapping the entire cross-section with PBO stirrups at an angle 90° to the longitudinal axis, with overlap at the compressed surface of the cross-section. Beam B2 was strengthened with composite strips inclined to the longitudinal axis of the beam at 45°, and for beam B3 strips were inclined at three angles 30, 45 and 60°. The beams B2 and B3 were longitudinal incised at the bottom and at the top, in the middle of the width of the cross-section to a depth of 20 mm. The strips for beam B2 were anchored by adhering the ends of the mesh into incision at both sides with epoxy resin. A method of anchoring for beam B3 was the same as in the beam B2, but the ends of strips were attached into the incision at the bottom with epoxy resin, and at the top with mineral mortar. All beams were strengthened with strips of 100 mm width.

Destruction of the beams was a result of the weakening of external overlap/anchorage and rapid development of diagonal cracks. The failure mechanism of the beam B1 consisted of delamination of

the overlap on the upper surface of the element (Fig. 2). Beams B2 and B3 failed after pulling out PBO mesh from the anchoring (Fig. 3). Strain of the anchored PBO stirrup measured at half height of the beam reached the value of 3.7-5.0‰. This represents significant improvement of the effectiveness of PBO-FRCM strengthening compared to research conducted on beams strengthened without end-anchoring (U-shaped strengthening).



Figure 2. Failure of beam B1 – delamination of the lap on the top surface



Figure 3. Failure of beam B3 – pulling the endings of PBO stirrups out of the lap

A second series of tests was carried out on 3 T-shaped beams strengthened in a shear with PBO mesh with anchorage in the flange of the beam. Beams were tested as a simply supported in three-point bending. All beams were strengthened with strips of 150 mm width, and the inclination of fibres in the main direction toward the longitudinal axis of the beam was 90°. Each of the beams had the same type of anchorage. A gap of 20x20 mm and a length equal to the length of the beam was made under the flange, and glass fibre bar with PBO strip wrapped around was glued into a gap. The bar was glued using a mineral mortar which is also used for bonding PBO mesh to the surface of element (Fig. 4).

All specimens failed in shear (Fig. 5). Before the damage, a large diagonal crack from the force to the bar and then along the bar was created in the flange (Fig. 6). Anchoring was not pulled out. For each of the beams debonding of the composite in a thin layer of mortar-fibre contact, at the location of diagonal cracks, were observed. After debonding, composite further took part in the transfer of shearing forces, but separately from the concrete, therefore the diagonal crack could increase to the destruction. Deformation of anchored PBO stirrups in the second series of tests, measured at mid-height of the composite, amounted to 7.5-8.0‰. This value is higher than that obtained in the previous test series and higher than for composites without anchorage. This may indicate that the proposed anchoring allows for better use of composite materials than in the beams without anchors. It should be noted that in all presented tests no rupture of PBO fibers was observed.

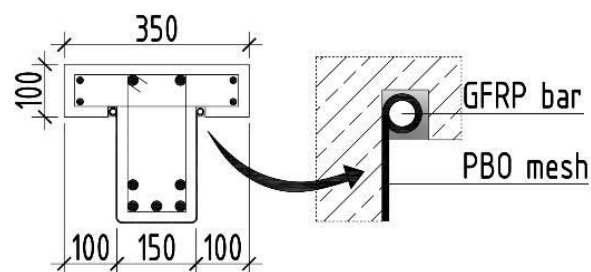


Figure 4. Cross-section of the beams – series 2



Figure 5. Failure of beam—debonding of the PBO mesh



Figure 6. Failure of beam – crack along the bar and PBO debonding

3. Strengthening of compressed elements

The advantages of wrapping the concrete with the CFRP outer sheet are well-known. However, when introducing a new reinforcement system, it was necessary to assess the effectiveness of the reinforcement and compare the behaviour of the elements confined in the CFRP sheet and the PBO mesh [1, 2].

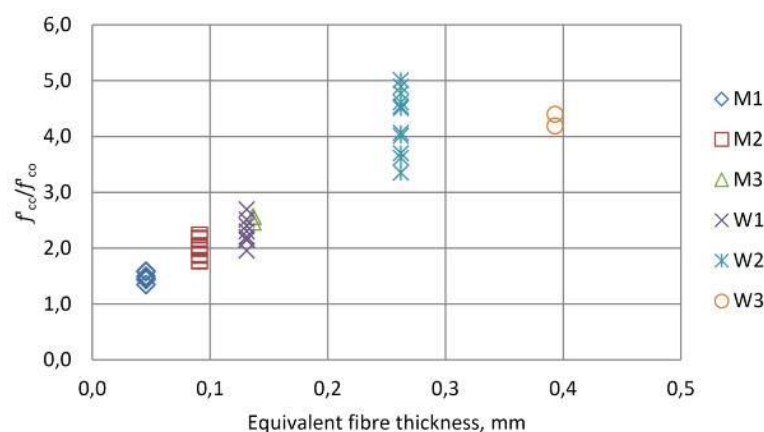


Figure. 7. Compressive strength of confined concrete f_{cc} relative to fibre thickness [1, 2]
designations: W – CFRP sheet, M – PBO mesh, i – number of layers,
 f_{cc} – compressive strength of confined concrete, f_{co} – compressive strength of unconfined concrete.

As expected, the CFRP system produced noticeable effect of number of the sheet layers circumscribing the section on the increase in the load-bearing capacity. The thickness of the composite coat and the type of fibres applied affect the measured limit load-bearing capacities. When applying one layer of the CFRP sheet, the similar value of the failure load to the one with the application of the three layers of the PBO mesh is obtained (Fig. 7).

The comparison of tensile strength of the fibers in the PBO mesh and CFRP sheet (Table 1) suggests that the PBO-FRCM system should give even better reinforcement results. However, greater tensile strength of the PBO mesh does not translate directly into greater increase in load-bearing capacity and the value of the compressive strain. It is caused by graininess of the mortar and filling the composite with it as well as adhesion to concrete and between its layers.

From the destruction mechanism (Fig. 8), to the nature of the paths of strain, to the limit values of load-bearing capacity and strain, research has shown that these two systems cannot be compared to each other at the same intensity of reinforcement (number of layers). All elements reinforced with the CFRP sheet were destroyed in a violent manner, by breaking the shell. The mechanism of destruction of the elements reinforced with the PBO mesh was quite different. None of the attempts resulted in breaking the fibre and the initiation of destruction always occurred on the external overlapping zone.



a) overlapping zone $z=70$ mm, where $z/u=0.2$
(u – perimeter of the sample, 113 mm)



b) elements without overlapping zone

Figure 8. Typical failure of PBO confined concrete cylinders in compression test

The value of the limit peripheral strains depends essentially on the length of the overlapping zone and the factors that determine delamination are the smallest strains at the length of the overlapping zone. At the same time, it should be noted that the distribution of the strains along the length of the composite overlapping zone is non-linear. Along with the increase of the overlapping zone, delamination strains increase. The coefficient of utilization of the PBO mesh in the end zone of the overlapping zone is within the range of 0.28-0.44, depending on its length. At the same time, by analysing the strains of the transverse outside the overlapping zone, it can be seen that the coefficient of utilization of the PBO mesh is 0.55-0.80.

Undoubtedly, the PBO-FRCM system is competitive with the CFRP system. The nature of functioning of the elements reinforced with the PBO mesh is more predictable to use in more complex structural systems rather than separate compressed elements. The indicated and slow increase in strains in the area of the destructive load allows the redistribution of the internal forces and joining of other, less stressed elements.

4. Conclusion

Therefore, the PBO-FRCM system is not intended to replace or eliminate the FRP resin composites. However, the presented papers demonstrate great potential of the composites based on mineral mortar as the reinforcement of concrete structures. Both systems - FRP and PBO-FRCM differ a lot, even though both of them derive from the same idea involving the restriction of freedom of stretched and compressed concrete element strains.

The conscious decision to choose the reinforcement system must be dictated by the fact that the selected system can ensure the achievement of those objectives both temporarily and in a long term. This selection should be accompanied by full knowledge of the reinforced element, including one which will help predict potential threats to the reinforced structure and help choose the most suitable system. On the basis of the acquired knowledge it is important to take into account what benefits and risks are offered by both technologies – FRP and PBO-FRCM, and the fact that there is no perfect system, and for each one you can specify both the number of advantages, as well and defects.

The most important issue for the future is to develop an effective method of anchoring the PBO mesh on the external overlapping zone, in order to fully utilize its strength properties. Only then will it be possible to analyse, among others, rheological characteristics, the impact of variable loads, etc.

Based on the described research it can be seen that the use of appropriate anchorage effectively improves the use of the composite. In the case of PBO-FRCM shear reinforcements problem is the occurrence of premature debonding of composite from the surface of the element in a thin layer of mineral mortar. This is related to the use of mineral mortar which loses its properties after exceeding its resistance to tensile stresses. In order to better use of characteristics of PBO fibres is recommended to prevent this phenomenon.

5. References

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