

Experimental research on RC beams strengthened in shear with PBO-FRCM composites

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Abstract. The article presents an experimental research conducted on beams with PBO-FRCM shear strengthening with end-anchorage system. PBO-FRCM (Fibre Reinforced Cementitious Matrix) composites consist of mineral mortar and PBO (p-Phenylene Benzobis oxazol) composite fibres. Using of mineral mortar makes them as a good alternative to the commonly used FRP composites, especially in structures exposed to high temperatures and historical buildings. For FRCM composites most commonly failure mechanism is debonding of the fibers from mineral mortar with no rupture of fibres. To prevent premature debonding of the composite and increase the effectiveness of reinforcements FRCM suitable anchorage should be used. In this case, experimental research was conducted on 4 T-shaped reinforced concrete beams strengthened in a shear using PBO-FRCM with anchorage. One beam was a control beam without strengthening, and 3 beams had the same shear strengthening with PBO strip anchorage. All elements failed in a shear with formation of main diagonal crack. Despite the presence of anchorage, the failure mode of all strengthened beams was associated with debonding of PBO mesh accompanied by the development of diagonal crack. The PBO fibres were not ruptured in any of the beams. Despite the debonding, composite further transferred shear force. The failure mechanisms and strain in composites were analysed and described. The results confirmed that the PBO-FRCM system is an effective way of strengthening RC beams in a shear and that the effectiveness of this system is influenced by the presence of the anchorage.

1. Introduction

FRCM (Fibre Reinforced Cementitious Matrix) composite reinforcements are a good alternative to the FRP (Fibre Reinforced Polymers) system, mainly in historic buildings and structures exposed to high temperatures, owing to the use of mineral-based mortar, instead of epoxy resin, as the matrix bonding the composite with the element being strengthened. In this way epoxy resin's main drawbacks, i.e. low resistance to high temperatures, toxicity, poor thermal compatibility with concrete and sensitivity to a wet substrate, are eliminated.

Elements strengthened using the FRCM system are distinguished by their performance – more plastic than that of elements strengthened using the FRP system because of the less perfect bond between the fibres and the matrix than in the case of epoxy resin-based composites. Due to its granularity mortar is unable to thoroughly cover each fibre, which results in nonuniform deformations of the fibres relative to each other in a single bundle. Composites of this type usually fail in the mortar/fibres interfacial zone due to the premature debonding of the fibres and their slip. Thus the



FRCM system is less effective than the FRP system and the recommendations for FRP reinforcement calculations can be inappropriate for FRCM materials.

The existing literature reports successful implementation of FRCM systems for strengthening concrete reinforced beams in a shear [1-9]. The research primarily concerned beams with a rectangular cross-section, strengthened with carbon, glass, basalt or PBO fibers [1-6]. As far as the strengthening scheme is concerned, the FRCM system was applied either in a side-bonded [4,6], U-wrapping [3,4,5] or full-wrapping [1,2]. Very little research deals with the subject of beams with a T-section, with end-anchorage [7-9]. The existing literature showed that the anchorage positively influences the load capacity of the beam, preventing premature debonding of the composite and increasing its effectiveness.

This paper presents the results of an experimental study conducted on four RC T-shaped beams, critical in shear. Three of the beams were shear strengthened with PBO-FRCM composites applied to the bottom and both sides of the web (U-wrapped). The aim of this study was to examine the effect of the end-anchorage of the FRCM strips under the slab.

2. Experimental research

Four 2300 mm long RC T-beams 150×400 mm in cross section were subjected to tests. Three of the beams were strengthened with a PBO (p-Phenylene Benzobis Oxazole) fibre mesh bedded in mineral mortar (PBO-FRCM) and one beam was not reinforced (the reference beam). Flexural reinforcement in the form of 5 bars 20 mm in diameter was designed for prevent destruction due to bending before exhausting the shear strength. Stirrups in the form of bars 8 mm in diameter were spaced at every 250 mm along the whole length of the beam (Fig. 1)

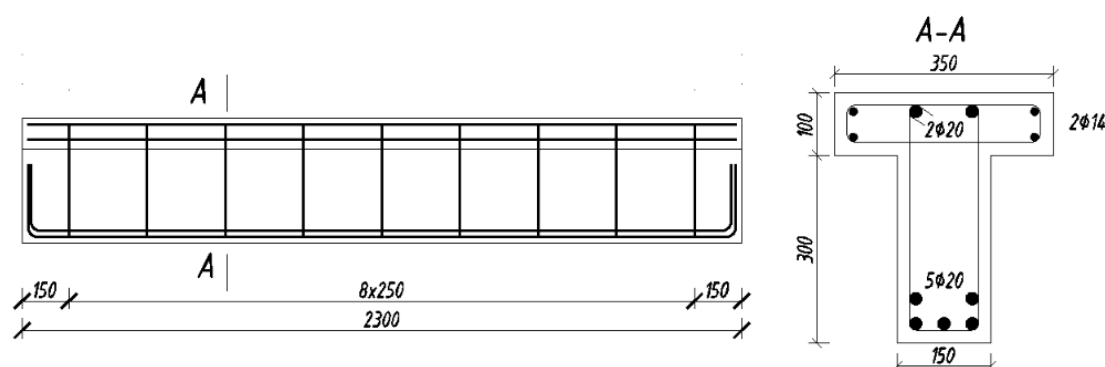


Figure 1. The scheme of steel reinforcement and cross-section of beams

2.1. Material properties and test setup

In order to determine the strength qualities of concrete the specimens were made as 150x150x150 mm cubes and cylinders with height of 300 mm and 150 mm in diameter. Compressive strength and modulus of elasticity of the concrete were defined prior to commencing the tests:

- 1) mean cubic compressive strength of concrete $f_{cm,cube}=45.95$ MPa,
- 2) mean cylinder compressive strength of the concrete $f_{cm,cyl}=44.75$ MPa,
- 3) mean modulus of elasticity of the concrete $E_{cm}=32.13$ GPa.

What is more, strength parameters of reinforcing bars were also defined:

- 1) mean yield stress of steel bars $f_{ym}=526.2$ MPa,
- 2) mean ultimate strength of steel bars $f_{tm}=626.3$ MPa,
- 3) mean modulus of elasticity of bars $E_{sm}=206.7$ GPa.

The beams were shear reinforced with a mesh made of PBO fibre (p-Phenylene Benzobis Oxazole) Ruredil X Mesh Gold and mineral mortar Ruredil X Mesh M750. The main mechanical properties of PBO fibers, determined according to manufacturer, are collected in the Table 1. In the table is also reported the mechanical properties of the PBO-FRCM system, adopted from the ACI549.4R-13.

Each beam was tested under three-point bending. The vertical displacement underneath the load was measured at each load step by a Linear Variable Displacement Transducer (LVDT). One strain gauge was attached to the flexural reinforcement bar at the location below the loading point and seven strain gauges were attached in the middle of the height of all stirrups in span. Strain gauges were also bonded on the central fibre bundle of outer PBO fabrics at the mid-height of the U-wrapped PBO-FRCM strips and on the anchorage.

Table 1. Mechanical and geometrical parameters of the FRCM strengthening materials [10]

	Tensile strength f_{tz} [MPa]	Young modulus E_f [GPa]	Ultimate tensile strain ϵ [%]	Thickness of composite [mm]
PBO fibre mesh	5800	270	2.15	0.0455
PBO-FRCM system	1664	137	1.76	-

2.2. Shear strengthening

The utilized PBO-FRCM system consisted of one layer of the fabric with the associated mortar. FRCM strengthening was applied on the both sides and bottom of the web. This type of strengthening configuration is called U-wrapped. Beams were strengthened in shear discontinuously with 150 mm wide FRCM strips with spacing of 100 mm (Fig. 2). To ensure a good bonding the bottom and side surfaces of each beam were cleaned of laitance, dusted and washed. The corners of each of the beam were rounded in the areas where the reinforcing was applied, in order to prevent the local stress concentration. The surfaces of the web were saturated with water for 15 min prior the placing the FRCM strips. Then first layer of the mortar was applied and fabric strips were placed. The second layer of mortar was applied in place of the strips and under the slab along the entire beam. The PBO strips with 150 mm wide and the length equal to the length of the entire beam, was placed under the slab as an anchorage (Fig. 3). The direction of the main fibers in this strip was perpendicular to the main fibers in shear strips. Finally, the second layer of mortar was applied to the anchorage. (Fig. 4)

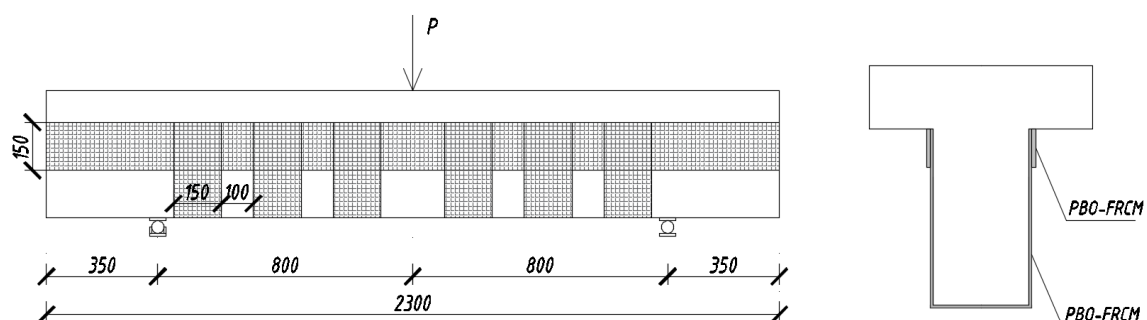


Figure 2. The scheme of shear strengthening with end-anchorage

3. Experimental results and discussion

The reference beam reached an ultimate load of 396.6 kN and failed by shear after the formation of main diagonal crack in the shear zone. At failure the rupture of one steel stirrup in shear zone was observed and longitudinal steel bars were yielded.

All strengthened elements failed in a shear with formation of main diagonal crack. Table 2 shows summary of the test results for strengthened beams. The measure of the effectiveness of strengthening is the ratio of capacity of strengthened beams to the capacity of the control beam.



Figure 3. PBO strip application along the beam under the slab



Figure 4. Anchorage after applying the outer layer of mortar

Table 2. Test results for strengthened beams

	Peak load P [kN]	Deflection at the peak load [mm]	Maximum composite strain $\epsilon_f^{\max}$ [%]	Shear strengthening effectiveness [-]
B_W1	505.58	14.75	5.18	1.27
B_W2	474.72	15.23	6.34	1.20
B_W3	458.03	14.50	3.68	1.15

The average enhancement in the load carrying capacity for strengthened beams was 21% compared to the reference specimen.

The same failure mechanism, consisting in composite debonding in the fibres/matrix interfacial zone, was observed in all the strengthened beams, whereby the diagonal crack could develop freely. In each beam the matrix/concrete zone was intact, which is evidence of good mortar/concrete bonding. Despite the presence of the anchorage no fibres were ruptured in any of the elements. The slip of PBO fibers on the cement mortar was visible on the top of the PBO strips. This phenomenon is characteristic for FRCM materials in which mortar is used as a matrix. In FRCM composites cannot be obtained such a good coverage of the all fibres by the matrix, as in the case of FRP systems, because the cement mortar has higher granularity and does not reach all fibres in every bundle of the mesh. A single external fibers of the bundle are in direct contact with the matrix and are closely connected to each other, while the fibers inside the core of the bundle are not in direct contact with the mortar, and due to less friction slippage between the fibers may occur. This phenomenon is described in the literature as the telescopic effect [11-13]. The debonding occurs in the fiber-mortar layer, confirming that the crucial point of this type of composite materials is bond between fibers and matrix

With the increasing load, the PBO strips were debonded, which was visible on the surface of the longitudinal PBO strip (performing the role of anchoring) in the form of vertical cracks at the edge of the vertical strips (Fig. 5, 6). This resulted in the detachment of the entire anchorage along the length of the shear span of the beam. The ends of the longitudinal PBO strip, which were attached beyond the

supports, did not become debonded, but the slippage of the fibers was visible on them (Fig. 7). This means that the length of anchoring the longitudinal strip beyond the support (350 mm) was sufficient.

3.1. Crack propagation and strain results

The reference beam showed typical shear failure characteristics within the critical shear span. The major diagonal crack existed was below the loading point and extending downwards at approximately 45° . Main diagonal crack at the same inclination was observed for all strengthened beams. The use of strengthening had an impact on the development of cracks. During the increase of load on the web for a long time only vertical cracks appeared, which then ran along the longitudinal strip. Diagonal cracks in the strengthened beams appeared under almost twice the load (load approximately 300-350 kN), than in a reference beam without strengthening (with a load of approximately 150 kN). Diagonal cracks appeared primarily on the shelf, and on the web in the mid-section of the shear span. Due to the inhibition of diagonal cracking, a delay in the yielding of steel stirrups was also observed. For the control beam, stirrups has yielded at a load of about 100-150 kN, while for the strengthened beams the value of this load was about 300-400kN.

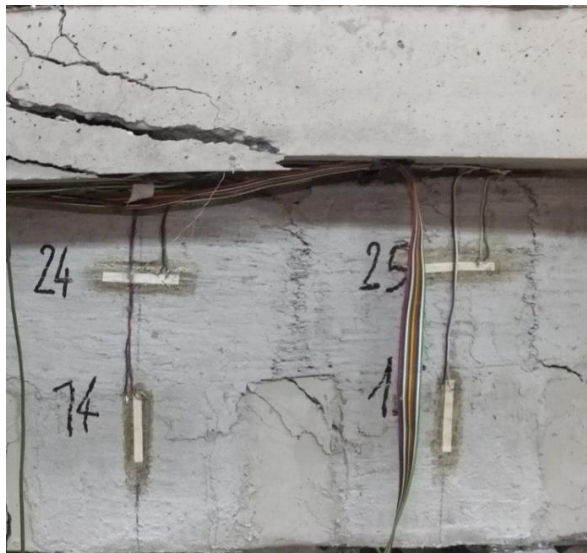


Figure 5. B_W2 failure. Vertical cracks at the edge of the vertical strips

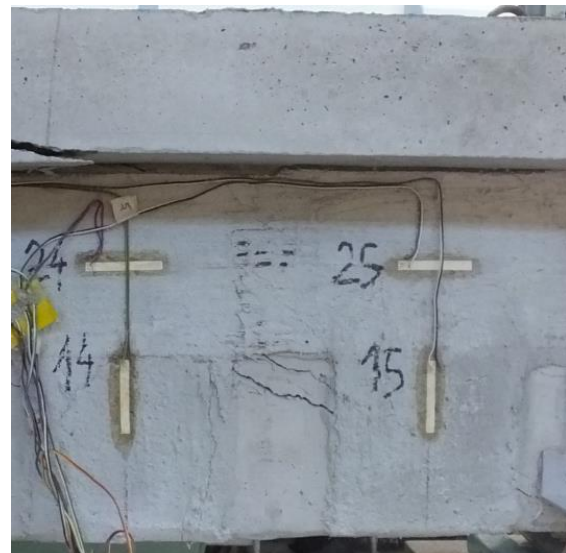


Figure 6. B_W3 failure. Vertical crack at the edge of the vertical strip and slippage on longitudinal strip



Figure 7. B_W1 failure. Vertical cracks at the edge of the vertical strips and slippage of the fibers at the ends of the longitudinal PBO strip, beyond the supports

The maximum strain of the PBO-FRCM composite measured in the middle of the height of the PBO strips reached a value of 6.34‰, which means the use of total tensile strength of PBO fibers of around 30% (according to the manufacturer [10,14]), and which represents about 36% of load capacity of PBO-FRCM system in tensile test (Table 1). Until the diagonal cracks appears, PBO-FRCM composites behave linearly, and the increment of deformation is very small. At the moment of exceeding the shear strength of the concrete diagonal cracks are formed and strains in the PBO stirrups suddenly increase, which means that composite begins fully cooperate in transfer of shear forces and begin to behave nonlinearly. Due to the high stiffness of the composite reinforcement, the diagonal cracks appeared relatively late, so only in the last phase of the load the composites joined the cooperation in transferring shear stresses. Therefore the utilization of the strength of the composite is relatively low.

4. Summary and conclusion

On the basis of the test results it can be confirmed that the PBO-FRCM system is an effective way of strengthening RC beams in a shear. It is possible to draw the following conclusions:

1) The effectiveness of PBO-FRCM strengthening is influenced by the presence of the anchorage, which further increases the load capacity of the beam and prevents premature debonding of PBO mesh. For strengthened beams with anchorage the increase of shear capacity of 15-27% was obtained, compared to not strengthened beam. In this study the maximum strain of the composite amounting to 6.34 ‰ was achieved, which represents about 30% of tensile capacity of PBO dry fibers and about 36% of load capacity of PBO-FRCM system in tensile test. In comparison to studies of RC beams strengthened in a shear with PBO-FRCM without the anchorage, wherein the maximum strain of the composite amounted to 3.5 ‰ [5], the use of the anchorage has allowed better use of the composite properties.

2) The proposed method of anchoring of external stirrups did not ensure a complete utilization of tensile strength of the PBO mesh. The PBO fibres were not broken in any of the beams. Destruction occurred due to debonding of the PBO mesh from the cement mortar, and developing of diagonal cracks under the strengthening.

3) Until the first shear crack appeared and crossed the PBO stirrup, the composite cooperates with concrete in the scope of tensile strains of the concrete itself during shear.

4) The PBO-FRCM can be successfully used as a shear strengthening of structural elements, but it is important to be aware of the specific mechanism of work of these composites, which is very different from FRP composites. In FRCM composites cannot be obtained such a good coverage of the all fibres by the matrix, as in the case of FRP systems, because the cement mortar has higher granularity and does not reach all fibres in every bundle of the mesh. For this reason, in FRCM debonding, slippage of fibers and telescopic effect occurred.

References

- [1] T C Triantafillou, C G Papanicolaou: Shear strengthening of reinforced concrete members with textile reinforced mortar (TRM) jackets, *Materials and Structures* (2006) 39:93–103
- [2] Trapko T, Urbańska D, Kamiński M Shear strengthening of reinforced concrete beams with PBO-FRCM composites, *Compos Part B-Eng.* 2015; 80, pp. 63-72.
- [3] T Blanksvard, B Taljsten, A Carolin: Shear strengthening of concrete structures with the use of mineral-based composites, *ASCE Journal of composites for construction* 2009, p. 25-34More references
- [4] A Si Larbi, R Contamine, E Ferrier, P Hamelin: Shear strengthening of RC beams with textile reinforced concrete (TRC) plate, *Construction and Building Materials* 24, October 2010, Pages 1928-1936
- [5] Ombers L Structural performances of reinforced concrete beams strengthened in shear with a cement based fiber composite material. *Compos Struct*, 2015; 12, pp. 2316-329.
- [6] Yousef A Al-Salloum, Hussein M Elsanadedy, Saleh H Alsayed, Rizwan A Iqbal: Experimental and Numerical Study for the Shear Strengthening of Reinforced Concrete Beams Using Textile-Reinforced Mortar, *ASCE Journal of composites for construction* 2012, p. 74-90
- [7] A Mofidi, O Chaallal, B Benmokrane, K Meale: Preformance of End-Anchorage systems for RC beams strengthened in shear with epoxy-bonded FRP, *ASCE Journal of composites for construction* 2012, p. 322-331
- [8] Tzoura E & Triantafillou T C 2016. Shear strengthening of reinforced concrete T-beams under cyclic loading with TRM or FRP jackets, *Materials and Structures*, 2016, 49, pp. 17-28.
- [9] Zoi C Tetta, Lampros N Koutas, Dionysios A Bournas: Shear strengthening of full-scale RC T-beams using textile-reinforced mortar and textile-based anchors, *Composites: Part B* 95 (2016), p. 225-239
- [10] ACI 549. 4R-13: Guide to Design and Construction of Externally Bonded Fabric-Reinforced Cementitious Matrix (FRCM) Systems for Repair and Strengthening Concrete and Masonry Structures
- [11] D'Antino T, Sneed L H, Carloni C, Pellegrino C Influence of the substrate characteristics on the bond behavior of PBO FRCM-concrete joints. *Constr Build Mater*, 2015; 10 , pp. 838-850.
- [12] Carozzi F G, Poggi C Mechanical properties and debonding strength of fabric reinforced cementitious matrix (FRCM) systems for masonry strengthening. *Compos Part B-Eng*, 2015; 70, pp. 215-230.
- [13] Bertolesi E, Carozzi F G, Milani G, Poggi C Numerical modelling of Fabric Reinforce Cementitious Matrix composites (FRCM) in tension. *Constr Build Mater*, 2014; 70 , pp. 531–548.
- [14] Ruredil X Mesh Gold Data Sheet, Ruredil SPA, Milan, Italy, 2009