Performance of GFRP bar anchored PBO-FRCM composite on one-way RC slabs under flexure

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Abstract. The use of FRCM (Fabric Reinforced Cementitious Matrix) composites for reinforced concrete elements structural strengthening is gaining increased popularity. This causes the need to better understand the work of the material and to propose an effective way of using it. The mechanical behaviour of FRCM composites related to their ductility and tendency to debond or delaminate causes that its typical use, known from the older FRP (Fibre Reinforced Polymers) technology, is inefficient, that was the reason for the anchoring concept. This paper presents the results of the research based on three slab type elements, two of which were strengthened with one layer of PBO-FRCM composite with GFRP rebar anchorage of the composite mesh ends. The most important mechanical properties of the elements were measured and analysed.

1. Introduction

Strengthening composites are present in civil engineering for around 40 years [1] and have now become an inseparable element in the construction repair situations. The most popular technology of strengthening composites named FRP (Fibre Reinforced Polymers), consisting of the fibres embedded in a polymer matrix, is characterised by good strength-to-weight ratio, adaptability and flexibility of application, and resistance to aggressive and corrosive environment [1]. The main problem with the FRP composites is related to the properties of polymer matrix, which is usually made of epoxy resin. The glass transition temperature (Tg) of the epoxy resin is about +50°C [2], which means that its operation in a fire situation is not effective, because after exceeding the glass transition temperature threshold it starts to become liquid. Additionally, the epoxy resins are expensive and they are characterized by a limited possibility of use in high moisture or cold, and have poor compatibility to the substrate [3].

The majority of the problems related to FRP composites might be reduced or eliminated thanks to the use of FRCM (Fabric Reinforced Cementitious Matrix) composites made of fibrous meshes in mineral mortar. Changing the matrix from epoxy resin to mineral mortar allowed to achieve higher resistance to higher temperatures and better compatibility with concrete substrate [1]. Due to different matrix structure and physical properties the fibrous material needs to be rearranged into loose meshes to allow the mineral mortar to pass through and create a binding. The change of the matrix has a positive impact on many aspects of composite usage, but it changes the mechanics of the material work compared to FRP. Mineral matrix is incapable of penetrating and covering all fibres in the yarns so only external fibres are bonded with the matrix, while internal fibres are subject to telescopic effect inside the yarn as shown in Fig. 1 [4]. FRCM composites usually show bi- or tri-linear behaviour and
their failure is generally related to debonding or delamination [4-6]. The slope of the first line of stress-strain curve depends mainly on the properties of mineral matrix, the third line is related to the fibres properties only, while the second line shows the moment of matrix cracking and is an intermediate point of the materials behaviour. Depending on the fibres used different material behaviours and ultimate stresses are obtained as shown in Fig. 2.

![Figure 1. Telescopic effect [4].](image1.png)

![Figure 2. Stress-strain curves of FRCM composites with different fibres used [4].](image2.png)

Such mechanical behaviour of FRCM composites leads to insufficient utilisation of high-strength fibres. To improve the performance of the fibres several ways of anchoring FRCM strengthening were proposed for elements subjected to flexure [7] and shear [8-10]. The anchoring of the fibres allows the higher strains to be obtained and hence improve the load bearing capacity of the composite. The research on the anchorage of the composites on slab type RC elements under flexure is limited. There is no present research in this field regarding FRCM composites, but the studies on the anchorage FRP strengthening of slab elements show that the use of anchorage can delay the debonding of the composite. It leads to higher strength of the RC slab and allows the element to gain much larger deformation [11, 12]. Despite the limited literature in the field of anchorage of FRCM composites in slab elements the effectiveness of FRCM strengthening of slabs has been confirmed [13-16]. The failure of the FRCM composites on slabs occurs due to slippage of the fibres in the matrix when one layer of mesh is applied or due to delamination of whole composite when more layers of mesh are applied [13]. Similar results were obtained by the other researchers who have compared FRCM and FRP strengthening of slab type elements. Despite the higher strengthening effect of the FRCM system, higher deformations of the elements were observed at the same load level when compared to FRP strengthening [14]. The initial strength of the element, dependent on the reinforcement ratio, has an impact on the strengthening effect. The more steel reinforcement is used in the element, the worse strengthening effect is observed [15]. Another interesting aspect of FRCM is connected with bi-directional meshes that also work in transversal direction of one-way slab element. It might help in gaining more load-bearing capacity and stiffness in strengthened RC slab [16].

The present research results clearly show that FRCM composites are a promising method of reinforced concrete elements strengthening. The benefits of composite materials connected with high thermal resistance make it a very interesting solution. Due to lack of research regarding anchorage of FRCM composites on slab-type elements the authors decided to take this topic and carry out a series of tests to recognize the phenomenon.

2. Experimental research

The research was carried out on the basis of three slab type RC elements under flexure. Two of the elements were strengthened with FRCM composite with anchorage of the mesh ends. One of the elements was left without strengthening as a reference element.
2.1 Test specimens and test stand
The slabs used in the research were 2000 mm long, 1000 mm wide and 150 mm thick. The elements were reinforced with 8 $\phi 10$ rebars in bottom surface and 8 $\phi 8$ rebars in top surface. Transverse reinforcement on top and bottom surface was made of $\phi 8$ rebars at 200 mm spacing. All test specimens were prepared at the precast plant to ensure stability of dimensions and strength. Slabs were subjected to flexure in 4-point bending test with the span length of 1700 mm and the spacing between load forces equal to one third of the span (567 mm). The set-up of the test stand is shown in Fig. 3.

![Test stand used in research.](image)

Five LVDTs were used to measure the deflections of the element – two over the supports, two directly under the forces and one in the middle of the span. Strain gauges were placed in three rows on the width of the element to measure strains of main steel reinforcement, top and bottom surface of the concrete, and composite mesh.

2.2 Materials
The elements were made with one batch of concrete and left to reach their full strength. Additional concrete cylindrical elements were made to measure its mechanical properties. The mean value of cylinder compressive strength was 38,8 MPa and the module of concrete elasticity value was 35,2 GPa. Steel reinforcement was made of steel with characteristic yield strength of 500 MPa. The meshes used in FRCM composites were made of PBO (p-Phenylene Benzobis Oxazole) fibres. They are characterised by very high value of tensile strength of 5800 MPa, while the module of its elasticity is 270 GPa, that results in the ultimate strain of about 2% [17].

2.3 Anchorage
To help the PBO fibres in obtaining higher strains the anchorage of the mesh ends has been applied. Grooves with dimensions of 20x20 mm were prepared in test specimens to create a mounting socket. The ends of the mesh were wrapped on a $\phi 8$ GFRP rebar and firmly pressed into the groove into which the mineral mortar was previously applied. Finally, the entire anchorage and mesh area was covered with a top layer of mineral mortar to complete the FRCM composite formation process.

3. Research results and discussion
All the elements tested failed after reinforcing steel yielding followed by compressed concrete crushing. In the elements with PBO-FRCM strengthening the steel yielding point was the beginning of the increased work of the composite, that was noticeable thanks to many clicking sounds that were heard during the cracking of the matrix and the tension of PBO fibres. The composite failed when the ends of GFRP bars torn out of the groove (Fig. 4), that lead to fabric debonding. No fibres were ruptured during the tests. It suggests that fibres ultimate strain was not obtained.
The ultimate failure force registered in the test of unstrengthened element was 171.4 kN, while the elements with bar-anchored PBO-FRCM strengthening showed the mean ultimate value of 216.2 kN. The composite with proposed way of anchorage gave 26% increase in the load-bearing capacity of the tested slab.

3.1 Load-deflection

The load-bearing capacity increase finds its confirmation in the analysis of the load-deflection curves of the element. Graphs obtained during the study are shown in Fig. 5. Reference element curve is marked black, while the curves referring to two strengthened elements are marked in colour.

![Figure 4. GFRP anchoring rebar torn out of the groove.](image)

![Figure 5. Load-deflection curves obtained in the research.](image)

The behaviour of all the elements is almost identical before reaching the load level of reinforcing steel yielding in reference element. FRCM strengthening does not show any noticeable effect in this range of load forces in terms of load-deflection curves. After exceeding the load of around 140 kN the unstrengthened element starts to deform rapidly, while the elements with FRCM composite attached show stiffness even at higher loads. The slope of the curve in the last phase of the elements work is more steep for the strengthened elements, what indicates the incorporation of external composite stiffness to the stiffness of the whole element. The failure of FRCM strengthened elements occurs at much smaller deflections of the slab (around 40 mm) compared to reference slab (around 55 mm). It may suggest that with better anchorage or fabric adhesion the load-bearing capacity increase can be even greater.

3.2 Strengthening composite and steel strains

The main task for the anchorage is to allow the fabric in FRCM composite to reach higher strains, that will allow them to reveal their full potential. The maximal measured composite strain values of around 10‰ are much below the ultimate value, which may indicate that this type of anchorage does not allow for optimal use of PBO fibers. Mesh strains development comparison on the elements width is presented in Fig. 6. Curve corresponding to the longitudinal axis of the element is marked black while the coloured ones describe the behaviour of the mesh closer to the edges. Strain values were measured until strain gauge failure. It is visible that strains in the middle longitudinal axis of the slab are higher than those closer to the edges. Before concrete cracking the differences are negligibly small, however, the result spread on both sides of the slab (two coloured lines in Fig. 6) may indicate that the mesh strain is mainly dependent on the cracking development rate in the immediate strain gauge surrounding. Another arrangement of the strain gauges could show greater strain values. Reinforced concrete slab strength depends mainly on the reinforcing steel. Application of the strengthening composite may reduce deformation of reinforcing steel, and hence stresses occurring in it. Middle
cross-section steel reinforcing strain values of strengthened and unstrengthened element are presented in Fig. 7. The reference element is marked black and the strengthened one marked in colour. Values are compared until the strain value corresponding to the destruction of the first strain gauge. However, it occurred after reinforcing steel yielding, so the results determined to the level shown allow for sufficient analysis.

![Figure 6. Middle cross-section strains of the composite in the element longitudinal axis and at the edges.](image1)

![Figure 7. Maximal reinforcing steel strains in strengthened and unstrengthened element.](image2)

The diagram clearly shows that steel strains for equal load levels are lower in the case of PBO-FRCM strengthened element. Before concrete cracking the difference is very small, but with further sample loading it becomes more visible. Curves shapes are almost identical in both cases, but they are mutually offset.

4. Conclusions
Externally bonded PBO-FRCM composite showed its effectiveness in one-way RC slab type elements strengthening. The following main conclusions have been drawn from the conducted research:

- Application of one layer of PBO-FRCM composite with bar anchorage have increased the load-bearing capacity of the tested one-way slabs by 26%,
- In addition to increasing the load-bearing capacity of the slab the reduction of deformation after steel yielding was also visible,
- The failure of the composite is initiated by the destruction of the anchorage, which may indicate that the anchorage is a critical element from the element load-bearing capacity point of view,
- The use of FRCM strengthening increases the stiffness of RC slabs after exceeding reinforcing steel yielding point,
- Strain values of around 10‰ and no fibre rupture indicate that the fibre potential has not been fully used,
- PBO-FRCM composite application takes over some of the reinforcing steel loads, thereby reducing its deformation and stress, which leads to increased load-bearing capacity of the element.
- More research in the field of FRCM composites anchorage is still needed in order to study this phenomenon thoroughly. The presented work is still in progress and the aim of the authors is to develop an optimal way of FRCM composites anchorage.

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