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DIC (Digital Image Correlation) method in the research of RC beams strengthened with PBO-FRCM materials

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Abstract. The article presents tests of a reinforced concrete beam strengthened in a shear with PBO-FRCM composite materials. Measurement of the deformation of the composite was carried out using two methods - with strain gauges and the optical DIC method (Digital Image Correlation). The DIC method consists in taking a series of photographs of the tested object before and during loading. The surface of the tested element must have randomly spaced spots that are applied to the object before measurement. During the study, the cameras monitor the shifting of spots against each other, which in comparison to the reference image before loading gives information about strains and stresses of the tested element. Measurements of deformation of composite materials using strain gauges are difficult to clearly analyse, because the strain gauge is in a specific, limited place, which does not correspond to the work of the entire composite. In addition, the strain gauge tends to break at the place of crack. The article discusses this problem by presenting the results of deformation of PBO-FRCM composite meshes measured in two mentioned ways, their comparison and discussion of results.

1. Introduction

Strengthening of reinforced concrete structures with FRCM (Fabric-Reinforced Cementitious Matrix) composite materials is an increasingly recognized way of repairing existing structures. This system can be used in environments exposed to high temperatures or fire, and in historical objects. It is related to the use of cement mortar as a matrix, This is related to the use of cement mortar as a matrix, the task of which is to combine fibers with each other and with concrete.

The main disadvantage of cement mortar is its granularity, due to which the mortar can not connect all the fibers together, which results in the formation of slip between the fibers and the premature debonding of the fiber mesh from the matrix. Due to the complex nature of the work of this composite, it is difficult to clearly define the design guidelines. Therefore, many researchers around the world were taking up the topic of strengthening reinforced concrete elements for bending, shear and compression in order to thoroughly investigate the mechanisms involved in this type of reinforcement [1-6].

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The mechanism of destruction and damage development in elements strengthened with FRCM composites has a local character and starts in places weakened by defects of the material, for example weaker fiber coverings with mortar. The feature that most interests researchers is the amount of strain that occurs at the time of debonding or slip of the fibers in the composite, because it is a necessary value to determine the effectiveness of reinforcement. Measurements of deformation of composite materials using strain gauges are difficult to analyse, because the strain gauges are located in a specific place on the surface of the composite, and allow to determine deformations only on a length equal to its length (often 20-50 mm). This does not translate into the work of the entire composite, because the destruction may begin outside the place of applying a strain gauge. What's more, the strain gauge very often ruptures at the place of crack, which makes it impossible to read the deformations during the further part of the test.

In tests carried out on reinforced concrete elements strengthened with FRCM composites, the strain gauges can be replaced with the DIC (Digital Image Correlation) method, which allows monitoring the entire element and determining the places where the destruction begins. This paper presents a description of the DIC method and the results of an experimental study conducted on reinforced concrete T-shaped beams strengthened in a shear with PBO-FRCM composites. The aim of the research was to compare two methods of measuring the deformation of the composite, using strain gauges and the DIC method.

2. Digital Image Correlation (DIC)

Digital Image Correlation is an innovative non-contact, full-field surface, optical technique for measuring displacement and converting it into strain. The measurement consists in making a series of digital photographs of the tested object before and during loading and tracking the movement of the naturally occurring, or applied surface pattern. The surface of the tested element must be properly prepared by applying a random speckle pattern on it, using airbrush, spray aerosol, transferable stickers or rubber stamp. The first reference photograph is usually made at zero load of the element, before starting the tests. Next the image surface is divided into subsets – a series of boxes containing n x n pixels ,with a recognizable pattern in each. During the test a cross correlation technique is used to analyse how each subset has moved. The measurement results are obtained in pixels, then they are scaled to mm using special boards with the pattern applied, whose image is registered in the reference photograph (Fig. 1).

Images can be obtained from a variety of sources, including CCD cameras, digital cameras, macroscopes and microscopes. Typical hardware for 2-D image correlation systems includes a CCD (or CMOS) camera, a computer system with digital image acquisition components, a sturdy tripod with mounting head and a lamp emitting monochromatic light, that limits glare on the tested element. 3-D measurements require two cameras. The cameras are mounted on a tripod with a transverse beam on which their spacing can be adjusted, which depends on the size of the area under examination. For the measurement to be correct, both cameras must be directed to the same area of the tested element.

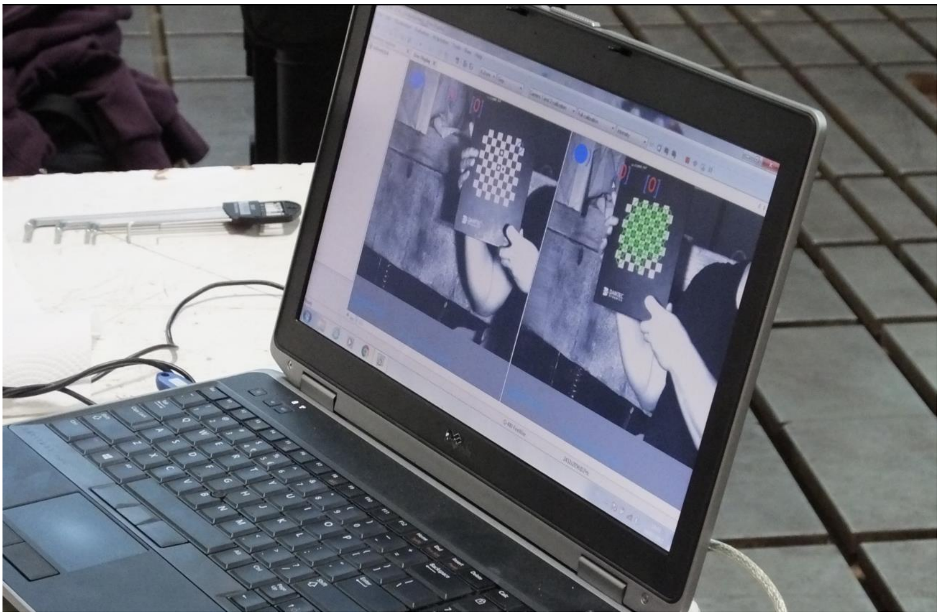

Fig. 1. Calibration using a reference plate.

Fig. 2. Elements of DANTEC DIC system – two cameras on a tripod [9].

3. Experimental research

Two 2300 mm long RC T-beams with 150×400 mm in cross section were subjected to tests. One beam was a reference beam, without strengthening, and the second one was shear-strengthened with a PBO (p-Phenylene Benzobis Oxazole) fibre mesh bedded in mineral mortar (PBO-FRCM). 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. 3).

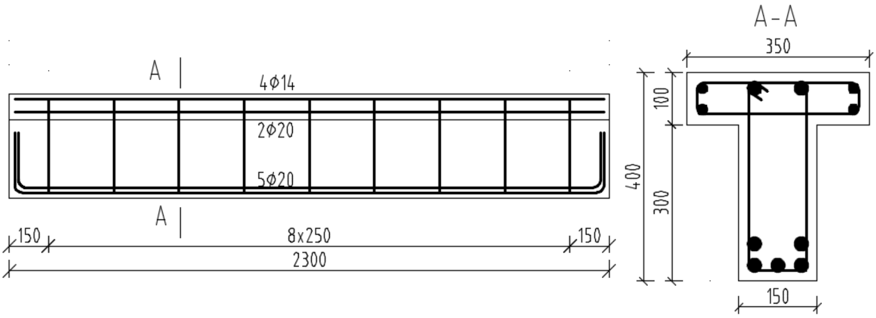

Fig. 3. The scheme of steel reinforcement and cross-section of beams.

3.1. Material properties and test setup

In order to determine the strength qualities of concrete the cylindrical specimens were made with height of 300 mm and 150 mm in diameter. The following compressive strength and modulus of elasticity of the concrete were defined from the tests:

1) mean cylinder compressive strength of the concrete fcm,cyl=44.75 MPa,
2) mean modulus of elasticity of the concrete Ecm=32.13 GPa.

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

1) mean yield stress of steel bars fym=526.2 MPa,
2) mean ultimate strength of steel bars ftm=626.3 MPa,
3) mean modulus of elasticity of bars Esm=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, were 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.

Table 1. Mechanical and geometrical parameters of the FRCM strengthening materials [7].

	Tensile strength f_{fz} [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	-

The elements were continuously loaded to failure, in a three-point bending with concentrated force placed in the middle of the span (Fig. 4). Deformations of concrete, steel and composites were measured using strain gauges. On the outer stirrups made of PBO mesh, the 50 mm long strain gauges were glued at half the height of the beams according to the main direction of the fibers (Fig. 4 – strain gauges 10-15). Strain gauges were also glued to the place of anchors on both sides of the beam (Figure 4 – strain gauges 20-25). The strain gauges on anchors were 25 mm long.

Half of the beam span was also analyzed by the DIC method. Due to the construction of a testing machine, that has a pillar in the middle of the span, it was not possible to use the DIC method to analyze the whole beam, because the image from both cameras would not show the same area. The right half of the beam, from the point of concentrated force to the support, was prepared for DIC measurements, by whitening the concrete surface with lime and spraying it with a black spray to give the speckle pattern. The resulting spots on the concrete surface are shown in Fig. 5, and the test stand in Fig. 6.

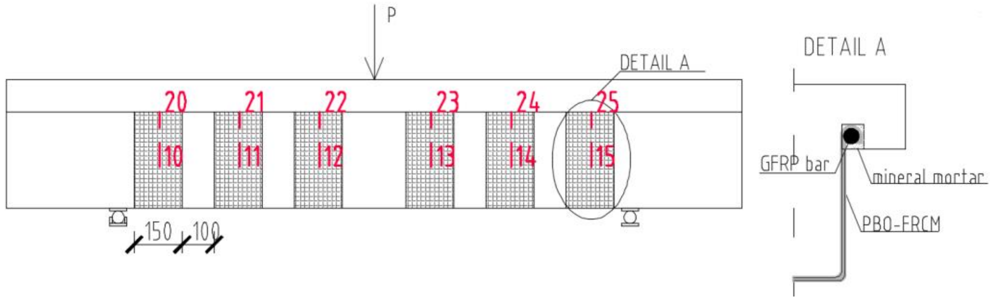

Fig. 4. The scheme of shear strengthening with end-anchorage.

Fig. 5. Speckle pattern on the surface of the tested element.

3.2. Shear strengthening

The beam was strengthened with one layer of PBO mesh with associated cement mortar, discontinuously with 150 mm wide FRCM strips with spacing of 100 mm. FRCM strengthening was applied on the both sides and bottom of the web. This type of strengthening configuration is called U-wrapped. Before strengthening, surface of the beam was cleaned of laitance, dusted and washed. The corners of the beam were rounded in the areas where the outer composite stirrups were 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 PBO mesh was applied after application of the first mortar layer and then pressed slightly into the mortar. In case of anchoring, 20×20 mm cuts were 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 (Fig.4)

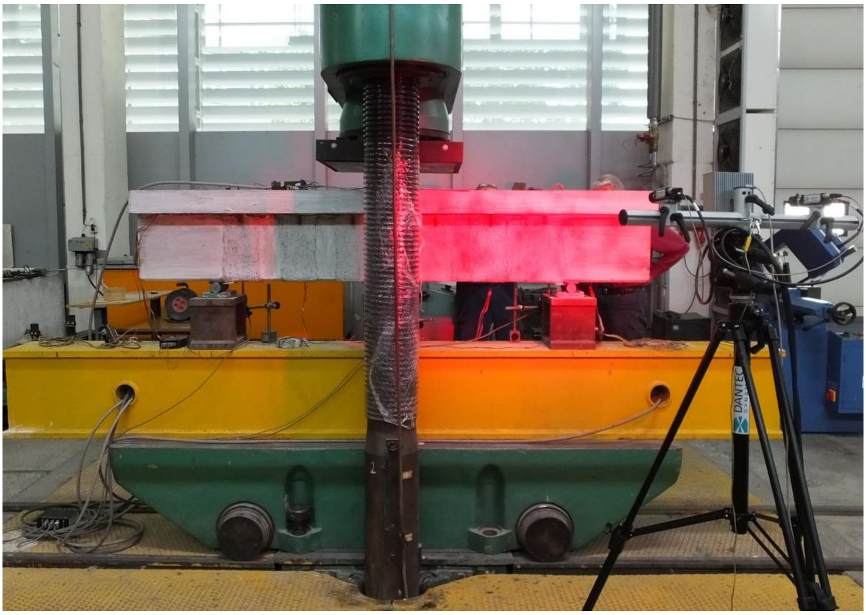

Fig. 6. Test setup.

4. Experimental results and discussion

The reference beam reached an ultimate load of 453.67 kN and failed in a shear after the formation of main diagonal crack on the shear span (Fig. 7a).

The strengthened beam also failed in a shear with formation of main diagonal crack, and reached an ultimate load of 527.40 kN. This diagonal crack developed on the half of the span, which was not included in the range of DIC cameras (Fig. 7b). Comparing the shear capacity of the strengthened beam to the capacity of the control beam, a load increase of 16% was obtained.

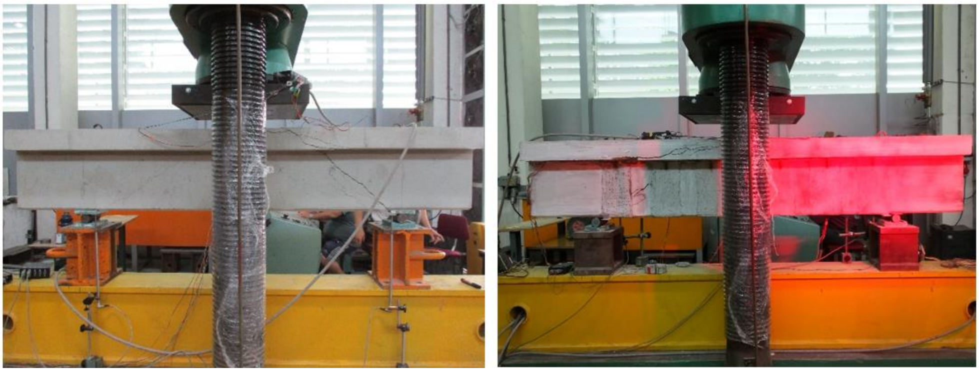

Fig. 7. Beam failure a) reference beam, b) strengthened beam.

The failure mechanism of strengthened beam consisted in debonding of the PBO mesh, which was accompanied by the development of diagonal cracks. There was no fiber rupture in any of the PBO-FRCM strips. The detachment had a local character and started at the place of the diagonal crack. Just before the destruction, there was also a sudden development of the diagonal crack on the shelf, which was not strengthened. As the load increased, the crack reached the anchorage and then ran along the GFRP bar. On the PBO mesh strips, the outer layer of cement mortar has also scratched due to the slip between the fibers and the matrix. This phenomenon is characteristic for FRCM materials in which mortar is used as a matrix and cannot be obtained such a good coverage of the all fibres by the matrix.

4.1 Analysis of the deformation of the composite

The maximum strain of the composite measured using strain gauges glued in the middle of the height of the PBO strip was 3.5‰, which means the use of its total capacity at about 20% (Table 1). At the anchorage, strains measured using strain gauges were at a maximum of 12‰, which corresponds to 68% of the total PBO-FRCM deformation limit (Table 1). These are values corresponding to the part of the span in which the destruction occurred. In the second part of the span, the maximum strain of the composite were 0.43‰ for the strain gauge number 15 (Fig. 4), and on the anchorage, 5.97‰ for the strain gauge number 24 .

An advantage of the DIC method is the ability to analyze deformations over the entire surface of the element. Thanks to this, it is possible to observe the development of cracks and the distribution of deformations on the entire composite strip. During the test, it was shown that diagonal cracks passed under the PBO strips and developed between them (Fig. 8).

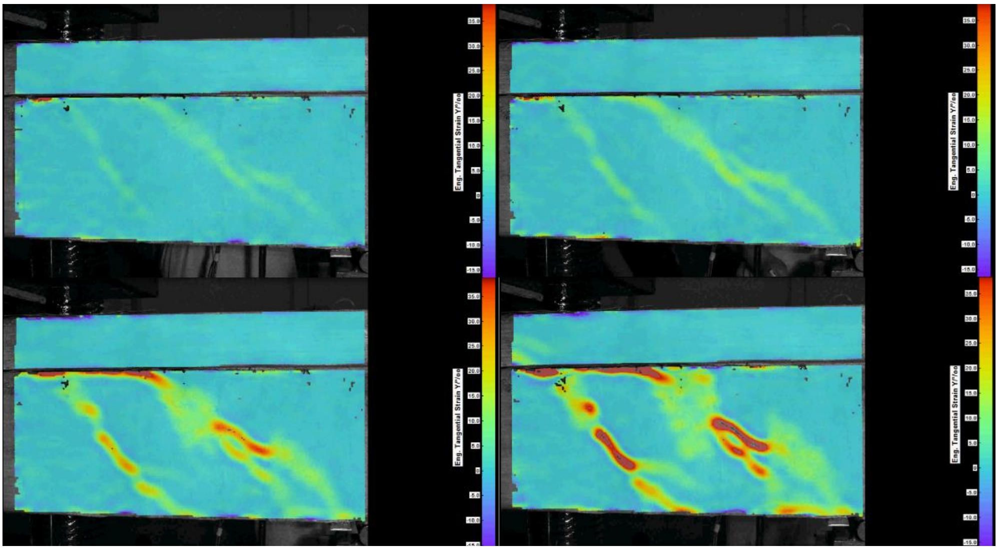

Fig. 8. Image from DIC cameras showing the development of diagonal cracks in the beam during test.

On the PBO-FRCM strips the first deformations occur in the place of the diagonal crack and then they are redistributed along the strip height. The maximum strains measured using the DIC method reached a value of more than 5‰ both at the anchor point for strip with number 13 and on the middle strip with number 14 (Fig. 9). On the basis of images from DIC cameras, it can be concluded that the maximum deformations of the composite occurred in other places than the strain gauges were glued, for example on the edge of the central strip at the place of diagonal crack, and on the left side of the anchor on the strip number 13. At the places where the strain gauges were glued, i.e. half the height and width of each PBO strip, very small deformations were recorded. These results are consistent with those of the strain gauges. In this case, the deformations obtained from strain gauges were not adequate to the real effort of the composite. In the case of testing beam with shear strengthening, the DIC method allows for a better and more accurate analysis of the work of the composite, its effort and location of the most stressed places.

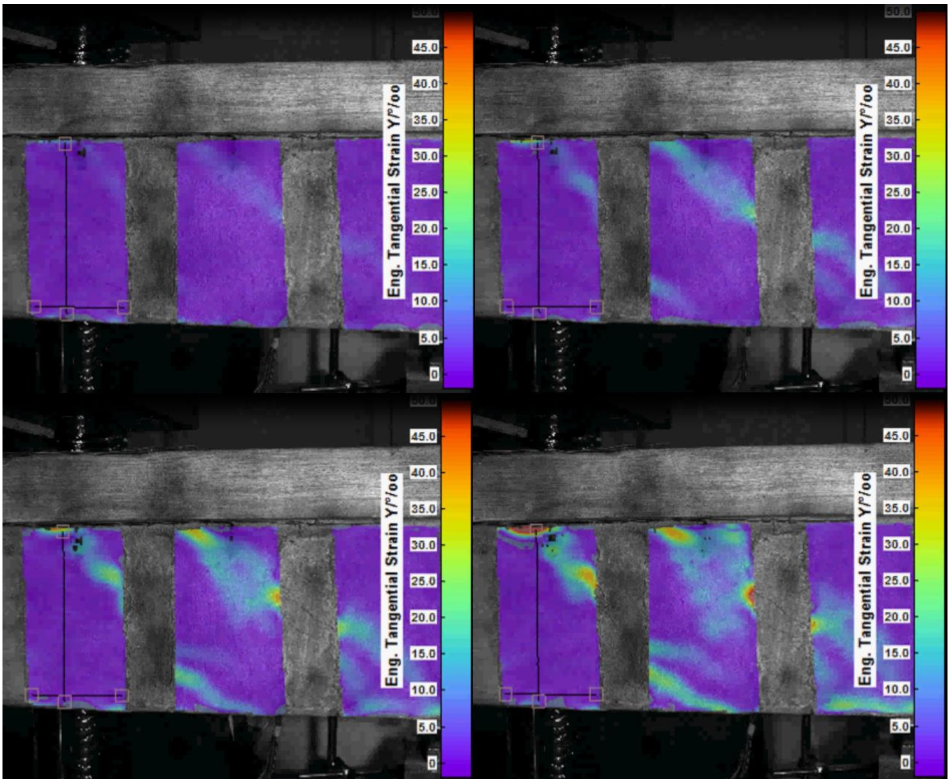

Fig. 9. Image from DIC cameras showing the deformation of PBO-FRCM composite strips with increasing load.

5. Summary and conclusions

The mechanism of failure and the development of damage for beams strengthened in a shear with PBO-FRCM composite materials is local in places weakened by defects in the material and in places of the diagonal cracks. For this reason, the analysis of the deformation of the strengthened elements is often difficult with commonly used strain gauges. A good alternative to strain gauges is the Digital Image Correlation (DIC) method, which allows effective measurements of the deformation of the entire element. The DIC method allows to determine the nature of the work of the entire surface of the tested element, giving the possibility to determine the most strenuous places, and deformations of composite and concrete. Using the DIC method, it is possible to determine what the course of the diagonal crack will look like before it is created, and it can be monitored throughout the research. By registering the changes taking place in the strengthened element during the entire loading, the mechanism of FRCM composites can be better understood.

Analyzing the deformation of the composite obtained in the research, it can be noticed that using strain gauges failed to determine the maximum deformations, because the strain gauges were in places where the deformations were smaller. Thanks to the DIC method, it was possible to determine the maximum effort of PBO fibers and show that in each strip of the PBO-FRCM composite as the load increases, there is a redistribution of deformations along its length and height, and stress concentration occurs at the edges of the strips at the intersection with the diagonal cracks.

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