Experimental Investigation on the Bond Behavior of FRCM-Concrete Interface via Digital Image Correlation

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Abstract. Digital Image Correlation (DIC) techniques have significant advantages in structural health monitoring compared to local measurements, being a non-contact method and providing distribution of engineering response indicators such as strains and displacements. In this paper, DIC is applied to investigate the bond behavior between Externally Bonded (EB) Fiber-Reinforced Cementitious Matrix (FRCM) fabric and concrete substrate. This is a popular strengthening technique for retrofitting existing concrete structures. Considering the different failure modes observed at the interface (e.g. cohesive debonding of concrete substrate, detachment at matrix-to-substrate interface, fiber sliding within the matrix, fiber rupture, etc.), a critical issue is to investigate the bond behavior of the EB composite fabric. To this aim, a series of concrete notched beams are prepared with the EB composite fabric applied onto the bottom face of the specimen and tested under three-point-bending. Results from the DIC measurements in two regions of interest of the beam, namely in the concrete area above the notch and at the FRCM-concrete interface, are then discussed and critically interpreted based on the observed macroscopic mechanical behavior and corresponding force-displacement curves. These outcomes are useful to identify the attainment of the concrete material strength, as well as the failure mode of the beam, and to investigate the stress transfer propagation at the FRCM-concrete interface. Moreover, DIC investigation may be potentially useful to anticipate the incipient crack development.

Keywords: Digital Image Correlation (DIC) · Fiber-reinforced cementitious matrix (FRCM) system · Bond behavior · Notched beams · Failure mode · Strain distribution

1 Introduction

Digital Image Correlation (DIC) is widely used in many areas of engineering and science to measure a full-field map of displacements and strains. It benefits from some significant advantages in structural health monitoring applications: its experimental setup is simple

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and inexpensive and has adjustable spatial and temporal resolutions; it allows the examination of samples with different characteristics, in terms of dimensions and involved materials; it allows the investigation of the crack initiation and development throughout the specimen dimensions and not just focusing on a specific area; it can be used under various loading rates ranging from static or quasi-static to high-speed dynamic loading [1].

Among the most promising applications of DIC, several authors used this technique to investigate the mechanical behavior of concrete structures. Concrete is a heterogeneous material with a complicate fracture behavior, difficult to be examined and described with conventional contact systems, such as local strain gauges or extensometers. A direct observation of this failure process is problematic because cracks exhibit micrometric dimensions, are widely distributed on the material and rapidly develop in the microstructure. In this context, DIC can be seen as a robust full-field measurement method having good accuracy. Choi et al. [2] were among the first to employ this technique to evaluate non-uniform displacements and deformations on the surface of concrete specimens tested in compression. Kozicki et al. [3] analyzed some notched concrete beams under three-point bending, identifying the effectiveness of DIC to determine the specimen deformation field and the crack evolution depending on the beam dimensions. Shah et al. [4] determined the mode I and II of the fracture toughness and the critical strain energy release rate for different concrete-concrete joint interfaces under three-point bending tests. Wu et al. [5] applied DIC to investigate the properties of the fracture process zone on notched concrete beams. They tested various dimensions of beams and notch by highlighting how the length of the fracture process zone depends on crack propagation and extension, specimen height and notch depth. Alam et al. [6] used DIC to monitor a typical crack growth in geometrically similar concrete beams having different sizes. In this study, the elastic strain was not studied due to the low camera resolution, while the initiation and rapid development of cracks were correctly identified, also estimating the crack length. Recently, Hu and Wu [7, 8] presented interesting applications of DIC to quantify shear cracking in reinforced concrete beams.

Externally Bonded (EB) Fiber-Reinforced Cementitious Matrix (FRCM) is a popular technique for retrofitting existing concrete structures via flexural strengthening of beams, shear strengthening of beams or confinement action of columns [9]. FRCM systems represent the natural evolution of the Fiber Reinforced Polymer (FRP) systems [10], with the main difference being related to the use of an inorganic-matrix rather than an epoxy matrix, which has well known advantages. For both FRP and FRCM systems, a critical issue concerns the bond behavior at the interface between composite and concrete substrate. Different failure modes have been observed at the FRCM-concrete interface, e.g. cohesive debonding of concrete substrate, detachment at matrix-to-substrate interface, fiber sliding within the matrix, fiber rupture, etc. In this context, DIC could be an effective technique to investigate the stress transfer mechanism at the interface. Coor et al. [11] studied the interfacial properties of a concrete block longitudinally strengthened with a carbon FRP sheet and subjected to a single-lap shear test. Apparently, the DIC images showed a low resolution, which is an important limitation for describing a clear failure behavior. Mahal et al. [12] evaluated the fatigue behavior of reinforced concrete beams strengthened with externally bonded carbon FRP plates and near-surface mounted bars. DIC results, such as displacement field, beam deflection, crack detection, were compared with those obtained with conventional techniques, e.g. linear variable displacement transducers (LVDTs), showing an excellent fitting and the possibility to predict the crack propagation. Sabau et al. [13] presented an experimental study on FRCM-concrete joints in single-lap shear test to compare DIC and electrical strain gauges. The deformation field was correctly identified on the surface, but some differences were observed by comparing the maximum strain measured from DIC and from electrical strain gages attached to the fiber. This consideration is an intrinsic feature of DIC technique, which is able of monitoring only the surface of the specimen and, consequently, the measured strain depends on the deformation transmission into the structure.

Along this research line, the present work presents an experimental investigation on the bond behavior of FRCM-concrete interface through DIC measurements. As an alternative to single-lap shear test, the experimental campaign involves three-point bending tests on notched concrete beams with the PBO-FRCM system being applied onto the bottom face of the specimen. Results from DIC measurements in two regions of interest of the beam, namely in the concrete area above the notch and at the FRCM-concrete interface, are illustrated vis-à-vis the corresponding force-displacement curves and interpreted based on the observed macroscopic mechanical behavior.

2 Materials and Methods

2.1 DIC Principles

DIC is a non-destructive and non-contact optical full-field technique used to measure displacement and deformation fields of structures [14]. The method is implemented in two steps: the first one is the acquisition of target digital images and the second one is the processing of these images through correlation algorithms. DIC is performed on a conditioned sample, by preliminarily creating an artificial stochastic pattern and/or point markers. This pattern makes it possible to track the variation surface during loading, and to calculate the corresponding mechanical response by means of digital image processing. DIC quality can be improved reducing the pattern dimensions and enhancing the image resolution.

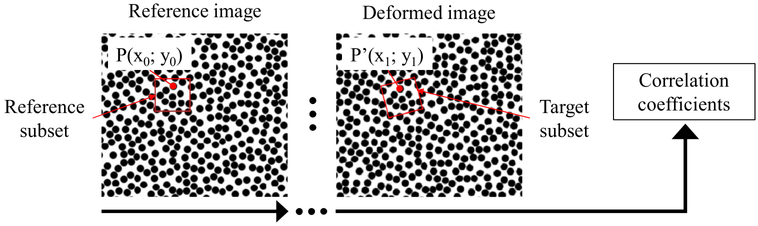

Fig. 1. Measuring process of DIC

DIC principles [15] are shown in Fig. 1. The initial condition of the sample, which generally coincides with the unloaded state, is acquired as a reference image. In this image, a region of interest is chosen and divided into subsets, called facets, i.e. an area of (2 M + 1) × (2M + 1) pixels. The reference subset, which contains the generic point P (x_0; y_0), is used to define the reference position. During the application of the stress on the specimen, a sequence of images is acquired and a sum-square difference correlation algorithm is then used to evaluate the subset motion in successive images. Mathematically, the matching procedure is achieved by searching the peak position of the correlation coefficients distribution. Once the maximum correlation coefficient is detected, the location of the target subset in the two images can be determined, allowing the displacement field calculation. To compromise between high-spatial resolution and computational efficiency, the interrogated subsets have to overlap each other.

2.2 Notched Concrete Beams with EB FRCM Sheets

Notched concrete beams are prepared using an ordinary Portland cement. The mean compressive strength of concrete (6 specimens) at 28 days is 47 MPa, with a CoV of 9% (UNI EN 12390–3:2009), while the mean flexural strength at 28 days (6 specimens) is 6 MPa with a CoV of 1.92% (UNI EN 12390–5: 2002). The FRCM system is made of a polybenzoxole (PBO) mesh and a cement-based mortar. According to the manufacturer's datasheets, the Young modulus of the composite system is 241 GPa, and the tensile strength is 3421 MPa (ultimate strain 1.42%).

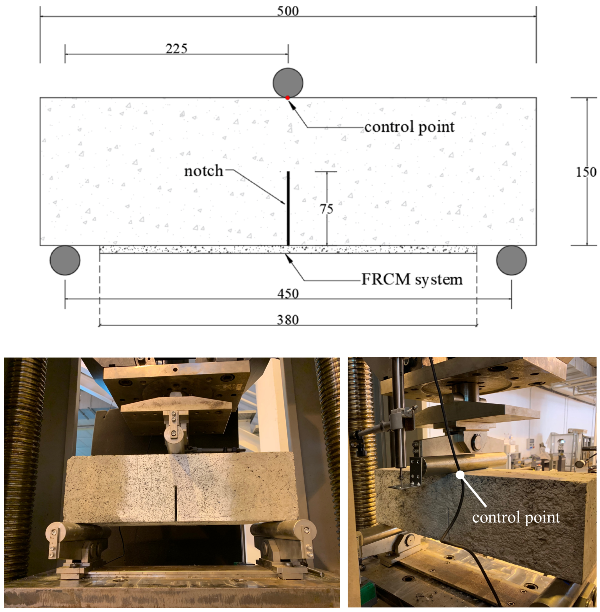

Fig. 2. Notched concrete beam dimensions in mm (top) and photographs of test setup (bottom)

After 28 days from casting, a notch of 2 mm width is made at the bottom side of the beam. The notch dimensions in relationship to beam size are established based on ASTM

D7958/D7958M. Then, the bottom surface of the beam is sandblasted and the FRCM system is applied. The samples are tested according to ASTM D7958/D7958M regulations under three-point bending, using a universal testing equipment (Zwick model) with 600 kN load capacity, under displacement controlled mode at a constant displacement rate equal to 0.05 mm/min. The load was recorded through an integrated load cell, while the displacement deflection (at the control point) was monitored through an auxiliary LVTD as depicted in Fig. 2.

2.3 DIC Setup

In many researches [16–18], DIC has been carried out without a sufficient consideration of the camera performance. The use of the correct lens and high-resolution images are fundamental to improve the technique quality and to obtain reliable results for structural health monitoring purposes. For this reason, an appropriate setup has been realized to guarantee a correct measurement and is detailed below.

The digital images are acquired by two reflex cameras (Nikon, mod. D3100 and Nikon, mod D300s), respectively equipped with a macro lens (Nikon, AF Micro-Nikkor 200mm f/4D IF-ED) and with a zoom lens (Tamron, SP AF 70–300 F/4–5.6 Di VC USD). The first camera is employed to monitor the FRCM-concrete interface, the second camera is used to examine the area above the notch. To guarantee the best field of view, focus and optical resolution, the cameras are respectively located at a distance of 72 cm and 98 cm from the sample surface. Two led lamps are used to have a constant brightness of 1000 lx in correspondence of the sample surface (Fig. 3).

The acquisition synchronization is performed connecting a trigger port of the testing machine with a remote control for the two cameras. In this way, a set of digital images are acquired taking a photo every 12 s until the sample failure. According to the two lens models, it is necessary to adopt different focal values. Table 1 reports the employed parameters.

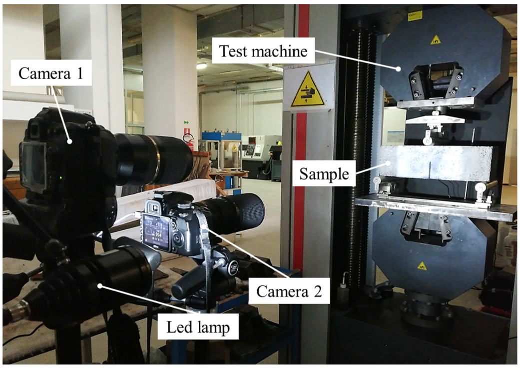

Fig. 3. Experimental setup of DIC: camera 1 and 2 are used to investigate FRCM-concrete interface and the concrete area above the notch, respectively

Table 1. Lenses optical parameters

	F-stop	Exposure	ISO sensitivity
Macro lens	f/8	1/15 s	ISO - 400
Zoom lens	f/8	1/10 s	ISO - 250

3 Results and Discussion

The results presented here concern only a representative specimen among those tested. Force-displacement curves of other specimens of the experimental campaign follow a similar trend; therefore, they are not reported here for the sake of brevity. As said above, the two cameras allow the examination of two different portions of the specimens, namely the concrete area above the notch and the FRCM-concrete interface, whose results are illustrated in the following Fig. 4 and Fig. 5, respectively.

In particular, the examination of some emblematic conditions is discussed here, indicated by a series of points A-F in the force-displacement curves. All the recorded curves show an initial elastic branch, in which the behavior of both concrete and FRCM composite system is linear. This is confirmed by the DIC strain maps shown in Fig. 4 and Fig. 5 for both concrete and FRCM system. With further load increase, the strain in concrete attains its tensile strain limit above the notch and, progressively, the neutral axis depth considerably decreases. Consequently, a main crack arises above the notch, with a tortuous path until reaching the top compressive fiber of the concrete beam (point C). At the same time, the mortar in the PBO-FRCM system also shows some visible cracks while the load increases from A to C. For displacements higher than that corresponding to point C, the force-displacement curve exhibits a marked softening branch from C to D, which is ascribed to residual tensile stress of concrete completely cracked in the range of narrow crack widths. This softening branch resembles the typical fracture behavior of plain concrete after the tensile strength is reached. However, from point D there is a gradual increase of the load-bearing capacity of the specimen, which is the due to the interacting FRCM contribution and, in particular, the sliding of the PBO mesh from the mortar. At this stage, the force-displacement curve is similar to the typical stress-global slid curve obtained for PBO-FRCM-concrete joints in single-lap shear tests [19]. From point D onward, the incipient debonding of PBO mesh from mortar matrix becomes more and more evident, as confirmed in the DIC images in Fig. 5. Therefore, the force-displacement curve can be separated in two distinct branches: from the origin to point D, the beam contribution and the FRCM contribution are mutually interacting. After cracking of mortar, debonding of PBO takes place and the FRCM contribution becomes dominant (as concrete is completely cracked). From point D up to point F, it can be seen that there is a load increase up to a maximum point in E, and then decreases from E to F, where the typical horizontal friction branch (residual strength) can be observed.

It can be noticed that the DIC measurements are very useful for interpreting the mechanical behavior of the specimen, the interaction of the two resisting contributions

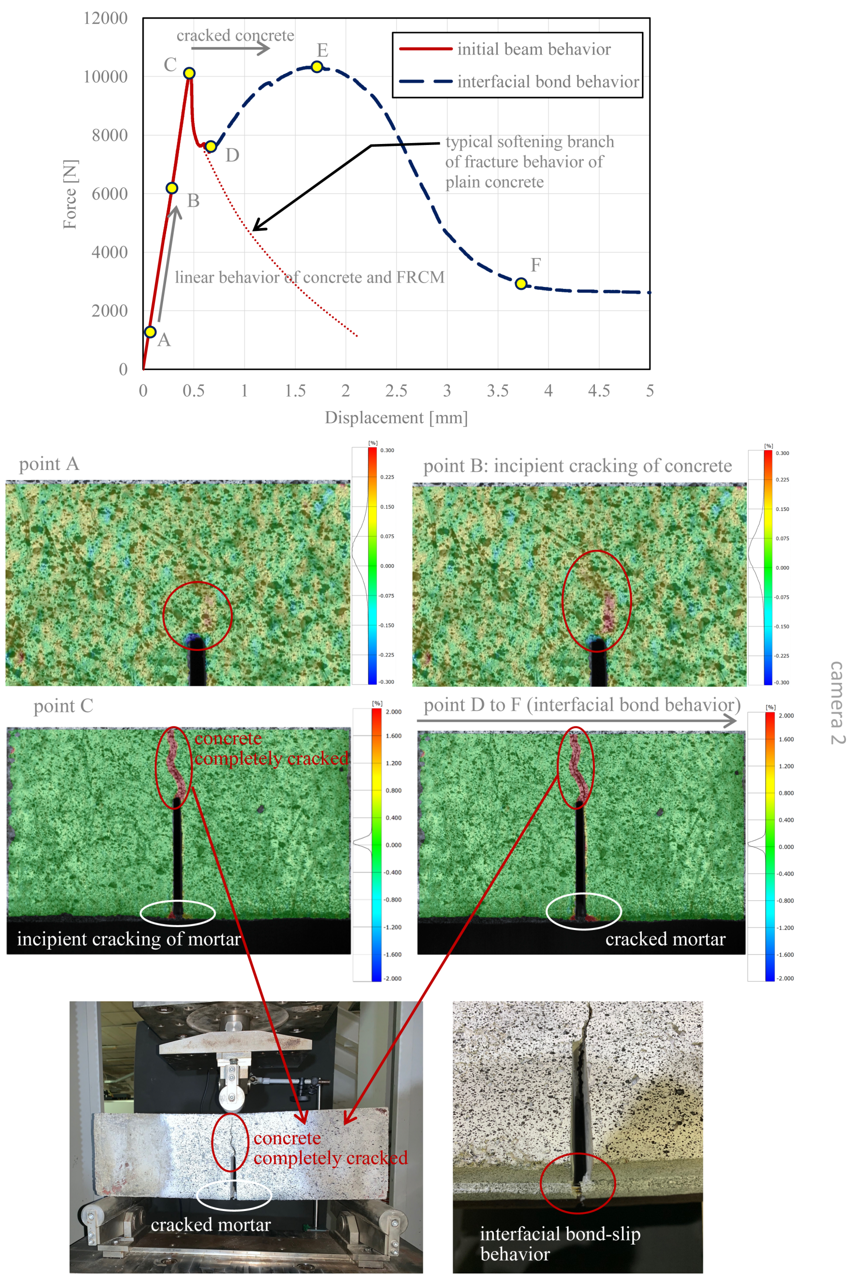

Fig. 4. Force-displacement curves and corresponding DIC-processed images for camera 2 investigating the concrete area above the notch

in the considered specimen (beam and FRCM) and the stress transfer mechanisms with increasing load conditions.

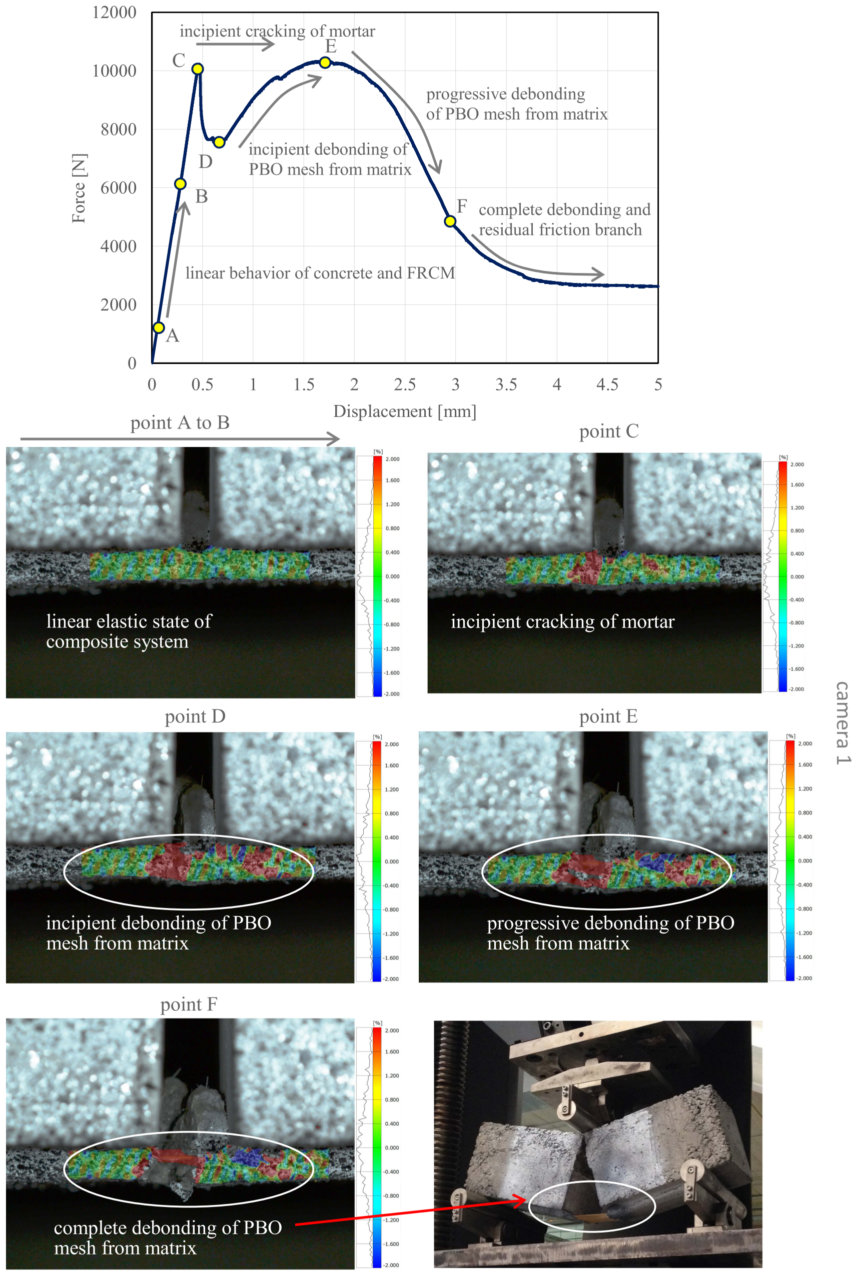

Fig. 5. Force-displacement curves and corresponding DIC-processed images for camera 1 investigating the FRCM-concrete interface

It is also worth noting that the above DIC strain maps at both concrete face and FRCM-concrete interface can be usefully employed in structural health monitoring, as these images can anticipate the crack initiation in existing structures under service loads or after exceptional events (e.g., seismic loads). In the authors' opinion, the rational use of the DIC technique in such contexts can allow engineers to check the bond behavior at the FRCM-concrete interface and to evaluate whether or not the interfacial properties are damaged, so as to plan a possible local repair intervention. Moreover, the DIC measurements allow the localization of the weaker parts of strengthened concrete structures in order to perform the structural interventions, if necessary, in a more suitable, effective and cheaper manner.

4 Conclusions

The paper has presented an experimental investigation on the interfacial properties of PBO-FRCM systems adhesively bonded to concrete substrate. This is a popular strengthening technique for retrofitting existing concrete structures. The bond behavior is investigated here via DIC technique. As an alternative to single-lap shear test, a beam test setup on notched concrete specimens under three-point bending is considered, wherein the PBO-FRCM system is applied onto the bottom face of the specimen. This configuration is more realistic and more in line with practical situations of flexural strengthening systems applied to concrete beams, as compared to single-lap shear tests in which the system is directly loaded. The images from DIC measurements are relevant to two regions of interest of the beam, namely the concrete area above the notch and the FRCM-concrete interface. The recorded strain maps from DIC are analyzed and discussed vis-à-vis the corresponding force-displacement curves and, thus, interpreted based on the observed macroscopic mechanical behavior of the beam. Based on the experimental findings reported in this contribution, the DIC can be a valuable tool for structural health monitoring purposes: it can be usefully employed to anticipate the incipient crack development, or, after some exceptional events causing localized damage to a concrete structure previously strengthened with composite systems, to plan a possible local repair intervention in specific, weaker parts of the structure in a rational, effective and cheaper manner.

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