DIGITAL IMAGE ANALYSIS FOR ASSESSMENT OF CONTACT ANGLES AND STIFFNESS OF FIBER REINFORCEMENT

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Abstract- Accurate assessment of fibers used as reinforcement of cementitious composites is quite demanding. Conventional techniques often lack the required accuracy and the measurement and analysis of results can be rather laborious. To eliminate these drawbacks a user-friendly software has been developed to (i) automatically evaluate the contact angle of fibers partially submerged in fluid, and to (ii) analyze the elongation of fibers during tensile and pull-out tests. The first procedure exploits the binarization of images, identification of contours, and calculation of tangents. The latter is based on digital image correlation (DIC) and tracking of pixel subset displacements. The results demonstrate that both of these methods are capable of providing valuable and accurate information with relatively low computational cost and labor of a human operator.

Keywords- Contact Angle Measurement, Digital Image Correlation, Image Analysis, Displacement Measurement, Fiber Reinforcement.

I. INTRODUCTION

Performance of fibers used as dispersed reinforcement in cementitious composites is closely related to their bonding with a cementitious matrix and their elastic stiffness. The first is tested directly by means of pull-out tests, or indirectly by assessing the contact angle with a liquid, usually water.

As the contact angles are optically measured on sessile drops by manual fitting of a circle, in the case of a submerged fiber a tangent to liquid meniscus has to be carefully placed. To that purpose in 1940's Bigelow et al. [1] set up a simple and convenient instrument called telescope-goniometer. This tangent placement is strongly dependent on the hand and accuracy of the human operator and consistent results cannot be guaranteed. The techniquehas been modified to, e.g., methods using a mirror reflection [2], captive bubble method [3], or tilting platemethod [4]. However, the main principle has not changed—either sessile drops or horizontal fibers [5, 6] are observed and the contact angles are evaluated from the shape of the liquid outline.

The stiffness of individual fibers can be directly tested by clamping both fiber ends to a testing frame and subjecting them to uniaxial tension. However, such test rarely provides accurate results, since the built-in extensometers cannot provide reliable data. The measured deformation consists of the deformation of a tested specimen, e.g. a fiber, and deformation of the testing frame components. Therefore, the fiber stiffness is usually overestimated. Such inaccuracy can be eliminated by employing optical methods that are capable to measure the relative deformation of fiber ends.
To measure the fiber elongation during a direct tensile test and assess its stiffness, we present a simple solution that employs digital image correlation (DIC) techniqueto track displacement of labels with a random pattern, firmly attached to fiber ends. DIC has become indispensable in experimental mechanics when monitoring and analyzing a development of displacement or strain fields in time by matching stochastic pattern of deformed images with respect to a reference one [7]. This full-field method is capable of tracking the entire specimen and capturing strain localization on its surface [8]. DIC has no inherent length or time scale, and substantial progress has been made in improving the spatial and temporal limits of DIC to view even microscopic deformations or evaluate the development of displacement or deformation fields from images taken by high-speed cameras.DIC is not limited to the relative measurement atchosen locationsand directions as conventional contact methods, and the accuracy is not compromised by the imperfect attachment to the measured surface. DIC reached its maturity during the last decade owing to the development of computers, digital cameras, and specialized software for image processing [9]. Besides commercial DIC packages, also new open source software solutions to perform DIC with differently optimized correlation functions and calculation methods exist, most recently summarized by Pan et al. [10].
As the first optical method for assessment of contact angles minimizes the required labor, the latter significantly increases the measurement accuracy when assessing the fiber stiffness.

II. CONTACT ANGLE ASSESSMENT

It is necessary to provide high-contrast images of a sufficient quality, with no blur or light spots, in order to analyze contact angles using the proposed technique.

The procedure starts with converting the images to grayscale (**Fig. 1**) to smoothing the boundary and placement of tangents (**Fig. 2**) was implemented in MATLAB [11] and requires no interaction with the analyst. After the color images are converted to grayscale, processes of binarization and elimination of small regions due to noise follow. The interface between gas and solid/liquid phases is then smoothed by means of local regression lines, differentiated and the point of liquid-fiber contact is identified as an extreme in the derivatives. Tangents at these points are simply found as the derivative of the interface.

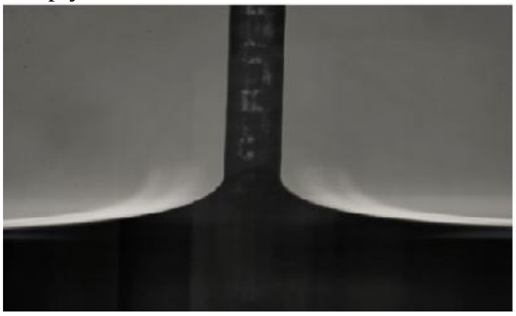

Fig. 1. Grayscale image of a fiber and a liquid meniscus taken by a digital camera positioned opposite to a source of diffused light; the use of plano-convex lens ensures cylindrical flux.

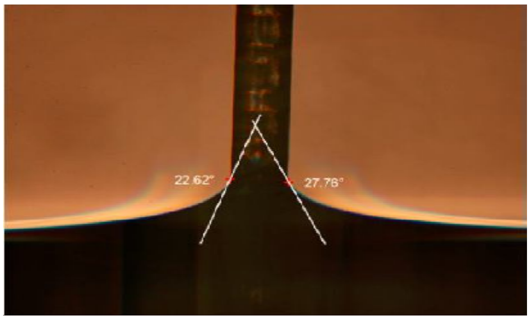

Fig. 2. Automatically assessed tangent angles after the image binarization, noise identification and removal, boundary smoothing, and differentiation.

The analysis results show a perfect agreement with laborious manual tangent placement in CAD software. On the other hand, other commercial systems such as DSA30 or SeeSystem did not perform that well and still require some interaction with the analyst.

III. FIBER STIFFNESS ASSESSMENT

The main ingredient of the fiber stiffness assessment is a reliable technique to measure elongation of fibers subjected to tension. This task can be tricky since most loading frames introduce a huge error into the crosshead displacement results because of compliance of their components.

In order to avoid such an error, a direct non-contact measurement technique must be addressed. Conventional strain gauges or extensometers fails at such a scale and modern techniques based on image analysis have to be employed. One of such is DIC that tracks the displacement and deformation of pixel subsets. To that purpose the investigated objects have to be sprayed to carry a stochastic pattern which is non-periodic. By tracking the peak of a correlation function a subset displacement is calculated and modern algorithms allow to measure subset displacements with high accuracy.

When applied to the tested polyethylene and polypropylene fibers, labels with random patterns were fixed to the fiber ends and their movement was tracked (**Fig. 3**). The experiment was displacement control in order to capture the softening of the investigated specimens.

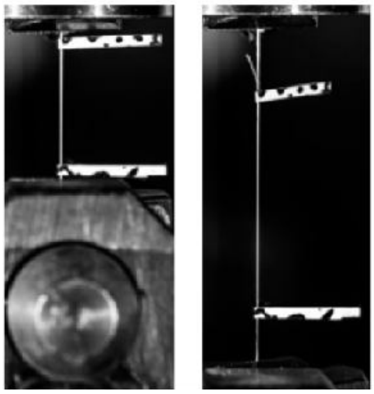

Fig. 3. Labels with an artificial random patterns fixed to a tested fiber subjected to axial tension

Common professional camera Canon EOS 70D was used to take the images to be analyzed. The focal length was set to 59 mm in order to eliminate distortions at the edge of the images. ISO speed was set to 100 since a powerful illumination was available. Individual images were shot in 3-second intervals. The images were processed using Python scripts and the DIC analysis was done using in-house software also programmed in Python. In total, 20 specimens were tested to represent each batch. The mean of the investigate parameters (elastic stiffness, maximum elongation, and strength) were in a perfect agreement with datasheets provided by the fiber producer. On the other hand, the direct crosshead measurement would yield over 20% error. The fields of displacements are presented in **Fig. 4**. The data from virtual extensometers are plotted in **Fig. 5** presenting the relationship between the tensile force and elongation of the specimens.

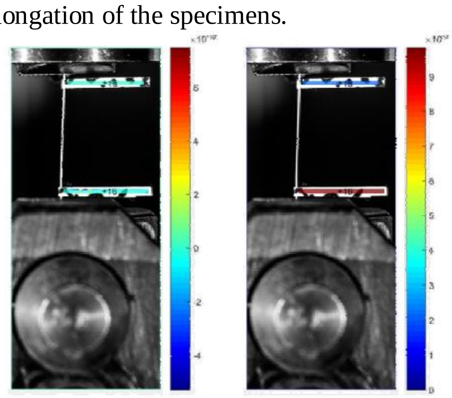

Fig. 4. Fields of vertical displacements overlaying labels attached to the tested fibers subjected to tension.

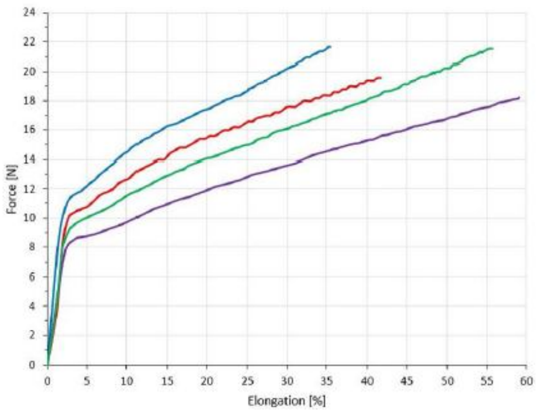

Fig. 4. Example of a force-displacement diagrams obtained by combining the data from force transducers and virtual extensometers provided by DIC.

CONCLUSIONS

Novel techniques based on image analysis were employed to analyze the behavior of fibers used as dispersed reinforcement to cementitious composites. In particular, contact angles were automatically assessed by recognizing and differentiating the fiber/liquid/air interface, and digital image correlation was employed to accurately measure the elongation of fibers subjected to axial tension. Based on the findings it can be concluded that:

1. Image analysis is more efficient than conventional techniques while the accuracy is not compromised but even enhanced.
2. Using image analysis, the assessment can be done automatically if proper algorithms are employed, eliminating the cost for a workforce; the consistency of the assessment procedure is another huge benefit – these fact favor modern computer aided quality assessment techniques on production or assembly lines to conventional ones.

ACKNOWLEDGMENTS

The support by the Czech Science Foundation under the research project No. 15-12420S is gratefully acknowledged.

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