XLI CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020 FOZ DO IGUAÇU PARANÁ - BRAZIL

Fracture Properties Analysis of Steel Fiber Reinforced Concrete Using Digital Image Correlation

K. de Souza[1], C. Várady Filho[2], R. Escarpini Filho[3], W. Lira[4]

Laboratory of Scientific Computing and Visualization, Federal University of Alagoas
Av. Lourival Melo Mota, S/N, Tabuleiro do Martins, 57072-970, Alagoas/Maceió, BRAZIL

[1]*kevin.tenorio98@gmail.com*
[2]*christiano_varady@lccv.ufal.br*
[3]*romildo@lccv.ufal.br*
[4]*william@lccv.ufal.br*

Abstract. This paper proposes a strategy to obtain fracture properties of steel fiber reinforced concrete (SFRC) based on the application of the digital image correlation method (DIC), where the data is taken from a three-point bending test (3PBT). The great demand for mechanical tests in engineering induces the usage and development of several alternative measurement methods. In this context, DIC is a practical, accurate and inexpensive technique for measuring surface displacement in a non-intrusive way. DIC consists in correlating pairs of images taken from the surface of the specimen under stress in distinct stages of load, resulting in the displacement fields. By using the concepts from linear elastic fracture mechanics (LEFM), the displacement fields can be applied to evaluate some fracture properties of the material. The strategy explored in this work uses images taken from a 3PBT of a SFRC specimen as input data and measures the displacement field by DIC using the open-source software NCorr. This displacement field is used to create virtual extensometers in order to study the crack opening. The fracture properties are then computed from LEFM equations with the displacement previously calculated. The results show a clear effect of the fibers on improving the support on Mode I cracks. It also indicates a smaller gap in the material's response between the transition phases of the double-K parameter analysis. The proposed strategy is a simple and inexpensive alternative, and it can be a powerful mechanism to analyze and validate the materials properties used in several engineering problems.

Keywords: Digital image correlation, Fracture mechanics, Steel fiber reinforced concrete, Three-point bending test.

1 Introduction

Development and enhancement of real-time measurement methods for mechanical tests have been one of the catalysts for the progress in the state-of-art of experimental mechanics for decades. Displacement and strain fields have usually been measured via intrusive methods, meaning they can potentially interfere with the results by having apparatus in contact with or inserted within the specimen. As alternatives to such methods, some techniques like the speckle method, the grid method and the digital image correlation (DIC) were developed to be non-intrusive.

Among them, DIC stands out as one of the simplest and inexpensive, yet accurate ways of measuring surface strain and displacement fields. Idealized by Peters and Ranson [1], the method consists in comparing pairs of images taken subsequently from the specimen's surface under distinct stages of load. As mentioned by Pan [2], the requisites for a two dimensional DIC setup consists of a constant light source, a specimen with a planar speckled surface, a camera fixed in a perpendicular position to the surface and a computer.

DIC has been vastly applied to a number of mechanical tests and is rapidly becoming on of the preferred methods among the academy. Thanks to its global measurement capabilities, it is possible to identify the elastic properties of the specimen's material, as done by de Souza et al. [3] and allows for the study of crack propagation and opening as seen in Oliveira et al. [4] and in Ghahremannejad et al. [5]. When applied to three-point bending tests (3PBT), the measured displacements can be used to compute the fracture properties of the material following a linear-elastic fracture mechanics (LEFM) formulation like on Yin et al.[6]. However, there's a potential on analysing fiber reinforced material parameters is still somewhat unexplored.

In this context, this paper proposes a method based on the LEFM linear interpolation method, coupling displacement fields and elastic property identification by DIC measurement with the objective of acquiring the fracture properties of a steel fiber reinforced concrete (SFRC) beam under a 3PBT following the EN 14651 [7]. The effects of the steel fibers on the results are then analysed and compared to the conclusions of other works documented in Khalilpour et al. [8].

2 Methodology

To achieve the proposed objective, the methodology adopted in this work is divided in three stages. The first one consists in the experimental setup and mechanical test itself, where the load and mid-span deflection profiles are obtained. The second consists in the acquisition of images, the application of DIC and the making of the virtual extensometers, where the displacement fields and crack opening displacements are measured. The final stage is the study of the fracture phenomena provoked by the 3PBT, evaluating the fracture parameters of the specimen.

2.1 Mechanical test

The experiment adopted in this work is a three-point bending test (3PBT) of a steel fiber reinforced concrete (SFRC) beam conducted by Oliveira et al. [4] following the instructions present on EN 14651 [7]. Here, the load/deflection profile is needed for the next stages. The concrete is composed of four main ingredients: rapid hardening cement, marble and granite processing residue, superplasticizer and steel fiber (1% mass fraction). To induce the formation of cracks, a notch is manufactured at the lower mid-span of the beam. The specimen is put under a constant 0.05mm/min load-point deflection. A linear variable differential transformer (LVDT) sensor is fixed in the bottom part of the notch to validate the DIC measurements. Further information can be obtained in Oliveira et al. [4]. A free-body diagram of the test is presented in Fig. 1.

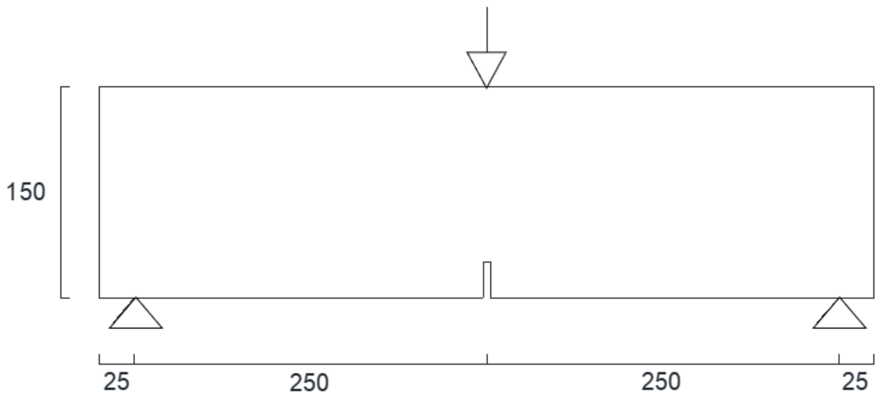

Figure 1. Free-body diagram of the three-point bending test (dimensions in mm).

2.2 Image acquisition and digital image correlation

A set of images is obtained by a Nikon D5500 camera from the specimen during the 3PBT. Several precautions are taken in order for the images to be appropriate for a DIC algorithm. The camera need to be static, positioned perpendicular to the specimen's surface. The irregularity of the concrete surface assures speckled gray pattern and, to enhance picture contrast, the beams were illuminated with blue-colored LEDs. These measures are adopted to minimize any potential cause of noise in the image acquirement process, because any movement or light variance can induce errors, as seen in Pan [2]. The software used for this study is NCorr, a highly regarded open-source algorithm written in Matlab by Blaber et al. [9]. NCorr receives as input pairs of images taken from the mechanical test and measures the displacement fields by comparing them. The global displacement data measured by DIC allows access to data at any point of the specimen's surface. This allows the creation of multiple virtual extensometers along the crack line. This results in the crack opening displacement profiles used in the next section.

2.3 Fracture analysis

The information obtained from the first two stages is used to compute the parameters of a Mode I fracture for 3PBT. Following a combination of the linear interpolation method presented by Yin et al. [6] and the Hillerborg recommendations (RILEM) [10], the proposed formulation starts with the identification of the Young's modulus as

$$E_c = \frac{6 S a_o V_\beta (a_o)}{B D^2 C_i}, \tag{1}$$

where S, B and D are respectively the span, width and depth of the specimen. a_o is the notch length, C_i is the initial compliance of the load to crack mouth opening displacement curve (P-CMOD curve) and V_β is a geometric factor defined by Yin et al. [6].

The double-K fracture toughness parameters are defined as

$$K_{Ic} = \sigma_N \sqrt{\pi a} F_\beta (a), \tag{2}$$

where a is the crack length, F_β is another geometric factor and σ_N is the nominal stress evaluated from

$$\sigma_N = \frac{3 (P + Q/2) S}{2 B D^2}, \tag{3}$$

where Q is the weight of the beam and P is the applied load. Equations 3 and 4 are firstly applied for the initial fracture toughness K_{Ic}^{ini} using the notch length a_o as the crack length and the initial load P_{ini}, in which the specimen transitions from elastic to plastic deformation.

For the calculation of the unstable fracture toughness K_{Ic}^{uns}, the same equations are applied to the maximum load P_{max} (registered at the critical fracture instant) and the critical crack length a_c, that is computed by

$$CMOD_c = 4 \frac{\sigma_N a_c V_\beta (a_c)}{E_c}. \tag{4}$$

Equation 5 computes the fracture energy of the material, where W_t is the total work done by the load and δ_{max} is the maximum load point deflection.

$$G_F = \frac{Q \delta_{max} + W_t}{B (D - a_o)} \tag{5}$$

Lastly, the critical crack tip opening displacement $CTOD_c$ is acquired by

$$CTOD_c = CMOD_c \sqrt{\left(1 - \frac{a_o}{a_c}\right)^2 + 1.081 - 1.149\, 1 a_c \left(\frac{a_o}{a_c} - \frac{{a_o}^2}{{a_c}^2}\right) \left(D \left(\frac{a_o}{a_c} - \frac{{a_o}^2}{{a_c}^2}\right)\right)^{-1}}. \tag{6}$$

3 Results and validation

Observation of the load-deflection curve (Fig. 2) taken from the mechanical test allows for the P_{ini} and P_{max} detection, as well as the exact instant of their happening. Then, the DIC technique is applied to the image taken in the critical instant, resulting in the displacement field presented in Fig. 3, where the position of the 21 virtual extensometers can also be seen. The data measured in these extensometers, compared with the LVDT measured displacement, form the chart in Fig. 4.

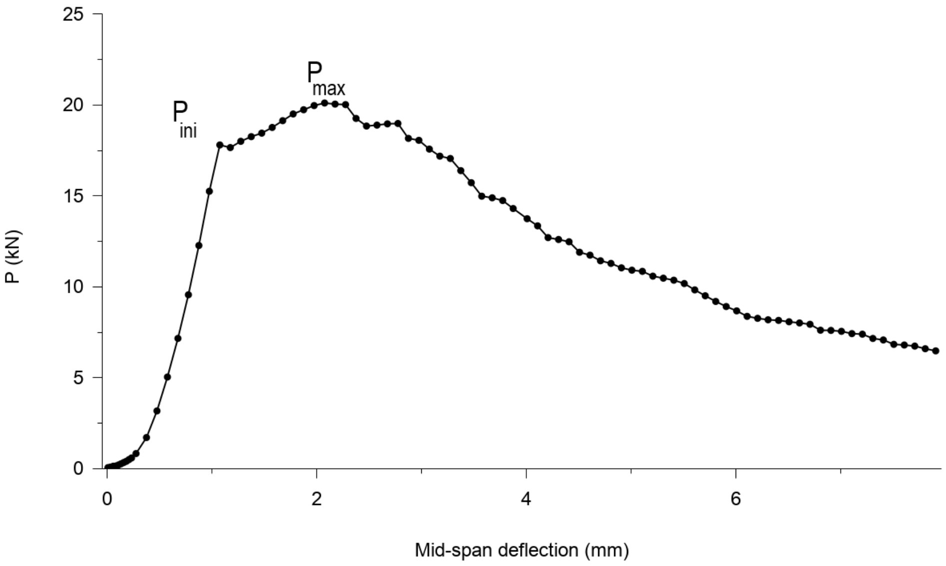

Figure 2. Load vs load-point deflection curve of the experiment.

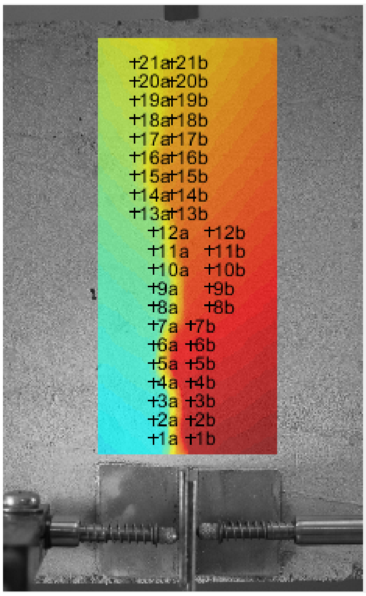

Figure 3. Displacement field.

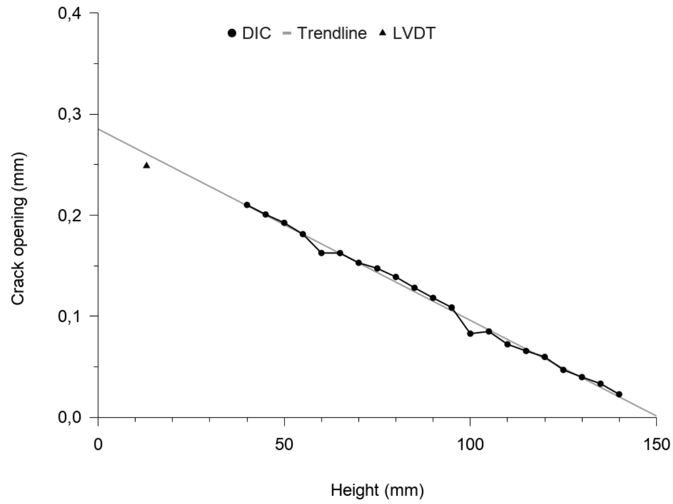

Figure 4. Opening along the crack line.

P_{ini}	P_{max}	$CMOD_c$	$CTOD_c$	E_c	a_c	K_{Ic}^{ini}	K_{Ic}^{uns}	G_F
$17.8kN$	$20.1kN$	$.28mm$	$.26mm$	$35.8GPa$	$97.9mm$	$.72MPa\sqrt{m}$	$.71MPa\sqrt{m}$	$7.2\frac{kN}{m}$

Table 1. SFRC fracture parameters found in this study.

From the trendline in Fig. 4 $CMOD_c$ is inferred. At this point, all of the necessary data for the equations to be applied is either previously known or was just acquired. The formulation present in Section 2.3 is then applied to compute the other material fracture properties. Results are shown in Table 1.

By comparison with the expected behaviour of regular concrete beams, it is possible to verify some major differences. Both transition loads P_{ini} and P_{max}, critical crack displacements $CMOD_c$ and $CTOD_c$, critical crack length a_c and specially fracture energy G_F are significantly higher. This shows that the fibers vastly increase the ability of the beam to support Mode I cracks. Also, the parameters related to each transition instant are much closer to each other, which could be because of the elastic deformation of the fibers after the beginning of the plastic deformation of the concrete. By observing the crack path, it can also be noted that it is significantly more convoluted, which is a result of the crack avoiding the resistance of the fibers.

4 Conclusions

This paper explores a methodology for the fracture parameter acquirement of a SFRC beam under a 3PBT. During the experiment, the specimen was photographed in order to measure the displacement fields via NCorr, an open-source DIC software. By observing the load-deflection curve the transition instants of the material were detected. The crack opening profile along the crack line was made by applying virtual extensometers in the DIC data. The displacement measurements are validated by the comparison with the point measured by the LVDT sensor. The fracture parameters were then inferred by the formulation here presented, based on the linear interpolation method and the Hillerborg recommendations.

The results obtained in this study shows the effects that steel fiber reinforcement can have on concrete beams. It can be noted that the fibers improve support capabilities of Mode I cracks, reduce the gap between the initial and critical stages of crack formation and convolutes the path of crack propagation. All of those divergences from regular concrete behaviour could also be related to the differences in dosing. Also, a lot of error could have come from the graphic measurements, image noise and numerical approximations. However most of the observed phenomena have theoretical explanations and/or are documented in the literature, as seen in Khalilpour et al. [8].

The low-cost and practicality of the DIC setup enables this methodology to be viable, not only for this specific experiment, but for many materials and mechanical tests. Therefore, this methodology can be adapted for further study of the effects of fiber reinforcement on concrete and fracture phenomena, leading to a higher understanding of fracture mechanics.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] Peters, W. H. & Ranson, W. F., 1982. Digital imaging techniques in experimental stress analysis. *Optical Engineering*, vol. 21(3), pp. 427–431.

[2] Pan, B., 2018. Digital image correlation for surface deformation measurement: historical developments, recent advances and future goals. *Measurement Science and Technology*, vol. 29, n. 8, pp. 082001.

[3] de Souza, K.; Escarpini Filho, R. & Várady Filho, C., 2019. Use of digital image correlation and finite element method to solve inverse problem using displacement fields. In *Proceedings of the XL Ibero-Latin American Congress on Computational Methods in Engineering*, pp. e6307, Natal, Brazil. ABMEC.

[4] Oliveira, K., Dias, G., Várady Filho, C., Kohler, C., & Barboza, A., 2019. Aplicação da correlação digital de imagens no estado de formação de fissuras do CRFA. In *Anais do 61º Congresso Brasileiro do Concreto*, Fortaleza, Brazil. IBRACON.

[5] Ghahremannejad, M., Mahdavi, M., Saleh, A. E., Abhaee, S., & Abolmaali, A., 2018. Experimental investigation and identification of single and multiple cracks in synthetic fiber concrete beams. *Case Studies in Construction Materials*, vol. 9, pp. e00182.

[6] Yin, Y., Qiao, Y., & Hu, S., 2020. Determining concrete fracture parameters using three-point bending beams with various specimen spans. *Theoretical and Applied Fracture Mechanics*, vol. 107, n. September 2019, pp. 102465.

[7] EN 14651, 2010. Test method for metallic fiber-reinforced concrete – measuring the flexural tensile strength (limit of proportionality (lop), residual). Standard, European Committee for Standardization, London, England. 15p.

[8] Khalilpour, S., BaniAsad, E., & Dehestani, M., 2019. A review on concrete fracture energy and effective parameters. *Cement and Concrete Research*, vol. 120, n. January, pp. 294–321.

[9] Blaber, J., Adair, B., & Antoniou, A., 2015. Ncorr: Open-Source 2D Digital Image Correlation Matlab Software. *Experimental Mechanics*, vol. 55, n. 6, pp. 1105–1122.

[10] Vandewalle, L., 2000. Rilem tc 162-tdf: Test and design methods for steel fibre reinforced concrete. *Materials and structures*, vol. 33, n. 225, pp. 3–6.