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Procedia Materials Science 3 (2014) 1585 – 1590

Procedia Materials Science

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20th European Conference on Fracture (ECF20)

Application of Digital Image Correlation to reinforced concrete fracture

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Abstract

The fracture process in reinforced concrete structures is complicated because it is associated with the development of both micro cracks and major cracks. The fracture behavior is also connected to other phenomena including strain localization and crack bridging and depends on the heterogeneity of concrete, the type of reinforcement, and the concrete and reinforcement properties. The purpose of this study is to investigate the mode I crack propagation in reinforced concrete using Digital Image Correlation (DIC). DIC is a robust, non-contact and precise tool for fracture measurements. Digital images are taken at different loading stages and by comparing the images it is possible to infer the deformation of an object subjected to external loads. In this paper, the relationship between the fracture properties and the properties of the concrete and steel reinforcement is investigated experimentally. Tests were performed on small-scale reinforced concrete specimens in three point bending. By means of the DIC technique the visualization and quantification of the fracture properties of reinforced concrete could be determined. The DIC technique was found to be an effective mean to measure the crack opening displacements.

Selection and peer-review under responsibility of the Norwegian University of Science and Technology (NTNU), Department of Structural Engineering

Keywords: Fracture; Reinforced concrete; Crack opening, DIC

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1. Introduction

Due to the low tensile strength of concrete, it is common to use concrete with internal reinforcement to carry the tensile stresses and the presence of the reinforcement affects the crack development and crack propagation in

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doi:10.1016/j.mspro.2014.06.256

reinforced concrete. Fracture in reinforced concrete is complicated because it involves diverse phenomena such as the formation of cracks, crack propagation, the existence of micro-cracks, interactions between the reinforcement and the concrete, and the concrete microstructure e.g. cement and aggregate (Hillerborg et al., 1976). Internal reinforcement affects the crack propagation behaviour since it bridges the crack and improves the fracture toughness of reinforced concrete. The concept of “crack bridging” emerged as a result of application of fracture mechanics models to reinforced concrete structures where a stitching action prevents the crack face opening and controls the crack growth by increasing the energy demand for the crack advancement (Carpinteri and Massabo, 1997). Fracture mechanics is a field of solid mechanics that deals with the mechanical behavior of cracked bodies. It provides rules and principles for crack propagation and is one of the most frequently used approaches to study and model cracks in concrete structures. Both linear elastic fracture mechanics (LEFM) and non-linear elastic fracture mechanics (NLFM) have been applied to concrete (Kapalan (1961), Hillerborg et al. (1976), Bazant and Oh (1983), Carpinteri (1984), Jeng and Shah (1985), and Carpinteri et al. (2007)).

Experimental investigations are invaluable for the purposes of checking and testing the validity of various theoretical models. In the field of fracture mechanics, several crack measurement techniques have been developed to measure the crack profile such as holographic interferometry, dye penetration, scanning electron microscopy, and acoustic emission (Alam et al., 2013). One of the main advantages of using image processing technique to analyze the cracking process is the possibility of obtaining a complete reconstruction of the crack geometry without any complicated measurements. Digital Image correlation (DIC) is a non-destructive and non-contacting method for measuring the surface deformation of an object subjected to forces by comparing images taken under different loading conditions. An image of the targeted area is divided into small subareas. A subsequent image then analyzed by comparing the small subareas and following their new positions. It is then possible to measure the full field deformation of an area (McCormick and Lord, 2012). Over the last decade there has been rapid development in image processing techniques as well as in high resolution digital cameras. Pan et al. (2009) considered that the DIC method is currently one of the most promising optical measurement technologies with broad application prospects. New advances in this field can provide tools to measure fracture processes and provide insight into the concrete cracking process. In addition, DIC measurements may enable researchers to identify the most promising fracture mechanics approaches to model concrete and reinforced concrete. The usage of the DIC in structural engineering has increased over the last two decades e.g. Choi and Shah (1997), Wattrisse et al. (2001), Corr et al. (2007) and Alam et al. (2013). In this paper, DIC will be used to analyze reinforced concrete. Experiments were designed to study how different concrete and reinforcement properties affect the cracking parameters and crack bridging.

2. Experimental program

To investigate the fracture behavior of reinforced concrete beams using DIC, two series of reinforced concrete beams were cast and tested. Each series included seven reinforced beams with similar dimensions and loading arrangements but with different concrete strengths, reinforcement ratios, concrete covers and reinforcement surface profiles. The second test series was used to determine the repeatability of the results but for the sake of brevity only the results of the first series will be discussed. All the beams were designed to fail in flexure and were tested using a three point bend test. A crack inducer was located at mid-span. Fig. 1 shows the beam dimensions and reinforcement details.

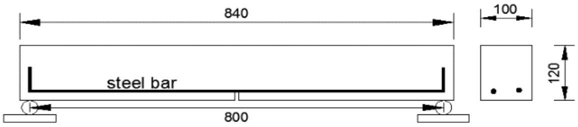


Fig. 1. Beam dimensions (in millimetres).

Steel deformed bars with different nominal diameters were used as the flexural reinforcement. The bars were three sided deformed bars where each bar has three longitudinal ribs and additional circumferential ribs that cross the longitudinal ribs. In order to study the effect of the reinforcement bar surface profile on crack propagation and crack bridging, the ribs of the full deformed bars (FD) were ground to about half of the rib height to produce half deformed bars (HD) and to almost zero height for the non-deformed bars (ND). Using this method, the other bar properties like the yielding strength and elastic modulus remain unchanged. There are many ways to grind down the reinforcement ribs such as the use of an electrical milling cutter or electrical disk sander. Although these methods are fast, they lack a certain control and can lead to a varying rib height along the bar surface. The bars were therefore ground manually using a steel file. This allowed greater control of the height of the ribs. A small proportion of the ribs was left to avoid inadvertently reducing the core cross sectional area of the bars.

Table 1. Details of the first series of test specimens

Concrete cube compressive strength (MPa)	Reinforcement (Percentage of the reinforcement)	Deformation of the reinforcement ribs	Cover (mm)	Designation
M_1= 45	1T6 (0.25%)	FD	20	M_1,0.25,FD,20
	1T8 (0.5%)	FD	20	M_1,0. 5,FD,20
	1T8 (0.5%)	FD	10	M_1,0. 5,FD,10
M_2 = 36	1T6 (0.25%)	FD	20	M_2,0.25,FD,20
	1T6 (0.25%)	ND	20	M_2,0.25,ND,20
	1T6 (0.25%)	HD	20	M_2,0.25,HD,20
	1T6 (0.25%)	FD	30	M_2,0.25,FD,30

The wooden formwork was smeared with oil before casting the specimens. Insulation foam was used as a crack inducer where it was cut into pieces of 20 mm height and 6 mm width and was inserted vertically in the middle of the formwork. The reinforcement was then assembled in the wooden mold with the required cover. A C-clip was attached to the bottom of each beam to measure the crack mouth opening during the test. All the beams were tested using a three point bend test (Fig. 2). Each beam was supported at both ends by two plates with a roller which allowed rotation and horizontal displacement. The distance between the centers of the two roller bearing pads was 800 mm, and the point load was applied 400 mm away from each support (in the middle). The width of the bearing pads was 75 mm. In order to obtain stable loading conditions, all tests were performed under a controlled displacement rate of 0.1 mm/min. Consequently, the load was applied as a function of the mid span deflection. This allowed a gradual increase in the mid span deflection and the crack mouth opening, as well as a steady decrease of the load bearing capacity of the beam in the post-peak regime. To achieve the targeted loading conditions, a servo controlled INSTRON machine was used to perform the tests (Fig. 2). The clear span between the vertical supports of the testing machine is 560 mm but the total length of the beam is 840 mm. The beams were positioned in the machine at an angle such that the side faces were visible.

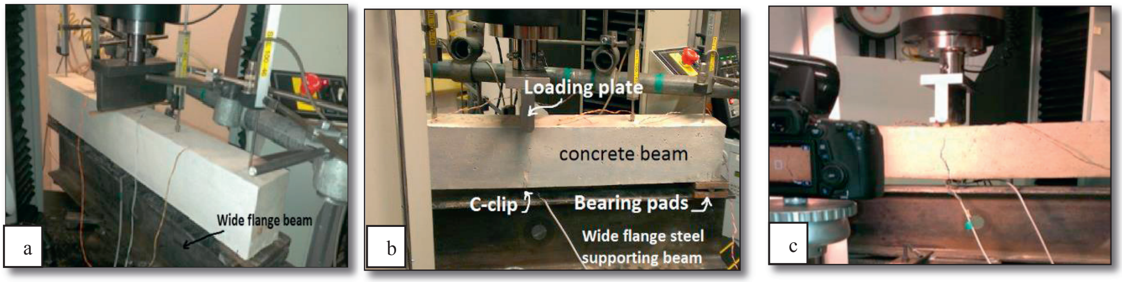


Fig. 2. The testing setup.

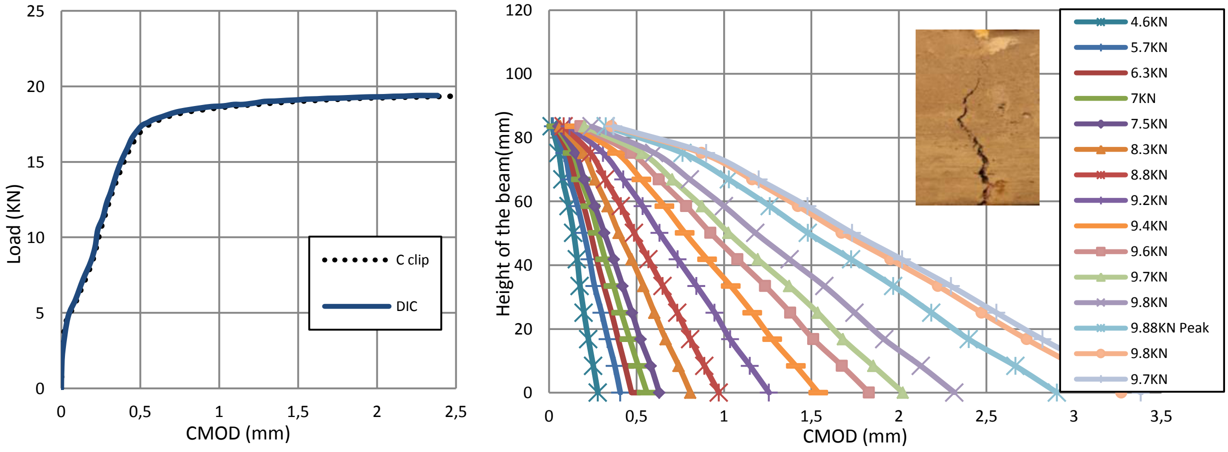
2.1. DIC experimental setup

A digital single lens reflex (DSLR) camera was used to record digital images of the test specimens under loading. The measurement accuracy can be enhanced by increasing the resolution of the camera because the displacement errors are fractions of pixels. The camera used in this testing has a resolution of 5472 x 3648 pixels which is a relatively high resolution when compared with the camera resolution in the work of Wattrisse et al. (2001), Alam and Loukili (2010) and Dutton et al. (2013). The camera was mounted on a tripod with its axis perpendicular to the area of interest. The camera had a normal focal length of 55mm. Out-of-plane movement is not expected to be an issue in this testing but to nevertheless minimize the effect of any out-of-plane movement, the camera was fixed away from the specimen surface as recommended by Hoult et al. (2013). External lighting was directed toward the region of interest to enhance the images. The texture of the specimen surface was kept the same because the concrete surface has a random color intensity distribution and a fairly good variation in the surface texture. For this setup and field of view, one pixel in the image represents about 30μm on the surface of the beams.

3. Analysis and results

The DIC analysis in this research uses a software package called GeoPIV (White and Take, 2002) which was developed at the University of Cambridge. Sub-pixel accuracy is obtained by using a sub-pixel interpolation scheme to interpolate between the discrete correlation coefficient values surrounding the maximum value. To further increase the accuracy, higher order interpolation techniques can be used. GeoPIV has been shown by Hoult et al. (2013) to decrease the bias error to very small values where the correlation coefficient is calculated using a normalized cross correlation.

For each specimen, the images taken under different loading conditions were analyzed using GeoPIV. The crack mouth opening displacement (CMOD) values for the tested specimens were determined from the displacement vectors of the DIC analysis results. The obtained values of the CMOD using DIC were verified against the C-clip gauge experimental results. Fig.3a shows the CMOD readings for beam M_1,0.5,FD,10 where it is clear that the two graphs are matching to high degree. This indicates that the DIC approach used in this paper is effective to measure the CMOD.



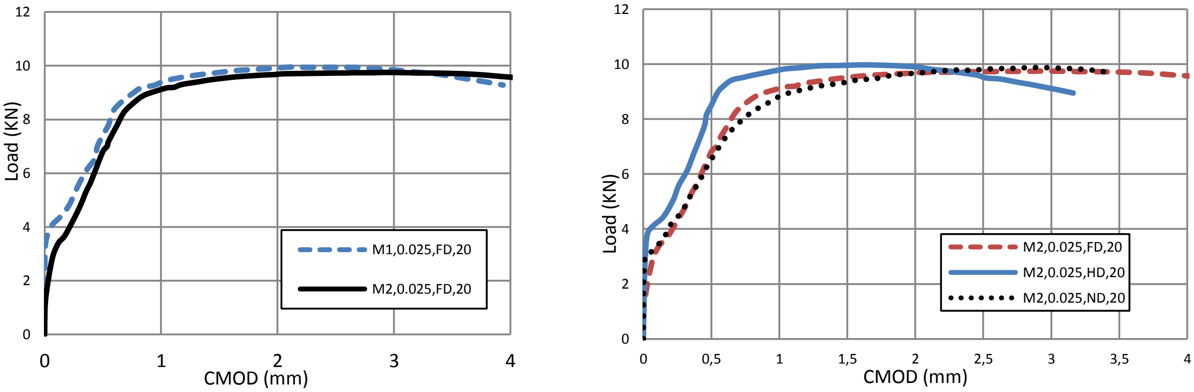
(a)

(b)

Fig. 3. Some of DIC results (a) CMOD in M_1,0.5,FD,10 using DIC and C-clip (b) Crack propagation in M_2,0.25,ND,20.

The cracks in reinforced concrete structures follow a tortuous path. To identify the crack profile, the crack opening was determined between points at an equivalent vertical distance from the bottom of the beam. To determine the crack opening at different locations along the crack, two DIC patches were selected on both sides of the crack with a mean distance between the patches of 5 mm. The displacement vectors of these patches were tracked with increasing loading. The crack opening was determined at different heights of the beam. Fig.3b shows the crack propagation of M_2,0.25,ND,20. For all the test beams, it is noted that at load levels up to 50% of the peak load the surface displacements showed a certain scatter suggesting that there are micro-cracks rather than a macro-crack. After a main crack starts to form and propagate, the crack opening is smaller at the level of the reinforcement which is evidence of the crack bridging provided by the reinforcement.

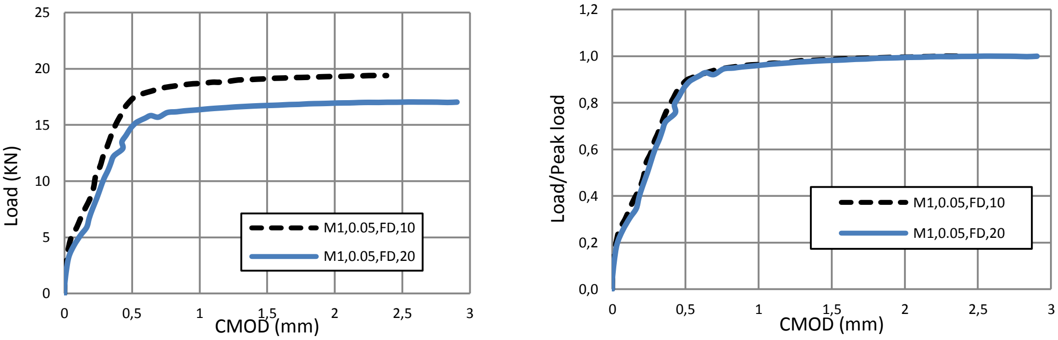
The CMOD results obtained from DIC analysis can be used to investigate the effect of the different properties of the reinforced concrete beams on the CMOD. Fig. 4a shows the results of beams M_1,0.025,FD,20 and M_2,0.025,FD,20. The two graphs have the same trend but M_2,0.025,FD,20 which has a lower concrete strength exhibited slightly higher values of CMOD when compared with M_1,0.025,FD,20. These initial test results suggest that the concrete strength has a limited influence on the CMOD values of the test beams. However, for the same reinforcement ratio the effect of concrete strength is more noticeable before the yielding of the reinforcement. The beams with a higher concrete strength had a smaller CMOD than those with a lower concrete strength.



(a) (b)

Fig. 4. CMOD of beams with (a) different concrete strength (b) different reinforcement surface profile.

Fig. 4b presents the CMOD for beams with the same concrete strength but different reinforcement profiles. It is of note that the beam with half deformed bars has the smallest CMOD when compared with the full and non-deformed bars. These characteristics were tested repeatedly in the second series and the same behavior was observed where the half deformed bars showed the best behavior in terms of the crack bridging. This means that the bond stresses between the concrete and the reinforcement can play a role in the crack propagation and crack bridging in reinforced concrete structures. However, the fully deformed bars and non-deformed bars exhibited a similar behavior in terms of crack opening. This was rather unexpected so further investigations are being undertaken to help explain this behavior.



(a) (b)

Fig. 5. CMOD of beams with different concrete cover.

The effect of the cover was studied by comparing beams M_1,0.05,FD,10 and M_1,0.05,FD,20 as shown in Fig. 5a Decreasing the cover increases the lever arm between the tension force in the reinforcement and the compressive force in the concrete and hence enhances the capacity of the beam. The CMOD is presented in Fig. 5b against the ratio of the applied load to the peak load. The same trend is noted in the two beams.

4. Conclusion

The DIC technique enabled the visualization and quantification of the fracture properties in reinforced concrete. The DIC technique is found to be very effective in monitoring the crack profile in small-scale reinforced concrete beams. The crack mouth opening displacement was extracted from DIC analysis and was used to compare the influence of different reinforced concrete beams parameters. It was found that concrete strength has a limited influence on crack opening, however, the bond stresses between reinforcement and concrete seemed to play a role in the observed crack propagation and crack bridging.

Acknowledgements

The authors would like to thank Yousef Jameel Foundation for their financial support of this research.

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