Crack monitoring of RC beams using digital image analysis technique

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Abstract: Conventional crack-width measuring techniques such as utilizing demountable mechanical strain gauge (demec gauge), linear variable differential transformer (LVDT) and crack width measuring microscope have been widely used in structural tests all over the world. Despite some certain benefits of these conventional measuring techniques such as simple use, high accuracy and real-time data logging, there are some limitations related to high cost, time-consuming setup and extra charges for data acquisition. The aforementioned drawbacks have led researchers to develop non-contact measuring techniques. Particle image velocimetry (PIV) is a recently developed displacement measuring technique in the field of experimental fluid mechanics and geotechnical tests. Due to excellent ability of the PIV technique in displacement measurements, the intention of the current study is to show the potential of the technique in crack-width measurements of RC beams. To do so, two reinforced concrete (RC) beam specimens with dimensions of 120 ×140 × 1000 mm were cast and subjected to four-point flexural loading. Successive digital images were taken from each specimen during loading process and different cracks of each specimen were monitored using PIV analysis. The results show that the PIV technique can be widely used as an alternative to conventional techniques for crack monitoring of RC members during test process.

Keywords: bending test, crack-width, image analysis, particle image velocimetry (PIV), RC beam.

1 Introduction

Over the last few years, due to extreme increase in experimental investigations in the field of structural engineering, the necessity for accurate deformation measurements is felt more than ever. Crack monitoring of reinforced concrete (RC) members during test process is from the most important parts of experimental studies leads researchers to investigate the cracking behaviour of RC members including cracking load, cracking patterns and crack width. Conventional crack-width measuring techniques such as utilizing demountable mechanical strain gauge (demec gauge), linear variable differential transformer (LVDT) and crack width measuring microscope have been widely used in structural tests all over the world. Despite some certain benefits of these conventional measuring techniques such as simple use, high accuracy and real-time data logging, there are some limitations related to high cost, time-consuming setup and extra charges for data acquisition. Apart from these certain drawbacks, as concrete originally is a highly heterogeneous material, crack locations could not be predicted before crack appearance. Consequently, the main disadvantage of conventional crack-width measuring techniques is requiring prior-knowledge of crack locations; however, this could not be possible in most experimental tests. The aforementioned drawbacks have led researchers to develop non-contact measuring techniques.

Photogrammetry and digital image correlation (DIC) methods are two of the new non-contact image-based techniques for deformation measurements in structural tests. Photogrammetry is the process of obtaining accurate measurements from physical objects using photography. Few investigations have been conducted using this technique in the field of structural engineering [1, 2]. In summary the technique operates by monitoring coloured targets which are placed at selected locations on the field surface using specially designed cameras. The accuracy of the system is mainly dependent on the camera hardware, scale of the object and geometry of the survey [1]. Adrian and Al-Mahaidi [2] and also Lee and Al-Mahaidi [1] utilized the photogrammetry technique to investigate torsional and shear behaviour of RC beams strengthened with CFRP by means of crack monitoring during test process. However, despite certain benefits of photogrammetry, some disadvantages may be noted in the technique such as complexity of test setup and time-consuming specimen preparation including installation of numerous targets. Moreover, due to complex test setup, loading of specimens should be paused at several steps to capture the whole field using different cameras [2].
Another recently developed method for obtaining displacement fields is digital image correlation (DIC) method. In general, DIC is an image analysis procedure which uses the mathematical correlation functions to analyse digital images of a field undergoing deformation. This technique offers the advantage of obtaining continuous measurements of the whole displacement field. In order to obtain the displacement field, surface preparation consisting of creating a random sprayed-on speckle pattern, should be done. After the surface preparation, digital images should be recorded during deformation of the object. Finally the correlation between the deformed images and the undeformed reference image will be used to obtain a two-dimensional displacement field [3]. The accuracy of this technique generally depends on the camera resolution. Based on experimental investigation, an image displacement accuracy of approximately 0.01-0.005 pixels can be expected [4]. Due to certain advantages of the method, DIC has been utilized in numerous experimental studies, especially for investigating bond behaviour of FRP-to-concrete bonded joints [3, 5-7].

Particle image velocimetry (PIV) is another recently developed deformation measurement technique in the field of experimental fluid mechanics and geotechnical tests. PIV is originally a velocity-measuring technique developed in the field of experimental fluid mechanics [8]. The technique was originally implemented using double-flash photography of a seeded flow and the resulting photographs were divided into a grid of test patches. For PIV analysis, the displacement vector of each patch during the interval between the flashes is found by locating the peak of the autocorrelation function of each patch. The peak in the autocorrelation function indicates that the two images of each seeding particle overlaying each other, so the correlation offset is equal to the displacement vector [9]. A modified approach was used to implement PIV in geotechnical testing by White et al., 2003. Although fluid requires seeding with particle to create features upon which image analysis can be operate, natural sand which is used in geotechnical tests, has its own texture in the form of different-coloured grains and the light and shadow formed between adjacent grains when illuminated [9]. According to White’s investigations, the modified PIV technique offers an order-of-magnitude increase in accuracy, precision, and measurement array size compared with previous image-based methods of displacement measurement. An image displacement resolution of 0.005 pixels can be expected from the PIV technique [9, 10], Slominski et al. [10] and also Hajialilue-Bonab et al. [11] investigated the performance of PIV technique for deformation measurement during granular silo flow and 3-D soil deformation pattern around laterally loaded piles, respectively. Consequently, due to excellent ability of the PIV technique in displacement measurements, the intention of the current study is to show the potential of the technique in crack-width measurements of RC beams.

2 Experimental procedure

In order to investigate the ability of PIV technique in evaluating crack behaviour of RC beams in common bending tests, two reinforced concrete beams were exposed to four-point flexural test. The concrete compressive strength of the RC beams was 34.1 MPa, obtained from three 150 × 300 mm cylindrical specimens subjected to uniaxial compression test. The specimens’ dimensions and the test setup are shown in Figure 1.

![Figure 1: Beam specimen dimensions and loading arrangement](image-url)
As it was mentioned earlier, it is necessary for the images to have a texture to create features upon which digital image processing can properly operate. Thus, since the concrete surface of RC specimens does not originally show a suitable texture, natural coloured sand between sieve no. 50 and 100, obtained from mixing same fraction of five different colours, was stuck to the beam specimens' faces using suitable two-component epoxy adhesive, i.e. Sikadur C 300.

The beams were then subjected to four-point flexural load by means of a 2000 kN displacement control hydraulic jack. An LVDT with a resolution of 0.1 mm was mounted at the mid-span of each specimen to capture the load-displacement curves. The camera was placed perpendicular to the beam face at a distance equal to 1.0 m. In order to eliminate any probable parasitic lights, the specimens were illuminated using two white light projectors. Digital images were taken using a remote control at regular intervals and a digital data logger was used to monitor the load cell, LVDT and image numbers. The test setup and the camera view are shown in Figure 2.

![Test setup and camera view](image)

**Figure 2:** a) Test setup; b) Camera view

### 3 Image analysis using particle image velocimetry (PIV)

Digital images were taken from the deformed beam specimens using Nikon D80 digital camera with a resolution of 10.0 megapixels (3872 × 2592 pixels) during the loading process. The images then were processed using GeoPIV8 software, developed at Cambridge University [12]. PIV analyses were undertaken using patches of 64 × 64 pixels located in each side of the flexural cracks at a distance of 5 mm from bottom of the beam. A search area of 20 × 20 pixels was considered in all PIV analyses which provided sufficient area to give good tracking of the patches.

### 4 Results and discussion

In order to verify the accuracy of the PIV technique in deformation measurements, at first mid-span deflection of the first beam specimen was evaluated using PIV technique and the results were verified utilizing LVDT’s data. Afterwards, crack widths for main flexural cracks of both RC beam specimens were obtained using the PIV technique and load-crack width diagrams for all cracks were presented and discussed.

#### 4.1 Displacement verification

Load-deflection diagram for the first beam specimen which was obtained from the PIV analysis is shown in Figure 3. In order to evaluate the accuracy of the PIV results, load-displacement curve obtained from the LVDT have also been plotted in Figure 3. The PIV analyses for evaluating the mid-span deflection were undertaken using one 128 × 128 pixel patch.
As it is illustrated in Figure 3, the load-deflection curve obtained from PIV analysis, very well matches the load-deflection curve obtained from LVDT’s data. Obviously, the results show the strong ability of the PIV technique in evaluating the beam’s deformations.

4.2 Crack-width monitoring

As it was mentioned, the excellent ability of the PIV technique in evaluating precise deformations of the tested beam specimen was verified. In order to investigate the performance of the technique in crack monitoring of RC beams during test process, the data obtained from images taken during flexural testing of the first RC specimen was used at locations of three main flexural cracks to plot load-crack width diagrams utilizing PIV technique. As it was mentioned earlier, PIV analysis was undertaken using 64 × 64 pixels patches located in each side of the flexural cracks at a distance of 5 mm from bottom of the beam. A picture from the specimen under ultimate load along with the three investigated cracks is shown in Figure 4. Furthermore, the load-crack width diagrams of the tested specimen are shown in Figure 5.
The experiment process was exactly repeated for another RC beam specimen in order to more investigate the performance of the PIV technique in crack monitoring of RC beams during test process. Similarly, a picture from the second RC specimen under ultimate load along with the three investigated cracks, and also load-crack width diagrams for this specimen are shown in Figures 6 and 7, respectively.
As it is obvious in Figures 4 and 6, the RC specimens were designed under-reinforced in order to prevent brittle shear failure mode, so the cracking behaviour of the specimens could be investigated through a ductile failure. Also, as it is shown in Figures 5 and 7, three different zones can be considered in load-crack width diagrams as follows:

a) Elastic zone, from beginning of loading process up to approximately 12 kN of load. Cracking occurs at the end of this zone.

b) Linear zone, between load levels of about 12 kN to 40 kN for the first and 12 kN to 42 kN for the second specimens. The load-crack width curves are linear in this zone due to linear behaviour of internal reinforcements.

c) Yielding zone, from load levels of about 40 kN to the end of loading process. In the beginning of this zone, where the load level increases due to strain hardening of internal reinforcements; however, the load level will be approximately constant up to failure, due to complete yielding of the internal reinforcements.

Obviously from Figures 4 to 7, all details of cracking behaviour of the tested RC beams could be easily investigated utilizing the PIV technique without requiring prior knowledge of crack locations or installing any mechanical devices; which clearly show the excellent performance of the PIV technique in crack monitoring of RC beams during test process.

5 Conclusions

In this paper, an experimental study was conducted on the performance of particle image velocimetry (PIV) technique for crack monitoring of reinforced concrete beams during test process. Based on the experimental results of the current study, the following conclusions can be drawn:

- Mid-span deflection obtained from PIV analysis extremely matches LVDT’s data, consequently the accuracy of the technique in deformation measurements of RC beams was strongly verified.

- As concrete is a highly heterogeneous material, the exact cracking locations could not be predicted before cracking in experimental investigations. However, utilizing PIV technique, cracks propagation of the tested RC specimens during loading process was investigated. Moreover, load-crack width curves for the three main flexural cracks of both tested RC specimens were drawn without requiring prior knowledge of crack locations using PIV technique.

- Due to lower cost and potential of investigating the whole field, the PIV technique can be widely used as an alternative to conventional contact-techniques for crack monitoring of RC members during test process.

References


