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Strain and deflection analysis in plain concrete beams and reinforced concrete beams by applying Digital Image Correlation

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ABSTRACT: Throughout history invasive methods for analyzing deflections and deformations have been used in concrete structures at the laboratory, but the advancement of technology has allowed the development of new non-invasive alternative methods such as digital image correlation (DIC). With this technique, it is possible to obtain information about the deflections, strains and strain fields in a structure. The current study consists of performing a flexural test on plain concrete beams and concrete arches reinforced with FRP reinforcement. All tests were recorded with a cheap, small camera, then transferred into a series of images in order to apply the digital image correlation technique. The analysis with DIC results in the displacements, strains and strain fields of the surface under analysis. Finally, the percentage of error between the displacement derived from the DIC technique and the displacement measured by Linear Variable Differential Transformers (LVDTs) is calculated. In conclusion, the study shows that it was not possible to reach accuracy on the values of deflections and strains by the applied method and that a higher-speed camera is necessary to capture the moment of failure.

1 INTRODUCTION

The digital image correlation is an experimental technique that uses images obtained in a test. From these images, the technique can calculate displacements, strains and strain fields occurring in a structure during this test. The digital image taken at the beginning of the test is considered as the reference situation, and all consecutive images are considered as a deformed state. This technique has the following advantages: the test is easy to perform and only needs a digital camera, it is versatile because it can be applied for several testing methods, it does not generate discontinuities by clearly identifying the area of study and the software algorithm used does not need exceptional hardware requirements and the analysis can be run on a standard personal computer and also the test can be set to have results in real time.

The disadvantages of the technique are the following: the images need to be high quality for the analysis, which relies on the color contrast of the images; and the camera needs to be able to record several frames per second to capture the moment of failure in an experiment.

The application of this technique in plain concrete and reinforced concrete has increased, given the development of digital cameras and their ability to record at least 60 frames per second. The displacements and strains obtained from the test are very small and thus high quality images are needed. Moreover, plain concrete elements fail in a rapid and brittle way, so that a high-speed camera is necessary to capture the crack development and failure process.

For this reason, it is important to analyze the feasibility to use an inexpensive camera and a free software, in order to analyze if it is possible to reach accuracy in this test with unsophisticated equipment.

The technique of digital image correlation is developed in the 80s. One of the first studies to apply the technique was performed by (Sutton et al, 1983). In the beginning there were two methods for carrying out the test. The first was to measure the relative displacement between two specific points on the surface of the object; however, the overall strain distribution of the object could not be determined directly. For the second study, the main objective was to set a mesh on the object’s surface before deformation occurred.

A clear example of the new techniques is the speed particle image, which is based on evaluating the displacement and strain fields on analyzing successive images under deformation, the great advantage of this technique is that it allows evaluating the whole field deformation of the object (Hosseini et al., 2014). Most publications agree that the accuracy in the technic of digital image correlation in concrete beams is very high, such as accuracy of the results were 0.01 pixel in displacements and 0.01% in strains. (E. Lopez-Alba, 2010). Moreover the method can be used in different types of tests such as: simply supported reinforced concrete beams that failed in flexure (Kozicki et al., 2007) and loading and unloading beams of a bridge (Kuntz et al., 2006).

2 METHODOLOGY

Before the tests, the test specimens have to be prepared. To have sufficient contrast for the DIC technique to carry out its color-based analysis, the beams were painted white and round red stickers (target points) were applied at intervals of 1 cm center to center. Given the size of the specimens, and with the correct position of the camera, it is possible to capture the entire face of the beam, see

Figure 1.

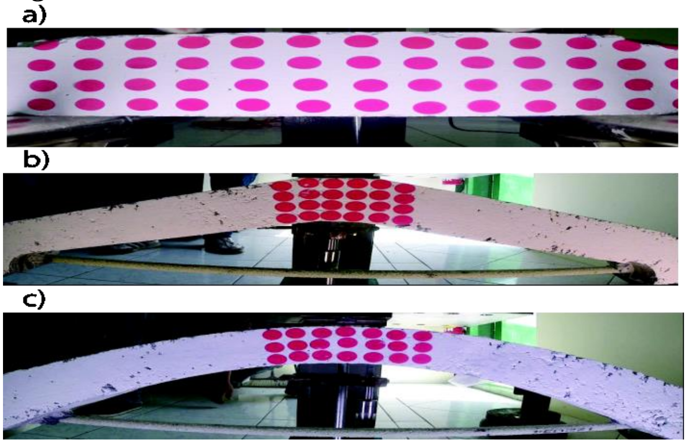

Figure 1: Images captured with the digital camera from each analyzed geometry. (a) Plain concrete beam; (b) Reinforced concrete triangle; (c) Reinforced concrete arch.

The laboratory tests are conducted on concrete beams and reinforced concrete arches (Mejia, 2015). The images taken with the digital camera are then analyzed with the DIC algorithm to study the strains and deflections. The deflections produced in the test were measured by LVDTs placed in the middle of the specimens. The plain concrete specimens were tested in four-point bending, according to ASTM C78/C78M (ASTM, 2010). A sketch of the test set-up is given in

Figure 2. Both reinforced concrete beams were tested in three-point bending, according to ASTM C293/C293M (ASTM, 2010). The distance between the supports is 90 cm. The load is applied in the center of the beams. The support consists of rollers; their width can be assumed to be no more than 5mm. The load is applied through a square plate of 5 cm × 5 cm. A sketch of the test setup for the plain concrete beams can be seen in

Figure 2. The sketch of the test for reinforced concrete arches can be seen in

Figure 3 and

Figure 4.

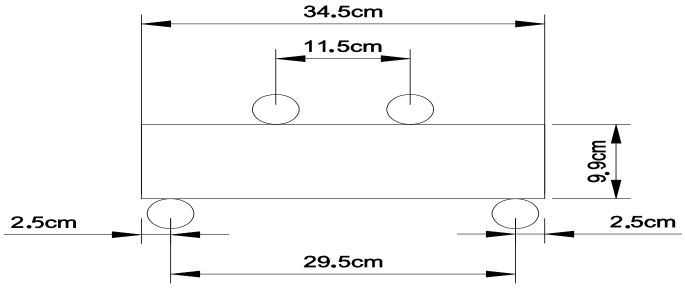

Figure 2: Test setup for beams 1-8

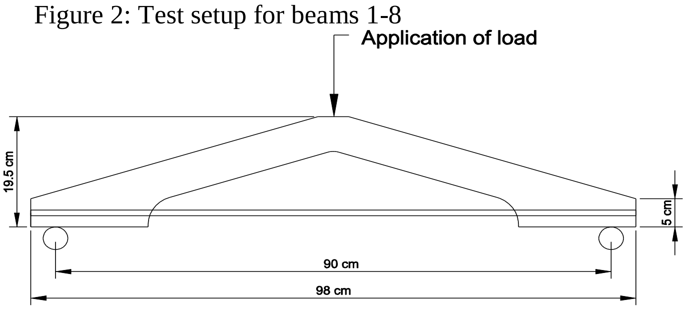

Figure 3: Test setup for reinforced concrete specimen 1

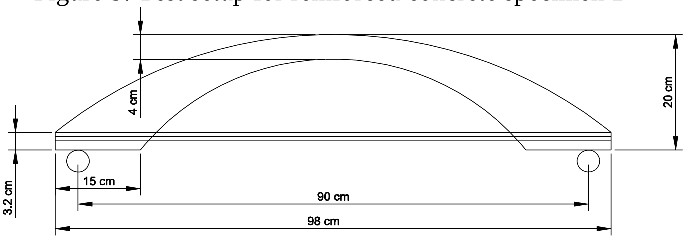

Figure 4: Test setup for reinforced concrete specimens 2

The experiment was filmed, and this recording was then transferred into a series of pictures. The number of pictures corresponds to the frames per second of the digital camera. The video camera should be completely isolated from the test, so that there is no external movement that can cause image distortion.

2.1 *Equipment*

A Go Pro Hero 3 camera was used. This camera has a video capture of 720 pixels and a speed of 60 frames per second. When converting the video into pictures, the resolution of the images is 1920 x 1080 pixels. Light was provided by LED lamps located on the right and left of the exposed face of the beam, to avoid shady regions on the face of the beam that is filmed.

2.2 *Software*

The analysis of deflections and deformations is carried out by using the code written in Matlab platform (MathWorks, 2014) and published on the exchange of files from CENTRAL MATLAB (Jones, 2015)

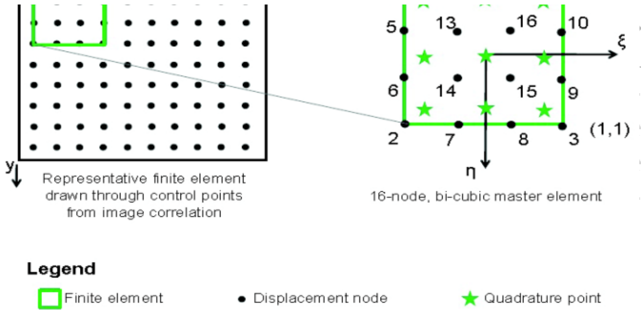

Figure 6 shows how the program calculates the strains based on given displacements at a grid of control points (black circles). A 16-node finite element (green box) is drawn through the control points. This element is mapped to a master element, with local coordinates ξ and η, and the displacements are interpolated over the master element using bi-cubic finite element shape functions. The derivatives of the interpolated displacements are calculated at the nine Legendre-Gauss points of the element (green stars), and then mapped back to the original element (Jones, 2015)

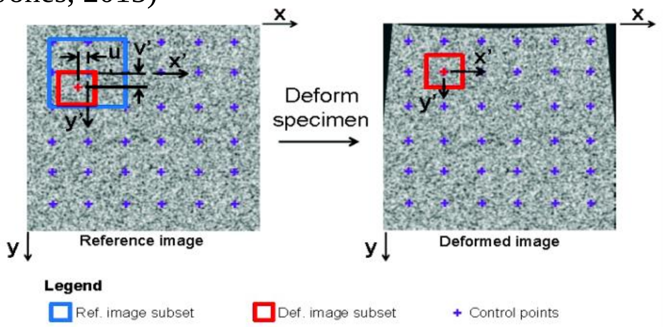

Figure 5: Schematic presentation of digital image correlation methodology

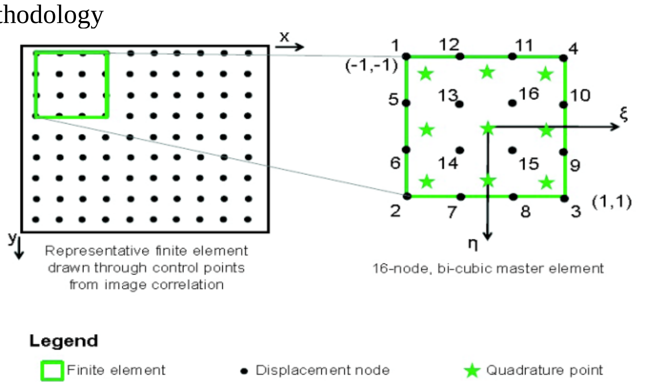

Figure 6: Schematic presentation of finite element methodology used in strain calculations

3 PROPERTIES OF THE SPECIMENTS

All the specimens were tested at 28 days. The geometry, weight and concrete compressive strength of the specimens are given in Table 1 and

Table 2.

Table 1: Properties of the plain concrete beams

Beam Nr.	Weight (g)	Width (cm)	Height (cm)	Length (cm)	f'_c (MPa)
1	7800	9.9	9.9	34.5	31
3	7460	9.9	9.9	34.5	31
4	7620	9.9	9.9	34.5	31
5	7450	9.9	9.9	34.5	31
6	7830	9.9	9.9	34.5	31
7	7490	9.9	9.9	34.5	31
8	8080	9.9	9.9	34.5	31

Table 2: Properties of the reinforced concrete specimens.

					Reinforcement bar	
	Weight (g)	Width (cm)	Height (cm)	f'_c (MPa)	f_y (MPa)	f_u (MPa)
1	15000	8.7	19.5	55	435	435
2	14500	8.7	20	55	435	435

The reinforced concrete specimens had a length of 98 cm. The reinforcement used was a glass fiber reinforced polymer (GFRP) with a diameter of 12 mm, with a failure and ultimate tensile strain of 0.45 %. Its yielding and ultimate tensile strength are shown in

Table 2.

4 DIC RESULTS

4.1 *Analysis of Plain concrete beams*

For the analysis of eight plain concrete beams, an area of 29.5 cm wide and 9.9 cm high was selected to define the study area. As shown in

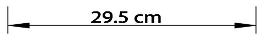

Figure 7, the distance between the reference dots in the area of study was 1.3 mm. Beam 2 was used for calibration of the equipment, and is not discussed here.

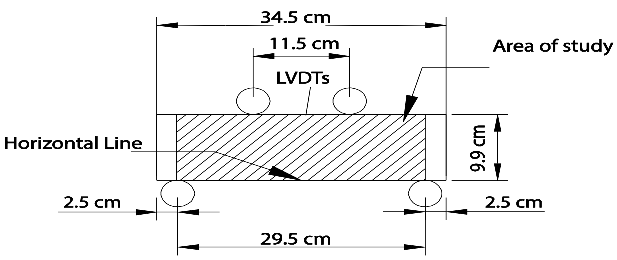

Figure 7: Area of study in beams 1 to 8

The maximum load in the experiment was predicted with a hand calculation. The prediction indicated a maximum load of 8 kN, based on the estimated flexural strength of the concrete. During the experiment, the average ultimate load was 23 kN. This observation corresponds to earlier research (Rashid and Mansur, 2005), where larger failure loads, cracking moments and deflections were found than based on ACI 363-11 (ACI 363, 2011)

4.1.1 *Deflection analysis*

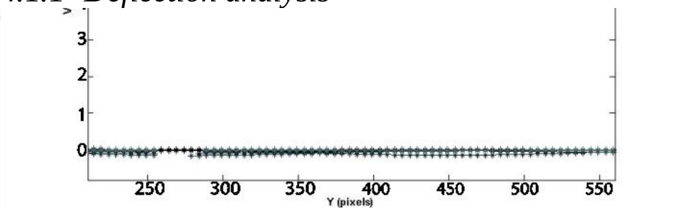

Figure 8, deflections of the reference and failure state are given, and the results in between are omitted, which leads to a gap in the graph. The analysis only considered the ultimate 60 images, as only the ultimate deflection was used for comparison with the LVDT measurements.

The results obtained with the technique of DIC and measured with the LVDTs for the seventh beam are shown in

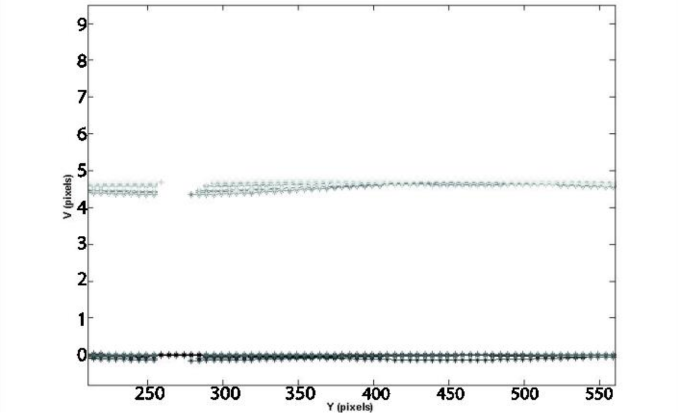

Figure 8 and **Error! Reference source not found.**.

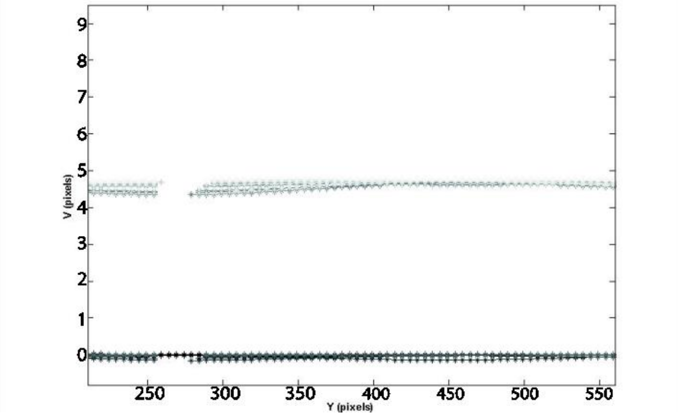

Figure 8: Results from DIC Analysis

Figure 8 shows how the deflection increases before failure. The points follow the same trend over horizontal lines: the lower horizontal lines describe the measurements from the first 60 images and the upper horizontal lines describe the last 60 images before failure. The LVDTs measured a maximum displacement of 0.328 mm and the DIC technique measured 0.325 mm. The other results are shown in the discussion section.

4.1.2 *Strain Analysis*

Based on the maximum load in the experiment and assuming an uncracked section, the strain at failure was calculated and expected to be 249 με. The strains from beam 7 are shown in Figure 9 and

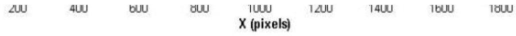

Figure 10 shows the strain field.

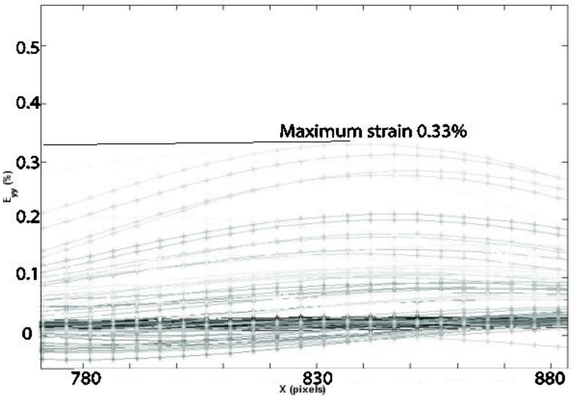

Figure 9: Results from DIC Strain Analysis for the seventh beam

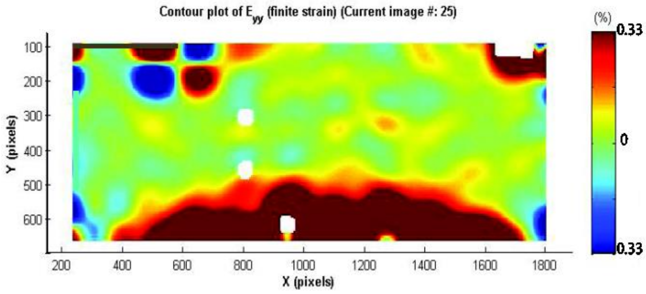

Figure 10: Strain Field of the seventh beam.

Figure 9 shows the variation in the strains along a horizontal line located at the lower end of the beam’s tension zone, where the maximum strain value is 0.0035.

Figure 10 shows the strain field, with tension in red and compression in blue. The analyzed image corresponds to the instant when the beam reached the maximum deflection.

4.2 *Analysis of Reinforced concrete beams*

The DIC analysis of the reinforced concrete beams was done in three areas with measurement points (see Figure 11). The distance between the points was 1.3 mm and the area of the sub-image 5.5 mm × 5.5 mm. This paper will only show the results obtained in the central area.

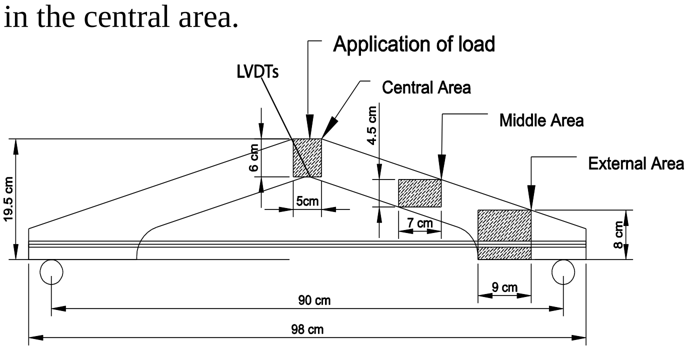

Figure 11: Areas of study in RC beam 1

4.2.1 *Deflection Analysis*

Only the central area (see Figure 11) was analyzed for the deflection, as only this point can be compared to the measurement of the LVDT. The LVDT was removed before failure to avoid damage to the sensor. Therefore, a comparison is shown between the DIC results and the LVDT measurements at the last measurement point of the LVDT, and the ultimate deflection is derived from the DIC results only. Figure 12 shows the results of the deflections in pixels obtained at the last measurement point with the DIC technique.

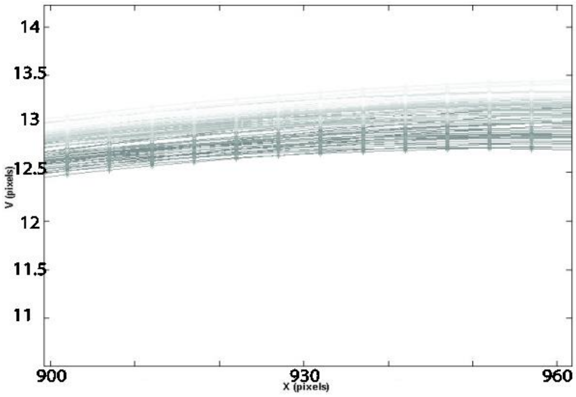

Figure 12: Results of DIC analysis in RC beam 1

The DIC technique results in a deflection of 13.5 pixels, which is equal to 3.57 mm, and the LVDTs measured a deflection of 3.93 mm. Finally the ultimate deflection obtained by DIC technique was 4.07 mm.

4.2.2 *Strain Analysis*

During test an ultimate load of 37.67 kN was reached in the first RC beam and of 29.87 kN in the second one. Using internal horizontal and moment equilibrium, and assuming Thorenfeldt's stress-strain diagram for concrete, the ultimate strain in the concrete was calculated as 0.0019 in the first RC beam and as 0.0016 in the second beam, given that the specimens failed at the anchorage.

Figure 13 shows the strains obtained with DIC in the central area. The technique calculates a compressive strain of 0.006. The DIC results indicate that the entire area is under compression and the central area is where the greatest strain of the entire structure is concentrated.

880 900 920 940 960 980 1000 1020 1040
X (pixels)

Figure 14 shows the strain field where the larger compression strains are in blue and the smaller strains in red.

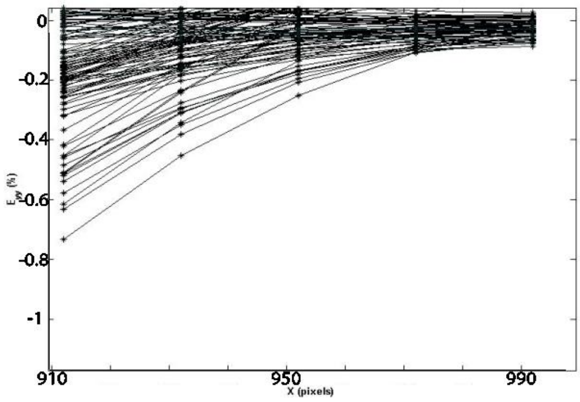

Figure 13: Results from DIC Analysis measured in the haft of the central area for RC beam 1.

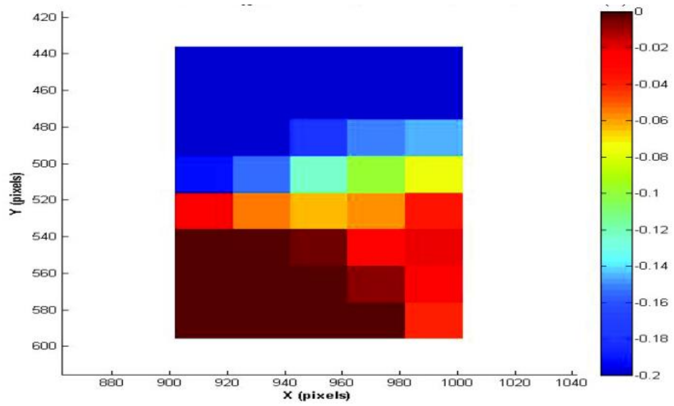

Figure 14: Strain field for RC beam 1 at the instant when the maximum deflection was reached

5 DISCUSSION

5.1 *Deflections*

Table 3: Deflections measured with DIC and LVDT for plain concrete beams

Beam Nr	LVDT (mm)	DIC (mm)	Error %
1	0.328	0.33	0.9
4	0.964	0.61	58.6
5	0.964	1.01	4.1
6	0.961	1.22	21.0
7	0.738	1.11	33.5
8	0.747	0.79	5.8
		Average	20.7
		STD	22.3
		COV	1.07

The error % was calculated by:

$$\frac{Deflection\ DIC - Deflection\ LDVTs}{Deflection\ DIC} * 100 \quad (1)$$

Since the first 8 beams had the same geometry and were made with the same concrete mixture, the average, standard deviation (STD) and coefficient of variation (COV) of the comparison between the deflection from the DIC and LVDT measurements can be calculated. As can be seen from Table 3, for some beams a large difference in deflection is found with the DIC and LVDT measurements. As a result, the overall coefficient of variation is 107%. These results demonstrate that the method is not yet suitable for finding the deflections of plain concrete beams. This limitation is caused by the lack of tensile reinforcement, which leads to very small deflections.

A possible solution is to use images with a higher resolution. Other DIC experiments (Omondi, 2015), used images with a resolution of 2452 × 2056 pixels.

Table 4: Deflections measured with DIC and LVDT for reinforced concrete beams.

	LDVTs (mm)	DIC (mm)	Error %
RC beam 1	3.93	3.57	10.1
RC beam 2	3.75	3.70	1.4

The results of the deflections for the reinforced concrete beams are shown in

Table 4. For these beams, the deflection measured by LDVTs and by DIC was compared at the instant when the LDVT was removed. The largest error is 10.1%.

For reinforced concrete beams, better results are found because the deflections are an order of magnitude larger than the deflections in the plain concrete beams. More research needs to be done before this technique can be applied in the field on existing structures.

5.2 *Strains*

In plain concrete, the DIC found strains between 0.3 % and 0.43 % in tension. These results were unlikely to be correct, given that the horizontal line from where the strains were measured was located at the bottom in the tension zone. These strain values are only expected when concrete is under compression. The strains from the DIC technique were higher than according to the stress-strain diagrams of the material; therefore the technique used in the test didn’t output the desired precision.

The GoPro camera resulted in images with a resolution of 1920×1080 pixels. A solution for this problem would be to change the software because the code did not have accuracy with small displacements. Another solution would be using a digital camera with a larger resolution.

The compressive strains in the RC beams analyzed with the DIC technique output a maximum strain of -0.6% at the central zone and minimum strain of -0.12 % at the external zone, all the specimen’s area was in compression. It is not possible to compare these results, given that a finite elements analysis was not performed. As such, using the equipment and the Matlab script presented in this study, did not result in satisfactory results for the strains in the structure.

Comparing the results of plain concrete and reinforced concrete shows that the results are better for structures with larger displacements.

6 RECOMMENDATIONS AND FUTURE RESEARCH

It is recommended to use a higher resolution camera to obtain more precision.

To avoid errors that lead to poor correlation in the images, it is important to properly fix the camera and to avoid any movement of the camera during the test.

It is advisable to increase the number of frames per second that capture the failure process. A larger number of frames per second will result in a better accuracy for the maximum deflections and deformations. Finally, due to the limitations of the software in finding the strains based on small deformations.

7 SUMMARY AND CONCLUSIONS

This study deals with the analysis of deflections and strains using the Digital Image Correlation technique. The experiments consist of eight plain concrete beams with an average concrete compressive strength of 31 MPa and two beams reinforced with FRP reinforcement. These RC beams had an average concrete compressive strength of 55 MPa and an average ultimate tensile strength of 435 MPa for the reinforcement.

A GoPro camera with 60 frames per second and a resolution of 1920 × 1080 pixels was used and located facing one side face of the tested beam. During the tests, adequate lighting was provided.

After the experiment, the captured images were processed with a freely available Matlab script. As a result, the deflections, maximum strains and strain field of each specimen were determined.

The goal of the study was to find ways to use cheap equipment (GoPro camera and a freely available Matlab script that can run on a personal computer) for the determination of deflections, maximum stains and strain fields of plain and reinforced concrete structures. The study shows that the main limitation lies in the speed and resolution of the camera, as well as the applied software script. The limited number of frames per second of the camera resulted in a low accuracy of the measurements. The software script had difficulties determining the strains based on small displacements. However, the general shape of the strain fields calculated with the DIC script was according to the expectations.

8 ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of Francisco Jativa with his help in the laboratory and Mario Calderon for introducing the Matlab code and for his collaboration during the tests.

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