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Particle image velocimetry technique for measurment of deformations during destructive testing of concrete walls

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Abstract: *Experimental testing has been used to assess the strength and deformations of reinforced concrete structures in serviceability and ultimate limit state as well as to validate finite element codes.A full-field deformation measurement system based on digital photogrammetry and particle image velocimetry (PIV) was proposed and used in an experimental study. An examination of conventional measuring methods has established the potential of using this approach. The output of the technique compared well with the results obtained from conventional measuring instruments. The proposed deformation measurement system provided detailed deformation data and could be used to plot displacement and strain contours on the whole specimen surface. The availability of inexpensive, off-the-shelf, digital cameras and photogrammetry software systems made the technique more feasible and affordable for broad and diverse experimental testing applications.*

Keywords*: Particle Image Velocimetry; Destructive Testing; Concrete Structures; Strains; Deformations*

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I. Introduction

Experimental testing has been used to assess the strength and deformations of reinforced concrete structures in serviceability and ultimate limit state as well as to validate finite element codes. Experimental testing often requires an enormous amount of manpower in addition to being very expensive to set up and run. Therefore, it is very important to obtain as much information as possible from the test especially in destructive testing. This **paper** presents a full-field deformation measuring system for use in structural testing. The **main** disadvantages of the conventional measuring instruments and the potential for the proposed system are presented in detail. Then, the analysis technique is discussed briefly followed by evaluation of the proposed system against experimental results obtained from testing the units.

1.1 Conventional measuring instruments

Conventional methods for measuring displacement and strain during testing of concrete structures comprise of using; dial gauges or linear variable deflection transducers (LVDTs) to measure one dimensional displacement; demountable mechanical strain gauge (DEMEC) to estimate the strain on the concrete surface; and electric strain gauges for measuring axial strains either in reinforcement or concrete surface.

1.1.1. Dial gauges and transducers

Dial gauges and transducers are commonly used to measure the deformations during structural testing. Dial gauges presents an inexpensive instrument to measure the deformation especially when the data is not required to be registered electronically. Although LVDT is suitable for laboratory use and provide accurate results, its performance can be affected by the presence of any magnetic fields available nearby it. Another problem arise from using LVDT is the limited measuring range (travel) which bounds the magnitude of measured deformation and the accuracy is markedly reduced outside travel linear range. Moreover, a practical consideration should be taken into account, especially in destructive testing, damage to instrumentation that requires its removal, thus preventing deflection measurements at failure. In addition, armatures of the dial gauge and LVDT have to be fixed to a stable stand near the structure and the device must be pressed against the structure. Consequently, a considerable amount of preparation work is needed for the test setup including fixing of instrumentation and calibration of individual components resulting in spacious cabling amount with complex and laborious wiring[1, 2].

1.1.2. Electric strain gauges

Electrical strain gauges are regularly used to measure the uniaxial strains and they can be embedded in concrete to measure steel strains or attached to the concrete surface to monitor surface strains. Whilst very accurate and the only way to measure strains in embedded bars in concrete, strain gauges encounter problems during cage fixing, placing and concrete casting. Moreover, attachment of strain gauges to concrete surface is not convenient due to the multiphase nature of concrete [3].

1.1.3. Demountable mechanical strain gauge(DEMEC)

The cement and concrete association developed the demountable mechanical strain gauge system to measure the distance between two targets attached to a structure surface. The system involves a standard dial gauge fixed to an invar barwith two conical locating points, one fixed and the other movable on a special side. Two pre-drilled stainless steel discs, termed as targets, are fixed to the structure surface using an adhesive. Readings are taken from the dial gauge by inserting the conical points of the gauge into the holes in the discs. Using of DEMEC gauges requires direct access to the targets which make it unsuitable at all positions on concrete surface. Also, to measure the strain over a wide surface, an extensive arrangement of target grids must be attached to the surface which needs more time and effort. Moreover, DEMEC gauges normally give average strain values rather than local strain values. Therefore, a more convenient measuring system is needed to measure the deformation and strain during testing of structures [2]. The method of close-range photogrammetry was proposed to offer this possibility.

II. Background

Close-range photogrammetry has been used in various applications in the fields of industry, biomechanics, chemistry, architecture, automotive and aerospace. Although close-range photogrammetry has not been well known in measuring deformation and strains during structural testing as in other fields, the examination of current methods has established the potential of using this approach [4-7].

Two image-based approaches found practical application in measuring geometry deformations, structural test monitoring and historic documentation in structural engineering. These include laser-interferometry [8] and close-range photogrammetry.Photogrammetry is used to determine the three-dimensional shape of bodies by measuring and analyzing their two-dimensional images. The application of laser-interferometry, which is based on the interference of reflected waves of a laser light with the object, is still very restricted due to the limitations of cost, safety and other experimental constraints. On the other hand, the close-range photogrammetry method was used to measure planar deformations of a bridge deck and supporting beams by using video cameras, retro-reflective targets, highly convergent network layout, and digital computerized analytical tools [9-16]. This technique depends on tracking the movement of retro-reflective targets during load application.

The confidence on using retro-reflective targets has a number of short falls. A dense grid of targets needs considerable time and effort in fixing and adjusting them. A widely spaced grid of targets may result in sparse data [17]. This system posse a series problem comes from using video camera as the analogue transfer of video signals causes image degradation, and save on tape produces line jitter. However, digital images experience analogue–digital transformation inside the camera, avoiding additional noise during transfer and storage phases [17].

1. Particle image velocimetry (PIV)

In 1984 the term “particle image velocimetry (PIV)” was first introduced to measure velocities and related properties in seededfluids in the field of experimental fluid mechanics [18, 19]. The technique was adapted to be used in measuring soil planner deformation and strain. In this approach, sand own texture is used for image processing instead of fluid seeding. The analysis technique comprises two subsequent stages. In the first stage, the image-space displacements are estimated using the GeoPIV software [20]. While in the second stage, the image-space displacements are converted to object-space measurements using centroiding method.

To calculate image-space displacement vectors between two images, the first test image is divided into a uniform grid of patches. The patch movement during the interval between the images is obtained by detecting the crest of the autocorrelation function of each patch. The autocorrelation function is used to determine the offset between two subsequent images which gives the displacement vector of the patch, see Figure 1. The figure demonstrates the image manipulation during PIV analysis in which the image was split into a grid of patches,$I_{test}(U)$, of L X L pixels size. The patch movement between each image pair can be estimated through a search patch $I_{search}(U+S)$ in the second image. The correlation of $I_{test}(U)$ and $I_{search}(U+S)$ is assessed and normalised by the square root of the sum of the squared values of $I_{search}(U+S)$ over the range of U occupied by the test patch.The accuracy of the PIV measurements is strongly affected with software algorithm and image quality.Validation experiments proved the accuracy of the technique with an accuracy of 1/100thof a pixel. For full details about the mathematical approach used in the PIV analysis technique, the reader is referred to White et al.[17].

Since the data obtained from PIV is in image-space coordinates, i.e. units of pixels, a transformation technique should be implemented to get the data in object-space units (mm). A series of reference targets, with known object-space coordinates in image plane, is used for this transformation centroiding method. Also, this technique enables the detection and correction of any image space displacement of the control markers due to camera movement.

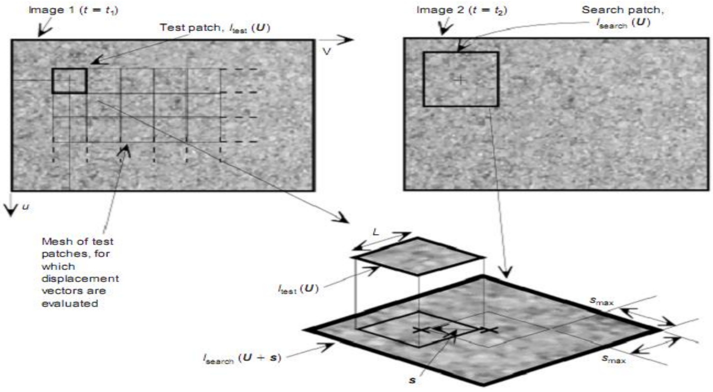
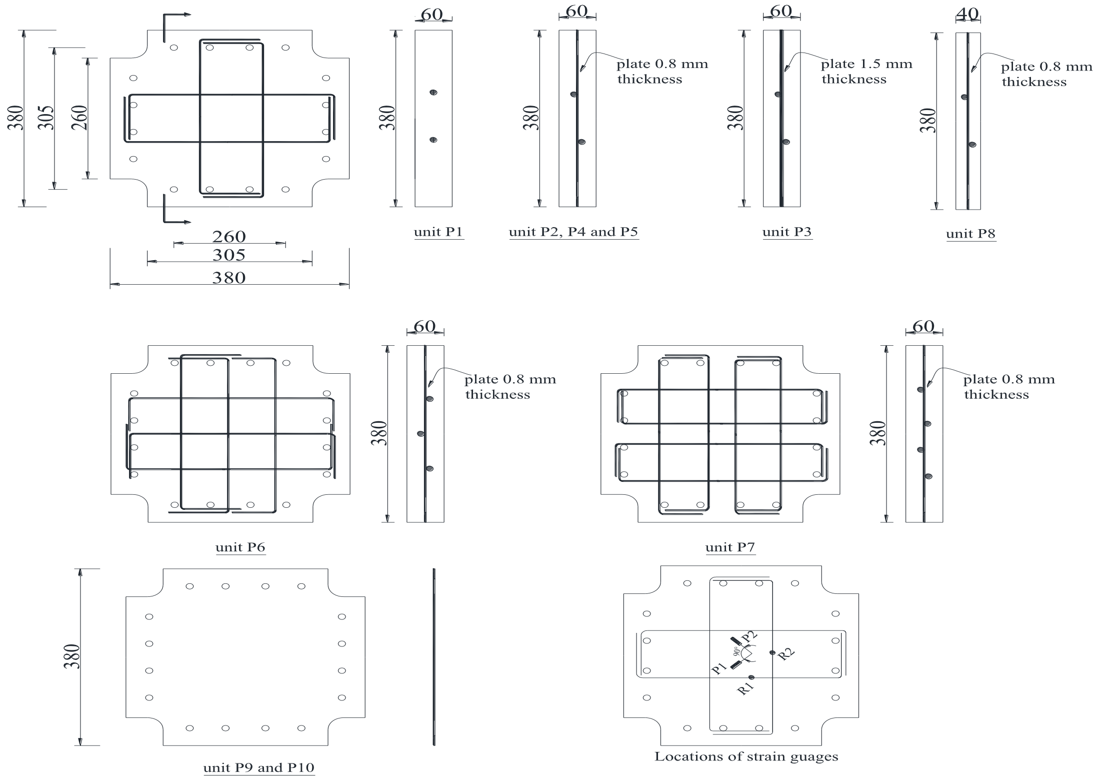


Figure 1-PIV processing technique [17]

2 Experimental work

In order to investigate the efficiency of using the particle image velocimetry (PIV) technique in measuring concrete deformations during structral testing, an experimental study was carried out on a number of small scale test units. The details, reinforcement layout, used materials, instrumentation and testing environments are given in Figure 2. Ten small-scale units were designed and testedunder pure inplane shear; two of them, P9 and P10, were unstiffened steel plates with different thickness; Unit P1 was conventionally reinforced; and seven Units, P2-P8 were encased-composite. All test units had a square shape with external dimension of 380 X 380 X 60 mm and effective dimension of 305 X 305 X 60 mm except Unit P8 which had smaller thickness of 40 mm. For more details about the experimental investigation, the reader is refeered to Reference [21].



all bars are 6 mm diameter
All dimensions are in mm

Figure 2-Dimensions and reinforcement details of test units

3 Application of PIV technique on test units

The PIV technique was used to measure the displacements and strains induced during the testing of concrete units under in-plane pure shear loading. PIV needs that the surface has a pattern of dark and light contrasting features that track with deformation. The surface of the concrete panel was painted with a thin coat of white emulsion paint then a black spry was spread over the surface to provide the spatial variation in brightness required by PIV to track the movements of the concrete surface, see Figure 3 (a). A series of control markers, with known object-space coordinates, was drawn on a Perspex sheet and placed in the front of the test unit. The control mark is a small black circle on a white background which gives an extreme contrast that can be located in image-space (Figure 3 a).

A Canon PowerShot G9 digital camera with a resolution of 3264 x 2448 pixel charge-coupled device (CCD) was used for image capturing. The camera was carefully located to reduce image distortion and was controlled remotely through a USB link from a personal computer and images were saved and checked during test progress. A halogen lamp was used to provide a stable and uniform lighting on the surface of the tested unit. The lighting was positioned carefully to reduce reflections from the marker points on the Perspex sheet and from the viewing windows, see Figure 3(b).

(a)Produced surface texure (b)Camera and lightening

Figure 3-Setup for PIV system

4 Evaluation of PIV performance

The PIV technique was extensively used in the field of geotechnical modelling and used to calculate soil deformation and strain dur55ing centrifuge modelling [22]. The technique was also used to quantify the development of strain over the surface of fibre reinforced polymer (FRP) confined concrete cylinders [23]. Since the displacement measurement points are the PIV patches defined in image-space, the movement of any point on a concrete surface can be monitored. Consequently, deformation fields and strain contours can be plotted for further investigation of results obtained during the test.

In order to check the performance of PIV deformation measurements, the technique was used to monitor the displacement of the vertical diagonal occurred during the destructive testing of all units under in-plane shear and compared to the data obtained using LVDT. One patch was placed on the top hinge to track its movement during the application of the diagonal load, Figure 4. The grid of control markers, placed in front of the units, allowed the conversion from image-scale to object real scale, Figure 4. In order to ensure compatibility between the PIV and LVDT results, the data obtained from the testing machine, the transducer and the images were collected every 20 seconds.

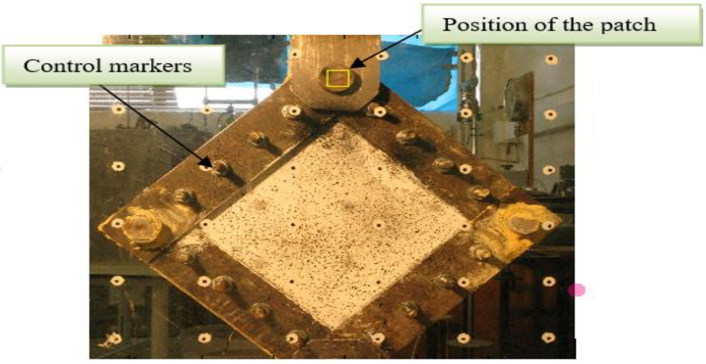


Figure 4-Typical test unit showing selected patch position

For comparison purposes, Figure 5presents the load-displacement behaviour obtained from the LVDT and the PIV systems for six units. The figure clearly indicates that the PIV measurement technique was successful in measuring the displacement of concrete structures under destructive testing. Consequently, it can be used to plot full-filed surface strains during the test. GeoPIV software [20] offers the capability to calculate wide range of strain components including principal, shear and volumetric strains.

No electric strain gauges were attached to the unstiffened steel plates; however, the PIV system was used to estimate the full-field displacement vector fields during the test. The full-field displacement vectors were found by placing a mesh comprising 180 patches distributed across the image.Figure 6 demonstrated the distribution of principal tensile strains at failure on the surface of unstiffened plate Unit P9, principal compressive strains on the surface of conventionally reinforced Unit P1 and principal compressive strains on the surface of encased-plate Unit P1. These results are a further evidence on the effectivness of using the proposed technique in mesuring surface strain on concrete and steel structures during structural testing.

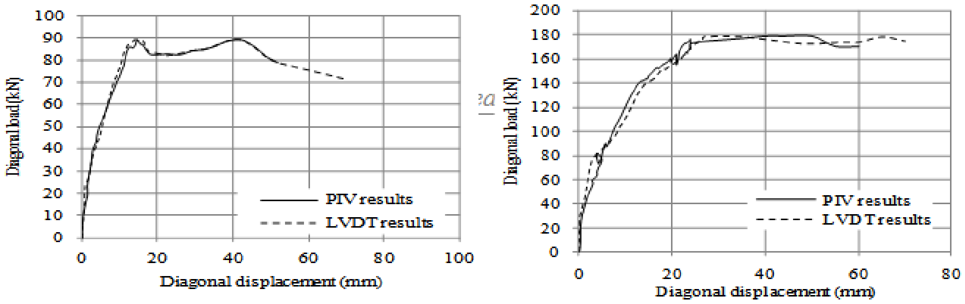


Figure 5-Diagonal load-displacement behaviour as obtained from LVDT measurement and PIV analysis

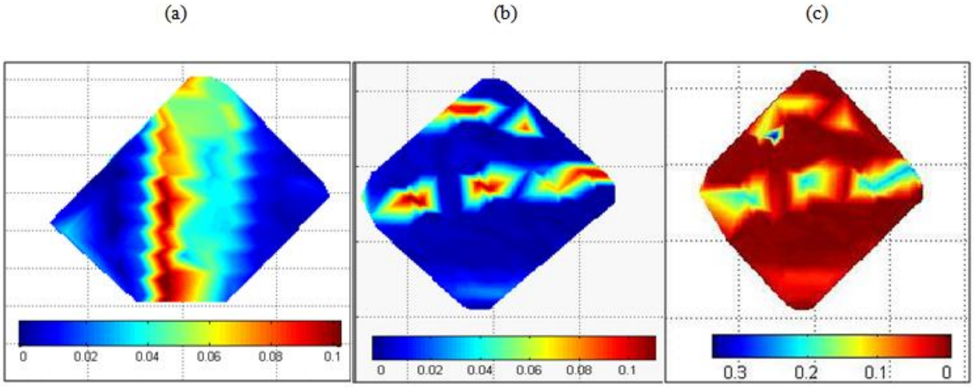


Figure 6-Distribution of (a) principal tensile strains at failure on the surface of unstiffened plate Unit P9; (b) principal compressive strains on the surface of conventionally reinforced Unit P1; and (c) principal compressive strains on the surface of encased-plate Unit P1

III. Conclusions

A full-field measuring system for use in structural testing is proposed. The system is based on digital photogrammetry and particle image velocimetry. The performance of the technique was assessed against the experimental results obtained from testing of six units. Results showed that the system was successfully used to monitor concrete displacement during destructive testing. The technique offers diverse unique advantages over conventional measuring techniques and they can be summarized as follow:

1. The full-field deformation measurement system based on digital photogrammetry and particle image velocimetry (PIV) offers diverse unique advantages over conventional measuring techniques.
2. The technique produces improved deformation data and can be used to plot displacement and strain contours throughout the loading regime;
3. The technique utilizes a relatively cheap off-the-shelf digital still camera with total costs less than $100;
4. The technique is non-contact enabling measurements on inaccessible structure surfaces;
5. The technique is effortless and requires minimal equipment, preparation time and manpower; and
6. Acquired images can be used as a visual records for the test and can be revisited for additional analysis at any time.

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