

IMAGE BASED DISPLACEMENT MEASURING TECHNIQUE FOR IN-PLANE LOADING

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Abstract: Displacement/ strain measurement plays a significant role in understanding structural and material behaviour. In the local context, commonly used contact based systems have a major limitation when it comes to measuring deformation of a surface. A measuring probe can record the displacement/ strain only at a single location and hence require a larger number of pre-defined measuring points in order to calculate the deformation of the surface. Furthermore, the comparative stiffness between the measuring probe and the object under consideration has to be significantly larger. A non-contact optic based system is an ideal candidate for overcoming the problems encountered in such systems. This research attempts to utilize image processing techniques in order to develop a low cost non-contact based deformation measuring technique to measure the in-plane deformation of an object. A set of pre-defined measuring points (targets) were marked on a timber block and a series of images with a commonly available camera was taken while applying a load in the mid-span. The images were then processed using the image processing tools available in MATLAB software to track the motion of predefined targets. The calculated displacements were validated against the physical measurements taken during the bending test.

Keywords: digital image correlation (DIC); deformation; non-contact displacement measurements; region of interest (ROI);

1. Introduction

Measuring deformations plays a vital role in structural engineering. Deformation measuring techniques can be divided into two categories as contact based and non-contact based systems. Contact based systems where a measuring gauge is physically attached to the object under investigation is being widely used in Sri Lankan context. Two such common examples are the dial gauges and strain gauges.

In the case of a dial gauge or a displacement transducer a probe is placed to be in touch with the structure and the displacement at the point of contact is measured, Figure 1(a). Hence, these type of sensors measures the overall deflection of the structure at the selected point which can be used to calculate the averaged strain over a selected region. In addition, the stiffness of the gauge and the stiffness of the structure under consideration has to be significantly different. Otherwise the deflection of the gauge itself affects the results. On the other

hand, a strain gauge is glued to a selected location (Figure. 1(b)) and change in resistance due to material stretching is used to calculate the localized strain at the selected point.

Applicability of contact based systems are limited by the comparative stiffness of the

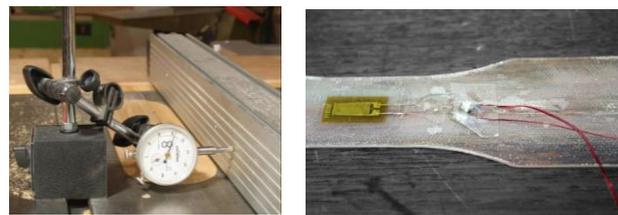


Figure 1: Contact-based measurement systems

(a) Dial gauge (b) Strain gauge

measuring probe and the structure under investigation. Furthermore, these systems are capable of measuring the localized deformation and hence a large number of probes has to be used in order to obtain deformation variation over the whole surface [1]. Cost associated with strain gauges and inability to reuse is another drawback.

Non-contact based measuring techniques can be used to overcome above drawbacks. In this system measuring probe and the structure will not be in contact. One of the specialised non-contact based techniques is imaging based system which involves taking images with a commonly available camera and analysing the photographs with an image processing software.

Digital image correlation (DIC) is one such solution where a series of digital images are analysed to track the movement of a selected point of a structure. Here the difference between the images taken before and after certain deformation is compared with a known scale [2]. Scale for an image to measure the actual deformation in structures has to be obtained from camera calibration process [3].

These measuring systems are already available in the market but the initial cost associated with acquiring such a system is very expensive [4]. There are some advanced techniques which can measure the 3D strain deformations very accurately and produce three dimensional holographic images which are very useful in the field by using DESPI (Digital Electronic Speckle Pattern Interferometry) and STI (Site Test Interferometer) techniques [5], [6]. One such example of 3D system (Q-300) using DESPI technique is made by "Dantec Dynamics GmbH" has been shown in Figure 2 where it measures a strain variation of a dog-bone metal specimen near to the centre hole [7]. But the affordability of such systems becomes questionable while considering capital and maintenance cost, since they are very high.

Hence an attempt is made to develop a MATLAB based algorithm to process a series of images taken from a commonly available digital camera to measure the deformation in a plane. So that the local industry can easily adopt such system at a low cost.

This paper presents an algorithm developed

to measure the in-plane deformation between predefined targets. Section 2



Figure 2: 3D ESPI-System (Q-300)

presents the experimental setup used to obtain the images and identify the important factors affecting this technique. Section 3 describes the image processing algorithm. Section 4 compares the results and Section 5 concludes the paper.

2. Experimental Setup

As described in Section 1, to measure the in-plane deformation two experiments were proposed to be for the purposes of,

- 1) Identifying the external factors affecting the accuracy of the measurements
- 2) Finding out displacements of predefined targets of a structure

2.1. Identifying external factors to be considered

A tensile testing apparatus, a Hounsfield Tensometer (Type 6645, Tensometer Limited, England), was used to identify the important factors which affect this method. Here it was used to apply tensile force on an Aluminium dog bone shape specimen as indicated in Figure 3. This specimen was specifically chosen because that the failure will not occur within the clamped region but within the parallel length (Figure 4). By this way, elongation would be visible without any obstacles. The entire specimen was painted with white colour first and then divided into three regions with four sharp dark black lines in order to have a set of contrasting targets (points of interest) as shown in Figure 5.

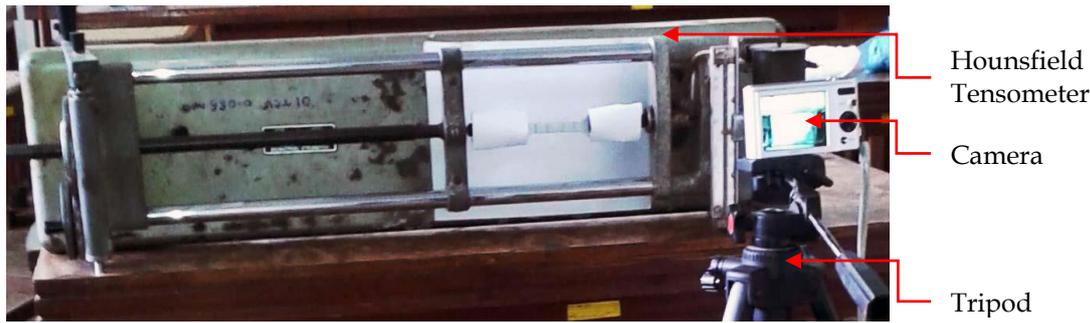


Figure 3: Experimental setup of Hounsfield Tensometer

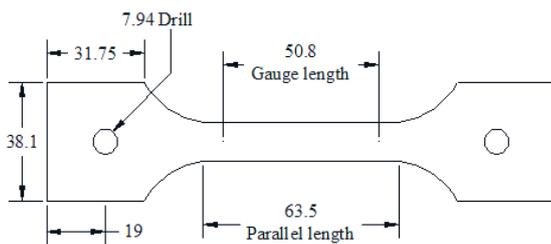


Figure 4: Aluminium dog-bone specimen
(Units: mm)

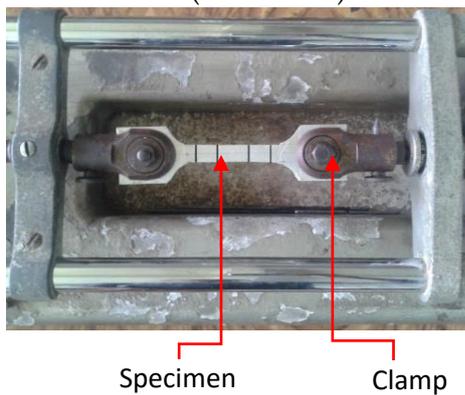


Figure 5: Clamped specimen

2.1.2. Contrasting background

Disturbances in the background make it difficult to clearly identify the intended targets and hence reduce accuracy during image processing stage [4]. Therefore, a mechanism depends on the application has to be used to avoid the distortions as much as possible. In this case, a piece of white colour paper was placed behind the specimen and the clamps were covered with white paper as in Figure 6.

2.1.3. Lighting

Adequate lighting condition is important to illuminate the targets and get rid of unnecessary shadows to have better results

in the image processing stage. LED lighting systems provide better lighting condition over ambient light to eliminate shadows [8]. Over illumination of an object leads to distortions around boundaries. Common causes of over illumination can be due to higher light flux created by the lighting system, environmental light sources, camera flash or having specimen with reflective surfaces. Hence these external factors had to be checked before conducting the experiment. Figure 7 illustrates how the camera flash and the shadows affect the images during the image processing stage [1].

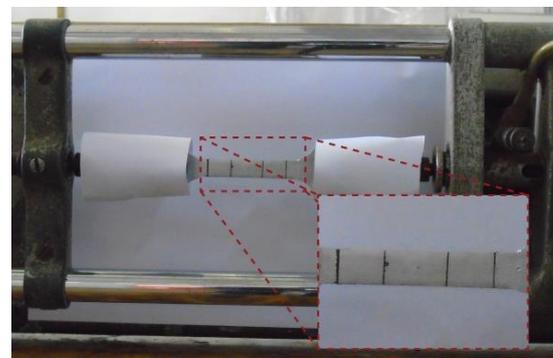


Figure 6: Zoomed image of specimen

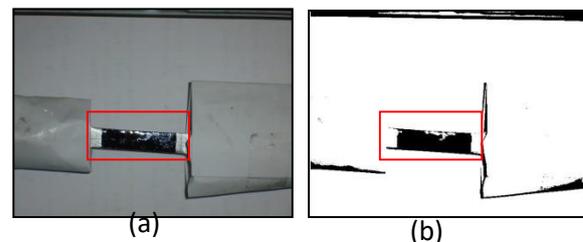


Figure 7 - Effect of over illumination

(a) Original photograph (b) Binary image

2.1.4. Position of the camera

The precision of this technique is governed by the number of pixels available within the region of interest (ROI). Hence it is important to focus on the ROI (Figure 6) and position the camera as close as possible to the experimental setup. While keeping the camera closer makes the precision higher, it makes the field of view shorter. In addition, the angle of incidence of further most positions within the ROI becomes larger and hence the scale across ROI varies at a higher rate [9]. Therefore, the camera was positioned at the furthestmost point from the apparatus while maintaining ROI to fit into the field of view of the camera. By doing this the utilisation of the resolution will be optimised.

2.1.5. Thickness effect of the targets

Selection of targets depending on the application plays an important part in this technique. It is better to select the point targets than selecting thick targets since the validation process with basic measuring techniques will yield fault reading since they are handled manually.

2.2. Experimental procedure

Validation of this technique before using it in the field must be necessary. Hence an experiment was carried out using bending test apparatus as shown in Figure 8. Here a

timber piece with a cross-section of 15.37 mm (vertical) x 25.93 mm (horizontal) and a length of 620mm was simply supported near to both ends. Then 5 predefined targets were made out of white paper in the shape of circles and they were pasted on the top of the vertical surface at different locations and the loading hook was kept at the mid-span of the timber block. Then on the top horizontal surface, dial gauges were setup vertically in a way to align with the target circle centres. The dial gauges used for this purpose were manufactured from Saginamiya (TDM 1050), Mitutoyo (QDV 806) and Baker (K06). For the initial phase without-loading at the mid-span all the dial gauges were set to zero. The location of the supports and the dial gauge pointers from one edge was measured with Vernier Caliper having 0.02 mm accuracy.

Then a Sony DSC-W800 Cyber Shot (Sony Corporation, Japan) (20MP) digital camera was fixed on to a Velbon PH-368 fluid head type tripod and set at a similar height (112cm from ground) to the specimen while maintaining the face of the camera approximately parallel (not necessarily) to the face of the specimen (Figure 8). Then the camera was focused to capture the ROI with a zoom of 1.6X at a distance of 71 cm from



Figure 8: Experimental setup of bending test



Figure 9: ROI

the specimen to capture the whole area of experiment. The pixel spacing at this range was 0.9mm. Then the experiment was carried out under natural lighting.

“Camera calibration” is a process which is used to estimate the camera parameters [3]. In this experiment camera was kept at a static position. Here a checkerboard pattern with 7 x 10 squares (Each square had a size of 21.79 mm) was selected as the calibration pattern, printed on a white sheet and pasted on a flat surface cardboard. This calibration pattern size should be selected to cover up the whole area of experiment. Then to calibrate the camera this checkerboard pattern was kept in different orientations (translated, rotated and slightly inclined) and 21 images of the calibration pattern were captured with the camera as shown in Figure 10. One of the calibration image should be taken exactly on the plane of the targets (vertical surface of timber faced towards camera).

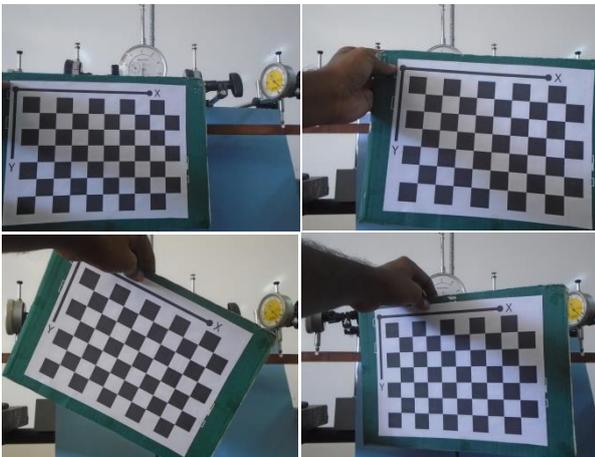


Figure 10: Calibration image samples

Once the camera and lighting systems were positioned a photograph of the unloaded specimen was taken. Then the specimen was loaded in steps by applying the weight on the bottom of the hook. While each load is applied on the bottom of the hook, the corresponding reading on each dial gauge was recorded and the photograph of that phase had been captured.

3. Image processing

After selecting all the camera calibration images, they were analysed with the help of Image Processing Toolbox (IPT) available in MATLAB software (MATHWORKS, Inc., US) R2014b version. Calibration images with high distortions can be eliminated on this process. Since this camera is a modern digital camera, distortions expected to occur due to skewness and tangential distortion during the calibration stage were not considered. Hence only the radial coefficient of 2 was considered for the calibration purpose. In this process reprojection error of the calibration images was having a mean value of 0.92 pixels. After the calibration process is done the camera parameters can be excluded.

The following flow-chart explains the important procedure that has to be followed to identify the target locations in the image.

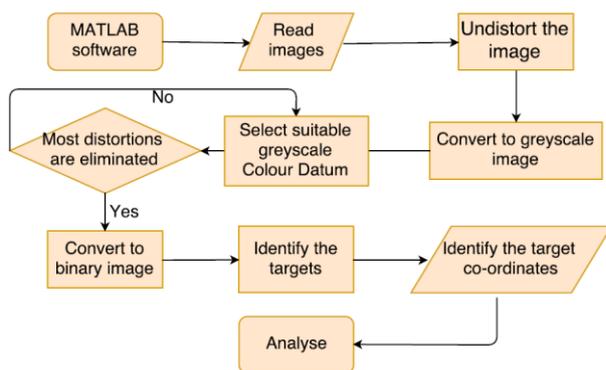


Figure 9: Flow chart for image processing

First the target images were selected and they were undistorted using the camera parameters as shown in Figure 12. After that they were converted to greyscale images to easily differentiate the targets from the background, since mean colour intensity of the targets can be easily defined in integers than having it in the coloured (RGB) image.

Then only the ROI was analysed to minimise the analysing time. In this process selection of a colour datum takes an important place to differentiate black and white pixels. A suitable colour datum range was selected through a trial and error process to minimize the distortions due to

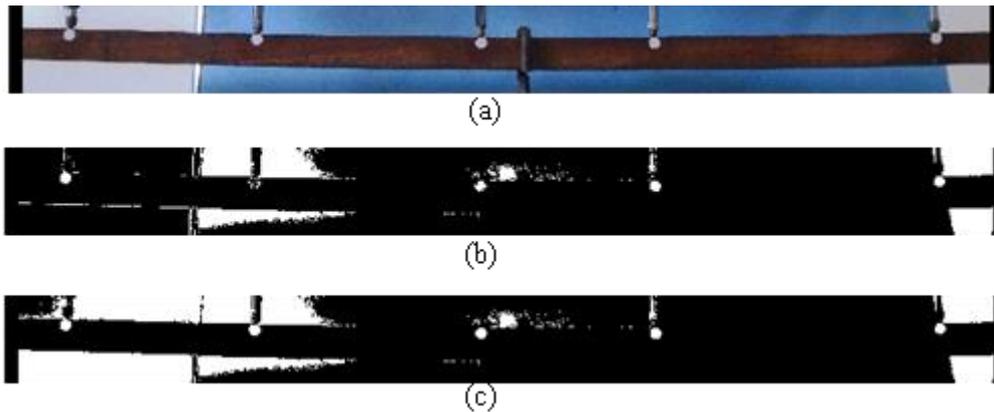


Figure 10: Selection of appropriate greyscale colour datum range (a) ROI (b) Inappropriate (c) Appropriate

shadows in the photographs as shown in Figure 13. This colour datum selection is mainly dependent on the amount of light flux used to lighten the specimen. This is done mainly due to differentiate the targets from the background. Then the adjacent pixels were filled with 8-connected neighbourhood pixels to get a perfect binary image.

In order to calculate the deformation in the predefined targets all the images under different loadings were processed through the developed MATLAB correlation algorithm. Here the centroids of the circles were identified in pixel terms. In order to convert this pixel co-ordinate system into world co-ordinate system (mm) the calibration image which was taken on the same plane of the vertical surface of the timber block was used. This world co-ordinate system had been transferred to the target image and the vertical displacements were measured in millimetres. To cross check the world co-ordinate system the centroids of the circles were projected on the same image as shown in Figure 14.

While calculating the vertical displacements, there are two angles that have to be taken into consideration.

- Camera inclination to the horizontal plane
- Corresponding calibration pattern co-ordinate system inclination to the horizontal plane.

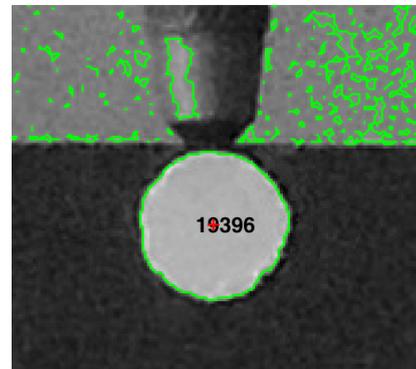


Figure 11: Projected centre of a target

4. Results and Discussion

Table 1 presents the results obtained for vertical displacement in between initial and the current position of the targets calculated with MATLAB algorithm against the experimental results from dial gauge readings.

From the Table 1 it can be observed that there is a maximum error of 0.18 mm. From Figure 15, the displacements were connected with a quadratic polynomial trendline through the reading points. Both trendlines show almost equal bending in both methods. This shows that the readings have a perfect correlation and the method is really precise in subpixel terms.

In this method, the consecutive images are not compared with each other to calculate the deformation. But it was calculated from the calibration image co-ordinate system.

Table 1: Comparison of displacements obtained from five targets

Image	Loading (kg)	Vertical Displacement of Targets (mm)											
		Experimental readings					MATLAB results						
		1	2	3	4	5	1	2	3	4	5		
01	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
02	1.0	0.30	0.58	0.74	0.73	0.38	0.43	0.58	0.77	0.78	0.43		
03	1.5	0.45	0.90	1.16	1.14	0.59	0.53	0.95	1.21	1.21	0.67		
04	2.0	0.63	1.24	1.61	1.57	0.82	0.65	1.23	1.59	1.56	0.85		
05	2.5	0.80	1.59	2.08	2.00	1.05	0.89	1.60	2.08	2.01	1.13		
06	3.0	0.98	1.90	2.49	2.41	1.25	1.08	1.93	2.51	2.43	1.37		
07	3.5	1.16	2.26	2.95	2.84	1.48	1.32	2.35	2.98	2.87	1.56		
08	4.0	1.33	2.59	3.39	3.26	1.59	1.41	2.63	3.36	3.23	1.74		
09	4.5	1.51	2.93	3.84	3.69	1.92	1.66	3.01	3.86	3.72	2.08		
10	5.0	1.69	3.29	4.30	4.14	2.15	1.84	3.35	4.31	4.16	2.33		
Maximum Error		-	-	-	-	-	0.16	0.09	0.05	0.07	0.18		

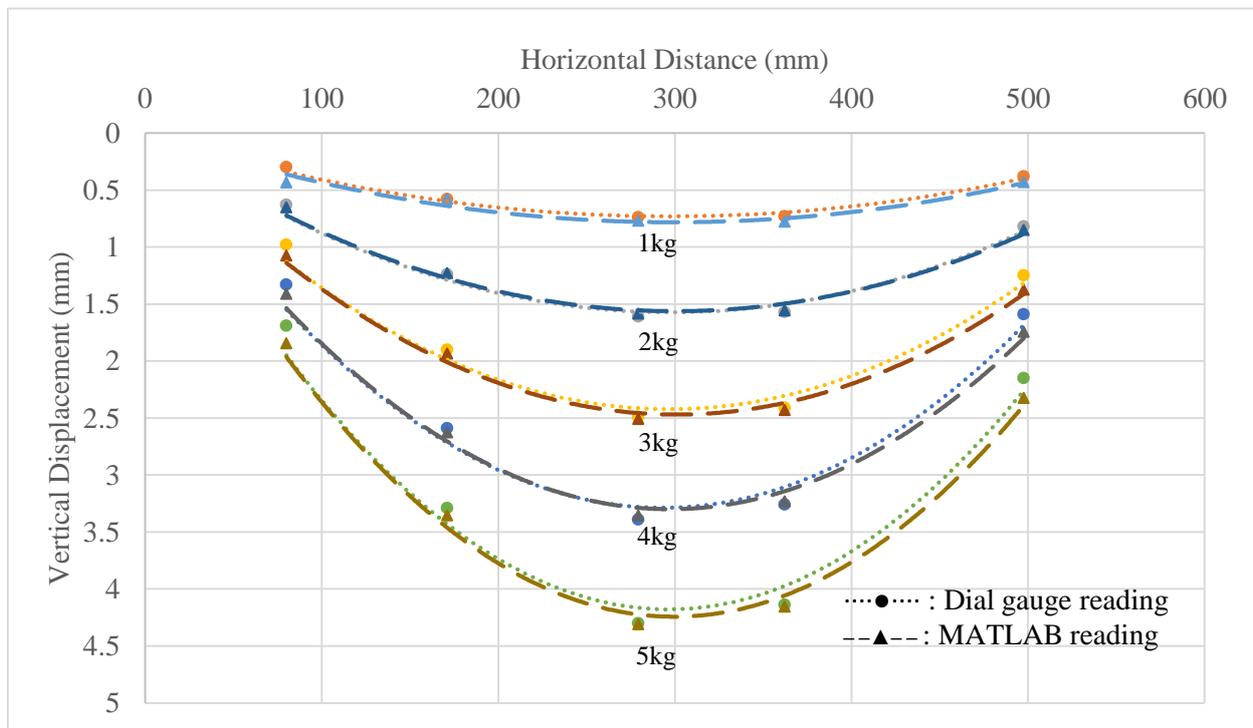


Figure 15: Comparison of vertical displacements of targets from dial gauge readings and MATLAB readings



Hence while taking the corresponding the calibration image there is a necessity to give extra care while keeping the pattern to the exact timber surface. Thus, all the deformation calculations are independent from other image calculations. Camera should not be repositioned by any means throughout the experiment. In case of failure, the experiment has to be redone with the newly positioned camera with new camera calibration process because there would be a change in both translation and rotation vectors of the camera.

The algorithm developed here is focusing on multi-directional variation of the targets and measures the distances in millimetres directly. In this particular scenario, the algorithm was modified to measure only the intended vertical displacements of the predefined targets. This method can be further developed to analyze the strain distribution on the elements in contour form which is done by creating multiple targets on the surface of an object and tracking the targets displacement over the surface. This process is known as pattern matching which would help to illustrate the full-field strain variation over the surface. However, for the strain measurements the accuracy has to be increased when there will be only a small amount of elongation either by using high resolution camera.

5. Conclusion

An attempt is made to develop a 2D (in-plane) image based non-contact displacement measuring technique using DIC technique. The algorithm was used to measure the displacement of a bending experiment timber specimen with the help of camera calibration. Results showed that two methods can measure the displacement to an accuracy of 0.18 mm. However, it should be noted that this test could measure only the vertical deformation at different points whereas the technique developed in this paper can measure the elongation between much smaller predefined regions as well.

The algorithm developed here is focusing on detecting multiple targets and their locations in multiple directions within predefined targets. It is intended to develop the algorithm to detect random targets in order to capture the full-field displacement in future by using the method of pattern matching.

Furthermore, the present technique is limited to in-plane measurements and hence cannot be used for any out-of-plane deformations like bending or buckling which are common in civil engineering applications. Hence it is intended to expand this technique to use two cameras instead of a single camera which will allow to capture out-of-plane deformation as well as provide a cross-reference between cameras better accuracy.

Acknowledgement

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References

- [1] P. Waterfall, N. McCormick, and A. Owens, "Optical imaging for low-cost structural measurements," *Proc. ICE - Bridge Eng.*, vol. 167, no. 1, pp. 33-42, Mar. 2014.
- [2] F. Hild and S. Roux, "Digital Image Correlation: from Displacement Measurement to Identification of Elastic Properties - a Review," *Strain*, vol. 42, no. 2, pp. 69-80, May 2006.
- [3] A. Diluxshan and H.M.Y.C. Mallikarachchi, "A Low Cost Optics Based Displacement Measuring Technique," presented at the Society of Structural Engineers Annual Sessions 2016 (SSEAS 2016), 2016.
- [4] J. Lord and N. McCormick, "Digital image correlation for structural measurements," *Proc. ICE - Civ. Eng.*, vol. 165, no. 4, pp. 185-190, Nov. 2012.
- [5] H. Kadono, Y. Bitoh, and S. Toyooka, "Statistical interferometry based on a



- fully developed speckle field: an experimental demonstration with noise analysis," *J. Opt. Soc. Am. A Opt. Image Sci. Vis.*, vol. 18, no. 6, pp. 1267-1274, Jun. 2001.
- [6] O. J. Løkberg, "Electronic Speckle Pattern Interferometry," in *Optical Metrology*, O. D. D. Soares, Ed. Springer Netherlands, 1987, pp. 542-572.
- [7] "Q-300 3D Electronic Speckle Pattern Interferometry (ESPI) System." [Online]. Available: <http://www.dantecdynamics.com/3d-espi-system-q-300>. [Accessed: 28-Oct-2016].
- [8] H. Haddadi and S. Belhabib, "Use of rigid-body motion for the investigation and estimation of the measurement errors related to digital image correlation technique," *Opt. Lasers Eng.*, vol. 46, no. 2, pp. 185-196, Feb. 2008.
- [9] C. Murray, W. A. Take, N. A. Hoult, and A. Hoag, "Field monitoring of a bridge using digital image correlation," *Proc. ICE - Bridge Eng.*, vol. 168, no. 1, pp. 3-12, Mar. 2015.