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A SIMPLE TWO-DIMENSIONAL DIGITAL IMAGE CORRELATION MODEL FOR OUT OF PLANE DISPLACEMENT USING SMARTPHONE CAMERA

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Abstract

Digital Image Correlation (DIC) is a full-field non-contact optical technique used for measuring displacement and strain. The considered technique, two-dimensional digital image correlation 2D-DIC is used for in-plane measurements. In this paper, a simple 2D-DIC model and smartphone camera were used to determine the out-of-plane displacement of a glass table. The out-of-plane displacement measurements were experimentally validated by comparing it with a dial gauge data at specific points. Further, analytical and numerical models were performed to validate the experimental results. The DIC results show a good agreement with the dial gauge and the analytical and numerical models. The current testing technique elaborates a promising simple, fast, and cheap testing technique for out-of-plane displacement measurements applications.

Keywords: Camera, Digital image correlation, DIC, 2D-DIC, 3D-DIC, In-plane displacement, Out-of-plane displacement, Smartphone.

1. Introduction

Digital Image Correlation (DIC) is a contactless full-field optical technique used for measuring displacement and strain. The concept of DIC is simply based on comparing pairs of digital images before and after deformation. Two-Dimensional Digital Image Correlation (2D-DIC) is strictly used for in-plane measurement of displacement and strains [1]. Further, the out-of-plane displacement is one of the significant factors that affect 2D-DIC accuracy during testing [1-8]. The out-of-plane displacement or rotation is inevitable during in-plane testing [4]. Different factors cause out-of-plane relative movement between the camera and the specimens. Among these factors are the imperfectness of the test setup and the effect of Poisson's ratio [9]. For these reasons, a 3D-DIC is used to tackle the issues of 2D-DIC and to capture all three-dimensional displacement data. However, the 3D-DIC requires a more complex setup and higher operational cost making it unfavourable for simple applications [7, 8].

Over the last few decades, detailed studies have been undertaken to reduce DIC computational complexity, achieve high precision, and extend its range of applications. Also, the out-of-plane influence on the in-plane displacement measurement accuracy has been studied by several researchers [1-8]. Sutton et al. [1] indicated a linear relationship between the out-of-plane displacement and normal in-plane strain. Haddadi and Belhabib [2] identified the out-of-plane displacement as a significant source of error of the 2D-DIC, proposing a linear parameter to improve the accuracy of the DIC technique. Hoult et al. [3] presented several solutions to significantly reduce the effects of out-of-plane displacement and achieving means strain errors of less than 5 μe than conventional strain gauges. Zhiqiang et al. [4] proposed two projected laser strips to measure the out-of-plane motion of a planar specimen. The author also established a theoretical model to predict the pseudo-strain caused by out-of-plane displacement [4]. The model was based on the pin-hole imaging model to eliminate the effect of out-of-plane motion [4]. Wittevrongel et al. [5] proposed a compensation system based on fixed compensation plates [6]. The technique allows correcting data from a 2D DIC system [5, 6]. Yan and Lin [7] suggested a "self-correction" method to correct errors due to out-of-plane displacement to use the initially extracted DIC strain values in different directions. Poling et al. [8] studied the effect of the out-of-plane specimen's movement relative to the camera sensor on the measured strains. It was concluded that the 2D system was able to measure strains as the camera focus was lost due to the out-of-plane displacement of the specimen, which had an effect of about 0.025% strain and 2.5 mm displacement [8].

In this paper, a simple 2D-DIC technique based on simple trigonometry is proposed to determine the out-of-plane displacement of the glass table using GOM correlate software and smartphone camera [10]. The out-of-plane displacement results were validated experimentally by comparing it with a dial gauge data at specific points. Further, analytical and numerical models were performed to validate the experimental results. The DIC results show a good agreement with the dial gauge and the analytical and numerical models. The current testing technique elaborates a simple, fast, and cheap testing technique for out-of-plane displacement applications such as out of plane deflection of structures.

2. 2D Digital Image Correlation DIC

The two-dimensional DIC can distinguish the out-of-plane movements by observing the relative perpendicular motion between the object and the camera lens. For illustration, suppose an object is having a height (h_t) placed in front of the camera at a distance (*d*). Therefore, the projection of its initial height on the camera sensor with a focal length (*f*) is (*a*), as shown in Fig. 1. If the object moved toward the camera lens at a distance (*m*), the sensor's new projection is (*b*). The out-of-plane movement toward the camera resulted in a pseudo-strain that can be easily captured using a simple 2D-DIC algorithm. In this case, GOM correlation software was used for analysis [10]. Based on object movement, the following equations can be derived.

$$\frac{a}{f} = \frac{h_t}{d} \quad (1)$$

Similarly,

$$\frac{b}{f} = \frac{h_t}{d-m} \quad (2)$$

Dividing Eq. (1) by Eq. (2) gives:

$$\frac{a}{b} = \frac{d-m}{d} \quad (3)$$

Providing,

$$m = d * (1 - \frac{a}{b}) \quad (4)$$

where *m* is the out of plane displacement. The value of *m* is positive when the object is moving towards the camera ($b > a$), while m is negative when the object is moving away from the camera ($a > b$). The equation resembles the prospective concept, where the object gets magnified as it comes closer to the observer [1].

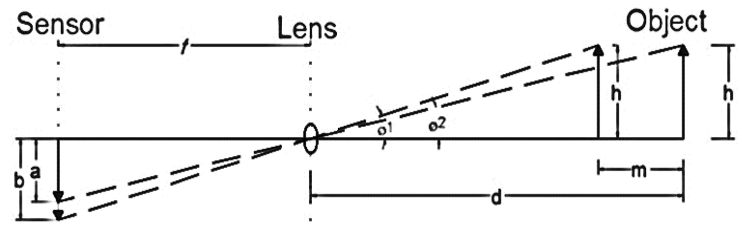
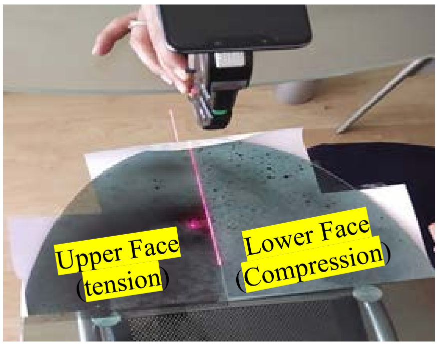


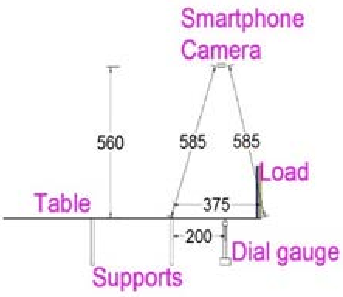
Fig. 1. Illustration of moving object projection on the camera sensor.

3. Apparatus and Methods

3.1. Surface preparation

The cantilever part of the table was spread with a random speckle pattern on both upper and lower faces, as shown in Fig. 2(a). The speckles were applied using water-based spray paint that can be easily removed after testing. The lower (compression) and upper (tension) face of the cantilever were equally divided into two halves, as illustrated in Fig. 2(a). The side view of the table sketch is illustrated in Fig. 2(b).





(a) Upper and lower half face speckles. **(b) Sketch of the test setup.**

Fig. 2. Test setup, all dimensions in (mm).

3.2. Experimental setup

The test was performed on a glass table having a 37.5 cm cantilever glass panel of an oval shape, as shown in Fig. 2. The test setup was comprised of DIC, which was exploited and performed using 12MP, f/1.9 Xiaomi Pocophone F1 smartphone dual camera. The smartphone camera specifications are presented in Table1. Horizontal and vertical alignments between the camera and the table surface were checked with a laser level to minimize lens distortion. It is worth to mention that no loads were recorded during the experiment, except for one trial for comparison with the numerical and analytical calculations. This experiment's main objective is to validate the simple trigonometric model to determine the out-of-plane displacement by DIC and compare it with dial gauge at specific points.

Table 1. Specifications of the smartphone camera.

Model	System version	Primary camera (dual)	Video recording	Camera pixels
Pocophone F1	Android MIUI Global 11.0.8	12 MP., f/1.9, 1/2.55", 1.4µm, dual pixel PDAF 5 MP, f/2.0, (depth)	4K@30/60fps, 1080p@30fps, 1080p@240fps, 720p@960fps	12 Million

3.3. DIC testing procedure

The load was applied manually to the edge of the table. The cellphone camera app with 4K, 4096 × 2160 pixels, at 30 fps video recording was employed to capture the table out-of-plane motion. The video recording was then converted to a series of images for processing with GOM correlate software. The cantilever beam was divided into multiple sections at various distances from the support, as shown in Fig. 3. The horizontal and vertical pseudo-strain was determined at each section by using virtual extensometers. The dial gauge was placed in section 200 mm from the support for comparison with DIC, as shown in Fig. 3. The assumption of strain in the Y-direction is negligible because the cantilever bends only in the X-direction. This assumption is justified as the pseudo-strain values resulting from the out-of-plane displacement are much higher than the material's actual strains. Therefore, the Y-direction's strain values have only resulted from the out-of-plane displacement of the cantilever, i.e., pseudo-strain.

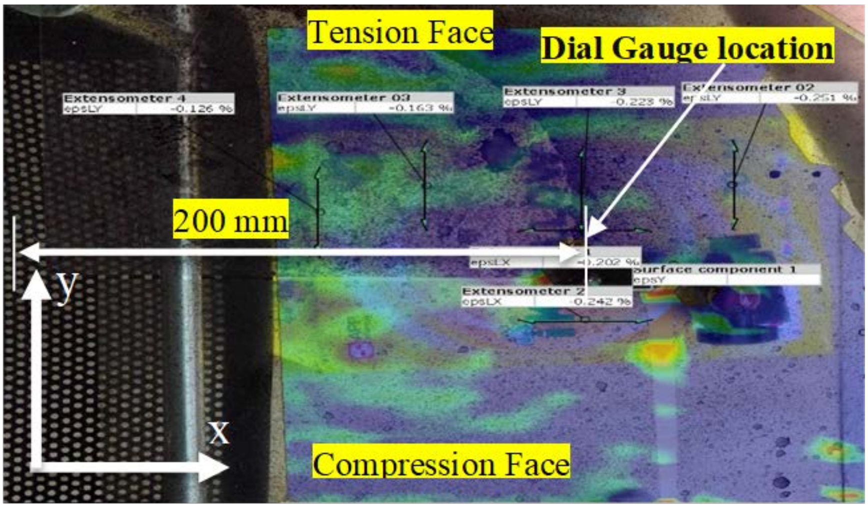
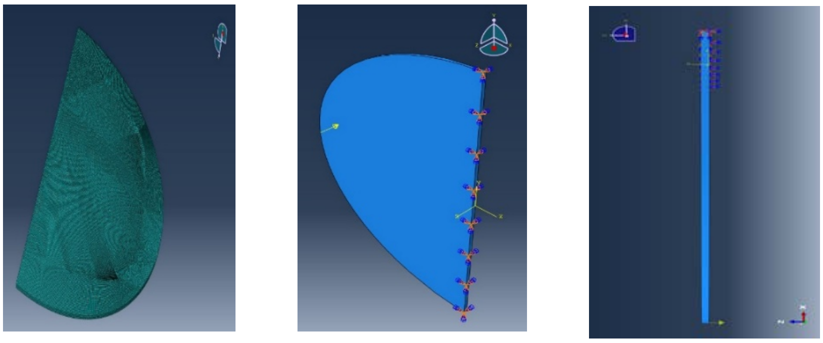


Fig. 3. DIC (Y-strain) measurements at multiple sections (time=20 s).

3.4. Analytical and unmerical procedure

The out-of-plane deflection of the cantilever was calculated analytically based on the moment area deflection method. The beam width was assumed to vary linearly across its length for simplification. The numerical model was employed using Abaqus 6.14 finite element software. The glass material was assumed deforms linearly (typical glass behaviour) under the static load. The glass material has a Young modulus of 70 GPa. The boundary conditions were assumed fixed edge, as shown in Fig. 4(b). Finally, the loading was 55 N static-general applied to the end of the cantilever, as shown in Fig. 4(c). A three-dimensional hex-dominated element with a sweep medial axis algorithm was used to simulate the table's cantilever part, as shown in Fig. 4(a). The simulation was performed utilizing an element mesh size of 1.75, creating the total number of elements =257472 and the total number of nodes =324100.



(a) Finite element mesh. **(b) Fixed boundary conditions.** **(c) Loading the edge of the table (side view).**

Fig. 4. Finite element modelling of the glass table.

4. Results and Discussion

The DIC's experimental results using the virtual extensometer to determine pseudo strain at Y-direction are shown in Fig. 5. The Y-strain values were determined at multiple sections, namely every 50 mm. The pseudo strain values were based on the linear trendline as the exported results fluctuate, which is typical of DIC result outputs due to noise and lighting effects. The out-of-plane deflection was determined using the simple trigonometric model Eq. (4), as shown in Fig. 6. The dial gauge data in section 200 mm were also shown in Fig. 6 for comparison with DIC in the same section. Furthermore, all experimental, analytical, and numerical out-of-plane deflection was determined and plotted at a load of 55 N, as shown in Fig. 7. Table 2 lists the stress, strain, and deflection results from the numerical model at different sections. Finally, the strain map in the X-direction of the table from both numerical simulation FEM and DIC were plotted side by side for comparison in Fig. 8.

The experimental results from DIC show comparable deflection values to the dial gauge. The results prove the 2D-DIC model validity for out-of-plane displacement determination. However, the experimental results were modified as rigid displacement and rotation at the table support. The deflection modification was computed based on the deflection values at the support. This is done by placing a dial gauge at the supports. The rotation modification was estimated by determining the deflection value near the support. As a result, it is assumed a negligible material deflection from bending near the support such that the rotation angle due to support rotation can be estimated. As shown in Fig. 7, the out-of-plane analytical and numerical models were also showing good compatibility with less than 7% deviation at the free end of the table. In addition, both analytical and numerical deflection values are compatible with the experimental results after modification. Finally, the glass table X-strain map is illustrated in Fig. 8, where both results were taken from Digital Image Correlation (DIC) and Finite Element Model FEM. Figure 8 shows the deflection contours similarity of both DIC and FEM methods estimating the deflection values throughout the table's bottom half.

The glass table experiment shows the importance of using DIC in determining global material behaviour and structure boundary conditions. Further, using the 2D-DIC technique and the out-of-plane pin-hole model provides a simple solution for out-of-plane applications. The 2D-DIC is much simpler than the 3D-DIC as it utilizes simple tools such as smartphones and a free GOM correlate software. However, the 2D-DIC structural application should not include structural behaviour complications such as two-way bending or excessive shear deformation.

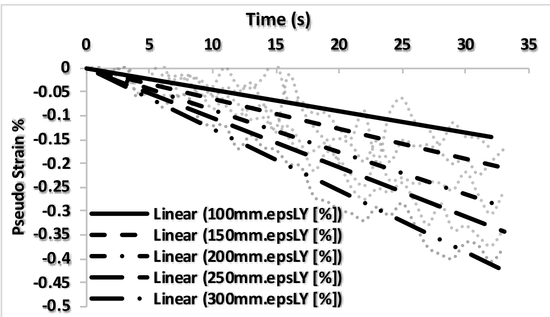


Fig. 5. Pseudo strain % at Y-direction of multiple sections.

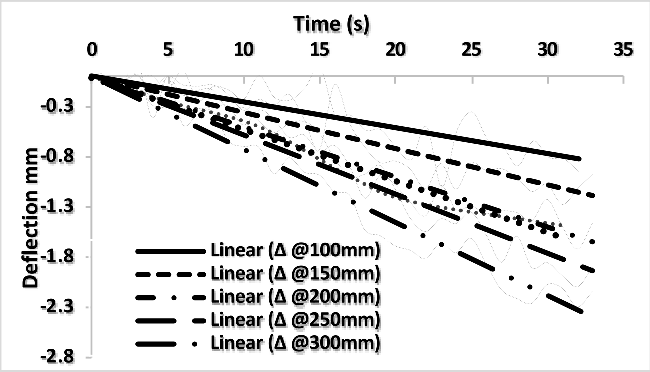


Fig. 6. Deflection values Δ (mm) of multiple sections.

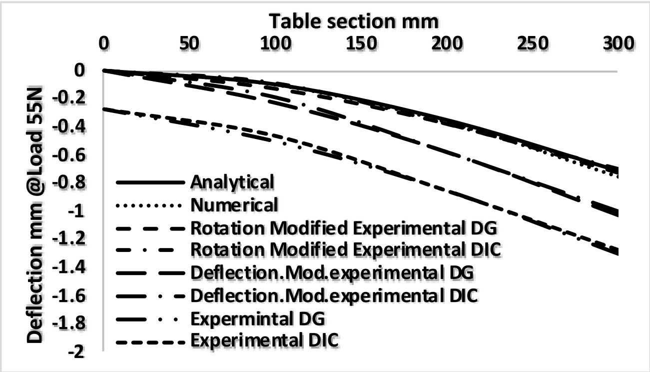
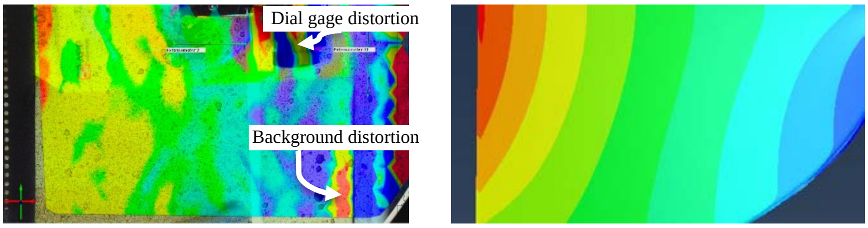


Fig. 7. Analytical, numerical, and experimental out-of-plane deflection of the glass table using DIC and dial gauge DG.



(a) DIC strain map, -X direction. **(b) FEM strain map, -X direction.**

Fig. 8. Glass table strain map, -X direction.

Table 2. Stress, strain, and deflection values of the glass table at all sections.

Section	Fixed end	100 mm	150 mm	200 mm	250 mm	300 mm	Free end
Strain (%)-x dir.	±0.006	±0.0041	±0.0035	±0.0031	±0.0026	±0.002	-
Stress (MPa)-x dir.	±4.2	±2.86	±2.55	±2.14	±1.81	±1.35	-
Deflection (mm)	-	-0.09	-0.22	-0.36	-0.55	-0.73	-1.08

5. Conclusions

The out-of-plane displacement results due to bending were determined using the 2D-DIC technique employing a simple trigonometric model. The displacement values were determined based on the pseudo strain values of the Y-direction. The out-of-plane displacement from DIC shows good compatibility with the results of the dial gauge. Further, the experimental results from both DIC and dial gauge show good agreement with the analytical and numerical results. This experiment and model validate the use of a two-dimensional DIC technique for out-of-plane displacement. Using readily available smartphones facilitates the testing procedure as the technological advancements made their cameras cheaper and more efficient. Future works may consider applying this technique on real-scale structures such as glass panes and bridge girders.

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