The measurement of out-of-plane displacement by using 3D-DIC technique in buckling experiment

Loc Tan Le[1], Arie Sukma Jaya[1], Lenny Iryani[1], Ichsan Setya Putra*[1],
Tatacipa Dirgantara[1], Djarot Widagdo[1], Ly Hung Anh[2]

[1]Faculty of Mechanical & Aerospace Engineering, Institut Teknologi Bandung
JL. Ganesha 10, Bandung 40132, Indonesia
[2]Faculty of Transportation Engineering, Ho Chi Minh city University of Technology
268 Ly Thuong Kiet street, District 10, Ho Chi Minh city, Vietnam
*Corresponding author: isp@aero.pauir.itb.ac.id

Abstract

One of the new methods to measure the displacement is by using Digital Image Correlation (DIC) technique. The displacement is measured by correlating two sequences of the images taken from the experiment unloaded and loaded condition. To obtain out-of-plane displacement by using 3D-DIC, two cameras were employed. The specimen used in this work is acrylic with the dimension 300 mm × 50 m m × 2 mm. It was found out that with the new image correlation function developed previously, the present experiment setup and the 3D-DIC program can measure the out-of-plane displacement field up to sub-pixel accuracy. Further more, the displacement results can be become a source to calculate strain, stress field and stress intensity factor.

Keywords: Displacement fields, 3D Digital Image Correlation, Correlation, Sub-pixel, Buckling.

1. Introduction

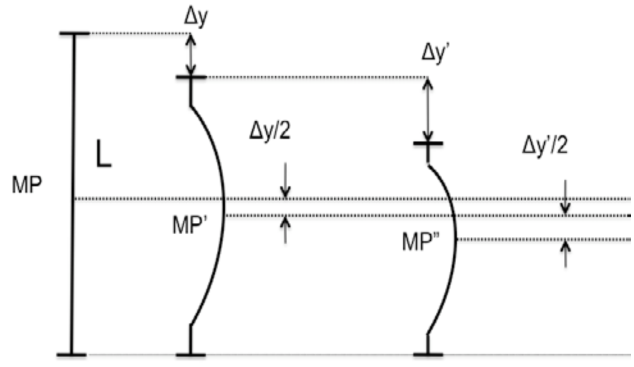
Out-of-plane deformation is one of the important parameter in a stress and strain analysis. By the advance of digital technology, the out-of-plane deformation can be measured by using Digital Image Correlation technique. Digital Image Correlation was first initiated with 2D fields and introduced by Yamaguchi (1981) [1], Peters and Ranson (1982) [2] with the topic focused on the determination of surface displacements. Based on these preliminary researches, in 1983 Sutton et al. [3] developed a numerical method using a camera recording image during experiment, which is known today as 2D Digital Image Correlation (2D-DIC). 2D-DIC measures only in-plane displacement, to measure out-of-plane such as complex buckling modes experimentally, a 3 D Digital Image Correlation (3D-DIC) was proposed by Luo et al [4].

By knowing that 3D-DIC technique is a wide range of applications and popular day by day, the laboratory of Lightweight Structure, Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung started to conduct research in that field to develop a low cost 3D-DIC system can be used for institute experiment. Starting from the 2D program [5], a 3D-DIC system was developed by Tran Nam Nguyen [6] who estimated its accuracy, optimized its error then generated a simple model of the 3D-DIC system. A software was developed to process the images and compute for 3D shapes and displacement fields. Following that research, a 3D-DIC system development program was continued to master the camera calibration toolbox developed by Bouguet and validated the 3D-DIC program with buckling experiment [7],. Much work on c amera calibration and experimental have been done to improve the system [8], [9]. This method can then be used for many other applications in the future research. Although the result has been obtained, up to this point, the system still need long processing time and the results need more accuracy and visibility in 3D reconstruction. Therefore, the purpose of this present work is to improve further the system, create a testing procedure, set up experiment, and compare the error of the program with the measurement, as w ell as optimized the 3D-DIC software with highly accuracy which was applied in column buckling test to measure the out-of-plane displacement.

2. Experimental Setup and Procedure

2.1 Deflection at the middle point

Following the experiment, the column buckling specimen is clamped by machine supports. The top support can move in *y*-direction to load the specimen while the bottom support is fixed. The middle point in y length is marked to arrange dial indicator before and after deformation.



$$MP = \frac{L}{2} \quad MP' = \frac{L-\Delta y}{2} = MP - \frac{\Delta y}{2} \quad MP'' = MP' - \frac{\Delta y'}{2}$$

Figure 1. Deflection at the middle point.

Consider Figure 1, when the column is compressed, the buckling phenomenon will occur. If the bottom end is fixed, and the top end can move a distance Δy in *y*-direction, then the displacement of the middle point also move downward of $\frac{\Delta y}{2}$. Thus, a millimeter ruler, as shown in Figure 2 will be used to move the dial-gage to new middle point after specimen was deformed.

2.2 Experimental Setup

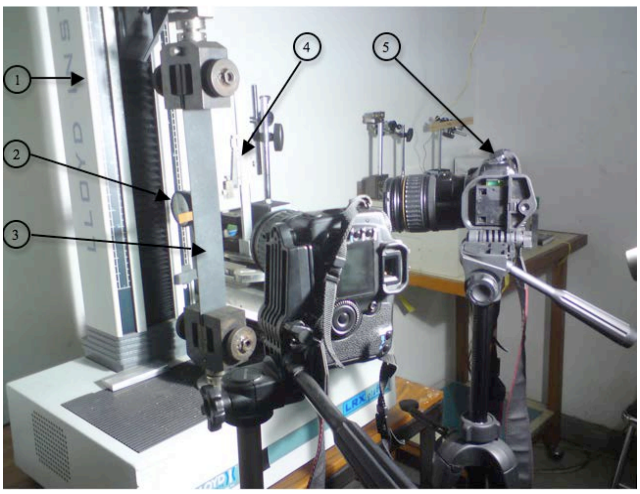


Figure 2. Experimental Setup
(1) universal testing machine, (2) dial-gage, (3) specimen, (4) millimeter ruler, (5) camera.

The buckling test is carried out on a universal testing machine. The dimension of the specimen is given in Figure 3a, one dial indicator is placed behind the specimen (see Figure 2) to measure the middle point displacement to compare with 3D-DIC software result. The limitation of the buckling test is set to 0.5 mm by the machine, the cameras record before and after deformation. The distance between camera and specimen is 600 m m, the distance between two cameras is 450 mm with the angle $\beta \approx 20^0$ and the focal length is 135 mm for each camera.

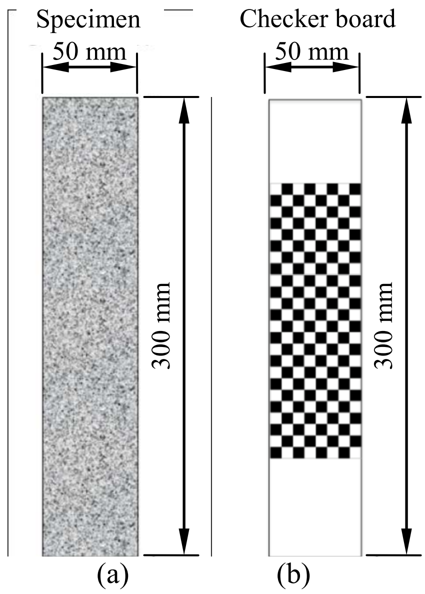


Figure 3. (a) Specimen and (b) Checker board.

2.3 Experimental Procedure

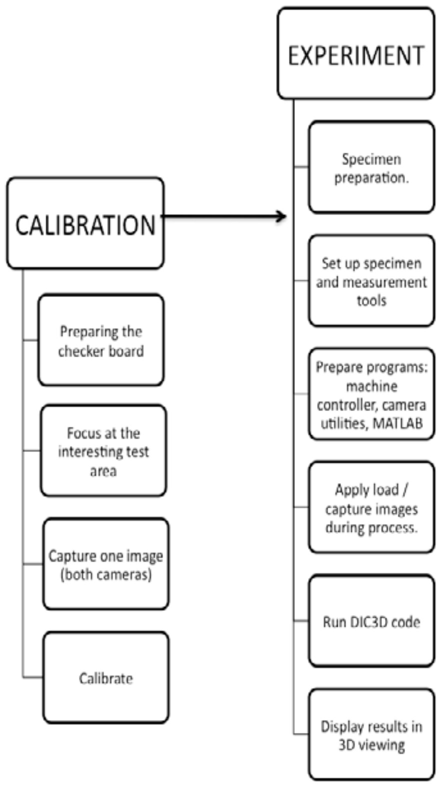


Figure 4. Experimental procedure.

Figure 4 shows the experimental procedure. In the present work, dimension of calibration board is the same as the dimension of the specimen (see Figure 3). Both checker board and specimen are made in 300 mm × 50 mm × 2mm in *x*, *y* and *z* direction. By using the same size for checker board and specimen, the different occur when changing checker board for calibration and specimen for testing can be decreased. After that, two pictures of checker board will be taken (one from left and one from right camera) when checker board is hold at the same position with specimen in the tension – compression machine. One point is marked on the checker board to ensure two cameras will "see" the same position together. The advantages of one calibration picture each cameras are faster and the image centre is kept as same for both cameras. First, after taking one picture, the calibration can be checked directly by using Bouguet's calibration toolbox. From that, the parameters of each cameras is collected before the real test and can adjust the cameras can be adjusted if necessary. Second, when rotating or changing position of checker board, the image center also change. Therefore, when calibrating, the center image coordinate point will not be matched. Thus, for one calibration image, the center image parameter can be ensured the same.

The calibration algorithm consists of capture one pair of images, then calibrate them by using Bouguet's calibration toolbox. Finally, a linear system of equations with 8 unknowns is solved to achieve the digital image coordinate of each point and the real location of each corresponding corner in the checkerboard. After calibrating, two types of camera parameters are recovered in pixel coordinates was shown in Table 1.

Table 1. Internal Parameters

	Left camera	Right camera
Focal length	[16209;16235]	[16030;15705]
Image center	[1167.5; 1751.5]	[1167.5; 1751.5]
Pixel skew	0	0
Lens distortion	[0.84 ; -60.64]	[0.56 ; -21.37]

The rotation matrix *om* and translation matrix *T* between the two camera coordinate systems are the external parameters which are obtained as follows:

$$om = [2.35e-04 \quad -5.77-01 \quad 2.49-02]$$
$$T = [476.48 \quad 6.69 \quad 111.59 \quad]^T$$

The specimen is made from acrylic with the dimension 300 mm × 50 mm × 2 mm. The required speckles for DIC were produced on surface of specimen using a white spray of matt black paint. After geometric calibration, the sensor of the camera is ready for the measurement of shape and 3D displacement field. The checker board at that time was replaced by specimen while the cameras was kept stable. The specimen was clamped on both ends and loaded in compression with a tension – compression machine. The experiment was displacement controlled with a displacement amplitude of 0.5 mm in *y* - direction.

3. Experimental Results and Discussion

After displacement load in y direction was applied to the specimen to make it buckle and recording its image, the image processing step of 3D-DIC system is done to analyze the 3D displacement field. To measure the buckling deformation, four images are loaded – two images of un-deformed and other two of deformed which are from left camera and the other from the right camera. Figure 5 showed the region of interest of the analysis for left and right images. In this position, the deflection of the column buckling in *z*-direction is maximum. After the region of interest is chosen in left image, the stereo matching is used to find the matched point in this process by searching the correspondence points on right image one by one. Then, the temporal-matching function also works by searching the correspondence points on deformed images one by one both on left and right side.

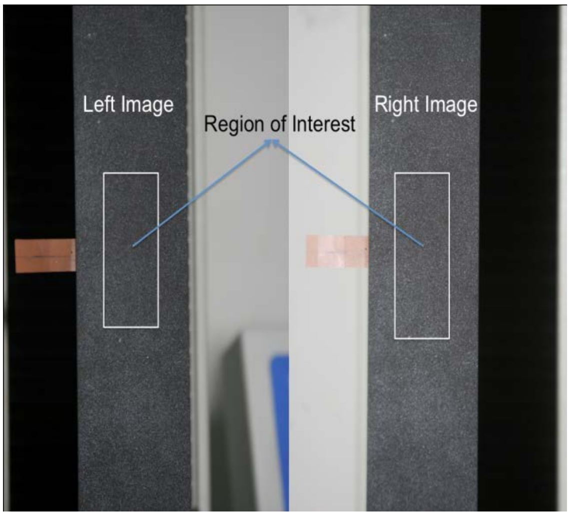


Figure 5. Region of Interest of Experimental Images.

The matched points from stereo and temporal matching process and the stereo-camera parameters are loaded beforehand to handle the function's duties. After loading the necessary data, the 3D shapes of specimen at two different stages are reconstructed. The 3D shape analysis is illustrated in Figure 6. The un-deformed model is on the left and the deformed one is on the right.

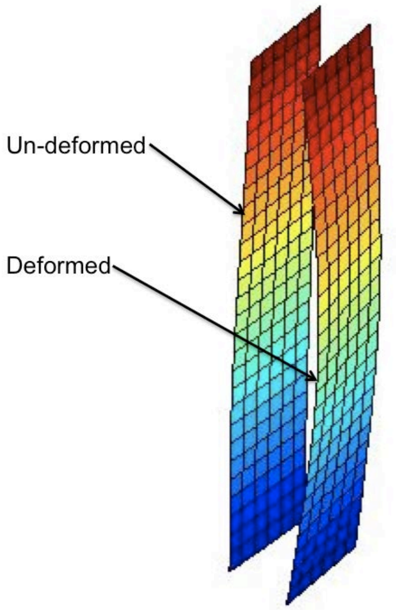


Figure 6. 3D surface reconstruction.

Figure 6 shows the result of surface reconstruction of the buckling experiment. When buckling happens, the buckling phenomenon can be seen clearly. From Figure 6, the un-deformed and deformed images are reconstructed, it can be seen that the 3D-DIC software can be display buckling shape.

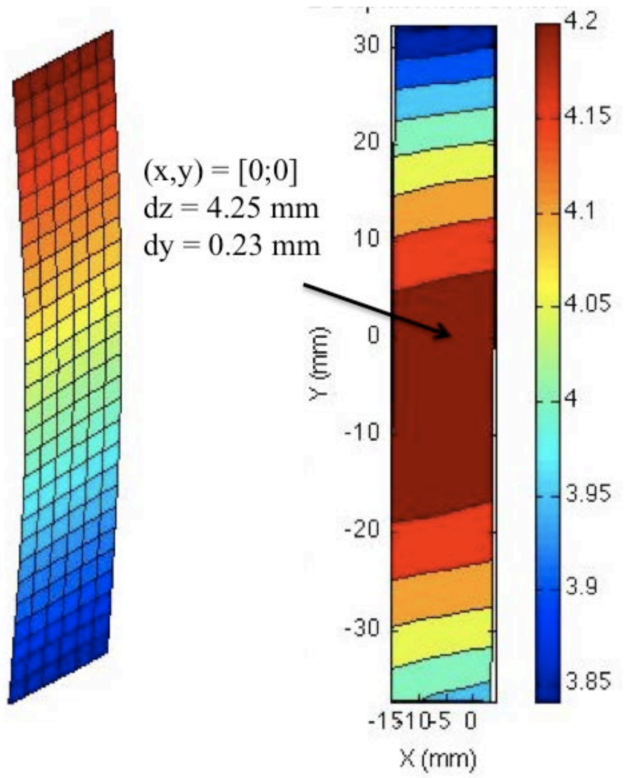


Figure 7. Displacement results: *z* - displacement

The result of column buckling which is calculated by using the 3D-DIC for a 0.5 mm displacement loading in *y* - direction was applied by the machine is shown in Figure 7. Following the deflection at the middle point, the middle point moved a distance is 0.25 mm in y direction. Therefore, the dial indicator was changed to new middle point position by using milimeter ruler to measure the z – displacement at middle point, and the dial indicator showed 4.44 mm. The results of displacement in z direction can be seen in Table 2.

Table 2. Ouf-of-plane Displacement Measurement Results

Displacement axis	Dial indicator [mm]	DIC [mm]	Relative Error [%]
z	4.44	4.25	4.3%

The *z* - displacement distribution in Figure 7 shows that the maximum deflection is in middle area. Refer to Table 2, it can be seen that the error of 3D-DIC method compares with other measurements is less than 5%. Due to that small of the error, the experimental setup and 3D-DIC software can be used to measure out-of-plane displacement with high accuracy. Moreover, the distribution of *z* - displacement are mostly symmetric, this is respect to buckling phenomenon.

4. Conclusion

In this present work, buckling experiment with 3D-DIC has been conducted. Experiment results show that the present experiment setup and the 3D-DIC software are able to reconstruct the un-deformed and deformed surface in buckling case. In addition, the present procedure is quite efficient to perform a 3D-DIC experiment. The accuracy of the out-of-plane displacement by using 3D-DIC is less than 5%.

Acknowledgement

The authors gratefully acknowledge financial support for this work from the AUN/SEED-Net (ASEAN University Network / S outheast Asia Engineering Education Development Network) and ITB Research grant.

References

1. I. Yamaguchi, “Speckle displacement and decorrelation in the diffraction and image fields for small object deformation”. Optica Acta 28(10), 1359-76, 1981.
2. W. H. Peters and W. F. Ranson, “Digital image techniques in experimental stress analysis”. Optical Engineering, 21:427–431, 1982.

3. M. A. Sutton, W. J. Wolters, W. H. Peters, W. F. Ranson, and S. R.McNeill, "Determination of displacements using an improved digital correlation method". Image and Vision Computing, 1(3):133–139, August 1983.
4. J. D. Helm, S. R. McNeil and M. A. Sutton, "Improved three dimensional image correlation for surface displacement measurement", *Opt. Eng.* 35(7), 1911-1920 (1996).
5. I. S. Putra, T. Dirgantara, L.R. Zuhal and A. Yani. On Development of Displacement Field Measurement Technique Based on Digital Image Correlation. Conference on Computational Mechanics & Numerical Analysis (2006).
6. I. S. Putra, T. Dirgantara, L.R. Zuhal and N. T. Nam, "Three-Dimensional Digital Image Correlation without Stereo-Matching", 2007.
7. P.V. Tran, I.S. Putra, T. Dirgantara and S. Mihradi, "An experimental method for evaluating the accuracy of camera calibration toolbox developed by Bouguet", *The 4th AUN/SEED-Net RC MeAe*, 2012.
8. T. Dirgantara, A. S. Jaya, I.S. Putra, "Performance evaluation of the correlation and smoothing methods of the Digital Image Correlation and Its application to the opening specimens", *4th International Conference on Experimental Mechanics*, Proceeding SPIE, Vol. 7522, 75224J, Editor: C. Quan, K. Quian, Anand K. Asundi, F. S. Chau (2010).
9. L. Iryany, M. R. Simbolan, T. Dirgantara, S. Mihradi and I.S. Putra, "Effect of DIC parameters to Stress Intensity Factor for Mixed Mode in-plane Fracture Mechanics problem", Proceeding of the International Conference on E xperimental Mechanics (ICEM 2010), November 29 – December 1 2010, Kuala Lumpur, Malaysia.
10. Zheng-Zong Tang, Jin Liang, Zheng-Zong Xiao, Cheng Guo and Hao Hu, "Three-dimensional digital image correlation system for deformation measurement in experimental mechanics", *Optical Engineering*, 2010.