STRAIN MEASUREMENT IN A SPECIMEN SUBJECTED TO OUT-OF-PLANE MOVEMENT:

Using an Open-Source Digital Image Correlation-Based Tool

Student Authors

Thomas Pfauth earned a BS degree in mechanical engineering with a minor in electrical engineering in May 2017. Areas of interest include mechanics of materials, fluid dynamics, and ballistics.

Joel Poling earned a BS degree in mechanical engineering with a minor in electrical engineering in May 2017. He performed overseas research at the Technical University of Denmark and had done other research projects over the past few semesters in the subject of photogrammetry. During this time, he honed his mathematics and engineering skills while tutoring both subjects at Purdue University Northwest–Westville. Areas of interest include mechanics of materials, vibrational analysis, and photogrammetry.

Mentor

Niranjana Desai did his PhD from the University of Louisville and is an Assistant Professor in the department of Civil and Mechanical Engineering at Purdue University Northwest. His areas of interest include structural health monitoring and nonlinear dynamic analysis.

Abstract

Structural health monitoring (SHM) helps engineers maintain structures, enhance their safety, and operate them cost-effectively. Digital image correlation (DIC) techniques applied to SHM are noncontact techniques; they are also fast, accurate, and simple to implement. The goal of this investigation was to determine the smallest strain accurately measurable by a standard open-source DIC-based tool, in a specimen subjected to out-of-plane movement (toward or away from sensor). The investigation builds upon an initial study which determined the smallest accurately measurable strains using the same DIC-based tool in a specimen that was not subjected to controlled out-of-plane specimen movement. This initial study was motivated by initially undetected damage at low strains in connections of the Storstrøm Bridge in Denmark. Timely identification of this damage would have prevented its spread, resulting in lower repair costs. It was observed in this initial study that the minute out-of-plane specimen movements that inadvertently occurred even in the controlled conditions of the laboratory created noise in the DIC-based strain measurements. Hence, before implementing this technique in a real-world structure, it is desirable to determine the bounds of out-of-plane displacement of the system within which it is practical to use this technique to measure strain. A cantilevered plate specimen was transversely loaded in the laboratory, and the longitudinal strain was measured at a selected location at different values of out-of-plane displacement of the specimen toward the sensor, using the open-source DIC-based tool. DIC-based strains were compared against those measured by conventional strain gauges. The smallest strains accurately measurable using DIC techniques, over a range of specimen out-of-plane displacement amplitudes, were determined.

Pfauth, T., & Poling, J. (2017). Strain measurement using the digital image correlation technique: Out-of-plane specimen movement. *Journal of Purdue Undergraduate Research*, 7, 41–49. <https://doi.org/10.5703/1288284316396>

Keywords

digital image correlation, structural health monitoring, open source, ARAMIS, strain, improved DIC, out-of-plane displacement, infinitesimal strain

INTRODUCTION

Structural health monitoring (SHM) helps civil engineers maintain infrastructure and operate it safely and cost-effectively by identifying structural damage or inadequate performance. The conventional SHM process involves employing global techniques to determine a structure's condition by studying changes in its dynamic properties by periodically sampling the dynamic response or deterioration obtained using an array of sensors. Subsequently, damage-sensitive features are extracted from these measurements and analyzed using statistical methods, thereby assessing the condition of the structure. Structural health can also be monitored at a local level using many techniques, including the acoustic emission technique, the X-ray radiographic technique, or the interferometry technique. The main drawbacks when using these techniques are cost, labor, and they involve making contact with the structure by placing sensors (Kaphle, Tan, & Thambiratnam, 2009; Ahlborn et al., 2010; Gentile & Bernardini, 2010).

Localized damage to stiff steel bridge connections was observed by Desai (2016), as well as Desai, Georgakis, and Fischer (2016), which originated behind the gusset plates. This region of the connections are hidden from sight, causing the damage to go unnoticed and allowing it to propagate (strains in stiff systems are small in magnitude). Early detection of this damage would have prevented its propagation and would have reduced the repair costs. This example shows that local structural damage may remain undetected using conventional SHM techniques that analyze changes in the global structural response parameters.

Consequently, an initial investigation was conducted by Desai (2016), as well as Desai, Georgakis, and Fischer (2016), which was focused on applying the state-of-the-art digital image correlation (DIC) technique to monitor structural health at a local level in order to determine the minimum resolution of this technique in making strain measurements. The DIC approach is a noncontact approach that is inexpensive and easy to implement, which circumvents the aforementioned drawbacks of other SHM techniques. By determining the lowest strains that can be accurately measured, it would help to ascertain whether damage in stiff systems that develop low strains could be detected before propagation since damage is related to the strains that develop within a structure.

Based upon previous work, it was concluded that the accuracy of the DIC technique is sensitive to both the relative orientation of the specimen and the sensor

(digital camera), as well as vibrations in the plane of the specimen created due to external movements (Desai, 2016; Desai, Georgakis, & Fischer, 2016). In the former case, movement of the specimen either toward or away from the sensor (out-of-plane specimen movement) can create a loss of camera focus, leading to a poor image quality. In the latter case, the frequency of the specimen vibration within its own plane (in-plane vibration) could affect the correlation of the digital images, directly impacting the strain measurements.

Consequently, a follow-up investigation was conducted by Poling and Desai (2017) into the effect of out-of-plane specimen motion on the accuracy of the strain measurements using a state-of-the-art, licensed, 2-D DIC-based tool, ARAMIS. The current investigation expands upon this investigation. Using the same 2-D images obtained by Poling and Desai (2017) in their initial study, the accuracy of an open-source DIC-based mathematical program for MATLAB, “Improved DIC,” will be determined. This paper describes the approach and results acquired from the Improved DIC software.

METHODOLOGY

Specimen

The specimen consisted of three 10 mm plates. The main beam was a high-density polyethylene (HDPE) plate measuring 850 mm long by 150 mm wide, which was sandwiched between two secondary steel plates and secured by nine high resistance bolts. The secondary plates were welded to a larger vertical plate, which was then mounted to a support that held the entire specimen in place while the tests were performed. HDPE was used for the main plate due to its flexibility, since the experiment involved subjecting the main plate to higher strains than those that a stiff steel plate would develop. The experiment involved measuring higher strains than those measured in previous work by Desai (2016) because the out-of-plane specimen displacement would test the bounds of the DIC system and result in strains as small as those measured in Desai’s initial study not being accurately measurable.

To prevent the flexible HDPE main beam from buckling laterally, it was braced above the main structure, as shown in Figure 1. Lateral displacement, relative to the camera, was applied to the beam using a threaded rod. Turning the threaded rod clockwise, the rod pushed directly onto the beam, creating an out-of-plane displacement. Displacements were accurate to within ± 0.01 mm. The displacement was measured by placing a digital caliper between the

beam and the structure that supported the threaded rod system, as shown in Figure 2 and Figure 3. When no displacement was applied, the caliper was zeroed so it only measured the lateral displacement of the beam relative to the stationary structure.

Figure 1. The specimen with the support to prevent buckling with the apparatus to apply the displacement.

Figure 2. The caliper to measure the displacements.

Figure 3. The threaded rod that applied the displacements.

Loading of the Specimen

A loading apparatus was suspended from the beam’s free end using a linkage comprised of a 100 kilonewtons (kN) load cell, a clevis, and the platform on which free weights were placed (see Figure 4).

Load magnitudes were selected to create strains in the specimen varying from higher strains that were easily measurable, to small strains that were hard to measure, so as to determine the accuracy in measuring strains of the DIC technique across a range of strains. Strain measurements were made for each load value with varying of out-of-plane displacements to understand its effect on the accuracy of the DIC strain measurements.

Figure 4. The loading apparatus. From top down: specimen, linkage, 100 kN load cell, clevis, platform.

Calibration of the Load Cell

A 100 kN load cell was used to accurately measure the load that was applied to the free end of the beam. The load cell rating had to be greater than the maximum load being applied on the specimen during the experiment. This allowed for the experiment to be carried out without damaging the load cell. The load cell output measured the load in millivolts (mV), so it had to be calibrated to convert the mV reading into units of force. Since the test loads ranged from 0 kg to 95 kg, the load cell was calibrated from 0 kg to 125 kg. The calibration was repeated four times and averaged to obtain a representative linear equation that converted the mV to kilonewtons. Figure 5 shows the graph of all four calibrations and the average calibration. The representative linear equation is presented as:

$$y = 5.6819 x + 39.9689 \quad (1)$$

Figure 5. Load cell calibration.

In Equation 1, x is the voltage and y is the load. The equation generally could be used for any digital acquisition (DAQ) system by modifying the equation's slope by the excitation voltage of the DAQ system being used for the calibration, resulting in the Equation 2.

$$y = 28.7349 x + 39.9689 \quad (2)$$

The load value is the same as before, but the new voltage is no longer just the voltage output from the load cell, but the output voltage divided by the excitation voltage of the DAQ system being used.

Strain Gauges

The strain gauge was placed near the center of the beam to balance the effects of the displacement and weight. On the constrained end, there would be a great deal of strain and miniscule displacement; on the free end, there would be a great deal of vertical displacement but little strain. The strain gauge needed to be calibrated, because its output was in mV, not the standard unit (ϵ) (length/length). The strain gauges that were provided by the laboratory were Vishay Micro-Measurements and SR-4 General Purpose Strain Gauges, which is a traditional electrical resistance strain gauge with a gauge factor (k) of 2.075, in a Wheatstone bridge configuration. The Equation 3 was used to relate the strain values to the mV output recorded by the DAQ.

$$\epsilon = (4 * \text{output voltage}) / (k * \text{excitation voltage}) \quad (3)$$

Strain Measurement Using the Open-Source DIC-Based Tool Improved DIC

As stated previously, the strain measurement was performed using the open-source DIC-based tool, Improved DIC, using a 2-D measuring technique. This is described in more detail below.

Improved DIC uses digital images of the area of interest (location of strain gauge) on the specimen,

as it was loaded, as the raw data. A Nikon D800 digital camera (resolution = 7360 x 4912 pixels), supported by a tripod stand, was used to take the pictures. The digital images were processed by the Improved DIC algorithms to compute the strain at the location of interest. For the algorithms to effectively track and measure the area of interest, a speckled paint pattern was applied to the beam, as shown in Figure 6. The lighting of the specimen was a crucial parameter in getting accurate results. The specimen was clearly, uniformly, and brightly lit, without being over-lit. An external lighting source was used (see Figure 7).

Figure 6. Final speckled spray pattern that was used for all tests.

Figure 7. The Nikon D800 camera is placed 100 mm from the specimen with a 60 mm lens. The light is also shown illuminating the specimen.

The Nikon D800 was placed with the camera lens approximately 100 mm from the specimen based on previous investigations (Desai, 2016; Desai, Georgakis, & Fischer, 2016; see Figure 7). This was the optimal distance, with the area of interest covering the strain gauge, within the camera lens's field of view for all the load levels considered. A 60 mm focal length lens was used for this experiment since it yielded the best results for the level of strain being measured in this experiment (Desai, 2016; Desai, Georgakis, & Fischer, 2016).

The following describes how the lighting, camera orientation, and timing were set up and affected the testing. Initially, it was attempted to focus the camera manually for a few tests. Following this, automatic focusing was also tested and was found to be just as good, if not better. Hence, the automatic focusing feature on the camera was used. The position and orientation of the camera was another crucial parameter. For 2-D applications, in order to obtain accurate results, it was vital for the face of the camera lens to be perfectly parallel to the specimen face. A timer was used on the camera that was programmed to take pictures every 20 seconds. This time delay allowed the specimen vibrations to cease prior to the capture of the subsequent image. The DAQ system was programmed to collect data from the load cell and strain gauge at the same time the camera captured an image. The specimen was loaded during the time between the camera captured successive images.

The beam was subjected to out-of-plane displacements of 0.0 mm (neutral position), 0.5 mm, 1.0 mm, 2.0 mm, and 3.0 mm. At each displacement, weights were incrementally added to the platform in the following order: no weight, 10 kg, 14 kg, 25 kg, 35 kg, 45 kg, 55 kg, 65 kg, 75 kg, 85 kg, and 95 kg. For all tests involving nonzero values of out-of-plane displacement, an initial picture needed to be taken in the neutral position. This was done because the software needs a reference image to account for and see the out-of-plane displacement. When applying the weights, it was crucial to apply them very steadily and carefully, thereby minimizing specimen vibrations. Vibrations in the specimen resulted in inaccurate strain computations. Tests had to be repeated several times in order to master and refine the test procedure and ensure that it was applied carefully and effectively.

The processing of the images by Improved DIC occurred in three stages: Stage 1, Stage 2, and Stage 3. Stage 1 took the least amount of time. In Stage 1, the images were set up for use in MATLAB. Once the images were set up for use, the initial correlation needed to be run. This initial correlation, or reduced correlation, is a correlation of reduced images. Improved DIC automatically reduces the images by a factor described by the user. The reduced images create a broad baseline of displacements for use in Stage 2. This allows for Stage 2 to be more accurate, as well as being able to account for large displacements. When selecting the parameters of Stage 1, multiple iterations had to be completed. The reduced correlations must be viewed by the user, with different parameters in order to decide which ones are best for each set of data. Once the parameters were determined, Stage 2 was started.

Stage 2 took the longest amount of time to run. Instead of correlating reduced images, Stage 2 correlates the entire image. This creates a dense correlation, which takes time but is more accurate than Stage 1. At the end of Stage 2, only the displacements between the pixels have been calculated. As in Stage 1, the full correlation needs to be viewed so the best parameters can be chosen by the user.

Stage 3 was the final stage in the open-source, Improved DIC. Here, the full correlation data, which are the displacements of the pixels, were converted into strains. All possible strains were calculated, and two different strain theories were used to find the strains. One theory is the finite strain theory. This theory is used when the specimen has large deformations in rotation and in strains. In this paper, the finite strain theory was not used for the final strains of interest. The second theory is the infinitesimal strain theory. This theory uses assumptions that certain properties of the specimen are assumed to be unchanging and have very small deformations. The infinitesimal strain theory is used in this investigation due to the small deformations and strains.

Once Stage 3 was completed, the data was pulled from Improved DIC and placed into Microsoft Excel to further analyze the data. A range of pixels was pulled from the images to denote the area of the strain gauge. This range was used to find an average for all the data in this range which was used to find the strain across the strain gauge. These averaged strain values were then used for the data and results section of this paper.

RESULTS

Figures 8 through 17 show comparisons between the strains measured using Improved DIC and those measured by the conventional strain gauge. The figures show that, as the load increases, Improved DIC provides increasingly accurate results. Also, as the specimen out-of-plane displacement increases, the measurements decrease in accuracy. Measurements of strains ranging between approximately 0.025%–0.091% are less accurate, whereas measurements of strains of magnitude greater than approximately 0.091% follow a consistent and relatively more accurate trend. To help show these trends, the R-squared (coefficient of determination) values were computed for each of the plots. These values served as a measure of the closeness of the DIC-based strains to the straight-line model obtained via the strain gauge measurements. The R-squared values obtained

are shown in Table 1 and plotted in Figure 18. Figure 18 provides information describing the level of accuracy with which strain can be measured at different values of out-of-plane displacement relative to the camera. An R-squared value of 100% implies that the strain measurement made by Improved DIC was identical to that made by the strain gauge.

■ **Figure 8.** 10 kg Test: Load vs Strain.

■ **Figure 9.** 14 kg Test: Load vs Strain.

■ **Figure 10.** 25 kg Test: Load vs Strain.

■ **Figure 11.** 35 kg Test: Load vs Strain.

Figure 12. 45 kg Test: Load vs Strain.

Figure 13. 55 kg Test: Load vs Strain.

Figure 14. 65 kg Test: Load vs Strain.

Figure 15. 75 kg Test: Load vs Strain.

Figure 16. 85 kg Test: Load vs Strain.

Figure 17. 95 kg Test: Load vs Strain.

Figure 18. R-Squared Values vs Strain Values.

Strain (%)	Out-of-Plane Displacement (mm)				
	0	0.5	1	2	3
0.024	99.46%	70.11%	-2.56%	-3.28%	98.74%
0.035	99.07%	81.99%	22.79%	7.56%	94.50%
0.063	98.24%	86.54%	45.79%	45.70%	95.55%
0.091	96.78%	83.85%	53.66%	64.53%	80.09%
0.117	99.54%	87.63%	86.50%	74.80%	93.50%
0.146	90.94%	92.26%	83.97%	83.09%	71.39%
0.172	97.65%	90.01%	85.32%	91.79%	64.28%
0.201	98.98%	97.51%	92.17%	84.67%	64.82%
0.229	96.20%	98.53%	88.16%	84.27%	68.35%
0.260	91.03%	97.24%	90.40%	90.31%	67.88%

Table 1. R-Squared Values.

There were some outliers from the tests, most of which can be credited with environmental errors. The most notably shown outliers were in the 3.0 mm displacement test. These tests contradicted the general pattern. For the 3.0 mm displacement, it became less accurate as the load increased and more accurate the lighter the load, as shown in Figure 18.

Table 2 shows the peak strain measurements obtained from Improved DIC and the strain gauges for each displacement. Table 3 shows the percentage change between the peak strain values while using the strain gauge values as the reference value. From viewing

Table 3, it shows where these outliers lay more effectively and also reinforces the notion that the 3.0 mm displacement tests are outliers.

CONCLUSION

After compiling, correlating, and analyzing the images of a cantilever beam as it was progressively loaded over a range of out-of-plane displacements, it was observed that Improved DIC was capable of determining specimen strain as the camera sensor lost focus due to specimen out-of-plane movement. Predictably, Improved DIC was most accurate when there was no out-of-plane displacement on the beam.

Load (kg)	Out-of-Plane Displacement (mm)									
	0		0.5		1		2		3	
	Percent Strain									
	DIC	SG	DIC	SG	DIC	SG	DIC	SG	DIC	SG
10	0.0272	0.0260	0.0318	0.0251	0.0519	0.0246	0.0487	0.0235	0.0211	0.0224
14	0.0369	0.0365	0.0265	0.0360	0.0479	0.0345	0.0617	0.0338	0.0272	0.0324
25	0.0674	0.0651	0.0521	0.0634	0.0443	0.0639	0.0909	0.0635	0.0666	0.0607
35	0.0868	0.0918	0.0781	0.0918	0.0547	0.0893	0.1110	0.0887	0.0587	0.0915
45	0.1197	0.1201	0.1147	0.1158	0.1045	0.1183	0.0798	0.1158	0.0938	0.1157
55	0.1619	0.1476	0.1438	0.1433	0.1336	0.1488	0.1393	0.1410	0.0886	0.1490
65	0.1813	0.1752	0.1674	0.1720	0.1410	0.1720	0.1430	0.1694	0.0977	0.1727
75	0.2124	0.2031	0.2101	0.2101	0.1829	0.2001	0.1432	0.1987	0.1108	0.2030
85	0.2557	0.2305	0.2398	0.2398	0.1918	0.2281	0.1639	0.2262	0.1399	0.2297
95	0.2025	0.2671	0.2864	0.2864	0.2184	0.2561	0.2025	0.2592	0.1542	0.2613

■ **Table 2.** Peak strains measured by Improved DIC and strain gauge.

Load(kg)	Out-of-Plane Displacement (mm)				
	0	0.5	1	2	3
10	4.81%	26.77%	110.98%	107.04%	-5.95%
14	0.88%	-26.58%	38.97%	82.44%	-16.09%
25	3.52%	-17.75%	-30.57%	43.04%	9.77%
35	-5.40%	-14.95%	-38.70%	25.05%	-35.83%
45	-0.38%	-0.89%	-11.65%	-31.09%	-18.95%
55	9.65%	0.36%	-10.23%	-1.18%	-40.50%
65	3.47%	-2.64%	-18.02%	-15.59%	-43.43%
75	4.58%	0.00%	-8.61%	-27.94%	-45.40%
85	10.94%	0.00%	-15.93%	-27.55%	-39.11%
95	-24.18%	0.00%	-14.72%	-21.88%	-40.98%

■ **Table 3.** Percentage change between peak strain measured by Improved DIC and strain gauge.

Strains greater than approximately 0.12% could be measured accurately. Accuracy was lost when the out-of-plane displacement increased to 3.0 mm or the measured strain was below 0.12%.

In comparison with ARAMIS used by Poling and Desai (2017) in their previous work, Improved DIC is a viable option. However, there are drawbacks to the open-source option. A balance between cost, time, and accuracy needs to be further analyzed. Improved DIC is a free program that provided accurate results, making it a very worthy option for those who do not have access to expensive licensed software. However, the major disadvantage to Improved DIC is that it takes a lot of time and computing power to properly analyze the data.

While decreased cost and labor are major benefits of DIC techniques, they have their drawbacks as well. Vibrations, both in the environment and in the specimen, result in noise in the DIC readings. Vibrations can be minimized under the controlled conditions of a laboratory, but not in a real-world application. Although this study showed that Improved DIC could be used to measure strains as the camera sensor lost focus due to specimen out-of-plane displacement, more research is needed to develop and further understand the processes and algorithms that are used for DIC in order to reduce the occurrence of noise in the measurements.

ACKNOWLEDGMENTS

The authors would like to thank Purdue University Northwest, Westville Campus for their support and

for the use of their computer laboratories. The authors would also like to the staff and professors at the Technical University of Denmark for the use of their laboratory, their equipment, and their guidance.

REFERENCES

- Ahlborn, T. M., Shuchman, R., Sutter, L. L., Brooks, C. N., Harris, D. K., Burns, J. W., . . . Oats, R. C. (2010). *The state-of-the-practice of modern structural health monitoring for bridges: A comprehensive review*. Retrieved from Michigan Tech Transportation Institute Retrieved from [http://www.mtri.org/bridgecondition/doc/State-of-PracticeSHMforBridges\(July2010\).pdf](http://www.mtri.org/bridgecondition/doc/State-of-PracticeSHMforBridges(July2010).pdf)
- Desai, N. (2016). Proceedings of SPIE (9805): *Small-strain measurement in bridge connections using the digital image correlation (DIC) technique*. Health Monitoring of Structural and Biological Systems. <https://dx.doi.org/10.1117/12.2234454>
- Desai, N., Georgakis, C., & Fischer, G. (2016). Proceedings from IAJC-ISAM International Conference: *A comparison between the minimum resolutions of two digital image correlation based tools in making strain measurements*. Retrieved from <http://cd16.iajc.org/mfg/>
- Gentile, C., & Bernardini, G. (2010). An interferometric radar for non-contact measurement of deflections on civil engineering structures: Laboratory and full-scale tests. *Structure and Infrastructure Engineering*, 6(5), 521–534. <https://dx.doi.org/10.1080/15732470903068557>
- Kaphle, M. R., Tan, A. C. C., & Thambiratnam, D. (2009, 22–25 November). Proceedings from Thirteenth Asia Pacific Vibration Conference: *Structural health monitoring of bridges using acoustic emission technology and signal processing techniques*. Retrieved from <http://eprints.qut.edu.au/29031>
- Poling, J., Desai, N. (2017). Proceedings of SPIE (10170): *Effect of out-of-plane specimen movement on the accuracy of the smallest specimen strain measurable using the digital image correlation technique*. Health Monitoring of Structural and Biological Systems. <https://dx.doi.org/10.1117/12.2258496>