Structural Health Monitoring of Bridges using Digital Image Correlation

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ABSTRACT

Due to the aging global civil infrastructure (e.g. bridges), there is a critical need for monitoring and assessing structural integrity of large scale structures. According to the ASCE, in 2008, the average bridge in the U.S.A. was 43 years old and 161,892 bridges were structurally deficient or obsolete. Currently, bridge health is assessed primarily using qualitative visual inspection, which is not always reliable because some damage is difficult to detect, quantify visually, or is subject to human interpretation. Traditional sensors such as strain gages, and displacement sensors, have been recently used to monitor bridges. These sensors only measure at discrete points or along a line, making it difficult to detect damage that is not in the immediate vicinity of the sensor or is difficult to interpret. To address these issues, this paper investigates the use of three-dimensional (3D) digital image correlation (DIC) as a sensing approach for improved bridge structural health monitoring. 3D DIC is a non-contact, full field, optical measuring technique that uses digital cameras to measure surface geometry, displacement, and strain. It is proposed that DIC can be used for monitoring by imaging a bridge periodically and computing strain and displacement from images recorded at different dates or operating conditions. In this paper, DIC is shown to locate non-visible cracks in concrete, quantify spalling, and measure bridge deformation. These techniques are first demonstrated in the laboratory. Field measurements are also made on three full-scale bridges. This paper discusses challenges and solutions to implementing DIC on large structures in the field. The results reveal that DIC is an effective approach to monitor the integrity of large scale civil infrastructure.

Keywords: Digital Image Correlation, Bridge, Structural Health Monitoring, Photogrammetry

1. INTRODUCTION

As the civil infrastructure (e.g. bridges) of the global highway system ages, there exists a need to perform structural health monitoring and inspection over large areas, on a wide scale that is robust, inexpensive, and easy to interpret. Bridges are usually built to last approximately 50 years [1]. According to the American Society of Civil Engineers (ASCE), in 2008, the average bridge in America was 43 years old. This means thousands of bridges are nearing or have exceeded their design life. In the next fifteen years, nearly half of America's bridges will exceed the 50-year design life [2]. As a result, in 2008, 161,892 bridges were classified as being structurally deficient or obsolete [1].

Thorough inspection of bridges is paramount to preventing bridge failures and ensuring public safety. Currently, bridge health is assessed primarily using visual inspection. Even though visual inspection is performed by trained personnel, there can be significant variability in the ratings assigned by each inspector [3]. Also, some types of damage are difficult to detect or quantify using visual inspection. For example, small cracks are difficult to find, concrete spalling is easily identified but difficult to quantify, bulging or sagging of girders can be difficult to recognize or measure, and damage to internal components such as rebar and prestressed tendons is very difficult to diagnose.

As a result, more advanced non-destructive test methods have been implemented to help assess bridge health. Instruments such as strain gages, accelerometers, fiber optic sensors, and displacement transducers are becoming more common in structural health monitoring [4, 5]. These types of sensors generally possess several drawbacks such as: requiring external power, cabling/antenna for data transmission, high data acquisition channel counts, and they only measure at discrete points or along a line. These sensors can be used effectively to continuously monitor for

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abnormalities that indicate damage, but the type and severity of the damage can be difficult to identify from discrete point measurements. Also, if the damage is outside the proximity of the sensor, the damage may be difficult to detect.

Three-dimensional digital image correlation (3D DIC) is an evolving measurement technique that has only very recently been proposed to enhance bridge inspection. 3D DIC is a full field, non contact optical, measuring technique that uses two digital cameras to measure surface geometry, displacement, and strain. All the DIC analysis in this work was performed using GOM^{TM}'s software ARAMIS. To perform these measurements, a stochastic pattern is applied to the surface of interest and a series of photographs (stages) are taken by both cameras as the surface deforms. Strain is computed by comparing the stochastic pattern of the deformed surface to the initial reference measurement of the pattern. Three-dimensional information is extracted using the principles of stereophotogrammetry. DIC can be used for structural health monitoring by comparing current surface geometry, displacement, and strain measurements to baseline measurements made days, months, or even years prior. Monitoring these parameters over time will allow inspectors to quantify displacement of structural members, crack growth, strain, and spalling.

DIC has been used previously to analyze bridges and concrete test objects. Several researchers have conducted tests on laboratory scale concrete and steel beams to study cracking behavior [6-12] and displacement [13-18] during bending tests. Most researchers located cracks using the displacement or strain fields. In some cases, the cracks were not visible to the human eye but were detected by DIC. The prior work suggests that DIC can provide more information than a visual inspection. The results of these papers confirm DIC is an accurate method of measuring full field displacement, strain, and locating cracks.

A very limited number of papers have been published involving field tests of bridges using point tracking and DIC. Discrete and full-field displacement measurements have been performed. For discrete displacement measurements/point tracking, points of interest were marked with photogrammetric targets and the target's displacement was recorded while loading the bridge [18-23]. Full field displacement was measured by tracking the natural surface pattern of concrete [24] or an applied pattern [21, 25]. In general, it was concluded the DIC system accuracy is comparable to existing displacement measurement techniques and DIC is an easier way to measure displacement of multiple points at once. Previous research has measured displacement over the course of several hours; where in this work, displacements are monitored over several months.

Researchers have also measured localized full field strain and displacements on bridges with 2D DIC. Sas *et al*. [26] recorded the strain on a concrete girder during a full scale bridge failure test and Küntz *et al*. [27] measured the displacement field on a cracked concrete girder during a bridge loading test. In both cases DIC was able to detect a change in loading condition and locate cracks. Sas *et al*. noted the DIC provides a much more comprehensive picture of the strain distribution as compared to a traditional strain gage and explains that based on the strain distribution, traditional strain gage measurements could indicate strains higher or lower than the true global strain. Both papers demonstrate the advantage of inspecting concrete bridges with DIC.

The prior DIC bridge tests recorded strain and displacement changes in response to an applied load over a relatively short time period (several hours) and primarily use 2D DIC. To the author's knowledge, this is the first research effort to explore using 3D DIC to monitor strain and displacement of bridges due to damage or degradation over a time period of several months. Also for the first time concrete spalling is monitored by comparing surface geometries measured with 3D DIC using a projected pattern. These damage detection capabilities are first validated on small scale laboratory tests and then utilized on real bridges in the field. The results of these experiments are discussed as well as some of the limitations and challenges of using DIC for bridge monitoring.

2. LABORATORY TESTS OF DIC DAMAGE DETECTION CAPABILITIES

Initial testing of the DIC damage detection capabilities were conducted in a laboratory setting. Specifically, the ability of DIC to measure strain and displacement, quantify spalling, and locate cracks was investigated.

<u>Laboratory Reinforced Concrete Beam Tests:</u>

Bending tests on several reinforced concrete beams were used to evaluate the strain and displacement measurement and crack detection capabilities of DIC. The dimensions of the concrete beam are shown in Figure 2.1.

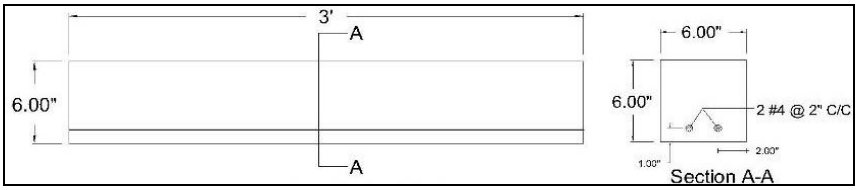


Figure 2.1 Dimensions of reinforced concrete beam with two embedded rebar rods

Three tests were performed on three separate beams having identical geometry and composition. Test #1 was a three point bend test and Tests #2 and #3 were four point bend tests. In the four point bend tests, the loading locations were 30 centimeters apart. In all tests, the ends of the beam were simply supported. One side of each beam was patterned using black and white spray paint for the DIC measurements. The beams were incrementally loaded until failure (details of the loading schedule are not included for brevity). Figure 2.2 shows axial strain contour plots of the beams in each test at a percentage of failure load applied.

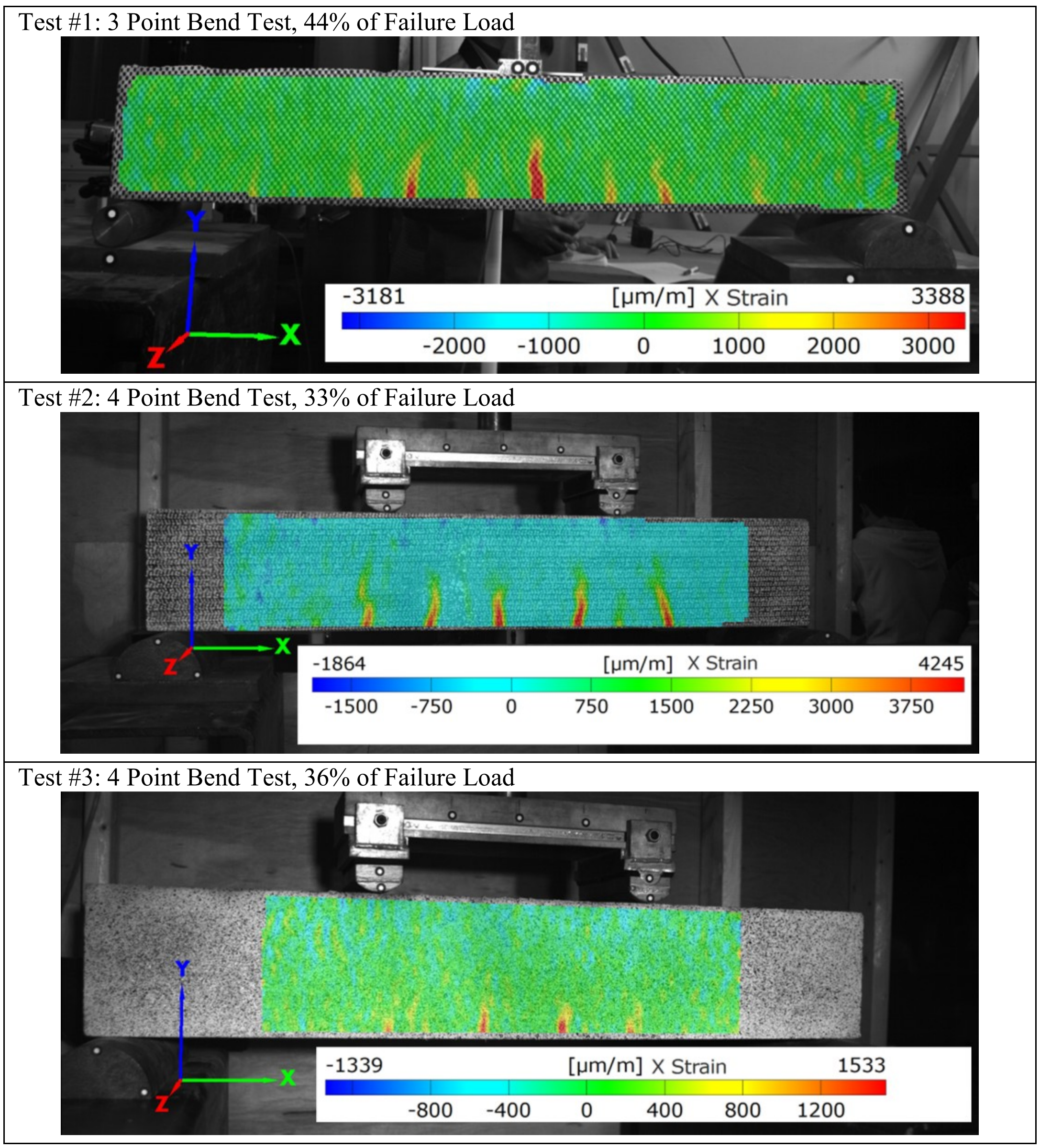


Figure 2.2 Reinforced concrete beam strain contours at different mechanical loading levels prior to failure

The beam bending test results (see Figure 2.2) show that it is possible to detect non-visible cracks based on the strain amplification well before a person could identify that there were changes in the structure. It should be noted these cracks were easily detected in all beams using DIC at 33 to 44% of the failure load. The beams were visually examined, at these loading levels, with a magnifying glass and the cracks were not visible to the human eye. When processing DIC data to detect cracks, the DIC strain gage length should be short to yield better spatial resolution.

The crack width can be estimated by plotting the axial displacement (X axis) along the bottom edge of the beam as a function of the position along the length of the beam. The data for this plot is measured by creating a section line near the bottom edge (dashed red line in Figure 2.3). The discontinuities/jumps in the X displacement are due to crack openings. The magnitude of the discontinuity is an estimation of the crack width. Figure 2.3 shows how a crack width is estimated using the results of Beam Test #1 (44% of the failure load) as an example.

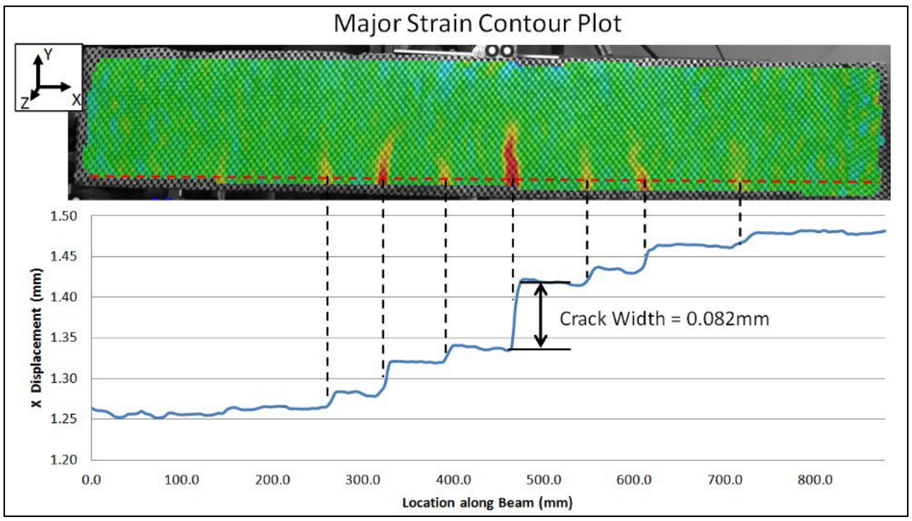


Figure 2.3 Crack width estimation of the 3 point bend test beam using the horizontal (X-axis) displacement

During the second beam test, the DIC strain was compared to a fiber-bragg grating optical strain gage. The optical strain gage was oriented horizontally (along the X-axis) and located at the center of the bottom surface at mid span. The optical strain gage length was approximately 20.6mm. The DIC strain data used in the comparison was an average of the axial strain of an area approximately 2cm high and 3cm wide, on the side of the beam, near the bottom edge at mid span. The sensor readings are not collocated but should record essentially the same strain because they are approximately the same distance from the beam's neutral axis and experience the same bending moment. It should also be noted, a crack in the beam developed at mid span and both sensors were measuring strain across the crack; therefore results in strain levels are much higher than normally observed in concrete. The strains over time are compared in Figure 2.4 for an increasing, then oscillating (4 cycles), and increasing load.

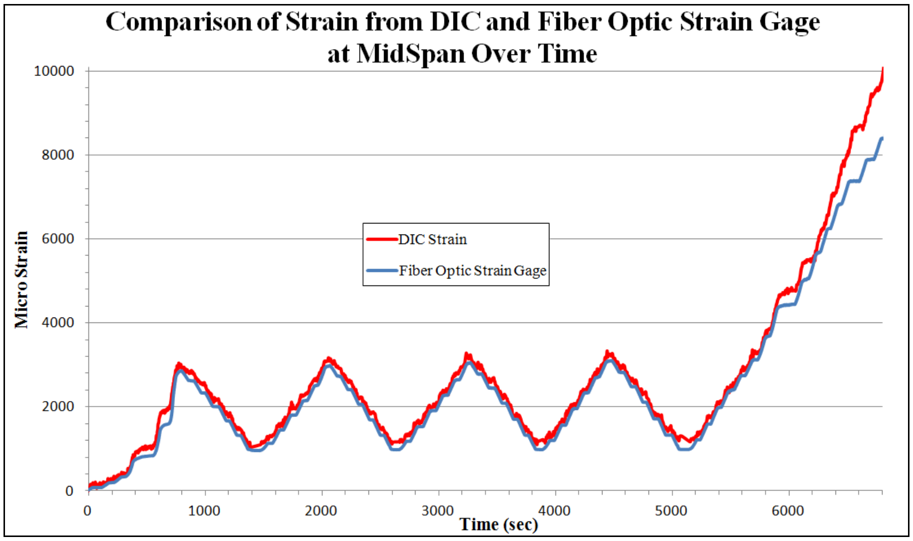


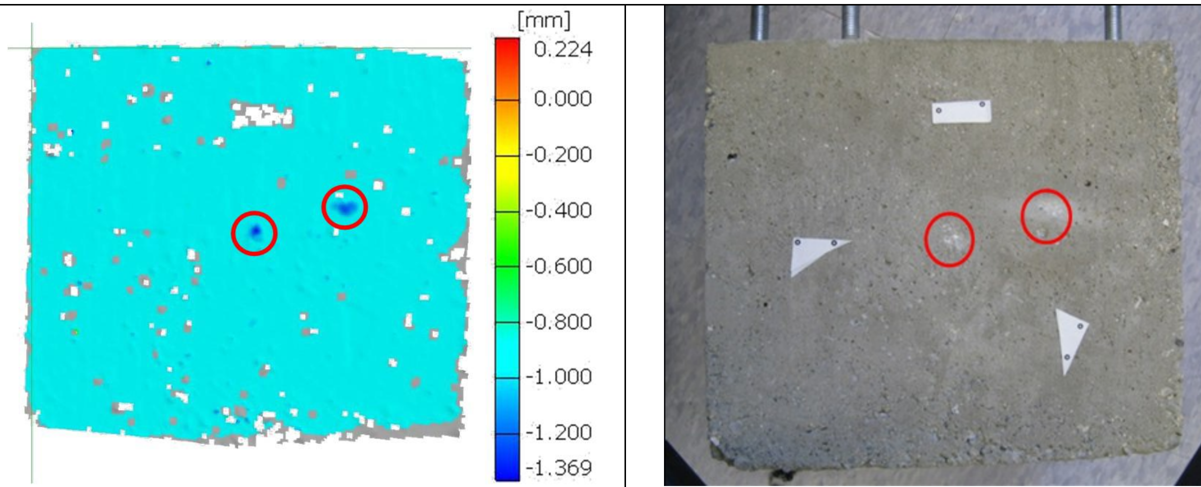
Figure 2.4 Comparison of fiber optic strain gage to DIC strain measured on bottom edge at midspan

Overall the strain curves compare very well throughout the test. The largest deviation between measurements occurs near the end of the test, just prior to failure. There are several probable factors that explain discrepancies between the measurements. (1) The sensors are not co-located and therefore the crack might grow differently at the bottom of the beam compared to the side edge, yielding different strains. (2) The DIC software strain gage length is not identical to the fiber optic gage length and the strain is especially sensitive to gage length when measuring across a crack. A majority of the gage elongation is due to the crack opening, not the concrete straining. The gage will experience essentially the same elongation regardless of gage length because of the crack. If the elongation from a crack is measured by a shorter gage length, the strain reading would be high than strain measured by a longer gage. (3) Close to failure, it is possible that the optical sensor experienced delamination from the concrete. Considering all the possible sources of error, correlation of the fiber optic sensor and DIC strain measurement can be considered accurate.

Laboratory Spalling Quantification Tests:

Two laboratory experiments were conducted to test DIC's ability to quantify spalling by monitoring the surface geometry over time. The traditional paint patterning technique for DIC is not feasible for spalling quantification because the pattern would fall off with the spalled concrete. To circumvent this issue, a pattern is projected on the surface with a LCD projector. Note projected patterns can only be used for surface geometry measurements; strain cannot be measured because the pattern does not deform with the surface.

First spalling quantification was tested on a small, 30cm x 30cm, concrete block. The test procedure was to measure the initial surface geometry, chip away concrete in two locations and take a final surface geometry measurement. Approximately, 1.4mm of concrete was chipped away. To quantify the spalling, the deviation between the initial surface and damaged surface was computed and is plotted on left side of Figure 2.5. The deviation between the two surfaces was computed in GOM™'s software SView. This software imports the surfaces, performs an automated best-fit alignment and calculates the distance between the two surfaces. The picture on the right side of Figure 2.5 shows the damaged surface. In both images, the red circle indicates the damaged areas.

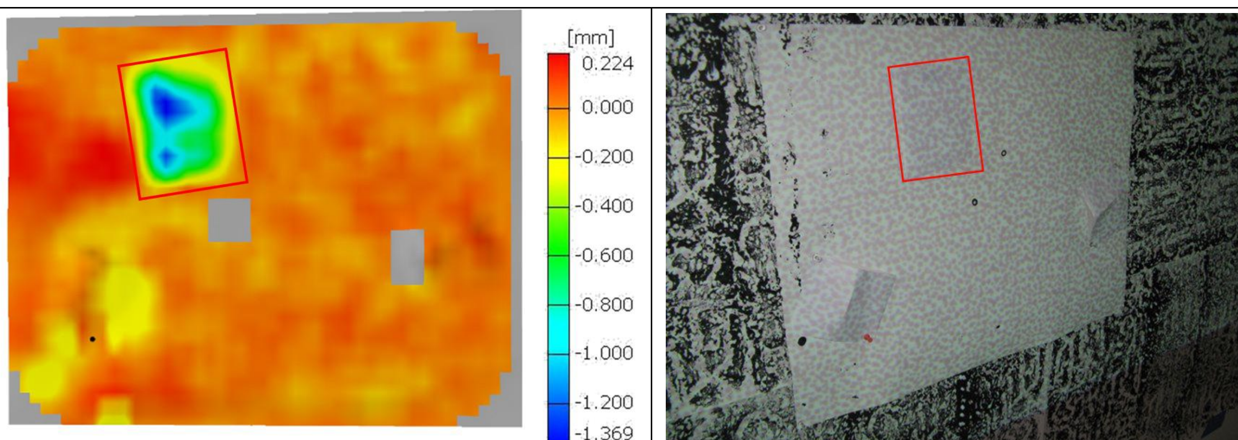


Surface Deviation Contour Plot | Photo of Damaged Surface

Figure 2.5 Contour plot of deviation between damaged and undamaged surfaces,
and photograph of damaged surface; red circles denote the locations of induced damage

From the contour plot, the locations and extent of material loss can be determined. Surface geometry data is missing for some areas of the surface due to cavities on the surface where pattern matching was difficult to perform.

A second spalling quantification test was performed on a larger area (approximately 5 meters x 3 meters). In this test, the surface was measured before and after a sheet of paper was taped on. The deviation between the two measurements was computed and shown in Figure 2.6.



Surface deviation contour plot | Photograph of attached sheet of paper

Figure 2.6 Contour plot of deviation between surface with and without sheet of paper,
and photograph of surface with paper; red box denotes the location of sheet of paper

These results show the sensitivity of this measurement technique; the thickness of a sheet of paper and tape, less than ~1mm thick, can be detected when viewing an area 3 meters by 5 meters.

The results of these laboratory tests confirmed DIC can be used to measure strain and displacement, locate cracks and quantify spalling. These laboratory tests serve as the basis for the field tests and are described in the following section.

3. BRIDGE MONITORING USING DIGITAL IMAGE CORRELATION

To review, the monitoring approach starts by making an initial measurement of an area of interest on a bridge (obtaining the reference surface geometry and pattern) and then the area is measured again a period of time later to quantify changes in the structure. Any change to the area can be quantified by comparing the current measurement to the initial reference measurement. Fifteen areas of interest on three bridges near Lowell, Massachusetts were monitored. For brevity, only four monitoring areas are presented in this paper. The monitoring areas were used to demonstrate spalling quantification, crack monitoring using photogrammetric targets, and long term strain monitoring.

To prepare the areas for strain and displacement monitoring, a black and white dot pattern was painted on. Developing methods to apply appropriate patterns over large areas was a critical part of this work. A 'good' pattern is one that has high contrast (large gray-scale variation) with appropriate size dots (~6 pixels in diameter). For smaller areas (~1m x 1m), the pattern was created by spray painting through a foam mesh stencil adhered to the bridge surface. For larger areas (~3m x 3m), a custom dot paint roller was used. The dot roller is shown in Figure 3.1. For both size areas, a white base coat was applied before adding the black dots to increase contrast and hence improve the measurement.

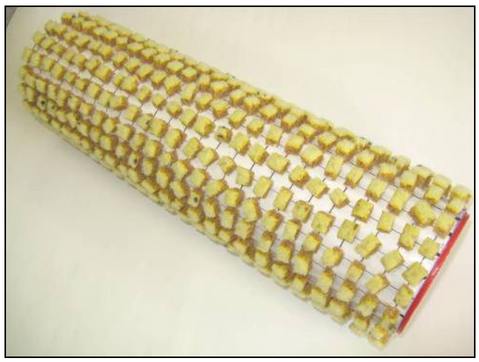


Figure 3.1 Custom dot roller for large area patterning

Photogrammetric targets were also applied to each monitoring area and serve two purposes. First, the targets can be used to define a coordinate system for the strain and displacement analysis. Second, the targets can be used as simple extensometers. This is especially useful for measuring the opening of cracks and joints.

<u>Field Spalling Quantification Tests:</u>

For spalling quantification areas, no surface preparation is required because the pattern is projected. A high power projector may be required if the area is in direct sunlight. Figure 3.2 shows the experimental setup for performing a projected pattern surface geometry measurement for spalling quantification.

Figure 3.2 Experimental setup for projected pattern measurement to quantify spalling on a bridge in Lowell, MA

Two locations with obvious and active spalling were selected to monitor spalling on a bridge abutment (Area 1-3) and on a bridge pier (Area 3-4). Spalling is quantified using the same approach as described for the laboratory tests; surface geometry is measured at two different times, the two surface geometries are automatically aligned in SView and the deviation between the surfaces is computed. For both areas, the initial surface geometry was measured on November 20, 2012 and the subsequent measurement on February 5, 2013. Figure 3.3 shows, photographs of the spalling areas and the corresponding surface deviation contour plots for Area 1-3 and Area 3-4.

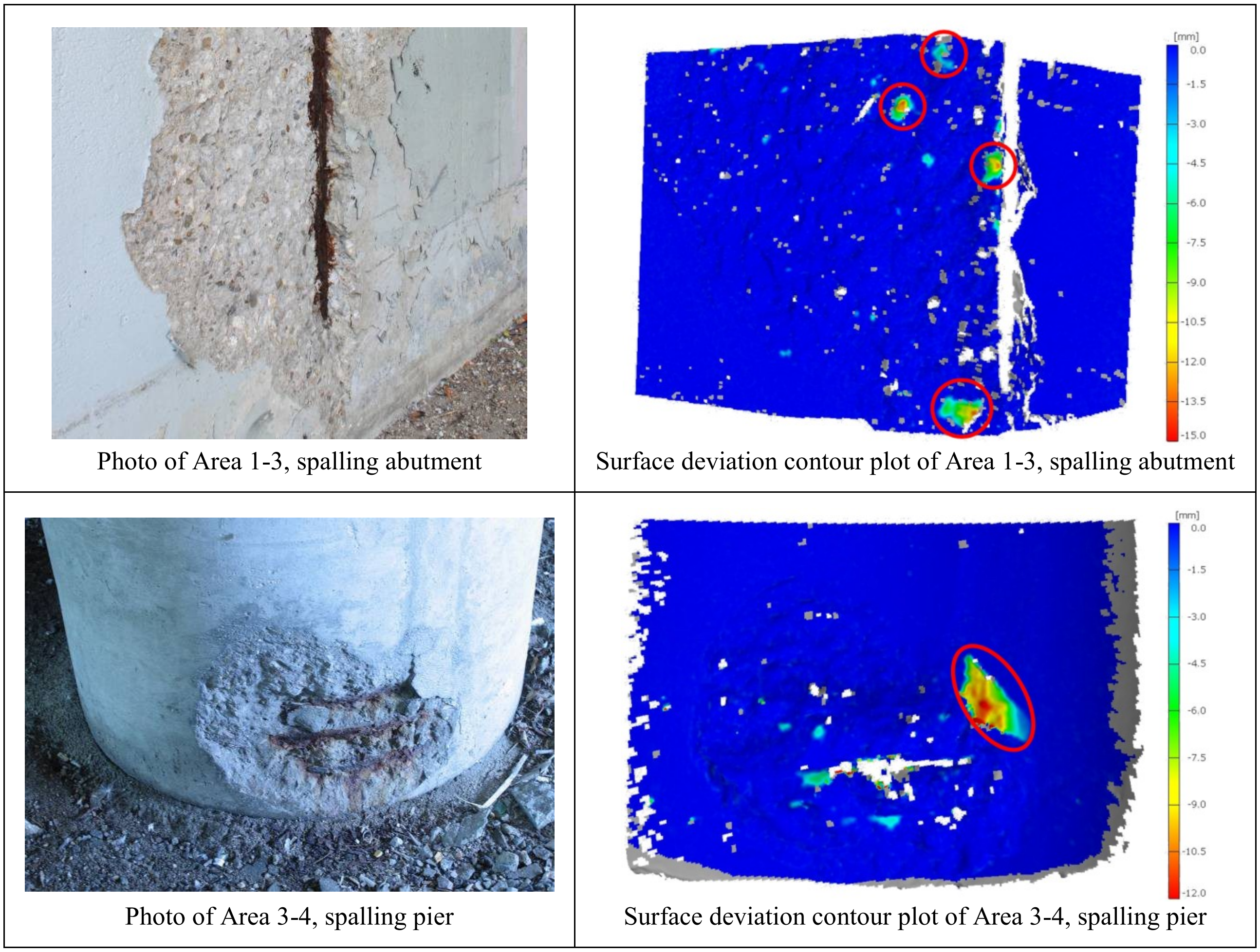


Figure 3.3 Photographs (left) and corresponding surface deviation contour plots (right) of spalling test areas. Largest areas of spalling are indicated by the red ovals.

The regions of large negative deviation specify the location and extent of the spalling. These results confirm DIC can be used as a long term monitoring tool to quantify and assess spalling. In the surface geometry measurement of Area 1-3 there is a strip of data missing at the ledge between the spalled surface and smooth surface. There is no data on this feature/surface because it is not visible from the right camera. To solve this issue, the area can be measured from multiple perspectives ensuring all features are visible from at least one of the perspectives. The measurements from different perspectives can all be aligned and merged to create a single complete surface geometry file. To aid the alignment process, temporary photogrammetric targets should be applied to the surface to provide reference points. This technique will be implemented on further spalling quantification measurements in future studies.

Field Photogrammetric Target Extensometer Tests:

In some situations, the full field strain is not necessary and only the distance between discrete points is desired. In these cases, photogrammetric targets can be used instead of a pattern. This would be useful for measuring the opening of large cracks and tracking the relative displacement of structural members. Applying photogrammetric targets is much easier and faster than patterning and the data processing is simplified compared to DIC post-processing.

In this paper, photogrammetric targets were used to monitor cracks in a bridge abutment and relative motion between the abutment and a retaining wall (Area 1-5). Simple point to point extensometers are used for monitoring. Figure 3.4 shows a photograph of the measurement area with the point and extensometers labeled. The abutment was patterned for DIC measurements, but for this analysis only the photogrammetric targets were considered.

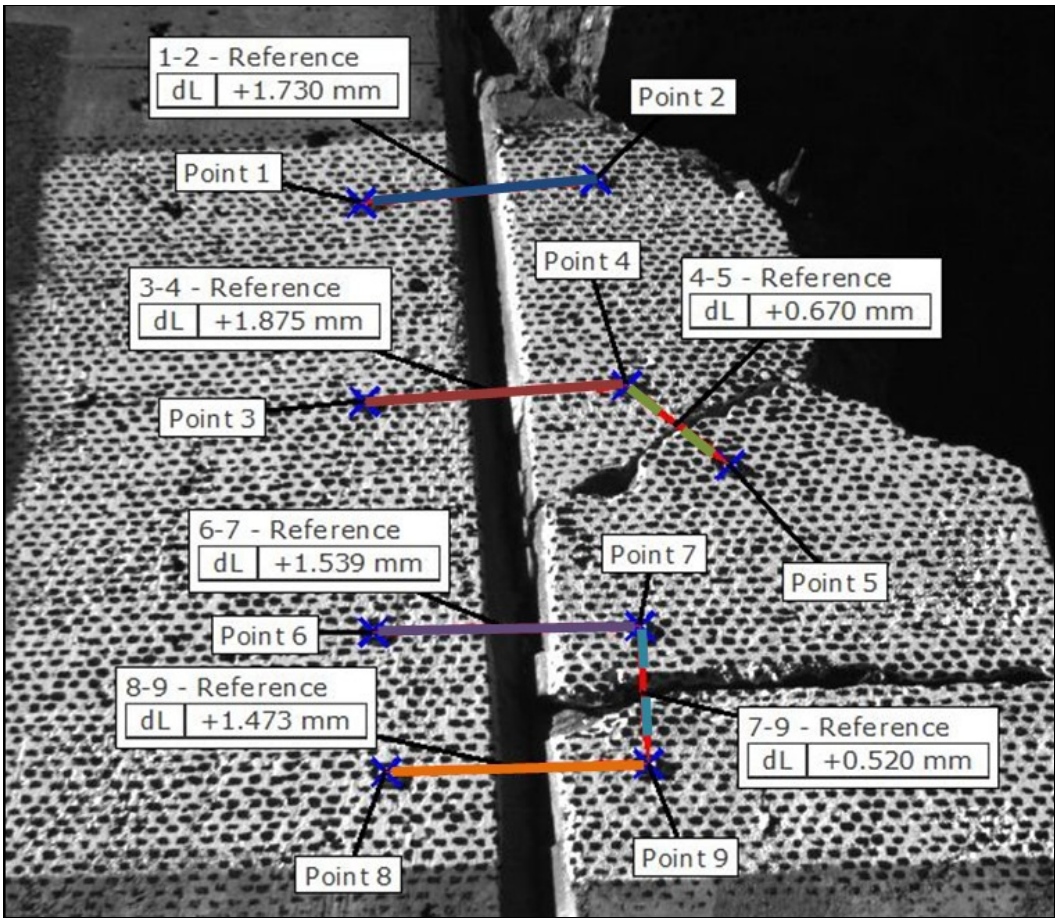


Figure 3.4 Photograph of Area 1-5 with nine photogrammetric targets denoted by blue X's and extensometers between targets labeled using red lines.

Area 1-5 was measured on three dates, September 14, 2012, October 11, 2012 and February 5, 2013. The extensometer labels show the length deviation between the initial measurement (9/14/2012) and subsequent measurement (10/11/2012) as an example. On each date, each of the extensometers were measured ten times and averaged to compensate for noise. Figure 3.5 plots the average deviation from the initial measurement for each extensometer, for the three dates measured.

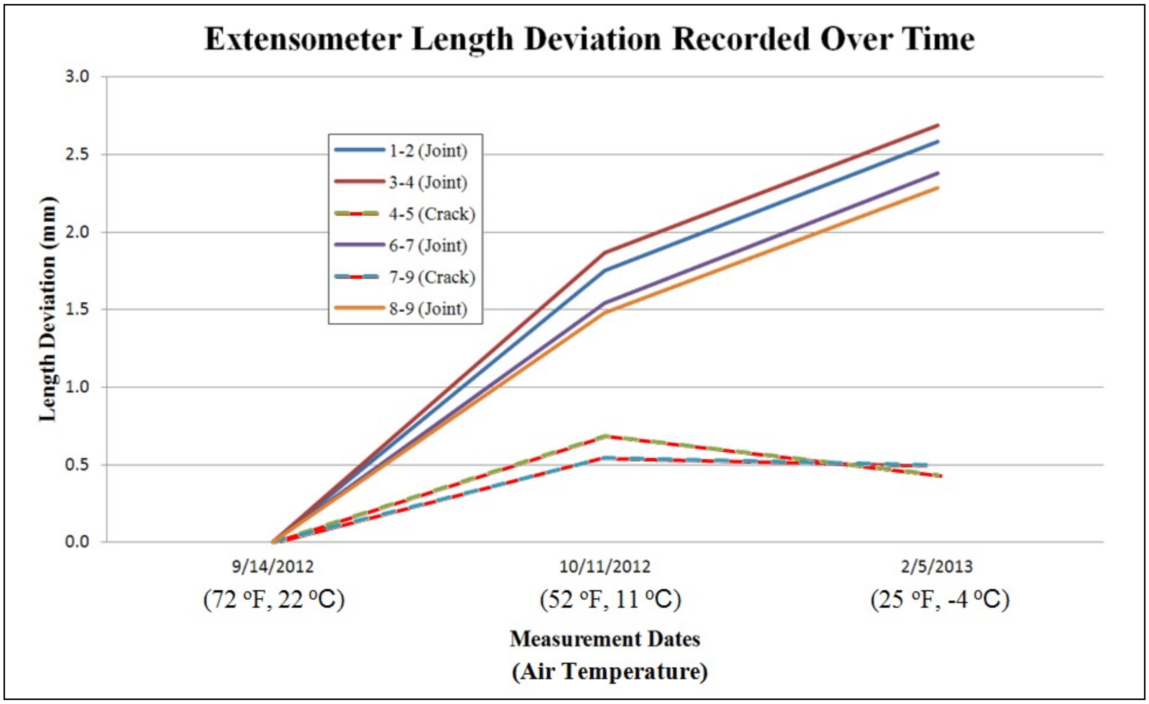


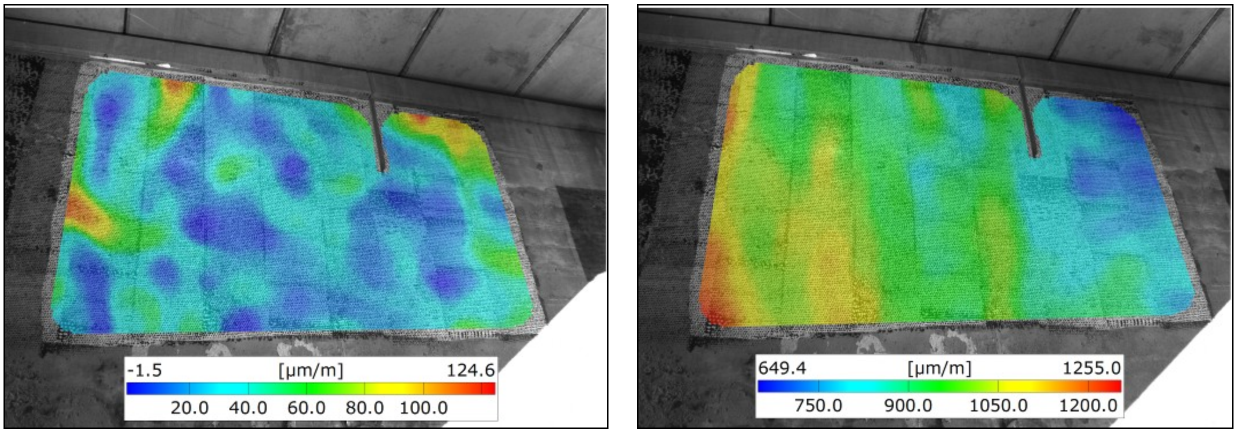
Figure 3.5 Length deviation of photogrammetric target extensometers for test Area 1-5 (see Figure 3.4)

The solid lines represent length deviations of extensometers measuring across the joint between the abutment and retaining wall and the dashed lines represent measurements across cracks. Figure 3.5 shows the gap at the joint between the abutment and retaining wall has expanded approximately 2.5mm over approximately 4.5 months and the abutment crack widths only expanded approximately 0.5mm. The opening of the joint and cracks are likely caused by thermal contraction, not damage. These results show that long term monitoring can be performed using photogrammetric targets.

<u>Field Long Term Strain Monitoring Tests:</u>

The methodology for long term strain monitoring involves imaging an area periodically and comparing the current strain pattern to the initial, reference measurement. The long term strain monitoring technique is still being investigated. Thus far the long term monitoring procedure has been used on multiple areas but initial results contain too much noise. The noise level was estimated by performing the long term monitoring technique over a short period of time on a surface that has no appreciable change in condition. The procedure involved taking a set of measurements over an area of interest at one camera position, then shifting the camera position, and taking another set of measurements to emulate long term monitoring. The cameras are shifted because during long term strain monitoring the cameras will never be in exactly the same position as the reference measurements. The two sets of measurements were taken within a minute of each other, and therefore the strain should not change significantly. The issue encountered is that the existing long term strain monitoring technique calculates high strain levels for measurements taken in the shifted camera position when using a measurement from the original camera location as the reference. The strain levels calculated is the noise floor, and essentially represent the lowest strain level than can accurately be measured. In order for long term strain monitoring to work, the noise floor must remain approximately the same when computing strain with measurements taken at different dates and camera positions. Figure 3.6 demonstrates the encountered noise floor issue using Area 2-1 as an example. The dimensions of Area 2-1 are approximately 11 feet by 7.5 feet (3.4m x 2.25m).

Noise Floors Calculated with Original Camera Position as Reference (Major Strain)



Noise Floor Measurement in Original Camera Position | Noise Floor Measurement in Shifted Camera Position

Figure 3.6 Long term strain monitoring noise floor issue demonstrated on Area 2-1, Area dimensions 11ft by 7.5ft.

The results in Figure 3.6 show the noise floor is significantly affected when strain is computed using a reference measurement that was taken from a different camera position. The noise floor of the measurement taken in the original camera position (left contour plot in Figure 3.6) is approximately -10με to 125 με, which is reasonable for a measurement of this type. However, when a measurement from the original position is used as a reference for computing the strain in the shifted position, the noise floor of the shifted measurements (right contour plot in Figure 3.6) increase to approximately -650με to 1260με, which is unacceptable. The source of the error is still under investigation but some possible reasons include; subpar camera calibration, a too shallow camera angle, lens distortion errors, or images that look *too* different in the shifted perspective for the pattern matching. If the camera calibration is subpar, the DIC system will incorrectly locate the square subset of pixels (facets) resulting in strain and displacement errors. The 3D pattern matching relies on a camera angle that is optimally ~25 degrees. Because of the large areas and camera working distance, the camera angle was closer to 15 degrees for our tests and may result in dimensional distortions. Lastly, if the perspective of the subsequent measurements is drastically different than the original, the pattern matching algorithms will have a difficult time locating the same facets in the subsequent measurements, resulting in strain and displacement error. Currently the research team is attempting to solve these issues by increasing calibration accuracy and using larger camera angles to improve out of plane displacement accuracy.

4. CONCLUSIONS

The effectiveness of three-dimensional digital image correlation for bridge structural health monitoring has been demonstrated. In the laboaratory, DIC located non visible cracks using the axial strain contour plots of a reinforced concrete beam subjected to mechanical 3-pt. and 4 pt. loading. It was shown that the crack widths could be estimated using the axial displacement measured along a section line that perpendicularly intersects the crack. On a reinforced concrete beam, the DIC measured strain was shown to agree well when compared to a fiber optic strain gage. The spalling quantification capabilities of DIC were demonstrated in the laboratory and on two full scale bridges by using a projected pattern to measure surface geometry. Using photogrammetric targets, the opening of joints and cracks were tracked over a 4.5 month period. A method for long term strain monitoring was presented and future work will be dedicated to reducing the noise produced in the computation. Understanding how the natural, benign changes in a bridge over time (e.g. daily temperature fluctuations) can be discriminated from mechanical damage remains to be addressed. The results of this paper show that DIC has great potential for quantitative bridge inspection. Although applications discussed in this paper are bridge related, these same technique can be applied to numerous other large scale concrete or metal structures.

5. ACKNOWLEDGEMENTS

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