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Use of Photogrammetry to Assess the Condition of Structural Concrete

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Abstract

According to the American Society of Civil Engineers (ASCE) 2013 report card, the Nation has a grade of a D+ in infrastructure. This is because civil infrastructure in the United States is reaching the end of its expected service life. Demolishing and replacing infrastructure is unsustainable both from an economic and environmental standpoint. There is a need for new methods in verifying the remaining life of the engineered environment, and photogrammetry (the science of making measurements from photographs) will satisfy this need. The purpose of this study is to validate the use of photogrammetry for determining strains and crack widths. This will be accomplished by loading a 150 mm x 150 mm x 460 mm concrete block and comparing strain measurements calculated from photogrammetry to those of strain gauges or extensometers. This project also compares crack width measurements from high-resolution orthorectified photographs to those obtained using a crack comparator card or microscope. This research is unique due to the scale of the project, and because strain measurements rather than deflections are being analyzed. Upon conclusion, it is anticipated that traditional measurement techniques (strain gauges, extensometers, crack comparator card, and microscope) will yield similar results to those obtained from photogrammetry. The implication of these results is that professional engineers can adopt photogrammetry methods to assess the condition of existing structures. With a large amount of infrastructure failing and in need of repairs, this research will benefit the engineering community because it is a robust and quantitative means of assessing the condition of the Nation's infrastructure.

Keywords: Photogrammetry, Concrete Strain Measurement, Crack Width

1. Introduction

Photogrammetry is the science of making measurements from photographs. This technology can be used to determine deflections of a structure from its original position, displacements over time, strains, and crack widths – data needed to assess the condition of structures. The objectives of this study are to validate a proposed photogrammetry crack measurement method, and compare strain measurements obtained from photogrammetry to those obtained from strain gauges and extensometers.

2. Background

2.1 past studies: crack width measurements

2.1.1 liang-chien chen et al. (2006)[1]

Liang-Chien Chen et al. aimed to implement a semi-automatic crack-edge detection method using multitemporal image processing to compare concrete cracks over time. For this study, seven individuals took five different readings using a crack comparator card, and compared these measurements to those collected from processed images. This method was more accurate for larger cracks. When the crack was around 0.1 mm, the crack width varied 34.5%, whereas when the crack width was around 0.6 mm, the measurements only varied 6.6%. The difference between measured crack widths varied no more than 0.05 mm for the different methods.

2.1.2 araújo et al. (2013)[2]

Araújo et al. aimed at combining photogrammetry and image processing in order to monitor concrete crack patterns over time. Targets were painted on a concrete specimen, and photographs were taken 90-cm away. Photogrammetry was used to determine the locations of the targets, the strain field, and crack pattern for crack widths larger than 0.2 mm. The strain field was determined with a strain-nodal displacement matrix used on each target. This accuracy was determined by comparing measured widths to known widths of a crack comparator card. The accuracy ranged from approximately 0.2 mm to 0.95 mm and was determined by comparing measured widths to known widths of a crack comparator card. A major drawback of this method is that cracks equal to or less than 0.2 mm in thickness could not be measured.

2.1.3 rivera et al. (2015)[3]

The authors developed a *MatLab*® algorithm named "I-Crack" for the purpose of measuring concrete crack widths as small as 0.254 mm. Through this image processing algorithm, surface area of the crack measured and the average crack width is determined by dividing crack area by its centerline length. Crack widths from *I-Crack* were compared with manual measurements with a crack comparator card. Cracks that were manually measured to be less than 0.508 mm had a much greater percentage difference on average than cracks measured to be larger than 0.508 mm. Cracks less than 0.508 mm had an average percentage difference of 61%, whereas cracks greater than or equivalent 0.508 mm had an average percentage difference of 21%. As a result, it can be concluded that this technique is effective when measuring crack widths larger than 0.508 mm.

2.1.5 need for current study

There is a need for a photogrammetry method that will reliably measure crack widths between 0.10 mm and 0.20 mm. There is also a need to measure crack widths using available software as opposed to experimental algorithms.

2.2 Past Studies: Displacement Measurements

Displacements obtained from photogrammetry have been compared to LVDTs (linear variable differential transducers). Past studies have shown that there is a strong relationship between the two methods of measuring displacements.

2.2.1 whiteman et al. (2002)[4]

Whiteman et al. tested multiple concrete beams to obtain displacement data from photogrammetry, and LVDTs. *Australis*® image processing software was used to process images. Flexural testing was done on three 6.6 m x 0.29 m x 0.6 m prestressed concrete beams. Targets were placed offset to the LVDTs. The author found a fairly large difference in the load vs deflection graph for photogrammetry vs LVDTs after 0.21 mm of deflection, which the author suspects is due to limitations in LVDT measurements. Shear testing was done on an inverted u-shaped beam reinforced with carbon fiber strips. During the shear testing, targets were placed in line with the LVDT to make a direct comparison between the two measurement techniques. The authors found that photogrammetry yielded displacement results within a millimeter of LVDTs.

2.2.2 valença et al. (2008)[5]

Valença et al. tested 20-m long beams undergoing creep testing and failure testing to compare photogrammetric displacement data to data collected from LVDTs. The results obtained from photogrammetry was very close to results from LVDTs, with a difference ranging between 0.07 mm and 1.13 mm. There was an average percentage difference of 0.83% between the two methods for creep testing and 0.96% for failure testing.

2.2.3 need for current study

Photogrammetry has been proven to reliably measure displacements, however, there is a lack of strain measurements obtained from photogrammetry using available photogrammetry software.

3. Experimental Program

3.1 Crack Widths

The purpose of this portion of the current study is to correlate crack width measurements obtained with photogrammetry to those obtained using a crack comparator card and crack microscope. A crack in a concrete beam was first identified. Three locations were identified and marked with arrows approximately perpendicular to the width of the crack. These locations were labeled crack 1, crack 2, and crack 3. A standard ruler was placed adjacent to the crack. Figure 1 presents the crack under investigation and ruler.

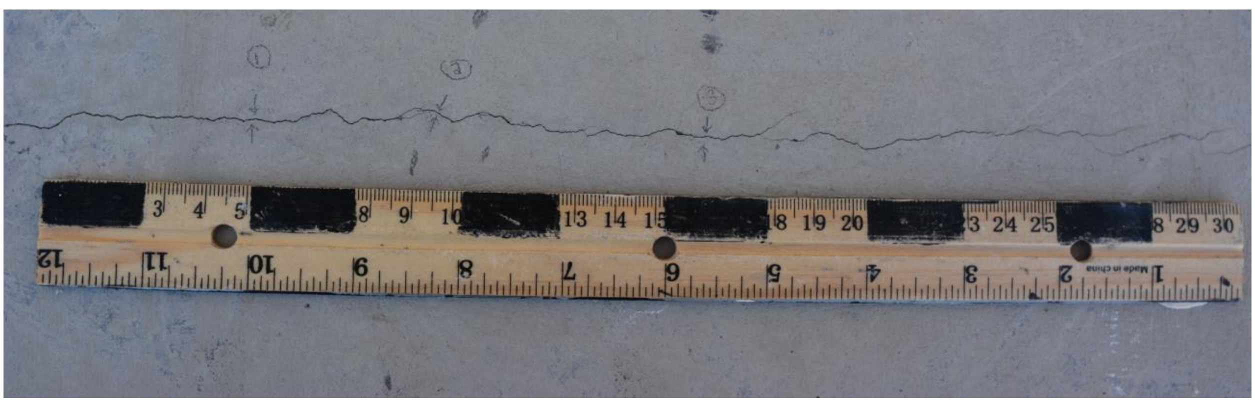

Figure 1. Crack width measured at location 1, 2, and 3.

A single photograph of the three crack locations (Figure 1) was taken approximately two feet from the concrete surface with a camera held approximately perpendicular to the surface of the crack. A Nikon D7100 digital single-lens reflex camera (DSLR) with a 24 mm fixed lens was used. The camera has 24.1 Megapixels and a 23.5 mm x 15.6 mm sensor. Autofocus was used to ensure the crack was in focus. The photograph was then opened in *Adobe Photoshop Elements*®, and the lens distortion was removed using the “remove lens distortion” feature in *Photoshop*. The success of the lens distortion removal was then checked by drawing a straight line along the ruler and ensuring the edge of the ruler was continuously aligned with the straight line. The photograph was then added to *AutoCAD*® as an external reference, and scaled based on the demarcations of the ruler. Finally, the width of the crack was measured at the three crack locations within *AutoCAD*.

In addition to measuring the crack photogrammetrically, the crack was also measured using a crack comparator card and microscope. For these measurements, to mitigate bias, ten separate individuals volunteered to measure the crack at the same three marked locations using a crack comparator card and a crack microscope. Five of the ten individuals measured the crack using a crack comparator card first and then the crack microscope, and the other five individuals measured the cracks using the crack microscope first and then the crack comparator card. All participants measured the first crack first, then the second, and, lastly, the third crack. The same crack comparator card and crack microscope was used by all participants.

3.2 Strain Measurements

A 150 mm x 150 mm x 460 mm concrete block equipped with strain gauges, extensometers, and targets for photogrammetry was loaded in compression. Three Nikon D7100 cameras were first calibrated with *PhotoModeler®*, a photogrammetry software. This allowed the program to determine the internal camera parameters such as the focal length, and lens distortion. Figure 2 presents the specimen and test setup for this portion of the study.

Figure 2. Test set-up and specimen.

Each camera was placed on a tripod and equipped with a remote trigger system. When the button on the main remote was pressed, all three cameras fired at the same time. The cameras were placed in a location such that all of the targets could be seen from each camera. *PhotoModeler* requires that each target be in a minimum of two photographs, however, there is less error when each target is in at least three photographs. After the three cameras were calibrated, the optimal ISO, f-stop, and shutter speed was determined. For the lighting conditions present where the concrete block was to be tested, an ISO of 200, f-stop of f13, and shutter speed of 1/2.5 resulted in the lowest total error of 0.31 in *PhotoModeler*, thus those parameters were used during testing. Next, a reference axis was fabricated. The reference axis has a fixed distance between targets and remains static throughout the loading. The size of the targets was determined using *PhotoModeler* based on the internal camera parameters and the farthest distance from the cameras to the targets. This ensured there would be a sufficient number of pixels for the software to detect all of the targets. *AutoCAD* was used to draw the reference axis with the centers of the targets on the horizontal axis exactly 5 inches (127 mm) apart, and the centers of the targets on the vertical axis exactly 2 inches (50.8 mm) apart. Lines were drawn connecting the centers of the targets vertically and horizontally to assist with leveling of the reference axis. The targets for the reference axis were then printed out on white cardstock paper and taped to a wood block. A hand level was used to orient the paper until the horizontal line on the reference axis was level. The locations of the strain gauges, extensometers, and reference axis are shown in Figure 3.

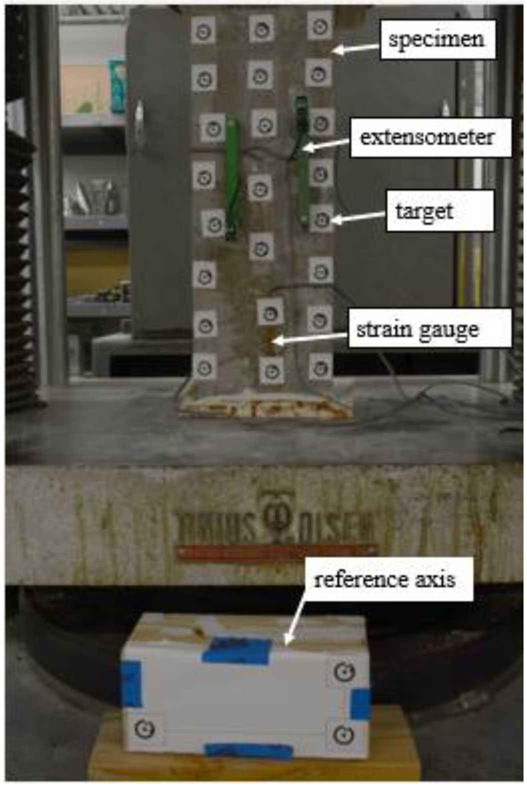

Figure 3. Test specimen with targets and instrumentation installed.

One extensometer was installed on the right side of the front face of the test specimen, and a second extensometer was installed on the left side of the front face of the specimen. One strain gauge was installed on the bottom center of the specimen face, and a second strain gage was installed above the first one. Twenty-three targets were printed, cut, and glued onto the face of the test specimen. One target was placed on the top and on the bottom of each strain gage, and two targets were placed adjacent to the top and bottom of the extensometers.

A photograph from each camera was taken at multiple loading stages. The first loading stage was defined as the unloaded state of the specimen. After that, the concrete specimen was loaded in compression up to 110 kip (489 kN) and a photograph was taken at 10 intermediate stages. When the trigger for the cameras was pressed, the values from the strain gauges and extensometers were concurrently recorded. A total of 11 photographs were taken from each camera, and 11 models of the test specimen were created in *PhotoModeler*.

The distance between the targets on the reference axis was defined, the horizontal axis was defined as being horizontal, and the corner target on the reference axis was defined as being (0,0). The coordinates during each loading stage were then extracted from *PhotoModeler*. As compared to the initial state of the test specimen, the strains were calculated using the two targets placed on the ends of the strain gauges and the two targets adjacent to each extensometer. The average strain values for the two extensometers and two strain gauges were plotted and directly compared to the average strain values obtained from photogrammetry during each loading stage using the targets on the two strain gauges and the average strain values for the targets adjacent to the two extensometers.

4. Results

4.1 Crack Measurement

Table 1 shows the average of 10 crack width measurements for the crack comparator card and crack microscope, as well as the crack width values determined photogrammetrically.

Table 1. Crack width values for crack comparator card, microscope, and photogrammetry

	Crack Comparator Card (mm) N = 10	Crack Microscope (mm) N = 10	Photogrammetry (mm) N = 1
Crack 1	0.133	0.147	0.152
Crack 2	0.116	0.116	0.107
Crack 3	0.110	0.170	0.137

For crack 1, the crack width measurements ranged from 0.1 mm to 0.2 mm for measurements made from the crack comparator card and crack microscope. Using the photogrammetry method, the crack width measurement for crack 1 was 0.152 mm. Crack 2 had crack width measurements ranging from 0.05 to 0.15 mm for the crack comparator card and from 0.1 to 0.2 mm for the crack microscope. The average crack measurement for the crack comparator card was 0.116 mm, and the average crack measurement using the crack microscope was 0.116 mm. Photogrammetry resulted in a measurement of 0.107 mm. Crack 3 had crack width measurements ranging from 0.05 to 0.15 mm for the crack comparator card, and 0.1 to 0.3 mm for the crack microscope. The average crack width measurement using the crack comparator card and crack microscope was 0.110 mm and 0.170 mm respectively. Photogrammetry resulted in a crack width measurement of 0.137 mm. Figure 4 visually represents the measured crack widths for each crack measurement technique.

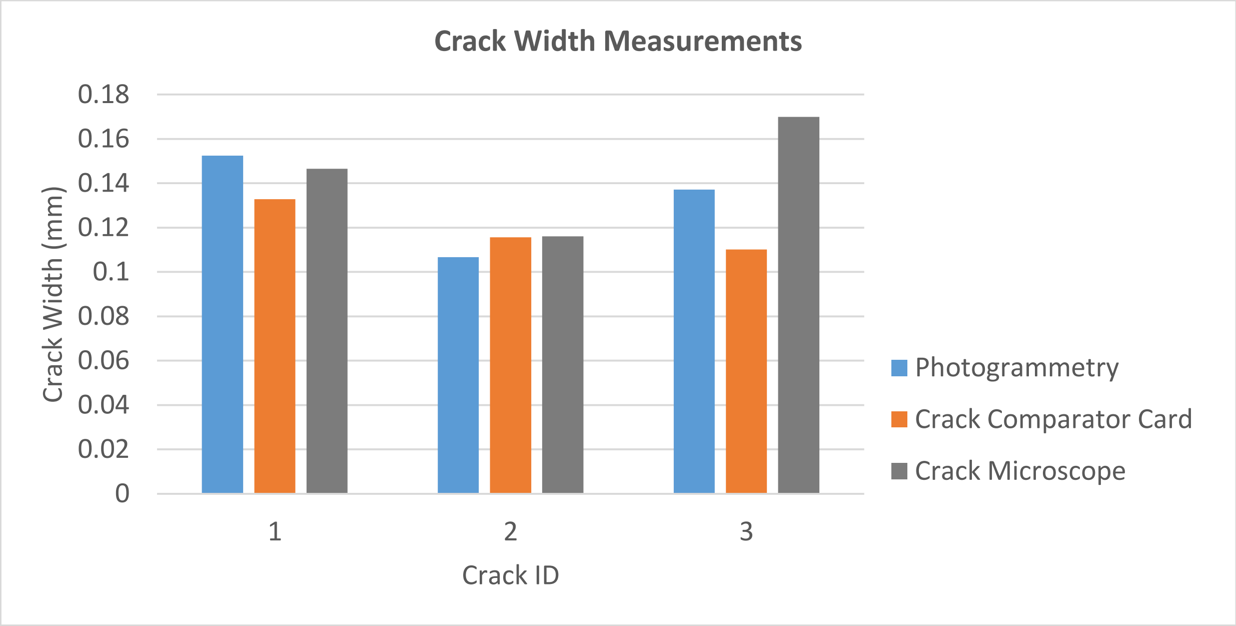

Figure 4. Crack width measurement comparison

For all three cracks, photogrammetry resulted in measurements on average 10.5% different than the crack microscope, while the crack comparator card resulted in measurements 14.9% different than the crack microscope. Photogrammetry resulted in crack width measurements 15.7% different than a crack comparator card.

Crack widths measured using photogrammetry were less than 0.033 mm different than average crack width measurements obtained from the crack microscope and less than 0.027 mm different than average crack width measurements obtained with a crack comparator card. Photogrammetry results is closer crack width measurements than a crack comparator card, thus it can be concluded that the proposed photogrammetric crack width measurement method is more accurate than a crack comparator card in obtaining crack width measurements. In conclusion, this method can feasibly be adopted in the field and during laboratory testing to reliably measure crack widths.

One advantage of the photogrammetry method to measure cracks using photogrammetry instead of a crack comparator card is the ability to collect photographs during laboratory testing and analyze later. As opposed to spending time pausing testing to measure crack widths. Also, this method is advantageous in that it can capture all crack widths within the field of view of the camera in the short amount of time it takes to press the shutter button.

4.2 Strain Measurements

Figure 5 shows the stress strain curve generated from the average strain values from the two extensometers and the photogrammetry average strain values obtained using the two sets of targets adjacent to the extensometers. Figure 6 shows the stress strain curve generated from the average strain values from the two strain gauges and the photogrammetry average strain values obtained using the two sets of targets on the strain gauges.

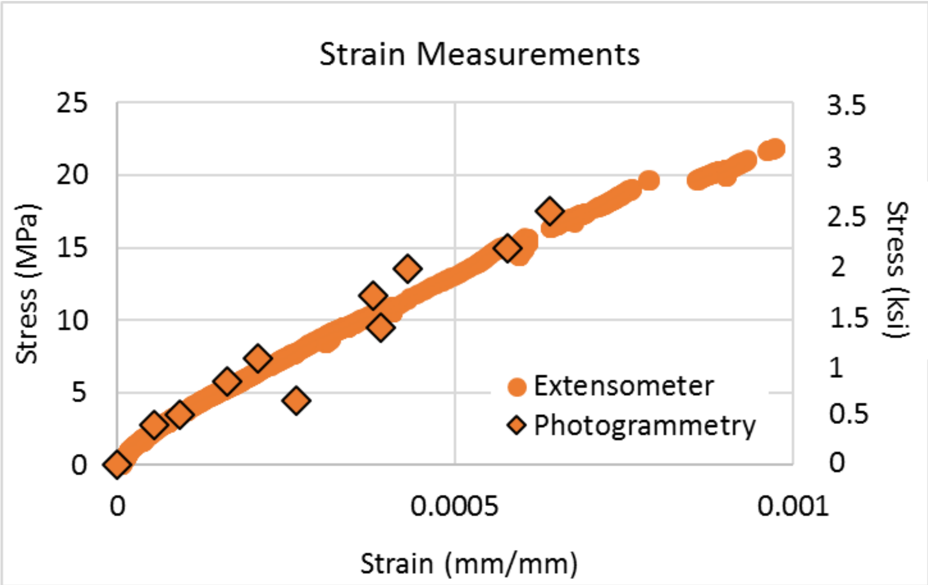

Figure 5. Photogrammetry vs Extensometer

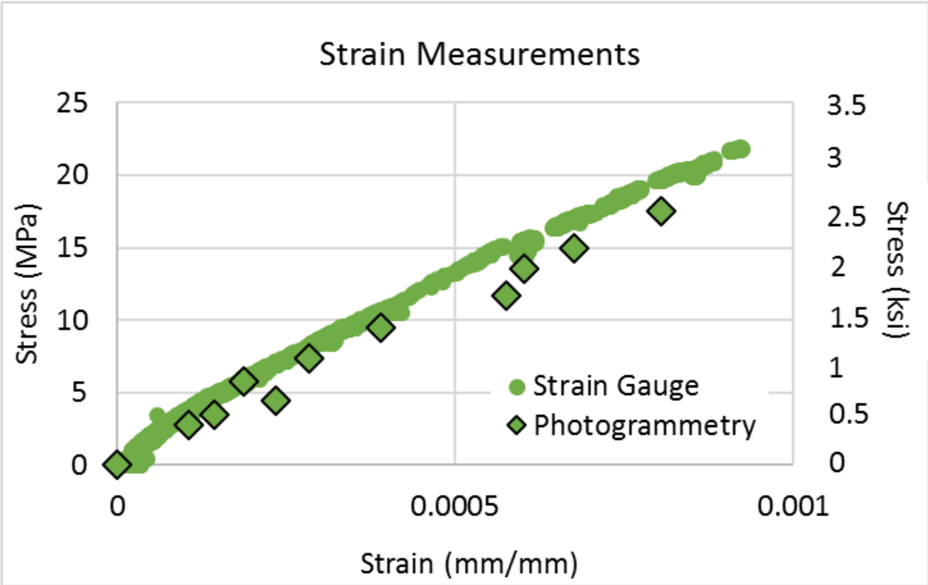

Figure 6. Photogrammetry vs Strain Gauge

As shown above, at the fourth loading stage (Figure 5), photogrammetry resulted in a maximum strain differential from the extensometer data of 0.00014 mm/mm. At the eighth loading stage, photogrammetry resulted in a strain differential from the strain gauge data of 0.00014 mm/mm (Figure 6). The photogrammetry strain measurements from the targets adjacent to the extensometer resulted in a coefficient of determination (R^2) of 0.937. The targets on the strain gauge resulted in an R^2 of 0.9875. As the R^2 values for photogrammetry are close to 1, it can be concluded that there is a close fit between photogrammetry strain measurements and those collected via traditional means. Additionally, the strain measurements obtained from photogrammetry are on average 0.000066 mm/mm different than strain gauges and an average of 0.000045 mm/mm different than extensometers. Strain measurements obtained from photogrammetry are very similar to those obtained from strain gauges and extensometer, and thus photogrammetry represents a reliable method for measuring concrete strain.

5. Summary

In conclusion, this study found the following:

- Cracks as small as 0.11 mm can be measured using the proposed photogrammetry method within 0.033 mm and 10.5% of crack microscopes
- The proposed photogrammetric crack measurement technique is more closely related to crack microscope measurements than a crack comparator card
- On average, photogrammetry resulted in strain measurements 0.000066 mm/mm different than strain gauges and 0.000045 mm/mm different than extensometers.
- The photogrammetry strain measurements from the targets adjacent to the extensometer resulted in an R^2 of 0.937, and the targets on the strain gauge resulted in an R^2 of 0.9875
- Strain measurements obtained from photogrammetry are comparable to those obtained with strain gauges and extensometers

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7. References

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