Abstract—Concrete stress-strain analysis provides an understanding of the response of the material under different loading conditions and is a measure of strength as well as structural capacity. Current laboratory methods to extract displacement and strain values require precise equipment with high accuracy and complex data acquisition systems. A simplified non-contact methodology to estimate surface displacement and micro crack initiation will be highly beneficial in terms of enhancing laboratory and field evaluations. Advancements in image analysis and correlation algorithms have allowed for the development of methods to estimate surface displacement and strain through video recordings. The process involves deconstructing a video into individual images per frame, which are then processed for feature detection and monitor those features over time. In this study, a preliminary algorithm was developed to perform the aforementioned tasks on a series of laboratory images. In this paper, video recordings of cylindrical concrete specimens, prepared in the laboratory under standard compression testing, are processed by the proposed surface displacement measuring algorithm and then compared to displacement gauge readings.

I. INTRODUCTION

The application of computer-based image correlation and analysis has been gaining popularity with increasing availability of advanced optical devices. Programs have been developed to follow movement by detecting key features in the image and comparing frame-by-frame images to track the features of interest. Those programs can benefit researchers to improve on existing inspection methods and structural health monitoring processes. Currently there are numerous applications for image-based analysis such as deformation monitoring of bridge elements, pavement surface crack detection, and crack identification on tunnel lining surfaces. Improvements being made for these applications and more practical image capturing methods such as unmanned aerial systems, can be pursued.

The image correlation algorithms can also be employed for evaluating the hardened property measurements of concrete specimens in the laboratory conditions and further applied in the field. Currently strain gauges are used to collect displacement data for compression testing. However, they require high-precision linear variable transducer connected to a data acquisition system to record the specific points on interest on the specimen surface. These measurements are usually localized and limited to a specified surface area. The need for a non-contacting strain measurement for concrete surfaces is highly sought after for both laboratory applications that could be further calibrated and expanded to field applications. These methods allow for unlimited tracking on any visible point on the captured image of the concrete surface and can produce a more in-depth analysis of the surface deformations.

The main objective of this study was to develop a method for utilizing video recordings of concrete specimen surface in the laboratory to estimate the surface displacement and strain. Several concrete cylinder samples were prepared and analyzed during both compression and splitting tensile strength tests to evaluate the preliminary results. There are various factors that contribute to the ability of the algorithm to accurately detect features and analyze them. An optimal test setting will be achievable upon availability of different testing conditions and refinement of the developed algorithm.

II. BACKGROUND

There has been a growing interest for non-contact test methods for evaluating the health and performance of structures throughout the literature. Concrete is a common material used in construction and understanding its properties ensure the safety and health of structures. The recent techniques that utilize image correlation and analysis, such as Speckle statistics, are being tested to eliminate the need for conventional methods [1]. Speckle statistics is a form of digital image correlation in which speckle patterns, with random intensity distribution, are compared during before and after images to evaluate displacement and deformation. The surface of a specimen is illuminated by a laser light to generate a speckled appearance. The speckled appearance is compared between frames and images to determine correlations between those patterns through superimposition. The displacement of the surface can then be measured by tracking the speckle patterns over time [2]. The setup consisted of a Diode-Pumped Solid-State laser, positive lens, screen, and a high-resolution video camera. The captured images were then processed for strain calculations and compared with results from three compression tests. Overlaying graphs from different methods demonstrated that the results were fairly accurate with a 5.6 percent average uncertainty, making this method a fairly reliable technique for measuring strain. That study established the potential of speckle statistics for measuring strain [2].

Another technique is Digital Image Correlation (DIC) which compares before and after images to measure deformation of an object surface. Introduced in the 1980s, DIC algorithms focus on increasing correlation speed and accuracy. DIC is highly sensitive to lighting conditions, requiring a specific setup in order to maintain consistent results during testing. Correlation between images is determined by tracking
matching pixel subsets. An image has a constant dimension size that is represented by number of pixels in the vertical and horizontal directions. Subsets are determined within this region and tracked throughout the deformation process. Recently DIC has been implemented to aid in problems such as fracture mechanics investigation and high temperature deformation analysis [3]. Developing strain and displacement measurement techniques that are accurate and cost effective are highly desirable. Studies on DIC attempt to achieve this by providing a method that is simple and practical for laboratory and field applications [4]. Although there are other techniques, such as laser shearography and speckle interferometry, DIC is simpler to apply in field conditions since required equipment is mainly an image capturing device. However, there are still challenges with accuracy due to effects from the environment and potential changes to surfaces being observed. Studies have demonstrated the potential applications of DIC but further work required to produce a method that is reliable for field conditions [3].

Deformation on concrete structure surfaces leads to crack formation which is an indication of failure thus requiring a monitoring system to ensure structural health. Image correlation techniques can be applicable to this situation to reduce manual inspections and improve detection rates. The validity of these techniques was investigated in a study reviewing 50 papers to evaluate the quality of image processing for crack detection and potential use in field conditions [5]. Typically, those studies have used image correlation and analysis methods following the procedure of capturing images, pre-processing, image processing, feature detection, and parameter estimation. Various methods were investigated such as DIC, morphological approach, speckle statistics, photogrammetric technique, and reconstruction technique to name a few. Each study attempted to measure various features of cracks on surfaces with varying results. The range of accuracy was between 70 to 95 percent with a few cases achieving higher than 95 percent accuracy. That review study demonstrated the potential that image analysis techniques have for practical use as well as shortcomings that need to be improved to increase accuracy [5].

Other applications of optical techniques include measurements of deformation in bridge elements. A study utilizing moiré photography and photogrammetry demonstrated the potential benefits of applying image analysis compared to existing monitoring and testing methods. A destructive load test on a bridge structure was measured and compared to the conventional technique [6]. The method required the surface be covered in dotted patterned paper. Sequential images were then collected with various cameras, using a point of intersection to calculate the position of feature being focused. Displacements in the x and y directions could then be measured by comparing images. Limitations of that method were target recognition and measurements of precise positions. Further development in that technique can lead to simpler evaluation and monitoring methods for structures while increasing accuracy [6].

The image correlation process is generally broken down into two parts, the detector and the descriptor. The detector process is meant to consistently detect interest points such as corners, blobs, and T-junctions. The ability of the detector should be robust with respect to changes in viewpoint. The neighborhood of the selected features is represented as feature vectors or descriptors. Ideally, captured sections should represent the most distinctive features. The descriptor is then compared and matched with different images. There are various algorithms that achieve this with varying results. Some algorithms process the images quickly (i.e. lower computational cost) with low accuracy while others require higher computation power but are more reliable.

The main objective of this study was to develop a preliminary algorithm to detect and track features in sequential images (or frames) of a concrete surface in laboratory conditions to estimate the surface displacement and deformations. The initial algorithm was evaluated with different image resolution and quality under different lighting conditions and various surface annotation. The optimum algorithm was then partially validated using a digital strain gauge during a compression test. The following sections include the details of algorithm development as well as discussion of preliminary results.

III. METHODOLOGY

For this research Speeded-Up Robust Feature (SURF) combined with and Binary Robust Invariant Scalable Keypoints (BRISK) methods were employed in order to achieve a robust algorithm for multiple applications. The initial detector-descriptor algorithm was SURF which is based on the Hessian matrix concept. Utilizing integrated images, computation time can be reduced. Although the detector implements the Hessian matrix, computation is improved by utilizing the determinant of the matrix for the scale and location. The descriptor is then composed of a distribution of Haar-wavelet responses within the neighborhood of the interest point. The Haar-wavelet is a rescaled sequence of square-shaped wavelets utilized by SURF to detect contrast in dark and light pixels from left to right, and top to bottom [7]. The BRISK algorithm utilizes a scale-space key point detector, key point descriptors, and matching algorithm for feature detection. The BRISK sampling patterns are concentric circles used to construct pairwise brightness comparison which help in increasing processing speed [8]. Attempts to improve image quality through better lighting impact the results of SURF and BRISK methods due to changes in lighting contrast. The algorithm utilizes the Hessian matrix \( H(x, \sigma) \) to determine instance in images where there is a change in lighting. Given a point \( x = (x, y) \) in an image \( I \), the Hessian matrix \( H(x, \sigma) \) in \( x \) at scale \( \sigma \) is defined as follows [9]:

\[
H(x, \sigma) = \begin{bmatrix}
L_{xx}(x, \sigma) & L_{xy}(x, \sigma) \\
L_{xy}(x, \sigma) & L_{yy}(x, \sigma)
\end{bmatrix}
\]  

(1)

where \( L_{xx}(x, \sigma) \) is the convolution of the Gaussian second order derivative \( \frac{\partial^2 g(x)}{\partial x^2} \) with the image \( I \) in point \( x \), and similarly for \( L_{yy}(x, \sigma) \) and \( L_{xy}(x, \sigma) \).

Assuming that the reference pixel in the original frame is located at \((x_0, y_0)\) and the point of interest at the location of \((x_i, y_i)\), after deformation and displacement of the concrete surface, these two points will be relocated to \((x_i', y_i')\) and \((x'_{0}, y'_{0})\), respectively. The correlation between the aforementioned points can be expressed as follows [10]:

\[
x'_i = x_i + \alpha(x_i, y_i) \\
y'_i = y_i + \beta(x_i, y_i)
\]  

(2)

(3)
where \( \alpha \) and \( \beta \) are the displacement mapping or shape functions. Assuming a rigid body transition, the following equations can be used to represent the deformed location of the interest points in terms of \( \Delta x = x_i - x_0 \) and \( \Delta y = y_j - y_0 \) [11]:

\[
\alpha(x_i, y_j) = a + a_x \Delta x + a_y \Delta y + 0.5 a_{xx} \Delta x^2 + 0.5 a_{yy} \Delta y^2 + a_{xy} \Delta x \Delta y
\]

(4)

\[
\beta(x_i, y_j) = b + b_x \Delta x + b_y \Delta y + 0.5 b_{xx} \Delta x^2 + 0.5 b_{yy} \Delta y^2 + b_{xy} \Delta x \Delta y
\]

(5)

where \( a \) and \( b \) are directional displacement components of the reference interest point in \( x \) and \( y \) directions, respectively. The first and second order gradients of the reference are denoted as subscript of \( x \) (or \( y \)) and \( xx \) (or \( yy \)), respectively. Figure 1 shows a schematic of the BRISK algorithm.

In this study, an algorithm was developed to detect and extract the features of interest from a series of images to estimate the surface displacement on a cylindrical specimen undergoing compression test. This algorithm deconstructs the video into individual images (frames) that are later scanned and checked for feature detection. Black dots on the surface of each sample were designated features to be detected. The surface area of the concrete sample was painted white to reduce the color distortion caused by concrete surface cavities and texture. Black dots were then marked on the painted surface to use as reference features for tracking during testing. Gridded dots consisted of a collection of hand drawn black dots in a specified matrix form with varying spacing size. Speckle patterns were sprayed on using a spray can and the speckles were randomly applied on the specimen surface. Figure 2 illustrates examples of speckled and gridded dot surfaces prepared for the image acquisition process.

For testing purposes, optimal environment settings were set to increase the ability to detect features. A digital camera capable of recording 30 frames per second at 1080p quality were used in this study to ensure that the number of pixels available for analysis are optimized. Stability is required to reduce the effect of noise in measuring displacements, however minor ground motion was inevitable. Optic Lens was utilized to further focus on the specimen at a safe distance in order to avoid damaging the camera during compression test while increasing size of focused image. The lens assists in optimizing the number of pixels available per frame. Lighting is controlled throughout the process with an LED source to ensure consistency. Placement of lighting source was at an angle to reduce reflection off the concrete sample surface which negatively effects the detection process. Figure 3 shows the laboratory setup for image capturing process.

Once the video is recorded, it is divided into individual frames for analysis. The algorithm then compares before and after images to determine the surface displacement and deformation by tracking the points of interest in the consequent images. The images would be cropped to focus on the interest area to reduce the number of false feature detection. A false detection could occur at edges where light and dark contrast are significantly higher. A base frame was analyzed to determine the initial locations of each feature on the specimen surface to create a matrix of interest points. Upon completion of the
analyses, the strain along x and y directions were calculated and visualized in both graph and heatmap format. The image capturing process was performed at a frequency of 30 frames per seconds.

**IV. DATA PROCESSING AND ANALYSIS**

Data was collected from cylindrical concrete samples prepared in the laboratory. Upon preparing the concrete surface for gridded or speckled marking, the specimens were capped and undergone a compression test at a constant loading rate. The imaging apparatus was setup to capture consequent images of the testing process for further analyses. Upon completion of the test and retrieval of images, the initial feature detection algorithm was performed on the series of captured images. Figure 4a illustrates the results of an initial feature detection process that was performed on a frame during testing. Figure 4b shows a series of features that were located and annotated by the algorithm on one of the initial frames. An area of interest was identified by the user to focus the feature detection and tracking within a specified area of the sample surface. One of the advantages of this algorithm over conventional strain measurement devices is that the user is able to track the movement of many specified points on the surface during the test. Figure 5 shows the images extracted from different stages of the compression test at different focus settings. The algorithm was able to plot a movement trajectory for all the point of interest on the specified images. This features enables the user to track and monitor the surface displacement at almost every point on the specimen surface during testing. The plots of accumulated strain in x-direction at 9 points of interest on the surface were illustrated in Figure 6. Most of the tracked features show a consistent pattern for displacement except for one of them. This could be due to false detection of features between some frames during the analysis period. Improving the lighting conditions and better preparation of surface before testing will reduce the possibility of false positives.
Fig. 6 Accumulated strain along x-direction for different points of interest on specimen surface. (Y axis: displacement in Pixel, X axis: Time x 1/30 of second)

The displacement signal obtained from the initial analyses of the images also reflect some noise due to the missing features or proximity of pixels during the analysis. These noisy signals could be smoothened using a moving average or other smoothing algorithms to produce a more uniform response.

To better represent the trend of developing displacements and surface deformations from the image correlation algorithm, a nested interpolation of strain data was performed on the specimen surface that was captured during imaging process. Superimposing the contour plots of surface deformation during the testing period, generates an animated representation of strain development on the sample surface in form of a heatmap. Figure 7 illustrates a screen captured of the animated strain heatmap during the compression test. The lighter areas in these figures represent higher strains and in some locations cracking of the specimen surface. A higher resolution of this heatmap enables the user to extract meaningful information regarding the crack initiation and propagation on the concrete surface under loading conditions.

Fig. 7 Heatmap of strain measurement in the x- and y-directions.

The next step in this study was to partial validate the results of image correlation algorithm with measured deformations using mounted local strain gauges. To perform the validation process, two linear strain gauges were installed on a frame around the cylindrical specimen to measure the extension and compression of the sample during the compression strength test. At the same time, the image capturing device was setup to acquire images of the sample during the testing process. The strain values calculated from both image correlation algorithm and strain gauge data were plotted on a stress-strain graph to compare the results. Within a reasonable accuracy range, the results of strain measurements from image correlation
algorithm are comparable to those captured by digital strain gauges. Figure 8 shows the results of this partial validation. A more in-depth validation and calibration process are undergoing. The discrepancy between measured and estimated displacements in these figures is mostly due to the unmatched timing of the image capturing process and the unsynchronized frequency of data collection between the gauge and image correlation algorithm. The more in-depth validation of the results from this algorithm is undergoing.

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V. SUMMARY AND CONCLUSIONS

A preliminary version of an image correlation algorithm was developed to capture the surface properties of concrete samples in the laboratory conditions. The accuracy of the developed algorithm is dependent on the stabilization of the image capturing device, lighting source and preparation of surface for proper feature detection. The preliminary results show potential of using this non-contact method to estimate the surface deformation and displacement of concrete samples.

Based on current version of the algorithm, it can be observed that the strain measurements are relatively close to those measured from a digital gauge. Further improvement is being explored in terms of increasing accuracy and speed of calculations. Further investigation into factors that can improve detection of features will improve accuracy of the algorithm.