VIDEO IMAGE-BASED DYNAMIC BEHAVIOR ANALYSIS OF CONCRETE STRUCTURES BY USING DIGITAL IMAGE CORRELATION METHOD

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This paper describes an experimental study on video image-based analysis by using digital image correlation (DIC) to acquire the dynamic behaviors of concrete structures. We used video images recorded by a high-frame-rate camera in laboratory and field tests and then calculated the time series of the in-plane displacement fields of the images to measure the behaviors of concrete structures, such as changes in deflection and cracking. The results obtained from a cyclic loading test on a damaged T-shaped concrete beam successfully proved that our method provided reasonable dynamic deflection and crack-opening displacement. A concrete bridge slab was measured from the ground in a field traffic loading test. It was found that the in-plane displacement of images was affected by deflection due to live loading; thus, we estimated deflection by using video images recorded under the slab. The estimated deflection was satisfactorily found to correspond to measurements obtained from a laser displacement sensor. Moreover, we demonstrated the extraction of the displacement in maximum crack opening by subtracting the estimated deflection.

Key Words: digital image correlation, displacement distribution, concrete, crack opening displacement

1. BACKGROUND

It is important to evaluate structural performance and soundness to maintain concrete structures, such as bridges. Structural behaviors such as displacement, strains, and cracks caused by environmental loadings, e.g., traffic, wind and earthquakes are often investigated in these evaluations. There are two kinds of techniques that are used to measure such structural behaviors: contact and non-contact. Contact techniques such as those involving linear voltage differential transformers (LVDTs) and electrical strain gauges have been widely used for measurements. These sensors have several advantages, such as high levels of accuracy, precision, and reliability. However, it is difficult to detect the occurrence of cracking in its structural behaviors, and trace its development using contact sensors because the places where cracking occurs cannot be determined beforehand. There is also a disadvantage in assessing...
multiple measurement points because each measurement point requires a sensor and a cable. Few studies have applied such contact sensors to in-situ crack measurements on real bridges for these reasons. 1), 2)

However, non-contact techniques of measurement, especially, optical measurement techniques, i.e., speckle interferometry, moiré interferometry, and digital image correlation (DIC) have attracted significant attention. These techniques have been expected to contribute to a wide range of applications, e.g., clarification of fracture mechanisms in material engineering. As these optical techniques are suitable for multiple point measurements of large areas, applications have spread rapidly in the field of civil engineering. Strain measurements on loaded specimens and vibration measurements of bridges have been reported3)-6) with the use of installed targets or grid patterns on monitored structures, or specifically featured surfaces of structures. As no specific optical equipment on monitored structures is particularly required for DIC, its unique advantages have attracted a great deal of attention from the structural monitoring field. The output of DIC exhibits in-plane displacement, i.e., the magnitude and direction of vectors of the whole area of the optical field. An earlier study proposed that concrete structures be evaluated by their deformation or strain fields based on in-plane displacements of DIC. Yoneyama et al. investigated the behavior of a deformed bridge by comparing photographs before and after a heavy vehicle was loaded7). Takano et al. successfully identified the location of a shear crack on a beam specimen, based on the direction of principal strain through the conversion of a strain field measured by DIC8). Additionally, various applications have been investigated, e.g., three-dimensional measurements by stereo cameras and the combination of DIC and field tests were analyzed by DIC, and we experimentally evaluated the technique in terms of the detection of deflection and crack openings calculated by in-plane displacement of DIC.

2. DIGITAL IMAGE CORRELATION

DIC is a method that is used to calculate the magnitude and direction of deformation vectors of a field, as a result of searching correlated areas in subsequent frames in comparison with the reference frame and dealing with digital image information on the surface of monitored structures. In fact, \( N \times N \) pixels can be found around a specific point by searching the area of subsequent frames by coarse and fine image matching based on the brightness information of a small area, which is generally called a subset. As shown in Fig. 1, DIC can measure in-plane displacements of small areas in the field of image sensors.

First, the location of the subset in the deformed digital image that matches the most correlated digital image information, e.g., brightness information, with an initial image as the reference image is selected as integral coordinates on the x-y plane of the image. A parameter is simultaneously introduced to evaluate the extent of its correlation. The following Eq. (1) describes the sum of squared differences (SSD), where \( Q(i,j) \) are the brightness values of pixels in the subset of the original image, and \( P(i,j) \) are those of the following image. The integral coordinates \( (x, y) \) correspond to the deformed location of the subset, when parameter \( R \) is the smallest in the field.

\[
R = \sum_{i=1}^{N} \sum_{j=1}^{N} [P(i,j) - Q(i,j)]^2
\]  

(1)

Next, the location of the subset in deformed image is re-calculated in sub-pixel order with the use of smoothing to provide the integral coordinates, which are given by coarse matching, as the initial values. The fitting of a quadric curve is presented in Fig. 2 as an example of smoothing discrete data. Location \( d \) is determined when parameter \( R \) in Eq. (1) has the minimum sub-pixel coordinates by introducing a quadric curve to fit the three adjacent pixels. Sub-pixel coordinates on the \( x \)- and \( y \)-axes, \( dx \) and \( dy \), are determined independently with this method. The following explains the calculation of sub-pixel coordinate \( dx \) on the x-axis. Parameter \( R_{sm} \) is given by

![Fig. 1 Conceptual overview of DIC.](image-url)
substituting \((x, y)\) that are the minimum parameters in coarse matching into Eq. (1), and parameters \(R_{1x}\) and \(R_{1y}\) are given by substituting \((x-1, y)\) and \((x+1, y)\) that are placed along the \(x\)-axis, \(dx\). The \(dx\) is the difference between coarse and fine matching, and is expressed by Eq. (2):\(^{18}\)

\[
dx = \frac{R_{1x} - R_{1x}}{2R_{1x} - 4R_{0x} + 2R_{1x}}
\]  

Similarly, the sub-pixel coordinate \(dy\) on the \(y\)-axis is expressed by Eq. (3).

\[
dy = \frac{R_{1y} - R_{1y}}{2R_{1y} - 4R_{0y} + 2R_{1y}}
\]

The location of the subset, \((x+dx, y+dy)\), are calculated as a result of this coarse and fine matching. All the frames can be processed in the same way. Consequently, the time series of deformation vectors in the field can be observed. The SSD in coarse matching was introduced in this study as the evaluation parameter and the quadric curve in fine matching was introduced as the fitting curve.

The size of subset \(N\) is discussed for reference. The larger the size of subset \(N\), the higher the precision of matching by using the SSD parameter, in the case of movement of the subset in one direction. However, there are many directions in the subset, e.g., when the foreground in the frame moves in the opposite direction to the background, the value of SSD tends to be larger. Furthermore, poor SSD parameters result in worse precision in fitting, thus making it impossible to accurately determine matching coordinates. It is important to determine the size of subset \(N\) appropriately depending on the object because of the high possibility of change in the direction of movement with large \(N\). We concluded that \(N\) was 32 as a result of preliminary processing.

The outcome of DIC represents the displacement/strain field in image coordinates, i.e., in pixels. The length per pixel on the monitored structure is found by converting units. For example, the length can be calculated by using a mounted scale on the structure; otherwise, the fact that the ratio of the focal length to the camera-to-object distance corresponds to the ratio of the pixel size of the image sensor to the pixel size on the object will directly lead to the length. The length in the latter can be easily calculated by using the distance to the structure being shot and the specifications of both the image sensor and optical lens. Thus, we only have to measure the distance from the camera to the object; of course, we do not have to approach the structure as long as we use a laser range meter.

3. RC BEAM TEST

(1) Experimental setup

The deflection and crack opening under cyclic loading were measured in a beam bending test by evaluating the basic performance of high-speed recorded DIC. As outlined in Fig. 3, a three-point bending test on a T-shaped reinforced concrete (RC) beam was carried out, where the length of the span was 600 mm and that of the specimen was 1,800 mm. The beam specimen was already damaged and the largest crack at the center on the bottom had been placed towards 45 degrees and passed throughout the width of the specimen. The width of the crack was approximately 2.0 mm on the bottom surface. A linear relationship was confirmed before the beam bending test between the loading force and stroke of the jack in the range of 10–15 kN. The specimen in the test was repetitively loaded at 5 Hz, while the amplitude of the stroke was around ±45 \(\mu\)m. A random pattern was spray-painted on the side surface of the beam, which increased the correlation of image matching. Crack gauges were placed on the other side to directly measure the crack opening. The behavior of the specimen under loading was estimated by linear analysis using finite element method (FEM). The shape of the crack was only modeled in this static linear analysis and the interfacial effect of the crack and adhesion of the rebar were neglected to gain an approximate understanding of the behavior of the loaded specimen.

A video of the center of the specimen was recorded with a high-speed camera at 100 fps, which was illuminated by incandescent lighting. The length per pixel on the object was approximately equal to 244
μm/pixel, whereas the shooting distance was around 3.5 m. The stroke of the jack and crack opening were instrumentally recorded at 500 Hz. This reference measurement was not synchronized with the video; thus, time synchronization had to be post-processed. The deflection was measured with the jack stroke and the crack opening was measured with a clip gauge as a result of DIC. There is a photograph of the experimental setup in Fig. 4 and an example of the recorded frame in Fig. 5.

(2) Deflection measurements

The vertical displacement field used in the FEA and DIC measurements are illustrated in Fig. 6. The contours indicate the magnitude of vertical displacement at a specific moment, setting the beginning of the video as the initial value. The deeper the purple, the larger the area of vertical deformation. Maximum displacement occurred at the crack on the bottom in both results, and they indicate similar fields.

Vertical displacement that was calculated at point “a”, which can be seen in Fig. 6(b), is discussed in the following. The image coordinates of point “a” were (1045, 950) at the beginning of the video. First, the image coordinates in the next frame based on coarse matching by SSD parameters were determined as an integer by matching the 32×32 pixel subset at point “a” in the initial frame. After 1.7 s, i.e., the moment in Fig. 6(b), the minimum values were at (1045, 950). At that point, parameter $R(=R_x=R_y)$ indicated 598728. Next, subtle vertical displacement around coordinates (1045, 950) was calculated by fine matching with quadric curve fitting. It is a fact that $R_{1y}$ at (1045, 949) indicates 706789 and $R_{-1y}$ at (1045, 951) indicates 623361. Vertical displacement $dy$ results in 0.314 by introducing such values, viz., $R_y$, $R_{1y}$, and $R_{-1y}$, into Eq. (3). The length per pixel of the monitored surface can convert $dy$ to the length of a real coordinate. As a result of conversion by using 244 μm/pixel, which was actually measured by a scale attached to the specimen, we concluded that vertical displacement was 76.6 μm. This computation was repeatedly processed for all frames captured at 100 fps by knowing the time series of the displacement distribution in the field.

The measured displacements along the top of the beam, which correspond to deflection at points “a”–“d” in Fig. 6(b), are plotted in Fig. 7. Again, the initial value does not occur at the beginning of loading, but at the beginning of recording. The jack stroke, which can be assumed to be deflection at the center of the beam, is also provided in the figure. It can easily be seen that the beam was sinusoidally vibrated and the magnitude of vibration increased toward the center of the specimen. Although there was a difference between measurements at point “a” and the jack stroke because of the different locations of measurements, the DIC results are consistent with the reference measurements that oscillated with a 45-μm amplitude at 5 Hz. It can be concluded that DIC with high sampling frames provided the magnitude of deflection at multiple points; therefore, the deflection mode could be directly estimated.

Compared to the jack stroke, measurements with DIC seemed to have a little variation. Such error
might be derived from heated air due to illumination; in fact, we observed fluctuations in air reflective indices during the test.

(3) Crack opening measurements

The horizontal displacement field of FEA and DIC measurements are illustrated in Fig. 8. The contours indicate the magnitudes of horizontal displacements at specific moments, setting the beginning of the video as the initial value. The warmer the color, the larger the area of horizontal deformation. There is scattering in the contour in the unfocused region controlling both the focal length and the range of brightness to focus on the cracked region. The measurements indicate that the right half of the specimen moved in the opposite direction to the left half; thus, DIC provided similar findings to the analytical results. Furthermore, it can be observed that the displacement at the top of the specimen changes gradually along the specimen. As the crack has little effect, it can be assumed that a continuous displacement field due to strain mainly occurred at the top of the specimen. However, a discontinuous displacement field appeared at the bottom of the specimen. The location and the shape of this discontinuity corresponded to the observed cracking. Therefore, it can be concluded that discontinuous displacement was derived from the crack opening due to loading.

The measured displacements at the bottom of the beam, which correspond to displacements at points “L” and “R” in Fig. 8(b), are plotted in Fig. 9. Again, the beginning of shooting is the initial moment of measurement. Some fluctuations can be seen in Fig. 9 that are similar to those in Fig. 7; however, it can easily be observed that the left part sinusoidally moves in the opposite direction to the right part. The difference between these two movements can be assumed to correspond to the displacement of the crack opening presented in Fig. 10, which is accompanied by measurements obtained from the clip-on gauge. Both provide comprehensive information, viz., the crack opens and closes repeatedly at 5 Hz in the range of 20 μm, which is approximately equal to 1/12 of a pixel. The results indicate that DIC with a high frame rate has the potential of enabling the displacement of crack openings to be measured as well as automatic crack extraction due to live loading.

4. BRIDGE TEST

(1) Experimental setup

We applied the method to a bridge that was in service to demonstrate its practical performance in the field. Videos were captured when heavy traffic passed along a bridge built in 1989. The displacement field was measured by DIC with a high sampling frame camera at both an RC hollow slab and an RC slab. No painting on the surface of the structure was required in this test because its aged dusty surface fortunately worked as random patterns for image matching. The measured deflection and crack open-
ing displacement by DIC were evaluated by comparing reference measurements such as those obtained from a laser displacement sensor and clip-on gauge. The specifications of the reference measurements are tabulated in Tables 2 and 3. Since exact synchronization was beyond the scope of this study, no measurements were synchronized.

(2) Deflection measurements of RC hollow slab

The movement of a bridge railing was recorded by a camera with a 100-mm optical lens at 100 fps at the center of a span, which was made of an RC hollow slab with a length of 18 m, on an exit ramp. Deflection was calculated from the vertical displacement field captured from the ground at an elevation angle of 20 degrees, as can be seen from Figs. 11 and 12. The object in this case was located at a distance of 10.8 m from the camera, and the length per pixel on the object was 700 μm/pixel. The deflection of the slab was directly measured with a laser displacement sensor at 166 Hz for reference. A reflective target was placed on the bottom surface of the slab, and the laser was placed below the target to illuminate it vertically.

Deflection due to heavy vehicles was measured with both DIC and a laser, and the results are presented in Fig. 13. Based on the displacement field obtained by DIC, deflection was obtained by using the vertical displacement of a specific point on the bridge railing where the initial moment was the beginning of the video. As was previously explained, both results were not synchronized; thus, time was roughly calibrated to meet the moment at which maximum deflection occurred. No matter how much neither was synchronized, there were no problems as long as we investigated the time series behavior and the maximum deflection in terms of each measurement. Both measurements indicated that the maximum deflection at 600 μm occurred when traffic passed over the span. In more detail, the time series values of the two measurements differed because of different measurement locations. DIC measured deflection at the bridge railing, while the laser measured deflection at the center of the slab. DIC measurements were more successful and had higher resolution than the laser measurements. As a result, DIC measurements could clearly reveal that the slab

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**Table 2 Specifications of laser displacement sensor.**

| Laser output | Class 2 |
|--------------|---------|
| Measurement length | 0.15–70 m |
| Precision | ±2 mm |
| Repetitive accuracy | 0.5 mm |

**Table 3 Specifications of clip-on gauge.**

| Rating capacity | 2 mm |
|-----------------|------|
| Non-linearity error | Less than 1 %RO |
| Repetitive | Less than 1 %RO |
| Rated output | 2.5 mV/V (5,000×10^4) |

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![Fig. 11 Schematic of field test on RC hollow slab.](image1.png)

![Fig. 12 Experimental setup for field test on RC hollow slab.](image2.png)

![Fig. 13 Measured deflection in field test on RC hollow slab.](image3.png)
bounced up when traffic approached and departed. Unfortunately, obviously different behaviors occasionally occurred due to changing information on brightness, such as drastic changes in insolation due to fast-moving clouds during recording and reflected light from vehicles passing from adjacent lanes. In fact, over one pixel of error in displacement measurements never occurred with less than 10% in brightness variations. However, over one pixel in error occurred with more than 20% in brightness variations. As the SSD parameters were affected by the change in brightness, image matching might have failed. Another robust evaluation parameter has to be developed to solve such problems.

(3) Deflection and crack opening measurements of RC slab

The undersurface of the slab was recorded by a camera with a 180-mm optical lens at 100 fps at the center of a span, which was made of a steel-beamed RC slab with a length of 35 m. The crack opening displacement was estimated by using the measured displacement field, as shown in Figs. 14 and 15, by capturing the video vertically from the ground. The object in this case was located 8.433 m from the camera, and the length per pixel on the object was 333 \( \mu \)m/pixel. A clip-on gauge was installed on the existing crack for reference, which directly measured the crack opening displacement at 100 Hz. A reflective target was placed on the bottom surface of the slab, and a laser was placed below the target to emit a vertical beam. Thus, the deflection of the slab could be directly measured with a laser distance meter, as was explained in the previous bridge test. There is an example of a captured frame in Fig. 16.

Figure 17 outlines the effect of the out-of-plane displacement of the slab when shooting overhead from the ground. When heavy traffic is passing, the distance between the camera and the object \( l \) is shortened due to the deflection of the slab, as shown in Fig. 17. As a result, the captured image appears to have been enlarged from the center of the optical lens; in other words, “apparent displacement \( (\delta) \)” has occurred. Thus, the displacement field on the cracked surface is not only affected by pure in-plane displacement of the slab including crack opening displacement, but also by out-of-plane displacement of the slab. Such “apparent displacement” has to be extracted to identify the crack opening displacement. Equation (4) expresses “apparent displacement,” where \( x \) denotes the length from the optical axis to the observation point and \( f \) denotes the focal length.

\[
\delta = xf \left( \frac{1}{1 - \frac{\delta}{l}} - 1 \right) \tag{4}
\]

The displacement in the specific length of the
non-cracked surface, Un and Ln, and those in the cracked surface, Uc and Lc, are shown with clip-on gauge measurements in Fig. 18. The original distance between Un and Ln, and the distance between Uc and Lc are the same, i.e., 570 pixels, which is equal to ~187 mm. Let us focus on the displacement of Un-Ln. It can be estimated that the value of Un-Ln only includes “apparent displacement” due to slab deflection, as was previously explained. We found that such displacement was much larger than the measured crack opening displacement that we wanted to detect with DIC. Slab deflection was calculated by using both Eq. (5) converted from Eq. (4) and the “apparent displacement”, Un-Ln. The results in Fig. 19 are those obtained with measurements by the laser. We confirmed that the calculated deflection was in good agreement with that obtained by the laser, in fact, both approximately detected the maximum deflection of 2 mm. Slight differences were assumed to be errors due to the different measuring locations.

\[
\delta = 1 - \left(1 - \frac{xf}{l \delta + xf}\right) 
\]

We then investigated the displacement in Uc-Lc. Note that the value of Uc-Lc includes both “apparent displacement” due to slab deflection and in-plane displacement due to crack opening. Crack opening displacement was calculated by using the differences in Uc-Lc by removing the effect of “apparent displacement”, which was derived from the measured Un-Ln. The time histories of the calculated crack opening are plotted in Fig. 20. We found that DIC provided reasonable crack opening displacement; in fact, both provided 5 \(\mu\)m in maximum displacement. We measured crack opening displacement, which was a maximum of 5 \(\mu\)m for 0.05 s, by applying DIC to the video recorded at 100 fps. Although we needed to increase the accuracy of image matching and the speed of capture, this study revealed the possibility of measuring deflection using the displacement field measured with DIC, and indicated the possibility of measuring crack opening displacement by extracting “apparent displacement.”

5. CONCLUSIONS

DIC was used in conjunction with high-speed cameras in both laboratory and field tests, and the dynamic behaviors of concrete structures were then measured. The time histories of the distributions of wide-range displacements could be analyzed with this method by processing frames that were captured at high sampling rates. We derived two main conclusions from the results obtained from our experi-
mental study:

- The time series of displacement distributions could be calculated by DIC through repetitive dynamic loading tests on a concrete beam that was recorded by a high-speed camera at a distance of 3.5 m. The measured deflection of the specimen yielded consistent results, i.e., 40 µm, with reference to the stroke of the loading jack. Additionally, the occurrence of a crack opening was clearly observed. The differences in displacements between two points located across the crack corresponded to crack opening displacement, i.e., 20 mm, which is equivalent to 1/12 pixel at maximum, measured with a clip-on gauge.

- The bridge railing on a RC hollow slab, whose span was 18 m in length, was recorded with videos at high sampling rates, and the deflection of the slab, which was approximately 600 µm, was successfully measured by DIC from 10.8 m away. Deflection of the slab, which was approximately 2 mm, was calculated by “apparent displacement” due to out-of-plane displacement by using upward recorded videos of the undersurface of a steel-beamed RC slab, whose span was 35 m in length. Moreover, this suggested the potential to measure crack opening displacement, which would remove the need for “apparent displacement.”

The authors in this study examined the capabilities of DIC to dynamically measure deflection due to the live loading and crack opening displacement of concrete structures in-situ by recording videos with a high-speed camera. We experimentally confirmed that deflection could be measured by both shooting horizontally and vertically, i.e., specifically shooting videos on both the side surfaces and undersurfaces of bridges. It is not necessary to restrict traffic to monitor the deflection and its time series behavior of a bridge. The potential for measuring crack opening displacement is particularly suggested by the removal of “apparent displacement” due to out-of-plane deflection. Actually, cracks open immediately within only 0.05 s when heavy traffic is passing. This method never misses such rapid behavior in such short periods, as captured by a high-speed camera. Therefore, only loaded cracks might be selectively detected, while conventional methods sometimes fail to detect cracks in strained surfaces.

Increasing the range of applications such as the detection of concrete delamination by using characteristic vibrating properties can be expected in the near future with the improved frame rates of cameras and image matching\(^{(1)}\). Unfortunately, we found that DIC measurements were very sensitive to in-situ sunshine variations in the experiments. Investigations into video shooting configurations and image processing have to be done to achieve higher levels of robustness.

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