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OPTICAL FULL-FIELD DISPLACEMENT MEASUREMENT METHOD BASED ON PHASE-ONLY CORRELATION

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Abstract

Measuring the deformation of structural members is fundamental to evaluating the performance of structures. As an effective and practical method for measuring the deformation of structures, digital image analysis techniques are gradually becoming accepted in the field of experimental mechanics. In the present study, an optical measurement method for reinforced concrete frame structures based on the phase-only correlation method is proposed. The proposed method directly provides displacements and strains on the surface of a reinforced concrete frame by analyzing digital images. The proposed non-contact measurement method can be used to measure deformations of a measurement object and has a sub-pixel-level measurement accuracy when using an analytical algorithm. Moreover, the proposed method can be used to measure the full-field deformation and to visualize deformations. The main objective of the present study is to evaluate the validity of the proposed measurement method by conducting an experimental test on a reinforced concrete frame specimen. The proposed measurement method consists of optical imaging devices and computers for image analysis. After capturing digital images of the surface of the measurement object, the computer calculates the motion of each measurement point on the images by comparing the phase correlation of a subset field in the reference image and the deformed image. The variation of the center of the subset field is calculated as a displacement, by tracking the highest correlation subset. The measurement accuracy depends on the pixel size because the phase correlation of pixel values of the image data is used. However, the deformation of the structural members is smaller than the image pixel size. In order to measure the deformation with high accuracy using an optical method, measurement of the sub-pixel level displacement is required. The proposed method can be used to measure sub-pixel level displacement by using the phase-only correlation method. Verification is performed based on the measurement results of a test involving a reinforced concrete frame specimen. Comparison of the measurement results reveals that the accuracy of the proposed measurement method is approximately the same as that of the results obtained using a displacement meter. Moreover, the proposed method can track the behavior of a concrete specimen after it has cracked. The agreement between the concrete cracking position and the local strain position in the strain distribution confirms that the proposed method can be used to visualize the full-field deformation of an object surface.

Keywords: non-contact type measurement; digital image analysis; phase-only correlation method; reinforced concrete; beam-column joint

1. Introduction

In evaluating the seismic performance of reinforced concrete (RC) structures, it is of fundamental importance to measure the deformation behavior at the time of external force action. Conventionally, deformation measurement is performed through contact-type measurement methods using displacement meters or strain gauges. However, there are cases in which the physical constraints of the equipment complicate the measurement because the measurement requires contact with the target object. Furthermore, such methods require a large number of measurement devices when observing the deformation of a target object in detail. The detailed fracture behavior of RC structures is difficult to track using conventional measurement methods because strain gauges are difficult to measure after concrete cracking.

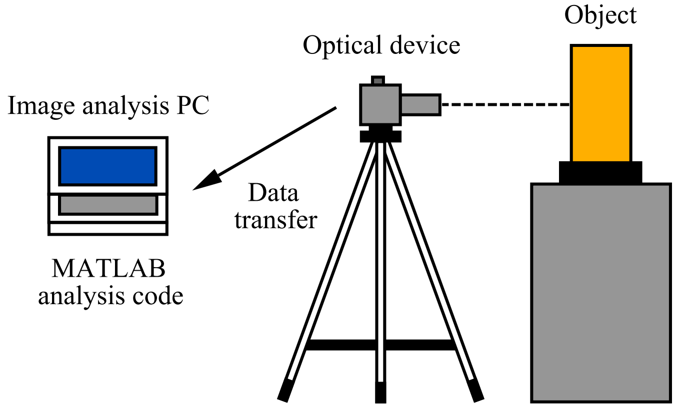


Fig. 1 – Basic configuration of the proposed measurement method

On the other hand, several optical full-field measurement methods using optical instruments such as digital cameras have been developed in recent years [1, 2 and 3]. Such non-contact deformation measurement methods can easily observe the deformation behavior of entire objects in detail. In previous studies on an optical deformation measurement method using digital image analysis, digital image correlation (DIC) method is generally used. Although DIC is very useful, a random pattern must be applied to the surface of the measurement object. Moreover, the measurement accuracy is greatly influenced by surrounding disturbances. Therefore, due to the occurrence of a large number of cracks in RC structures, the measurement accuracy is expected to decrease as a result of shape changes and peeling of the pattern on the concrete surface.

In the present paper, a new flexible, high-precision optical full-field deformation measurement method based on phase-only correlation (POC) method is proposed. The proposed measurement method is discussed with a focus on POC method, and a measurement test is performed using a cross-shaped RC frame specimen. In order to validate the proposed method, optical measurement of the deformation of RC specimens is performed and the obtained results are compared with measuring results using contact-type measurement method. Comparison of the measurement results revealed that the proposed measurement method can accurately track the deformation behavior of the specimen, and the detailed strain distribution on the surface of RC beam-column joints can be obtained.

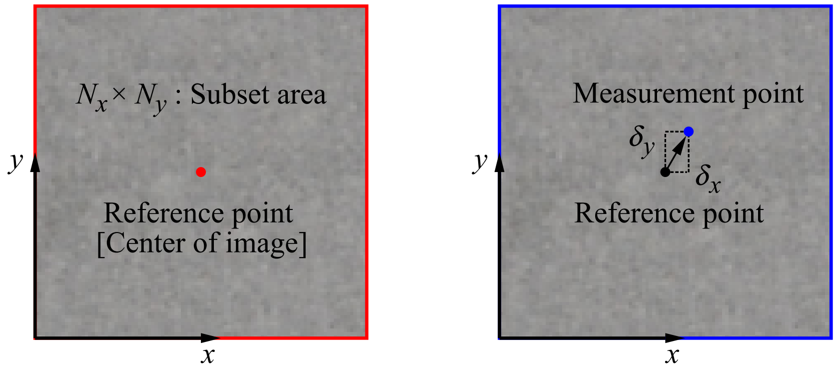
2. Optical full-field measurement method based on the phase-only correlation method

2.1 Optical full-field measurement method

Fig. 1 shows the basic configuration of the proposed measurement method. The proposed method uses a digital camera as an optical device and an image analysis PC for digital image acquisition. As auxiliary equipment, white LED lights provide constant illumination of the measurement target surface. The deformation of the entire measurement object is recorded as image information by the digital camera. After transferring the image data to the analysis PC, the full-field deformation of the target object in the non-contact state can be determined by analyzing the acquired image data. The proposed method has high practicality owing to be implemented using a commercially available digital camera.

2.2 Concept of image analysis method

In this section, an outline of the image analysis method used to calculate the displacement of the measurement point is presented. Fig. 2 shows the principle behind the calculation of the measurement point displacement with examples of analytical images. As shown in Fig. 2(a), an arbitrary point is set as the measurement reference point in the reference image, and the subset area is centered at this point. Furthermore, Fig. 2(b) shows the deformation or rigid displacement of the target object and indicates that the measurement reference point is



(a) Reference image (b) Deformed image

Fig. 2 – Measurement point and subset area used in image analysis

displaced within the subset region. In order to track the coordinates of the measurement point, the horizontal and vertical displacements, denoted by δ_x and δ_y, respectively, of the measurement point shown in the figure are computed by analyzing images before and after displacement. The phase-only correlation method described in the next section obtains the POC function from the subset area image, and the peak position can be tracked as the measurement point. In actual measurement, it is possible to determine the strain and deformation between measurement points by analyzing multiple reference points in the image data. Furthermore, by applying this image analysis process to all of the obtained image data, it is possible to determine the transition of the deformation of the entire measurement object.

2.3 Concept of the phase-only correlation method

The phase-only correlation (POC) method [4] is intended for use in digital image matching and is possible to detect parallel displacement between images with high accuracy. Furthermore, the POC method has high robustness against unavoidable noise such as lighting flickers or luminance variation in measurement. Thus, the POC method is expected to provide improved accuracy for optical deformation measurement. This fact is advantageous when optically measuring the minute deformation behavior of an RC structure. Fig. 3 shows the calculation flow of the POC method. The reference image $f(n_x, n_y)$ and the deformed image $g(n_x, n_y)$ are separated into amplitude and phase components by two-dimensional discrete Fourier transform (2D-DFT). The cross spectrum $R(k_x, k_y)$ obtained using only the phase component of the two images is given by the following equation:

$$R(k_x,k_y) = \frac{F(k_x,k_y)\overline{G(k_x,k_y)}}{\left|F(k_x,k_y)\overline{G(k_x,k_y)}\right|} = e^{j\{\theta_F(k_x,k_y)-\theta_G(k_x,k_y)\}} \tag{1}$$

where $F(k_x, k_y)$ is the two-dimensional discrete Fourier transform of the reference image, $\overline{G(k_x, k_y)}$ is the complex conjugate of the two-dimensional discrete Fourier transform of the deformed image, $\theta_F(k_x, k_y)$ is the phase component of the reference image, and $\theta_G(k_x, k_y)$ is the phase component of the deformed image.

The POC function $r(k_x, k_y)$ is the two-dimensional inverse discrete Fourier transform of $R(k_x, k_y)$ and is expressed as follows:

$$r(k_x,k_y) = \frac{\alpha}{N_x N_y} \frac{\sin\{\pi(n_x+\delta_x)\}}{\sin\{\pi(n_x+\delta_x)/N_x\}} \frac{\sin\{\pi(n_y+\delta_y)\}}{\sin\{\pi(n_y+\delta_y)/N_y\}} \tag{2}$$

where α represents the correlation peak height, N_x is the number of pixels in the horizontal direction in a subset area, and N_y is the number of pixels in the vertical direction in a subset area.

Fig. 4 shows three- and two-dimensional plots of the POC function. As shown in the figure, the POC

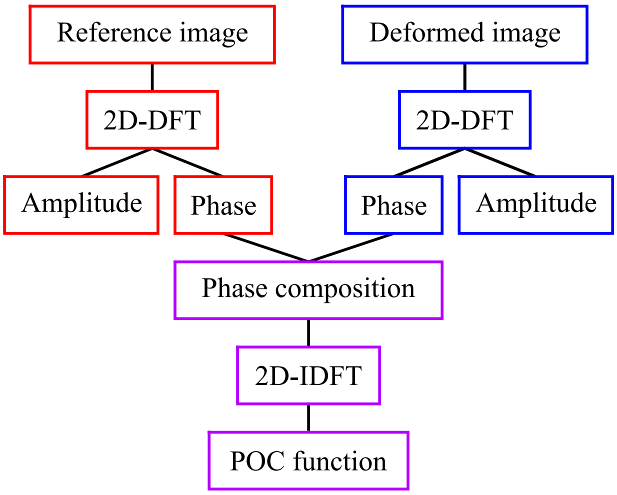


Fig. 3 – Computational flow of the POC method

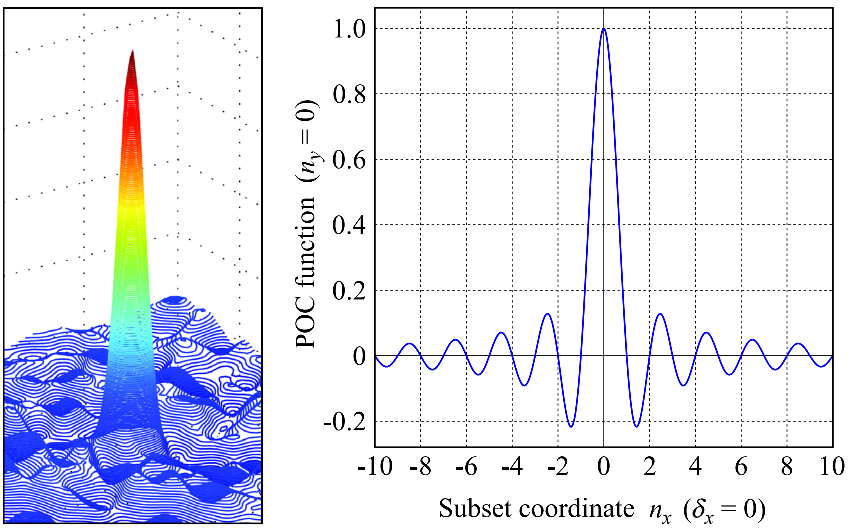


Fig. 4 – Three- and two-dimensional plots of the POC function

function is characterized by a very clear peak, which enables highly accurate measurement point tracking. Furthermore, by using the POC method to eliminate the amplitude component, which includes information on the luminance change and noise in the captured image data, robust image matching of the effects of the disturbance, is possible.

2.4 High-precision technique for optical displacement measurement

In the calculation process of the POC method described in the previous section, the minimum displacement as determined by tracking the measurement point depends on the pixel size of the image, which is the smallest unit of image data. In general, however, the order of the displacement required for the measurement of RC structures is often smaller than the pixel size of the image data. Therefore, in order to perform highly accurate measurement using an optical deformation measurement method, sub-pixel level displacement estimation is required. In the present study, high-precision techniques for optical measurement, as described in the following, are used in order to enable sub-pixel displacement measurement.

2.4.1 Window function for eliminating the effect of periodicity in discrete Fourier transform

A discontinuity appears at the edge of the image data in two-dimensional discrete, which is known to be problematic. In order to reduce the effect of this discontinuity, the following two-dimensional Hanning window function:

$$w(n_x, n_y) = \frac{1-\cos\left(\frac{2\pi n_x}{N_x}\right)}{2}\frac{1-\cos\left(\frac{2\pi n_y}{N_y}\right)}{2} \tag{3}$$

is applied to the measurement image data.

2.4.2 Application of the Gaussian weighting function

When a noise or disturbance is applied to a digital image and the signal-to-noise ratio of the high-frequency component is known to degrade significantly, the image matching accuracy of the POC method is reduced. In order to reduce the influence of high-frequency components, a Gaussian weighting function (low-pass filter) is applied during the calculation process of the phase-only correlation method. In the present study, an improvement in measurement accuracy is expected by applying the following Gaussian weighting function:

$$H(k_x, k_y) = e^{-2\pi^2\sigma^2\left(\frac{k_x^2}{N_x^2}+\frac{k_y^2}{N_y^2}\right)} \tag{4}$$

where σ represents the Gaussian width.

2.4.3 Estimation of sub-pixel displacement using the peak evaluation formula

The estimated displacement of the ordinary POC method is an integer number of pixels. Therefore, it is difficult to accurately estimate the displacement of the measurement point. In order to perform highly accurate optical displacement measurement, it is essential to compute the sub-pixel displacement that exists as a real number of pixels of image data. In order to determine the sub-pixel displacement, it is necessary to perform fitting of the correlation peak model using the correlation value of the measurement point in pixel-level estimation and the nearest neighbor point value. In the present study, the sub-pixel displacement of the measurement point (δ_x, δ_y) is estimated as follows using the peak evaluation formula of the POC function [5]:

$$\delta_x = \frac{\ln\{r(p_{x+})\} - \ln\{r(p_{x-})\}}{2\ln\{r(p_{x+})\} - 4\ln\{r(p_x)\} + 2\ln\{r(p_{x-})\}} - p_x \tag{5}$$

$$\delta_y = \frac{\ln\{r(p_{y+})\} - \ln\{r(p_{y-})\}}{2\ln\{r(p_{y+})\} - 4\ln\{r(p_y)\} + 2\ln\{r(p_{y-})\}} - p_y \tag{6}$$

where p_x is the horizontal displacement of the measurement point on the pixel size level, p_{x+} (= p_x + 1) and p_{x-} (= p_x - 1) represent the coordinates of the nearest neighbor p_x, p_y is the vertical displacement of the measurement point on the pixel size level, and p_{y+} (= p_y + 1) and p_{y-} (= p_y - 1) represent the coordinates of the nearest neighbor p_y.

3. Overview of the measurement test of the RC beam-column joint specimen

An RC beam-column joint test is conducted in order to confirm the validity of the proposed measurement method. Fig. 5 shows an overview of the RC beam-column joint specimen. The specimen is a cross-shaped RC beam-column joint of approximately one-third scale, and is designed to be preceding shear failure of the joint position. The red area indicates the image analysis range of the loading position and joint position in the optical measurement. The blue dot represents the measurement position of the displacement meter that is disposed in the loading position to correspond to the image analysis range. The lower end of the column is supported by a pin

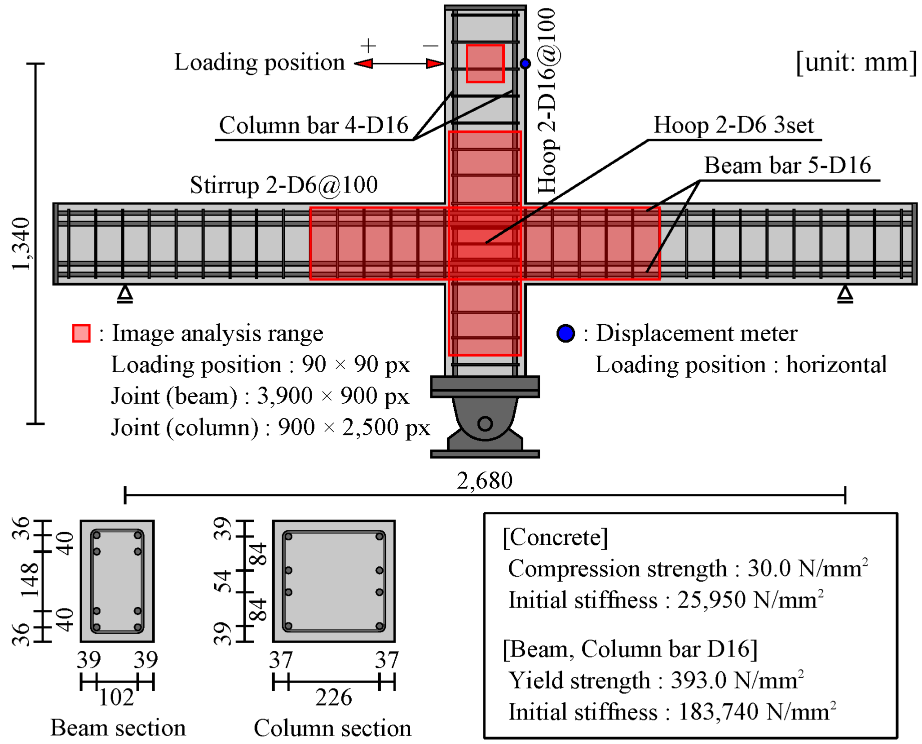


Fig. 5 – Overview of the cross-shaped RC beam-column joint specimen

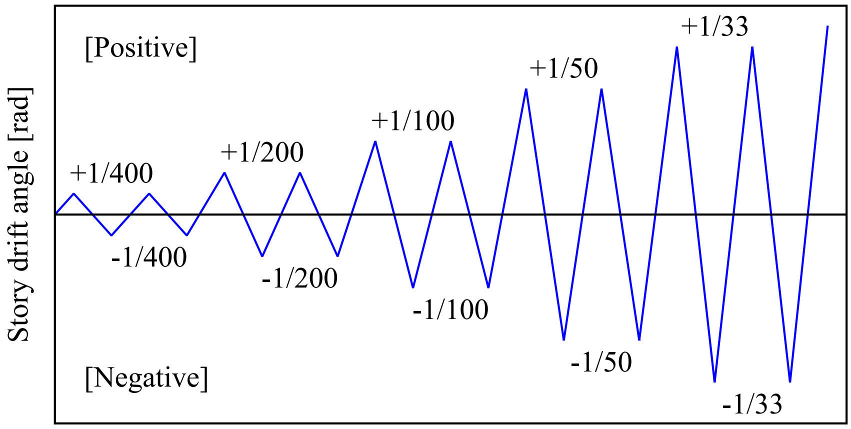


Fig. 6 – Loading schedule of the RC beam-column joint specimen

connection, and the right and left beam ends are supported by pin-rollers. The upper end of the column was subjected to cyclic loading: two cycles each at story drift angles of 1/400 [rad], 1/200 [rad], 1/100 [rad], 1/50 [rad], and 1/33 [rad] (Fig. 6).

Two digital still cameras (body: Nikon D300S, lens: AF-S DX NIKKOR 18-200 mm f/3.5-5.6G ED VR II) and a digital video camera as a spare (SONY HDR CX-900) were used in the measurement test. Furthermore, multiple white LEDs were used to maintain constant illuminance of the measurement target surface, and blackout cloth was placed on the back of the specimen to reduce the influence of disturbances generated in the measurement environment. As shown in Fig. 7, no special treatment, such as target markers or a random pattern, was applied to the concrete surface of the RC beam-column joint specimen.

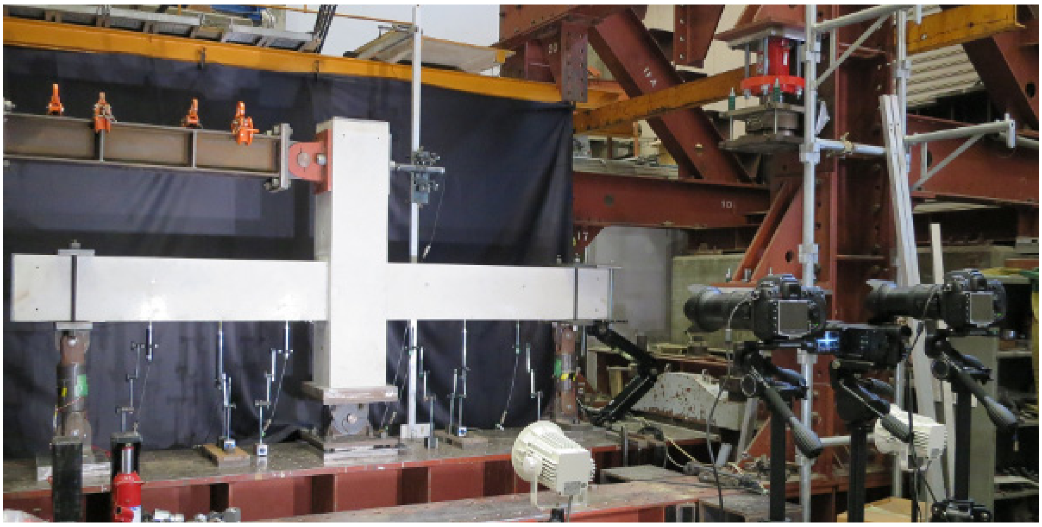


Fig. 7 – Setup for the measurement test

Table 1 – Settings used in the measurement and image analysis

Measurement distance	Measurement interval	Focal length	Diaphragm value	Number of cameras	Camera model
3,600 mm	10 second	135.0 mm	F10	2 cameras	Nikon D300S

Number of measurement points [Loading position]	**Number of measurement points [Joint (beam)]**	**Number of measurement points [Joint (column)]**
3 : 3 (horizontal : vertical)	391 : 91 (horizontal : vertical)	91 : 251 (horizontal : vertical)
Analysis gauge length [Loading position]	**Analysis gauge length [Joint (beam)]**	**Analysis gauge length [Joint (column)]**
45 px (horizontal, vertical)	10 px (horizontal, vertical)	10 px (horizontal, vertical)
Subset area [Loading position]	**Subset area [Joint (beam)]**	**Subset area [Joint (column)]**
129 px square	257 px square	257 px square
Conversion coefficient [Loading position]	**Conversion coefficient [Joint (beam)]**	**Conversion coefficient [Joint (column)]**
2.098 mm/px	0.314 mm/px	0.314 mm/px

The settings of the measurement test and the image analysis are shown in Table 1. In the measurement test, interval imaging was conducted with a measurement cycle of 10 seconds, and 812 images in total including information on the deformation behavior of the specimen were acquired. Moreover, an actuator load is applied and displacement meter readings are taken simultaneously during the same measurement cycle. Furthermore, in the image analysis range at the loading point and the joint position, analysis was conducted by setting number

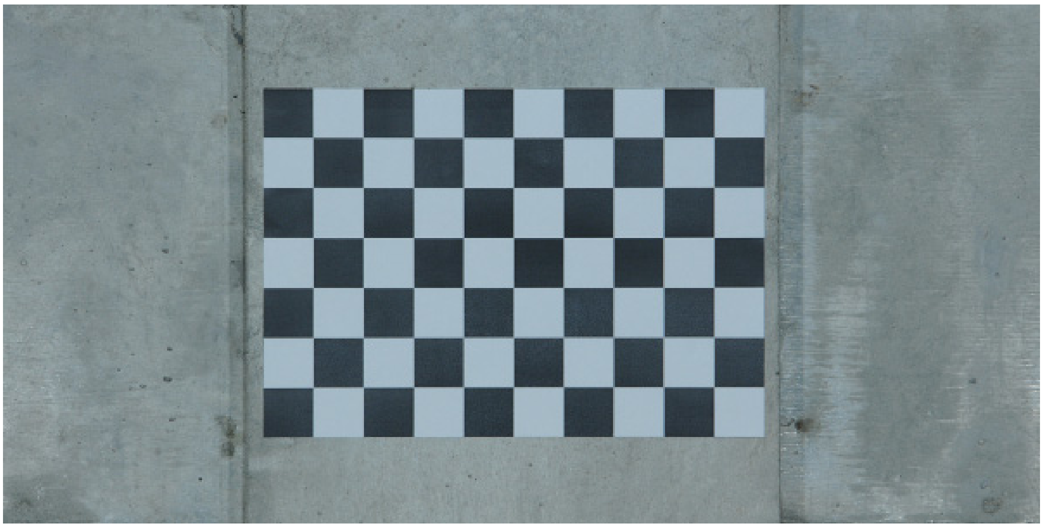


Fig. 8 – Example of image data used for camera calibration

of measurement points and subsets, as shown in Table 1.

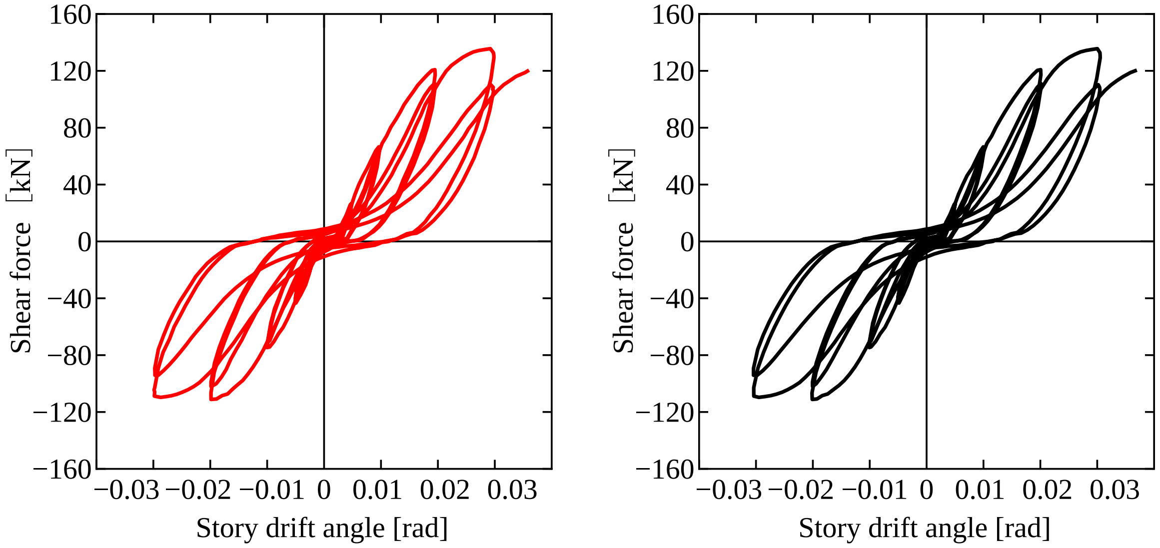
Fig. 8 shows an example of the image data used for the camera calibration in this measurement. When conducting an optical measurement using an image acquired by the digital camera, the lens distortion or the positional relationship between the camera and the measurement target causes a distortion in the image data. It is necessary to correct the distortion because it reduces the measurement accuracy. In the present study, a calibration method (Camera Calibration Toolbox for Matlab [6]) having the high applicability with the proposed method was used. As shown in the figure, several parameters necessary for distortion correction are determined using multiple images obtained by changing the position and angle of the checkered pattern board.

4. Comparisons of RC beam-column joint measurement results

In this chapter, comparisons of the measurement results obtained using the proposed measurement method and the contact-type measurement method is presented. Verification of the validity of the proposed method is performed based on the displacement and strain distribution results of an experimental test on an RC beam-column joint specimen.

4.1 Comparison of measurement results in shear force–story drift angle relationship

Fig. 9 shows the measurement results for column shear force–story drift angle relationship. This figure shows the measurement results obtained using the proposed method and the displacement meter. The image analysis results were obtained by averaging the measured displacement of nine points in the analysis range of the loading position. The results of the proposed measurement method exhibited exceedingly good agreement with the load-displacement relationship obtained by the displacement meter during the initial loading stage, the beam flexural stage, and the final stage. Table 2 shows the correlation coefficient, the average value, and standard deviation of the error for the image analysis results based on the displacement meter measurement results. As shown in this table, the correlation coefficient was 0.9999. Moreover, the average error was 0.341 mm, and the standard deviation of the error was 0.309 mm. These results indicate that the proposed measurement method has an exceedingly high accuracy and is capable of tracking the deformation behavior of the RC beam-column joint specimen during repeated cyclic loading. Furthermore, the measurement test was conducted such that the distance between the camera and the test specimen exceeded three meters, which is assumed to be a practical level. The measurement accuracy of the proposed non-contact method was confirmed to be equivalent to that of the conventional contact-type measurement method and to have sufficient practical applicability.



(a) Image analysis (b) Displacement meter

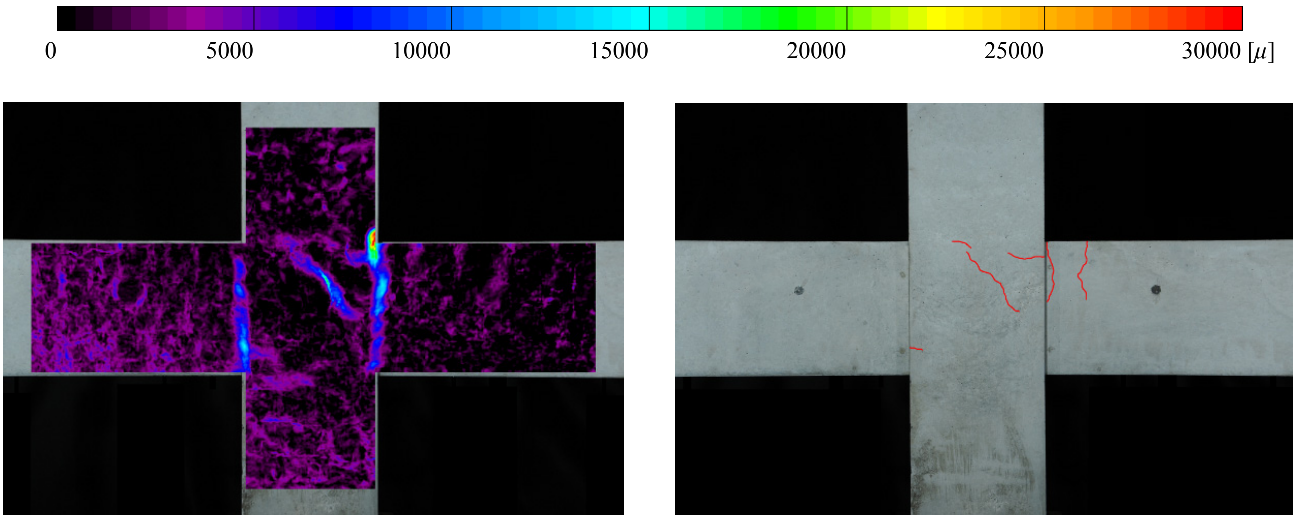
Fig. 9 – Comparison of column shear force–story drift angle relationship

Table 2 – Measurement accuracy of the proposed method

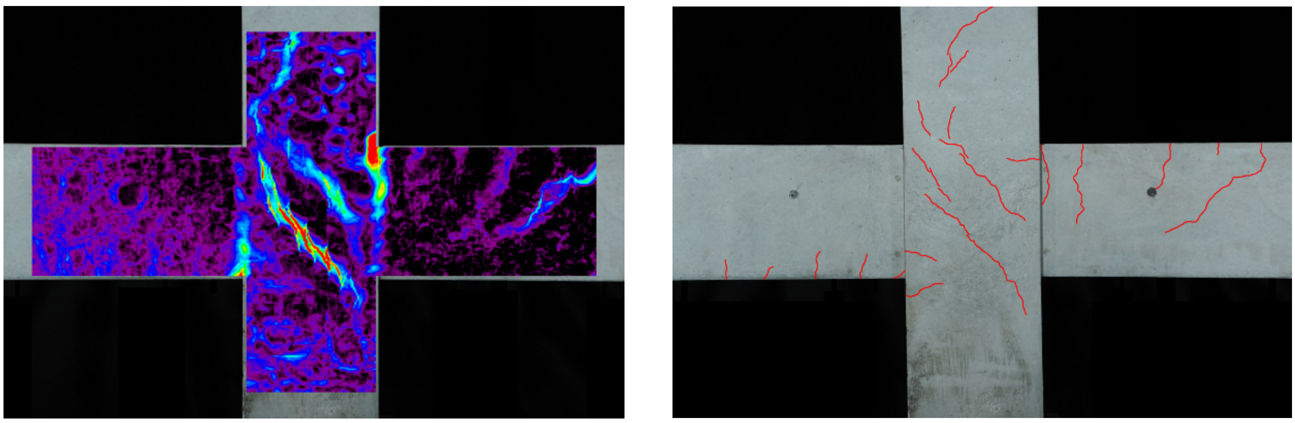
Correlation coefficient	**Average value of error**	**Standard deviation of error**
0.9999	0.3411 mm	0.3094 mm

4.2 Strain distribution on the surface of an RC beam-column joint specimen

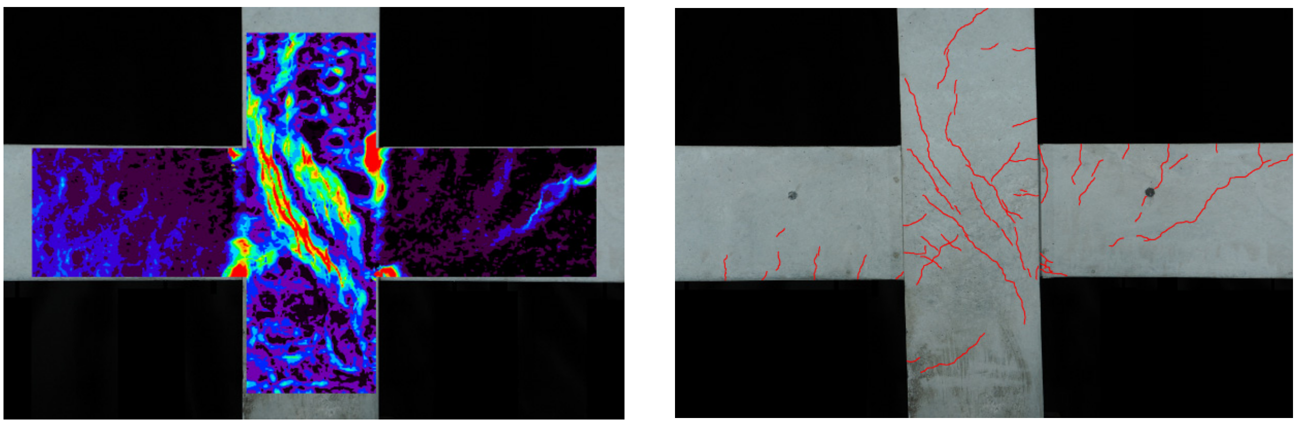
Fig. 10 shows contour plots of the maximum principal strain distribution in the periphery of the joint based on the image analysis results. The cracking in the concrete surface were also shown in this figure. Figs. 10(a)–(c) show the contour plot results at story drift angles of 1/100 [rad], 1/50 [rad], and 1/33 [rad], respectively, on the first cycle in the positive direction. The color scale indicates the magnitude of the maximum principle strain. The red line shown in this figure indicates cracks on the concrete surface. In calculating the strain, using arbitrary elements constituted by four neighboring measurement points in image data shown in Fig. 11. The horizontal strain, the vertical strain, and the diagonal strain are computed by dividing the displacement of each measurement point by the distance between the measurement points, and displayed it as an averaged value within the each element. In the analysis, this calculation of the strain is carried out at all of the elements in the range analysis. Moreover, the principal strain is determined using the general rosette analysis based on each calculated strain. In Fig. 10(a), the concentration of strain on the bending hinge regions of the beam and diagonal cracks on the joint were observed. Furthermore, the strain of the joint panel zone gradually increases as the story drift angle increases (Figs. 10(b) and (c)). With particular attention to cracks of the joint panel zone, the progress of shear cracks caused by complex factors at the joint and the strain distribution based on the results of proposed measurement method were in good correspondence. Although, it is necessary to confirm the validity of the strain value on the measurement range by comparing the results obtained using other measurement methods in future, however, this comparison reveals that the proposed measurement method can visualize full-field strain distributions generated on the surfaces of RC structures. Therefore, these results suggest that the proposed measurement method has the potential to capture the detailed behavior of the entire measurement object more easily as compared with the conventional contact-type measurement method.



(a) Story drift angle 1/100 [rad] (the first cycle in the positive direction)

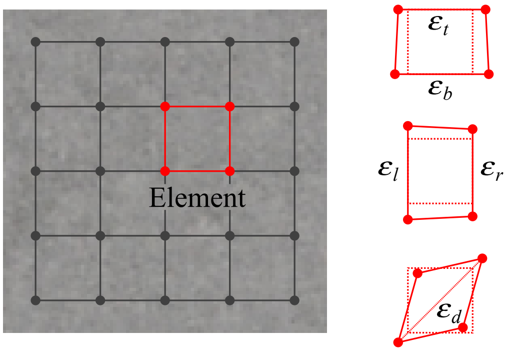


(b) Story drift angle 1/50 [rad] (the first cycle in the positive direction)



(c) Story drift angle 1/33 [rad] (the first cycle in the positive direction)

Fig. 10 – Maximum principal strain distribution and cracks on the RC beam-column joint specimen



Horizontal strain
$\varepsilon_x = (\varepsilon_t + \varepsilon_b) / 2$

Vertical strain
$\varepsilon_y = (\varepsilon_l + \varepsilon_r) / 2$

Diagonal strain
$\varepsilon_{xy} = \varepsilon_d$

Maximum principal strain
$\varepsilon_{max} = (\varepsilon_x + \varepsilon_y + \gamma_{max}) / 2$

Minimum principal strain
$\varepsilon_{min} = (\varepsilon_x + \varepsilon_y - \gamma_{max}) / 2$

Maximum shear strain
$\gamma_{max} = \sqrt{2\{(\varepsilon_x - \varepsilon_{xy})^2 + (\varepsilon_y - \varepsilon_{xy})^2\}}$

Fig. 11 – Concept of strain calculation in proposed method

5. Conclusion

A new optical full-field measurement method based on the phase-only correlation method was proposed. The proposed measurement method uses a digital camera and a PC to provide simple image analysis. Adopting the phase-only correlation method for the image analysis algorithm provides a highly robust, high-precision measurement method. A measurement test of a RC beam-column joint specimen was performed and the obtained results were compared with measurement results in order to validate the proposed measurement method. Comparison of the measurement results for the RC beam-column joint specimen indicated that the proposed non-contact measurement method can track with high accuracy the deformation behavior of RC structures without the need for surface treatments. Furthermore, observations of the principal strain distribution displayed from the measurement values based on the image analysis indicates that the proposed measurement method is capable of visualizing the full-field deformation behaviour on the RC structures, and to have the superiority in the practical use of measurement.

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