ABSTRACT

Measuring deformation of structural members is fundamental to evaluating the performance of structures. In recent years, as an effective and practical method for measurement deformation of structures, non-contact type optical deformation measurement method based on digital image analysis technique are gradually becoming accepted in the field of experimental mechanics. In such measurement method, deformation behavior on the entire object can be easily observed to the contact type measurement method. However, some problems are left in the previous image analysis method, and applicability of measurement to the structural materials such as steel and wood has not been sufficiently verified. From such research background, the applicability of the optical measurement method based on the phase-only correlation method for the structural materials is discussed in the present study. Main features of the present method based on the digital image analysis is that it is possible to be obtained displacements and strains on the surface of the target object in a non-contact state, to verify the detailed deformation distribution. In this research, verification is performed based on the measurement results of experimental tests involving typical structural materials. Comparison of the measurement results reveals that the accuracy of the present method is approximately the same as that of the results obtained using a conventional contact type measurement method. Furthermore, observations of strain distribution displayed from measurement values indicate that the presented measurement method is capable of visualizing the full-field deformation behaviors on the specimens, and to have the superiority in the practical use of measurement.

Keywords: Non-contact type measurement; Optical full-field deformation measurement; Digital image analysis; Phase-only correlation method; Deformation visualization

1. INTRODUCTION

In evaluating the seismic performance of structures, it is of fundamental and importance to measure the deformation behavior when the external force acts. In general, the deformation measurement is performed by a contact type measurement method such as displacement meters or strain gauges. However, since these type measurement methods require contact with the target object, there are cases in which the physical restriction of the measurement instruments complicates the measurement. Also these measurement methods require a large number of measurement devices when observing the detailed deformation of measurement object. Furthermore, the fracture behavior of structural specimens may be difficult to track with conventional type measurement methods, as deformation and cracks due to damage on the specimens may make measurement difficult.

On the other hand, as an effective and practical method for measuring the deformation of structures, non-contact type measurement method utilizing digital image analysis technique are gradually becoming accepted in the field of experimental mechanics. In such measurement method, it is possible to easily observe the deformation behavior of the entire measurement object, which is difficult to measure by the contact type measurement method. Digital image correlation (DIC) method is commonly used in previous studies on measurement method based on digital image analysis (Shah SG et al., 2011, Fayyad TM et al. 2014). However, in the DIC method, a random pattern as a target must

1Assistant Professor, Kanagawa University, Yokohama, Japan, takasuke@kanagawa-u.ac.jp
2Technical Assistant, Kanagawa University, Yokohama, Japan, satouh01@kanagawa-u.ac.jp
be applied to the surface on the target measurement object, and it has a problem that it is greatly affected by disturbance such as light change and noises in the measurement environment. Since the random pattern is attached to the measurement object by painting, the case on the occurrence of a large deformation in structural specimens, the measurement accuracy is expected to decrease as a result of object shape changes and peeling of the pattern on the measurement target surface. Furthermore, the applicability of optical deformation measurement for typical structural materials such as steel and wood has not been sufficiently verified in overall research of non-contact type measurement method for structural materials.

In view of such research background, the measurement applicability and precision of optical deformation measurement based on the phase-only correlation method for structural materials is examined in this research. By computing the acquired digital image data, the measurement method directly provides high precision displacements and strains of the specimen surface in non-contact state without applying any special surface treatment. And the measurement method can be used to simultaneously measure the full-field deformation of the specimens and to easily visualize the deformation distribution which is generally difficult to measure. In this paper, the optical deformation measurement method is presented with a focus on the phase-only correlation method, and overview of measurement tests for typical structural material specimens are described. Furthermore, from the comparison of the measurement results of structural materials, the validity of the measurement method and the applicability of the measurement are examined.

2. OPTICAL DEFORMATION MEASUREMENT USING PHASE-ONLY CORRELATION

2.1 Optical deformation measurement method

Figure 1 shows the basic configuration of the optical deformation measurement method. The concept of this measurement method is basically the same as the previously proposed measurement method (Saito T et al. 2017). In this measurement method, digital still cameras are used as optical devices, and an image analysis PC is used for acquiring digital image. Furthermore, as auxiliary devices, several white LED lights provide constant illumination on the surface of measurement object. 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 measurement object in the non-contact state can be determined by analyzing the acquired image data. In addition, this measurement method has high practicality and simplicity owing to be implemented using commercially available digital still cameras.

2.2 Concept of image analysis method

In this section, an overview of the image analysis method used for calculating the displacements of the measurement points is presented. Figure 2 shows the basic concept of calculation of the measurement point displacement using an example of analytical images. As shown in Figure 2(a), an arbitrary
Measurement reference point is set in the reference image, and an area called a subset centered on this point is set. Figure 2(b) shows the deformation or rigid displacement occurs in the target object and the measurement reference point is displaced within the subset area. In order to track the coordinates of the measurement point, the horizontal and vertical displacements, denoted by $\delta_x$ and $\delta_y$, respectively, of the measurement point shown in the figure are computed by analyzing subset area of reference image and deformed image. The phase-only correlation method described detail in the next section obtains the phase-only correlation function from the subset area image, and the image pixel at 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 setting and analyzing multiple reference points in the acquired image data. Furthermore, by applying such image analysis processing to all acquired image data, it is possible to determine the transition of the full-field deformation of the entire measurement object.

### 2.3 Concept of the phase-only correlation method

The phase-only correlation (POC) method (Takita K et al. 2003) is intended for use in digital image matching for the field of biometric authentication technology or robotics technology originally and is possible to detect parallel displacements between images with high accuracy. In addition, the POC method has the high robustness against unavoidable noises during image acquisition such as lighting flickers or luminance variation in measurement. Thus, the POC method is expected to provide improved accuracy for the optical deformation measurement method. These features are advantageous when measuring deformation behaviors of structural materials with high accuracy using optical deformation measurement method. Figure 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 the amplitude and the phase components by two-dimensional discrete Fourier transform (2D-DFT), respectively. The cross spectrum $R(k_x, k_y)$ obtained using only the phase component of the two images is given by the
Figure 4. Two- and three-dimensional plot of the POC function

following equation:

\[ R(k_x, k_y) = \frac{F(k_x, k_y) \overline{G(k_x, k_y)}}{F(k_x, k_y) \overline{G(k_x, k_y)}} e^{i[\theta_r(k_x, k_y) - \theta_d(k_x, k_y) + \pi]} \]  \tag{1}

where \( F(k_x, k_y) \) is the 2D-DFT of the reference image, \( \overline{G(k_x, k_y)} \) is the complex conjugate of the 2D-DFT of the deformed image, \( \theta_r(k_x, k_y) \) is the phase component of the reference image, and \( \theta_d(k_x, k_y) \) is the phase component of the deformed image. The POC function \( r(k_x, k_y) \) is the two-dimensional inverse discrete Fourier transform (2D-IDFT) of \( R(k_x, k_y) \) and is eventually expressed as follows:

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

where \( \alpha \) 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. Figure 4 shows two- and three-dimensional plot of the POC function. As shown in this figure, the POC function is characterized by a very clear peak, and it has high effectiveness for highly accurate measurement point tracking. Further, in the POC method, it is possible to perform robust image matching against the influence of disturbance by eliminating amplitude components including information on luminance change and noise of acquired image data.

2.4 High-precision technique for optical deformation measurement based on the POC method

In the computing 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 acquired image data, which is the smallest unit of image data. In general, however, the precision of the displacement required for the measurement of structural materials is often smaller than the pixel size of the acquired image data. Therefore, in order to perform highly accurate measurement for structural materials using an optical deformation measurement method, sub-pixel level displacement estimation is required. In the present study, high-precision techniques for optical deformation 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 2D-DFT

In the case of implementing 2D-DFT of digital image data, it is known that discontinuity appears at the edge of the image, which causes problems in optical measurement accuracy. Therefore, in order to
reduce the effect of this discontinuity, the following two-dimensional Hanning window function is applied to the measurement image data.

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

(3)

2.4.2 Application of the Gaussian weighting function

It is known that the signal-to-noise ratio of the high frequency component deteriorates in the case of the disturbance such as noise or flicker affects the digital image, and the image matching accuracy of the POC method significantly deteriorates. In order to reduce the influence of such high-frequency components, a Gaussian weighting function (low-pass filter) is applied during the processing of the POC method. In the present study, an improvement in measurement accuracy is expected by applying the following Gaussian weighting function to analysis images.

\[
H(k_x, k_y) = e^{-2\sigma^2 \sigma'^2 \frac{k_x^2}{N_x^2} \frac{k_y^2}{N_y^2}}
\]  

(4)

where \( \sigma \) represents the Gaussian width.

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

In the case of using the ordinary POC method, the estimated displacement precision is based on the integer pixel, therefore, it is difficult to accurately estimate the displacement of the measurement point. In order to perform highly accurate optical deformation measurement, it is essential to compute the sub-pixel displacements that exist as a real number of pixels of image data. In determining the sub-pixel displacements, 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 displacements of the measurement point \((\delta_x, \delta_y)\) are estimated as follows using the peak evaluation formula for the POC function (Nagashima S et al. 2006).

\[
\delta_x = \frac{\ln \{r(p_x)\} - \ln \{r(p_x)\}}{2\ln \{r(p_x)\} - 4\ln \{r(p_x)\} + 2\ln \{r(p_x)\}} - p_x
\]  

(5)

\[
\delta_y = \frac{\ln \{r(p_y)\} - \ln \{r(p_y)\}}{2\ln \{r(p_y)\} - 4\ln \{r(p_y)\} + 2\ln \{r(p_y)\}} - p_y
\]  

(6)

where \( p_x \) is the horizontal displacement of the arbitrary measurement point on the pixel sized level, \( p_x+1 \) and \( p_x-1 \) represent the coordinates of the nearest neighbor of \( p_x \), \( p_y \) is the vertical displacement of the arbitrary measurement point on the pixel sized level and \( p_y+1 \) and \( p_y-1 \) represent the coordinates of the nearest neighbor of \( p_y \).

2.5 Concept of strain calculation

In the presented optical deformation measurement method, the various strains are computed using arbitrary elements constituted by four neighboring measurement points in image data as shown in Figure 5. 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 them as the average value within the each element respectively. Moreover, the maximum principal strain, the minimum principal strain and the maximum shear strain are determined using the general rosette analysis based on the each calculated strain. In the analysis, detailed strain distribution
3. EXPERIMENTAL OVERVIEW AND COMPARISONS OF MEASUREMENT RESULT

In this section, comparisons of measurement results for the structural materials obtained by using the optical deformation measurement method and the conventional contact type measurement method are presented. Verification of the validity of the presented optical deformation measurement method is performed based on the displacement and strain distribution results of experimental tests on concrete specimen, steel tube specimen and wood specimen, which are representative structural materials. For the purpose of basic verification of measurement accuracy, measurement was performed for static test in this study. The overview of each test and the measurement results are described separately below.

3.1 Comparison of measurement results of square shaped concrete compressive test

Figure 6 shows an overview of concrete compressive test specimen. The specimen consists of 200 mm in length, 100 mm in width and 100 mm depth with square shaped cross section. In the experimental test, simultaneous measurement is implemented using three set biaxial strain gauges attached to the back of the specimen and two displacement meters arranged on the side of specimen. The red area in this figure indicates the image analysis range of the front of the specimen in the optical measurement. Table 1 show the settings used in the measurement test and image analysis of concrete specimen. Acquiring image data at five second intervals was performed using a consumer digital still camera (Nikon D300S). Total 54 axial measuring elements and total 27 transverse measuring elements are set for image analysis.

Figure 7(a) compares the measurement results of axial stress versus axial and transverse strain relationship in concrete specimen under compression load. The curved lines in this figure indicate the measurement results of image analysis with coloring and the measurement result of biaxial strain gauges with gray color, respectively. In this figure, the results of axial strain and transverse strain of the specimen are also shown. The results of each strain are indicated as the average value of the strain obtained at all measurement points. Comparison of measurement results shows that measurement value of the presented optical deformation measurement method and the strain gauges are roughly same measurement accuracy until the concrete compression strength. After the compressive strength, the several strain gauges attached in the vertical direction became impossible to measure, so it was not able to measure the strain in the axial direction correctly. On the other hand, the measurement result shows that the presented measurement method can track stably both axial and transverse strains up to the end of loading. This result also shows that the present measurement method has sufficient accuracy of the behavior of specimen even when many cracks occur in concrete after compressive strength. Figure 7(b) shows comparison of measuring axial load versus axial displacement relationship of concrete specimen. The displacement due to the image analysis result is obtained by integrating the axial element strain and the displacement due to the displacement gauge is represented by the average value of the two displacement meter measurement values. This comparison reveals that the presented measurement method can track the measurement result of the displacement meter with approximately...
Figure 6. Overview of square shaped concrete compressive test specimen

Table 1. Settings used in the measurement and image analysis for concrete compressive test.

<table>
<thead>
<tr>
<th>Loading speed</th>
<th>Measurement interval</th>
<th>Acquired images</th>
<th>Camera focal length</th>
</tr>
</thead>
<tbody>
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<td>78 images</td>
<td>50.0 mm</td>
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<tr>
<td>Measuring points (Axial)</td>
<td>Element length (Axial)</td>
<td>Measuring points (Transverse)</td>
<td>Element length (Transverse)</td>
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<td>28 points</td>
<td>20 pixel</td>
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<td>Image resolution</td>
<td>Image analysis range</td>
<td>Subset area</td>
<td>Conversion coefficient</td>
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<tr>
<td>3216 × 2136 pixels</td>
<td>540 × 1080 pixels</td>
<td>257 × 257 pixels</td>
<td>0.163 mm/pixel</td>
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</tbody>
</table>

the same accuracy. In particular, similar to the result of the comparison of the axial strain described above, this result shows that the presented measurement method can measure the post-peak behavior with high accuracy in case of cracks occur in concrete after the compressive strength of the specimen. Figure 8 shows contour plots of the maximum and minimum principal strain distribution of concrete specimen based on the image analysis result, and acquired digital image data indicating damage state. The red line shown in this figure indicates cracks on the concrete surface. The results at the compressive strength are shown in Figure 8(a), and the results after the compressive strength are also shown in Figure 8(b). In Figure 8(a), the two concentration point of maximum principal strain on the surface of specimen where cracks occurred later was observed. Furthermore, after compressive strength, the computed each principal strain gradually increases is indicated (Figure 8(b)). With particular attention to two cracks of the specimen at the post-peak, it is shown that the concentration of the maximum principal strain and cracked part correspond well. These results reveal that the presented optical measurement method can roughly visualize full-field strain distributions generated on the surface of concrete specimen. Therefore, these results also suggest that the presented optical measurement method has potential to capture the detailed behaviors of the entire measurement object more easily as compared with the conventional contact-type measurement method.

3.2 Comparison of measurement results of steel tube compressive test

An overview of steel tube compressive test specimen is shown in Figure 9. The specimen consists of 300 mm in length, 100 mm in width and 100 mm depth with square shaped hollow section. Simultaneous measurement using four set biaxial strain gauges attached to the back of the specimen and two displacement meters arranged on the side of specimen is conducted in the experimental test. In addition, any surface treatments are not performed on the surface of the test specimen, and it is a smooth surface condition. The red area in the figure shows the image analysis range of the front of the specimen in the optical measurement. Table 2 show the settings used in the measurement test and
image analysis of steel tube specimen. Acquiring image data at ten second intervals was performed using a consumer digital still camera (Nikon D300S). Total 63 axial measuring elements and total 18 transverse measuring elements which element length is 20 pixels each are set for image analysis. Figure 10(a) shows comparison of the measurement results of axial stress versus axial and transverse strain relationship in steel tube specimen under compression load. In this figure, on axial strain and transverse strain, the measurement results of image analysis with coloring and the measurement result of biaxial strain gauge with gray color are shown. The results of each strain are indicated as the average value of the strain obtained at all measurement points. Measurement result shows that measurement value of the presented optical measurement method and the strain gauges are roughly same measurement accuracy in any direction from the yield strength to the compression strength of the steel tube. At the post-peak, the several strain gauges became unmeasurable due to the buckling occurred in the lower part of the steel tube however the presented measurement method can conduct to measure stably. In the DIC method which is a past image measurement method, it is indispensable to apply random patterns in the measurement of a material having a smooth surface like a metal, but the
Figure 9. Overview of steel tube compressive test specimen

Table 2. Settings used in the measurement and image analysis for steel tube compressive test.

<table>
<thead>
<tr>
<th>Loading speed</th>
<th>Measurement interval</th>
<th>Acquired images</th>
<th>Camera focal length</th>
</tr>
</thead>
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<td>0.01 mm/sec</td>
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<tr>
<td>Measuring points (Axial)</td>
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<td>Measuring points (Transverse)</td>
<td>Element length (Transverse)</td>
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<td>64 points</td>
<td>20 pixel</td>
<td>19 points</td>
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<td>Image analysis range</td>
<td>Subset area</td>
<td>Conversion coefficient</td>
</tr>
<tr>
<td>3216 × 2136 pixels</td>
<td>360 × 1260 pixels</td>
<td>257 × 257 pixels</td>
<td>0.228 mm/pixel</td>
</tr>
</tbody>
</table>

The presented measurement method using POC method has sufficient accuracy without any special surface treatment. Figure 10(b) shows the comparison of axial load versus axial displacement relationship of steel tube. Calculation of each displacement is the same as concrete specimen on the previous section. Comparison of measurement results reveals that the presented measurement method can track the steel tube deformation behavior including post-buckling with high accuracy. Contour plots of the maximum and minimum principal strain distribution of steel tube specimen based on the image analysis result, and acquired digital image data indicating damage state are shown in Figure 11. (a)-(c) in this figure show the results of the strain distribution at each loading stage from yield strength to post peak. These results show that the minimum principal strain increases at the upper and lower end where compression occurs as the loading stage progresses. Furthermore, at the post-peak, the increase in strain caused by buckling at the lower end of the steel tube specimen is visualized, and the possibility of measurement application to the steel material of this measurement method is shown.

3.3 Comparison of measurement results of square shaped wood compressive test

Figure 12 shows an overview of wood compressive test specimen. The specimen has a square shape cross section with a length of 210 mm, a width of 105 mm and a depth of 105 mm. Simultaneous measurement was carried out using two displacement meters arranged on the side of specimen in the test. The red area in the figure indicates the image analysis range of the specimen. Table 3 show the settings used in the measurement test and image analysis of wood specimen. Acquiring image data at ten second intervals was performed using a consumer digital still camera (Nikon D7100). Total 90 axial measuring elements and total 45 transverse measuring elements are set for image analysis. Comparison of measuring axial load versus axial displacement relationship of wood specimen is shown in Figure 13. The displacement due to the image analysis result is obtained by integrating the axial element strain and the displacement due to the displacement gauge is represented by the average measurement value of the two displacement meters. Comparison of this measurement result shows that
Figure 10. Comparison of measurement results of steel tube specimen

(a) Axial stress versus strain relationship
(b) Axial load versus displacement relationship

Figure 11. Principal strain distribution and damage state of steel tube specimen

(a) At yield strength (axial stress = 345.6 N/mm²)

(b) At compressive strength (axial stress = 437.5 N/mm²)

(c) At post-peak (axial stress = 392.6 N/mm²)

the present optical deformation measurement method can measure the deformation behavior of the wooden material specimen from the initial loading stage to the compression softening with the same accuracy as the contact type displacement meters. On the wooden specimen, contour plots of the
The verification on the measurement applicability and precision of presented optical deformation measurement method based on the POC method for typical structural materials was discussed in this research. The basic concept of presented measurement method focused on the phase-only correlation method and the high accuracy method was described in this paper. Comparison of measurement results for various structural material specimens showed that presented measurement method can track deformation behaviors of specimens without any special surface treatment in a non-contact state and high accuracy. Furthermore, the consideration of the strain distribution displayed based on the measurement value indicated that the present measurement method can visualize the full-field deformation behavior on the specimen and the superiority of this measurement method in practical use.

5. ACKNOWLEDGMENTS

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