FULL-FIELD STRAIN MEASUREMENT OF COMPOSITE MATERIALS BY THE SAMPLING MOIRE METHOD

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ABSTRACT

Composite material is manufactured to generate and reinforce the desired material characteristics by combining different materials. Carbon fiber reinforced plastic (CFRP), one of the composite materials, possesses the characteristics of lightness, high rigidity and high strength by reinforcing plastics with carbon fiber. CFRP has the characteristics retaining high strength along the fiber direction but is easily broken along other directions. Therefore, the CFRP is used as laminated plates with fibers oriented various directions. In the layers with fibers oriented other than the loading direction, cracks easily occur. The damage tolerance design admitting the presence of cracks that does not cause a reduction in strength below the critical strength is applied to CFRP structures. In this study, we utilize the sampling Moiré method to observe the damage behavior on the surface of laminated CFRP materials. In the sampling Moiré method, the grating pitch can be measured with high accuracy. Therefore, the strain is directly determined from the changes of the grating pitch fabricated on the surface of specimen. The most attractive advantage of our method is both small strain in elastic-plastic region and larger strain distribution in failure-fracture region can be measured. Experimental results demonstrated that our method was effective to evaluate non-uniform full-field strain field with simple experimental setup. Furthermore, the maximum and minimum principal strains and theirs orientations could be measured by use of the measured strain results. Our technique is suitable for nondestructive deformation measurement and useful to detect the potential failure characteristics of various composite materials.

1 INTRODUCTION

Composite material is manufactured to generate and reinforce the desired material characteristics by combining different materials. Carbon fiber reinforced plastic (CFRP), one of the composite materials, possesses the characteristics of lightness, high rigidity and high strength by reinforcing plastics with carbon fiber. In recent years, from the viewpoint of environmental protection, reducing fuel consumption and resource conservation are recommended, therefore, lightening and reinforcing with CFRP are attracting attention. The application ranges over various areas such as automobile, airplane, sports and aerospace.

CFRP keeps high strength along the fiber direction but easily splits along other directions. Therefore, the CFRP is used as laminated plates with fibers oriented various directions and the orientation angle is an important factor to understand their mechanical behavior [1]. In the layers with fibers oriented other than the loading direction, cracks easily occur. This crack is the first damage mode in the laminated plate, and occurs at relatively low load compared with the strength in most cases. In the case of using the CFRP from the viewpoint of lightening, damage tolerance design is applied. Fouinneteau et al. reported the strain distribution measurement of the fibre/matrix interface damage by using digital image correlation (DIC) technique [2].

In this study, we utilize the sampling Moiré method [3] to observe the damage behavior on the surface of laminated CFRP materials. In the sampling Moiré method, the grating pitch can be measured with high accuracy. Therefore, the strain is directly determined from the changes of the grating pitch fabricated on the surface of specimen. The most attractive advantage of our method is both small strain in elastic-plastic region and larger strain distribution in failure-fracture region can be measured.

2 PRINCIPLE OF STRAIN MEASUREMENT BY THE SAMPLING MOIRE METHOD

The basic principle of the sampling Moiré method [3] based on the down-sampling and intensity interpolation image processing is illustrated in Fig. 1. First, when an original grating with pitch *p* is captured by a CCD camera as shown in Fig. 1(a), the recorded intensity of the grating [Fig. 1(b)] is presented in Eq. (1).

$$I(i,j) = I_a \cos\left(2\pi i / P + \varphi_0\right) + I_b = I_a \cos\left[\varphi(i,j)\right] + I_b \tag{1}$$

where I_a and I_b represent the amplitude of the grating intensity and background intensity. P is the captured grating pitch as pixel unit in the digital image, and $\varphi(i,j)$ is regarded as the phase value of the original grating.

In the sampling Moiré method, multiple phase-shifted Moiré fringes can be obtained by down-sampling the recorded grating image. In Fig. 1(b), as example, the sampling pitch is 4-pixel. When every four pixels from the first sampling point is picked up, a Moiré fringe with pitch $P \cdot T / |T - P|$ can be obtained. If the second, third, and fourth sampling points are selected as the sampling start point, multiple phase-shifted Moiré fringes can be obtained, as shown in Fig. 1(c). This process corresponds to the phase shifting. Next, by performing an image interpolation using neighbouring sampled intensity data, smooth phase-shifted Moiré fringes can be recovered. The *k*-th phase-shifted Moiré fringe image, shown in Fig. 1(d), can be expressed as follows:

$$I_m(i,j;k) = I_a \cos\left[2\pi\left(\frac{1}{P} - \frac{1}{T}\right)i + \varphi_0\right] + I_b = I_a \cos\left[\varphi_m(i,j) + 2\pi\frac{k}{T}\right] + I_b \tag{2}$$

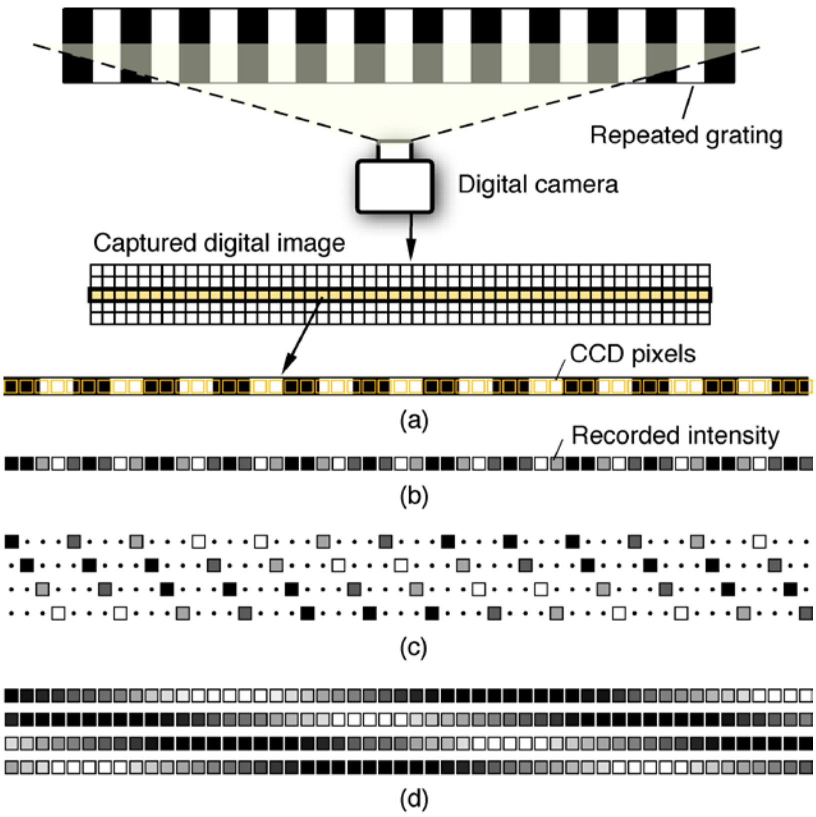

Figure 1: Principle and image processing procedure of the sampling Moiré method for phase analysis of a single fringe pattern: (a) relation between an original grating and pixel array of a CCD camera, (b) recorded intensity of the grating, (c) down-sampling process by changing the start point with a sampling pitch, and (d) intensity Interpolation process to generate multiple phase-shifted Moiré fringes

Then, the phase value of the Moiré fringe can be calculated by phase-shifting method using discrete Fourier transform (DFT) algorithm, as presented in Eq. (3).

$$\varphi_m(i,j) = -\tan \frac{\sum_{k=0}^{T-1} I_k(i,j;k)\sin(2\pi \frac{k}{T})}{\sum_{k=0}^{T-1} I_k(i,j;k)\cos(2\pi \frac{k}{T})} \tag{3}$$

The phase distribution of the Moiré fringe after deformation can be obtained in the same manner. The displacement can be obtained from the *phase difference* of the Moiré fringe $\Delta\varphi_m(i,j) = \varphi_m'(i,j) - \varphi_m(i,j)$ before and after deformation. The displacement is directly proportional to the phase difference of the Moiré fringe as follows.

$$u(i,j) = -\frac{p}{2\pi}\Delta\varphi_m(i,j) \tag{4}$$

If a cross two-dimensional (2D) grating is used, 2D distributions of deformation can be obtained. In addition, the grating pitch in *x*- or *y*-direction can be obtained from the phase of the Moiré fringe by following Equation:

$$P(i,j) = \frac{2\pi T}{2\pi + \nabla\varphi_m(i,j)T} \tag{5}$$

where $\nabla\varphi_m(i,j)$ is the *phase gradient* of the Moiré fringes, and can be calculated by Eq. (6).

Finally, the normal strain in *x*- and *y*-direction is simple obtained as the change of the grating pitches before and after deformations [4].

$$\varepsilon_x(i,j) = \frac{P_x'(i,j) - P_x(i,j)}{P_x(i,j)}$$
$$\varepsilon_y(i,j) = \frac{P_y'(i,j) - P_y(i,j)}{P_y(i,j)} \tag{6}$$

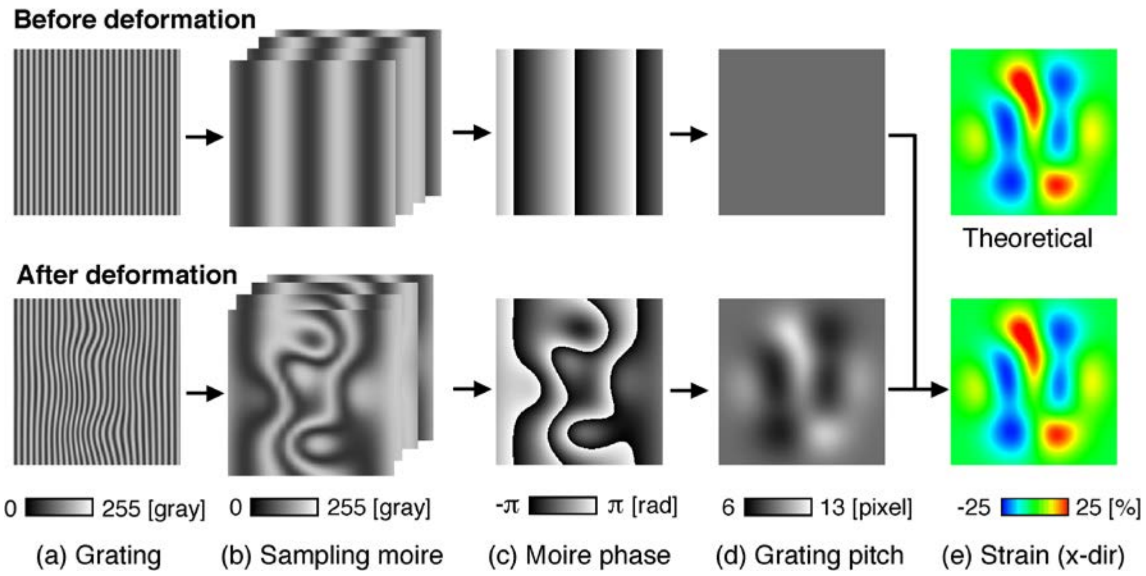

Figure 2: Principle of full-field strain measurement by utilizing the sampling Moiré method.

For a plane stress problems, the maximum and the minimum principal strains, the orientation of the maximum principal strain can be obtained by following Equation [5].

$$\varepsilon_{\max} = \frac{\varepsilon_x + \varepsilon_y}{2} + \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \frac{\gamma_{xy}^2}{4}}$$
$$\varepsilon_{\min} = \frac{\varepsilon_x + \varepsilon_y}{2} - \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \frac{\gamma_{xy}^2}{4}} \qquad (7)$$
$$\tan 2\theta_P = \frac{\gamma_{xy}}{\varepsilon_x - \varepsilon_y}$$

Figure 2 shows an example of the strain distribution measurement based on the sampling Moiré method by computer simulation. Figure 2(a) indicates the captured gratings before and after deformations. Figure 2(b) shows the phase-shifted Moiré fringes after down-sampling and 2-order (*B*-spline) intensity Interpolation. Figure 2(c) shows the phase distributions of the Moiré fringes using the phase-shifting method. Figure 2(d) shows the grating pitches determined by Eqs. (5) and (6). Figure (e) shows the *x*-directional normal strain by calculating the change of grating pitches before and after deformations. As shown in Fig. 2(e), the measured strain is in agreement with the theoretical results even a large strain was applied.

3 EXPERIMENTAL RESULTS OF TENSILE TESTING FOR A LAMINATED CFRP

To understand the damage behavior of a laminated CFRP specimen, both small and large strain distributions measurement was carried out by using the sampling Moiré method.

3.1 Specimen

In this tensile experiment, a laminated CFRP specimens with a fiber oriented angle of $[\pm 50]_{4s}$ was tested. Figure 3(a) shows the photograph of the CFRP specimen and the specimen size was 300 mm × 15 mm × 2.4 mm. A cross-grating with a 1 mm pitch was attached on the surface of the specimen by use of an adhesive seal, as shown in Fig. 3(b). The adhesive seals have excellent elasticity and show same deformation with the surface of the specimens. In addition, a strain gauge rosette (Tokyo-Sokki, FRA-3-23-1L) was adhered on the backside of the specimens on the edge.

A tensilon all-purpose test equipment (A&D, RTF-1350) was used. The tensile testing was carried out at a cross-head displacement speed of 1 mm/min. To record the grating images with a wide observation area, a digital single lens reflex (DSLR) camera (Canon, EOS-1D C, 4096 × 2160 pixels at 24 fps) and a macro lens (Canon, EF 100 mm F2.8L Macro IS USM) were used. The distance between the DSRL camera and the CFRP specimen was 950 mm.

In strain analysis, the sampling pitch is set to 18-pixel because the grating pitch is 17.6-pixel at beginning in small strain, and optimum sampling pitch close to the grating pitch is set for each grating images after large strain deformation. In order to separate the 2D grating to 1D grating and increase the strain measurement accuracy, a low-pass filter was applied. The low-pass filter size is 1 × 41 pixel.

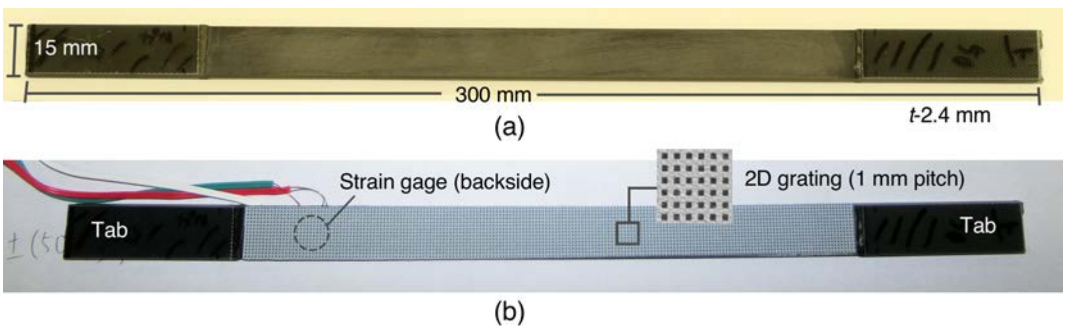

Figure 3: Photograph of a laminated CFRP: (a) specimen size, (b) attached strain gage and grating

3.2 Results

Figure 4 shows the strain-stress curve obtained by conventional strain gage and our sampling Moiré method under the tensile test for the laminated CFRP $[(\pm 50)]_{4s}$ specimen. Conventional strain gage could only measure the strain correctly up to 2%. After the strain larger than 2.1%, the strain gage was broken. However, our method could measure the strain distribution from the small distribution to very large strain until its fracture since the sampling Moiré method is an imaging measurement technique.

In this laminated CFRP $[(\pm 50)]_{4s}$ specimen, interestingly, a necking deformation process was observed. From Fig. 4, we were able to see the necking occurred from 2.8% to 16.3% strain. Finally, the specimen fractured at 116 MPa where strain reached 23.6%.

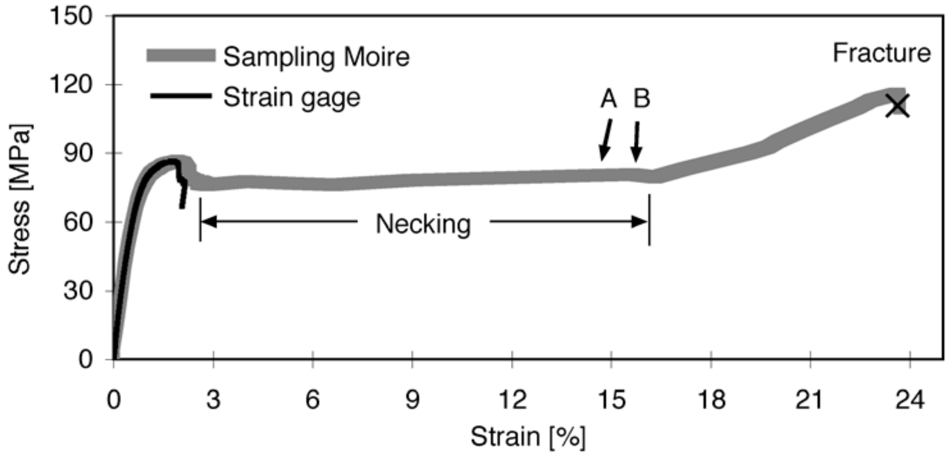

Figure 4: Strain-stress curve obtained by conventional strain gage and our sampling Moiré method under a tensile test for a laminated CFRP $[(\pm 50)]_{4s}$ specimen

Figure 5 shows experimental results of strain distribution (the case of A and B in Fig. 4) for a laminated CFRP $[(\pm 50)]_{4s}$ under a tensile test. The generation of necking (likely a metal material behavior) was confirmed, as shown in Fig. 5(a). By using the sampling Moiré method, we can successfully obtain full-field strain information during the propagation of necking deformation, as indicated in Fig. 5(b). Experimental results showed the strain concentration was started from left-side tab and propagated toward right-side tab via a necking deformation process. Figure 5(c) shows the photograph of part of CFRP after fracture.

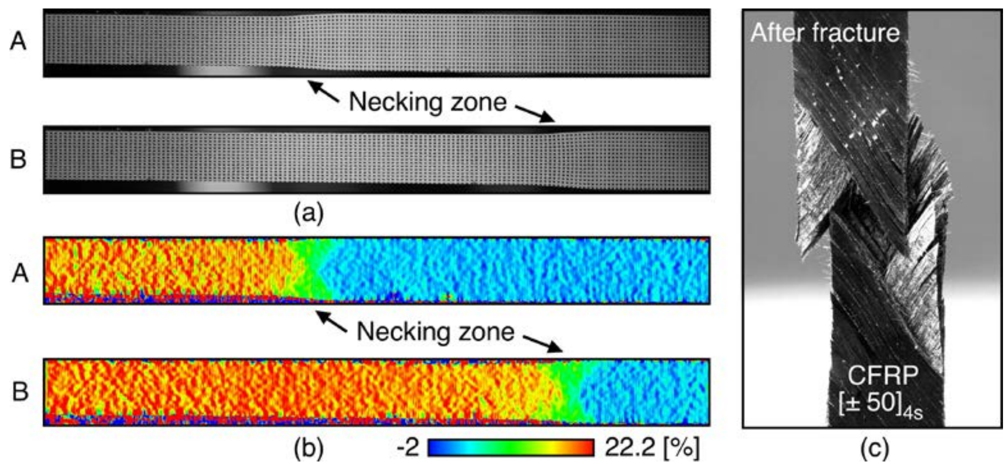

Figure 5: Experimental results of strain distribution measurement for a laminated CFRP specimen: (a) necking zone in the captured image, (b) strain distribution, and (c) photograph after fracture.

4 CONCLUSIONS

In summary, we developed an accurate strain distribution measurement technique that was capable of measuring the non-uniform strain field both in the elastic and plastic deformation, based on the sampling Moiré method. A tensile loading test for a laminated CFRP specimen was performed. Experimental results demonstrated that our developed method was effective to evaluate non-uniform full-field strain field with simple experimental setup. Furthermore, the maximum and minimum principal strains and theirs orientations were able to be measured by use of the measured displacement and normal strain results. Therefore, our technique is suitable for nondestructive deformation measurement and useful to detect the potential failure characteristics of various composite materials.

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