IDENTIFICATION OF GAGE FACTORS OF A UNIDIRECTIONAL CARBON FIBER REINFORCED PLASTIC BY MULTIPOINT POTENTIAL MEASUREMENT

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Abstract. Carbon fiber reinforced plastic (CFRP) has electrical conductivity both in parallel and transverse direction of fiber. Since the electrical network may be changed with applied strain, the electrical conductivity of the CFRP would also be changed. Strain monitoring of CFRP, therefore, can be performed without any additional sensor but by measuring the electrical resistance change. There has been many studies on the gage factors of unidirectional CFRPs, although significant mutual differences were found out in the results reported. It is considered that the differences may be caused by the strong electrical anisotropy and inhomogenity of the unidirectional CFRP. In this study, a new concept was introduced to measure the gage factors of a unidirectional CFRP. Finite element analysis was utilized to consider non-uniform electrical potential field in the unidirectional CFRP. The gage factors were obtained as a result of minimizing the error sum of squares of electrical potentials between experimental and analytical results. The gage factors obtained by the proposed method were compared to those by conventional method.

1. Introduction

A carbon fiber reinforced plastic (CFRP) laminate has superior specific strength and stiffness as compared to metals. It has been increasingly applying to primary structures of aircraft. However, a CFRP laminate is sensitive to an impact which causes a delamination. The delamination strongly reduces the mechanical property of the laminate, especially reduces compressive strength. Structural health monitoring is important to maintain structural reliability of CFRP structures.

A CFRP laminate is electro-conductive material which can be used as a strain sensor by itself. Self-sensing of strain in a CFRP laminate has been reported utilizing its piezoresistivity [1]. There are many reports on the gage factors of CFRP laminates although significantly different results were shown, that is positive piezoresistivity and negative piezoresistivity [2-10]. A CFRP laminate is composed of electro-conductive carbon fibers and insulative epoxy resin. Inhomogeneity and strong electrical anisotropy of a CFRP laminate may result in the difficulty to measure the macroscopic electrical property. The problem may lie on the conventional technique to measure gage factors. Piezoresistive behavior of a CFRP laminate has not been fully revealed yet.

In this study, some problems on conventional method to measure gage factor of a unidirectional CFRP laminate were pointed out. Then, finite element method (FEM) aided technique was proposed to measure the gage factors of a CFRP laminate precisely by considering the strong electrical anisotropy and inhomogenity. Gage factors in longitudinal and thickness direction of a unidirectional CFRP laminate were identified simultaneously using the same specimen. The advantages of the method were shown by comparing to the commonly-using conventional method.

2. Problems on conventional method

2.1 Electrical anisotropy

Gage factors of CFRP laminates have been reported in many papers [2-10]. However, the experimental results show discrepancy even though same stacking sequence was used. The problem may lie on the commonly-useing measuring method. Measurement of gage factor in longitudinal direction was possibly affected by gage factor in transverse direction because of highly anisotropic electrical property. Intervals between current electrodes should be sufficiently long while intervals between voltage electrodes should be sufficiently short even if four-probe method is applied. Defect of electrodes is also difficult to detect.

Fig. 1 shows electric potential distribution in a unidirectional CFRP laminate calculated by FEM. The finite element model was 200 mm long and 2 mm thick. Two electrodes were mounted on a laminate surface with spacing of 100 mm, which were 2 mm long. Electric conductivity in longitudinal (*x*-direction parallel to the fiber direction) and thickness directions (*z*-direction) were 45455 S/m and 3.25 S/m, respectively [5]. Note that the thickness direction was magnified in Fig. 1 for easy observation. As shown in Fig.1, electric distribution in the CFRP laminate is not constant throughout the thickness because of electrical anisotropy even though the laminate is very thin. It indicates that anisotropic electric potential distribution in the CFRP laminate should be considered in order to measure the gage factor in longitudinal direction. If gage factor is measured by commonly-using technique in which electric current is applied at the electrodes on the laminate surface, the gage factors may be affected by gage factor in thickness direction due to the electrical anisotropy.

There are few reports on gage factor of a CFRP laminate in thickness direction due to the difficulty for measurement because the laminate is thin plate [11, 12]. However, gage factor in thickness direction is important to perform precise strain monitoring of a CFRP laminate.

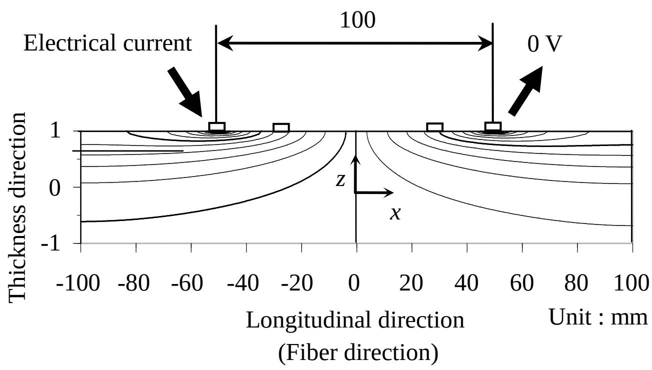

Fig.1 Contour plot of electrical potential in a unidirectional CFRP laminate

2.2 Electrical inhomogeneity

Electric current only flows in carbon fibers, which causes inhomogeneous potential field in a CFRP laminate. Fig. 2 shows schematic diagram of cross-section at electrode which is mounted on the laminate surface. Some carbon fibers may contact with electrode. Fig. 3 shows electric potential distribution on a surface of a unidirectional CFRP laminate which was calculated by FEM. Specimen size was 200 mm in length, 0.1 mm in width and 2 mm in thickness. Distance between current electrodes was 100 mm. Electric conductivity was 45455 S/m in fiber direction and 3.25 S/m in transverse direction [5]. Contact of fibers with electrodes was located alternatively to model the condition of Fig. 2. Electric potential on the surface of the laminate is not uniform because of the electrical anisotropy and inhomogeneity, which affect the measurement of the gage factor. Since transverse deformation may occur due to poisson's effect in longitudinal direction, gage factor in longitudinal direction may be affected by gage factor in transverse direction.

The method presented in this paper provides not only the precise measurement of gage factor but also the simultaneous measurement of gage factors in longitudinal and thickness directions in one test without preparing different specimens. Another advantage of the method was that defects of electrode can be recognize in the test which enable the reliable measurement.

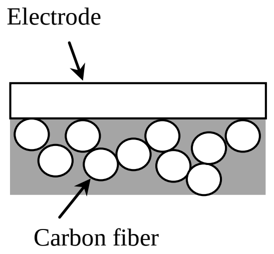

Fig.2 Schematic of electrode/carbon fibers contact

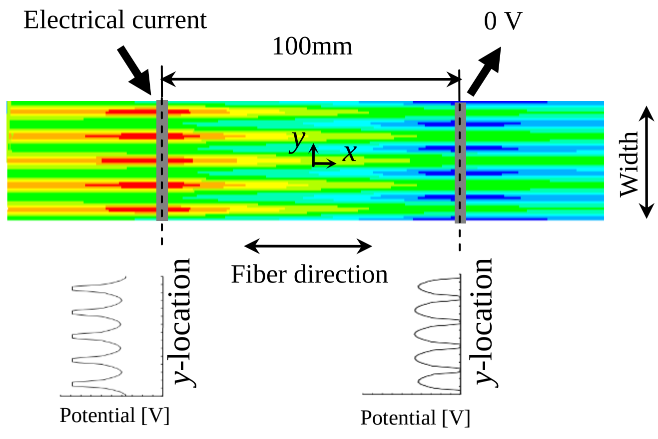

Fig.3 Non-uniform potential distribution on a unidirectional CFRP laminate due to the inhomogenity and anisotropy

3. Experiments

3.1 Specimen configuration

A unidirectional CFRP Laminate was fabricated from unidirectional prepreg sheets PYLOFIL#380 (Mitsubishi Rayon Co., Ltd). The autoclave molding method was used to fabricate unidirectional laminate. Specimens of 200 mm long and 15 mm wide were cut from the laminate after consolidation as shown in Fig. 4. Thickness of the specimen was 0.22 mm.

Two current electrodes (E_c and E_d) and five voltage electrodes (E_1 ~ E_5) were mounted on a laminate surface. Electric potential changes between electrodes due to tensile loading were measured utilizing the four-probe method. The electrodes were made using copper plating [13]. Before copper plating epoxy resin was eliminated from the laminate surface by sulfuric acid. Silver paste was used to connect lead wire to the electrodes. Electrodes were then coated with epoxy resin to prevent deboning between electrode and lead wire during tensile loading.

Strain gages were attached both surface of the laminate in order to measure the applied strain during tensile test. End tubs of the specimen were made by glass fiber reinforced plastic.

3.2 Tensile test

Tensile test was performed by universal testing machine (AG-IS 150kN Shimadzu Co., Ltd). The loading speed was 0.1 mm/min. The load was applied until the longitudinal strain reached to 2500 $\mu\varepsilon$. Several cycles of loading and unloading were applied to a specimen prior to the test. The maximum strain in the pre-loading was about 1000 $\mu\varepsilon$.

3.3 Measurement of electric potential change

Electric current of 150 mA was applied at a current electrode E_c and another current electrode E_g was connected to the ground. Electric potential changes between adjacent voltage electrodes (E_1-E_2, E_2-E_3, E_3-E_4, E_4-E_5) were collected by date logger (Kyowa electronic instruments Co., Ltd) after amplification by a differential amplifier.

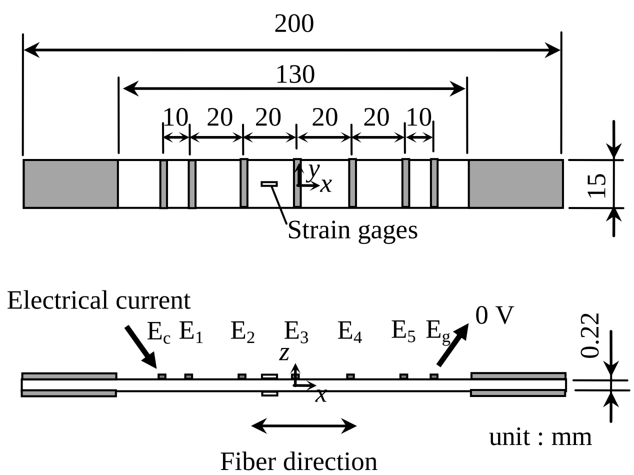

Fig.4 Specimen configuration of a unidirectional CFRP

4. Identification of gage factors by multipoint voltage measurement

4.1 Search of electric conductivity

Electric potential P satisfies Laplace equation inside the laminate.

$$\sigma_L \frac{\partial^2 P}{\partial x^2} + \sigma_T \frac{\partial^2 P}{\partial z^2} = 0 \tag{1}$$

Where σ_L and σ_T are electrical conductivities in longitudinal direction (fiber direction) and transverse direction (thickness direction).

The harmonic function which satisfies Eq. (1) and boundary condition of the laminate represents the electric potential field in the laminate. Here, Eq. (1) is divided by σ_L.

$$\frac{\partial^2 P}{\partial x^2} + \frac{\sigma_T}{\sigma_L} \frac{\partial^2 P}{\partial z^2} = 0 \tag{2}$$

As the governing equation and boundary condition are essentially the same even though the components of electric conductivity are divided by σ_L the contour of the electric potential is analogous. Same electric potential field is obtained if the components of electric conductivity ratio are unchanged. Therefore, the electric conductivity ratio σ_T / σ_L is searched first. Subsequently, σ_L is searched to obtain absolute value of electric conductivity of the CFRP laminate.

Electric potential changes between electrodes are normalized as follows.

$$p_i = \frac{P_i}{L} \ (i = 1 \sim 4) \ , \ L = \sqrt{\sum_i^4 P_i^2} \tag{3}$$

where p_i is the normalized electric potential change between electrodes, and L is a norm of electric potential change between electrodes.

Normalized electric potential changes between electrodes p_{i_exp} are obtained from the experimental result. Normalized electric potential changes between electrodes p_{i_fem} are calculated by FEM. The error sum of squares of these two normalized electric potential changes is calculated as follows.

$$\text{Minimize} \left\{ \sum_i^4 [(p_i)_{\exp} - (p_i)_{fem}]^2 \right\} \Rightarrow (1, \ \frac{\sigma_T}{\sigma_L}) \tag{4}$$

The electric conductivity ratio is obtained by minimizing the error.

Subsequently, the absolute values of electric conductivities are searched. Electric potential changes between electrodes P_{i_exp} are obtained from the experimental result. Electric potential changes between electrodes P_{i_fem} are calculated by FEM. The components of electric conductivity are obtained by minimizing Eq. (5) under the conditions of Eq. (4).

$$\text{Minimize} \left\{ \sum_i^4 [(P_i)_{\exp} - (P_i)_{fem}]^2 \right\} \Rightarrow (\sigma_L, \sigma_T) \tag{5}$$

4.2 Electric conductivity of a unidirectional CFRP laminate

The electric conductivity of a unidirectional CFRP laminate depends on carbon fiber, surface treatment of fiber, fiber volume fraction and waviness of fibers. Since the exact range of conductivity is unknown, it was approximated as follows [5,6,14-16].

$$\sigma_L = 1000 \sim 50000 \;\; S/m$$
$$\sigma_T = \;\; 0.1 \sim 1000 \;\; S/m \tag{6}$$

Electric conductivity was searched within above rage minimizing the electric potential difference between FEM results and experimental results, and then gage factor is calculated as follows.

4.3 Gage factors

Gage factors in longitudinal direction (K_L) and thickness direction (K_T) is obtained from the electric conductivity of a CFRP laminate before and after tensile loading.

$$K_L = \frac{1}{\varepsilon_L}\left(\frac{\sigma_{L0}}{\hat{\sigma}_L} - 1\right)$$
$$K_T = -\frac{1}{\nu_{TL}\varepsilon_L}\left(\frac{\sigma_{T0}}{\hat{\sigma}_T} - 1\right) \tag{7}$$

Where ε_L is longitudinal strain and ν_{TL} is poisson's ratio. Subscript 0 indicates "without loading". $\hat{\sigma}_L$ and $\hat{\sigma}_T$ are electric conductivity in fiber and thickness direction after loading which includes dimensional change due to loading.

$$\hat{\sigma}_L = \sigma_L \frac{L_{L0}}{L_L}\frac{A_L}{A_{L0}} \;,\; \hat{\sigma}_T = \sigma_T \frac{L_{T0}}{L_T}\frac{A_T}{A_{T0}} \tag{8}$$

In finite element analysis, electric potential was calculated without considering dimensional change of the specimen due to loading because $\hat{\sigma}_L$ and $\hat{\sigma}_T$ include effect of dimensional change.

4.4 Finite element analysis

Numerical analysis was performed with commercially available finite element code ANSYS. The finite element model is the same as shown in Fig. 4. Two-dimensional analysis was conducted in which potential distribution was assumed as uniform in the width direction (*y*-direction). Electric potentials of the nodes at each electrode were coupled to have same electric potentials.

Electric current of 150 mA was applied at a current electrode E_c and another current electrode E_g was fixed to 0 V. Electric potential changes between adjacent voltage electrodes were calculated as same as experimental procedure.

5. Measurement of gage factor in longitudinal direction by conventional method

Gage factor in longitudinal direction was measured by means of conventional method. In the later chapter, this gage factor was compared with that obtained by means of proposed method. Specimen used in this measurement was shown in Fig.4. Electric current of 150 mA was applied at a current electrode E_c and another current electrode E_g was connected to the ground. Electric potential change between electrodes E_1 - E_5 and E_2 – E_4 due to tensile loading was collected and shown in Fig. 5. From the result, gage factor in the longitudinal direction was different dependent on the distance between voltage electrodes. This gage factors in longitudinal direction may be affected by that in thickness direction due to the electrical anisotropy of the CFRP laminate.

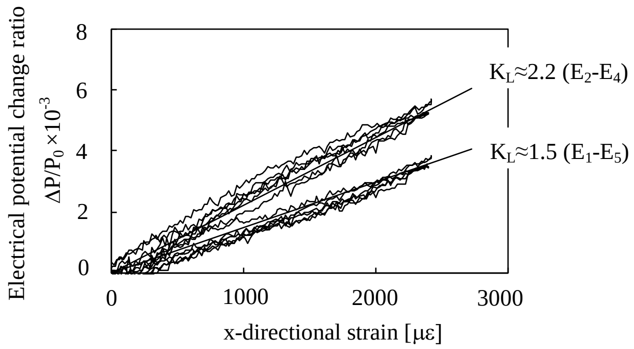

Fig. 5 Electrical potential change ratio between electrode E_1 and E_5, E_2 and E_4 due to tensile loading

6. Identification of gage factors

6.1 Electric conductivity of a unidirectional CFRP laminate before and after loading

Firstly, electric conductivity ratio of the CFRP laminate was obtained. The electric conductivity ratio which minimizes Eq. (4) was searched within the range of electric conductivity of Eq. (6). Minimum error was obtained under the particular electric conductivity ratio.

$$\frac{\sigma_{L0}}{\sigma_{L0}} : \frac{\sigma_{T0}}{\sigma_{L0}} = 1 : 0.98 \times 10^{-4} \tag{9}$$

Then the magnitude of the electric conductivity i.e. σ_{L0} is searched to obtain absolute values of electric conductivity. The electric conductivity which minimizes Eq. (5) was searched under the condition of Eq. (6) and (9). The components of electric conductivity of the CFRP laminate are obtained as follows.

$$\sigma_{L0} : \sigma_{T0} = 41500 : 4.067 \quad [S/m] \tag{10}$$

Electric conductivity after tensile loading was also searched as the same way. The components of electric conductivity after loading are obtained as follows.

$$\hat{\sigma}_L : \hat{\sigma}_T = 41290 : 4.170 \quad [S/m] \tag{11}$$

Fig. 6 shows comparison of electric potential changes between electrodes obtained by experiment and FEM result. FEM result almost coincided with experimental results in this study. Electric potential changes between electrodes should be same for E_1-E_2 and E_4-E_5, E_2-E_3 and E_3-E_4 because of symmetric potential distribution in the CFRP laminate (See Fig. 1). Defect of electrode could be recognized if the electric potential changes showed unsymmetrical pattern.

6.2 Gage factors

Gage factors of the CFRP laminate were then calculated from the above result using Eq. (7).

$$K_L=2.0,\ K_T=29.1 \tag{12}$$

Gage factor in thickness direction showed larger value than that in fiber direction. Only a few reports on gage factor in thickness direction are available, and more experiments are required to reveal the gage factor in thickness direction.

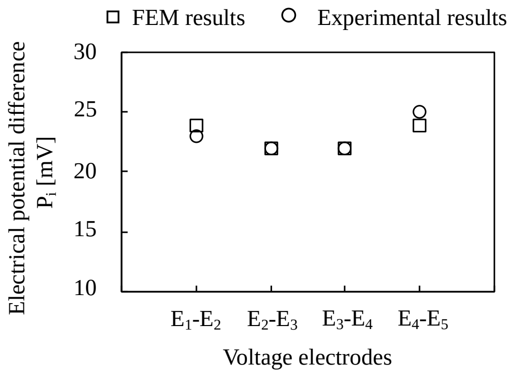

Fig. 6 Comparison of electric potential differences between experimental and FEM result under no-loading condition

7. Conclusions

Some problems on conventional method to measure gage factors of a unidirectional CFRP laminate were pointed out. FEM aided measurement technique was proposed to correctly identify the gage factors. Proposed method considered the potential distribution in the CFRP laminate which enabled the precise measurement of gage factors, and gage factors in fiber and transverse direction were measured simultaneously using one specimen. The results showed that gage factor in thickness direction was higher than that in longitudinal direction. However, only a few reports on gage factor in thickness direction are available, and more experiments are required to fully reveal the gage factor in thickness direction.

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