Electrical Resistance Change of Unidirectional CFRP Due to Applied Load

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Carbon Fiber Reinforced Plastic (CFRP) is composed of electric conductive carbon fibers and electric insulator resin. Self-monitoring system has been reported utilizing electric resistance change of unidirectional CFRP due to fiber breakages and to applied strain. Piezoresistivity is electric resistance change with applied strain. Many researchers have already reported the piezoresistivity of unidirectional CFRP. There is, however, large discrepancy in the measured piezoresistivity even in the fiber direction during tensile loading: both positive piezoresistivity (electric resistance increase) and negative piezoresistivity (electric resistance decrease) are reported during tensile tests. Electric resistance change at electrodes due to poor electric contacts are reported to be a main cause of this large discrepancy. In the present study, therefore, basic properties of piezoresistivity were measured with specimens made from single-ply and multi-ply laminates using a four-prove method. Many cases of electric resistance changes in the fiber direction transverse direction were measured during tensile loading. Effect of shear loading was also investigated using a shear test. To investigate the effect of poor electric contact at the electrodes, electrodes were made without polishing specimen surface and a tensile test was performed with measuring piezoresistivity. After the test, the specimen surface was polished, and a tensile test was performed again using the identical specimen. As a result, positive piezoresistivity was obtained for both single-ply and multi-ply specimens and negative piezoresistivity is confirmed that it was caused by the poor electric contact at electrodes.

Key Words: CFRP, Electric Resistance, Piezoresistivity, Four-Prove Method

1. Introduction

Similar to conventional strain gages, piezoresistivity is a phenomenon in which electrical resistance of a material changes with applied strain. Many researchers have been reported self-sensing systems of unidirectional CFRP (Carbon Fiber Reinforced Plastics). They have utilized the piezoresistivity to measure applied strain of CFRP structures (1)-(13). This sensing system uses reinforcement carbon fibers as strain sensors, and it does not require additional sensors except for electrodes to make contact with carbon fibers in the target CFRP structures. This is, therefore, called a self-sensing system.

Schulte and Baron (1) have reported the electrical resistance of a CFRP laminate in the fiber direction rises with the increase of applied tensile load in the fiber direction using a two-prove method. Other researchers have also reported this positive piezoresistivity (positive gage factor) (3)-(7): The electrical resistance in the fiber direction rises with the increase of applied tensile strain in the fiber direction.

Wang and Chung have revealed completely opposite results (8)-(13). They employed a four-prove method to measure precise electrical resistance change in the fiber direction during tensile loading in the fiber direction of a CFRP laminate, and they obtained negative piezoresistivity (negative gage factor): The electrical resistance in the fiber direction is reduced with the increase of applied tensile load in the fiber direction.

Wang and Chung have already published a paper (11) that describes the reason of the discrepancy between the two opposite results: Positive piezoresistivity and negative piezoresistivity of CFRP. They conducted the measurements with both of the four-prove method and the two-prove method, and they concluded that the true piezoresistivity...
tivity of a CFRP laminate in the fiber direction was negative and the apparent positive piezoresistivity was obtained due to the increase of electrical resistance at the proves for the two-prove method. They also describes that the negative piezoresistivity is obtained owing to the realignment of carbon fibers during tensile loading in the fiber direction.

Angelidis and others(6) have reported that the positive piezoresistivity has been obtained using the four-prove method with electrodes made from silver paste and the negative piezoresistivity has been obtained with electrodes made from carbon paste. They revealed that the low reliability of the electrodes made from carbon paste caused the negative piezoresistivity; Electric contact is attained only at several points with the electrodes made from carbon paste, and this makes a complicated electric current path in the specimen. This complicated electric current path is reported to be a cause of the negative piezoresistivity. They proposed a model of the apparent negative piezoresistivity using irregularly placed electrodes of dot shapes, and they showed the apparent negative piezoresistivity with the specimen on which electrodes are irregularly placed.

The objective of the present study is to obtain true properties of piezoresistivity of a CFRP laminate. Small size specimens are adopted here to prevent sparser electric contact points at electrodes, and the four-prove method with silver paste is employed to measure electrical resistance change precisely. Electrical resistance changes in several directions are measured with single-ply specimens and multi-ply specimens when the specimens are loaded in the fiber direction and the transverse direction. Electrical resistance change of the transverse direction when the specimen is loaded in the transverse direction is also obtained here.

In order to simulate the poor electric contact at the electrodes, we performed two kinds of tests using a multi-ply laminated specimen: Electrodes are made without polishing surface of the specimen and electrical resistance change was measured during a tensile test. After that, the surface of the identical specimen was polished with sand paper and electrodes are made with silver paste. Using this specimen, electrical resistance change was measured again.

For a shear-loading test, material only deforms with sliding and there is no change in length and volume. Therefore, no electrical resistance change is expected in the shear deformation in case of normal piezoresistivity. In the present study, a shear test was performed to make sure this electrical resistance change.

2. Principle of Electrical Resistance Change in CFRP with Loading

Carbon fiber has a high electrical conductivity and the epoxy resin matrix is an insulator. For regular-spacing ideal carbon/epoxy composites, the ideal electrical conductance can be calculated easily by multiplying fiber volume fraction by electrical conductance of the carbon fiber. On the other hand, electrical conductance of the regular-spacing ideal carbon fiber/epoxy in the transverse direction is zero because there is no electric current path in the transverse direction.

Actual carbon fibers in a unidirectional CFRP ply are not straight and amalgamate in some places as shown in Fig. 1 (a). The serpentine carbon fiber contacts with each other, and that makes a large carbon-fiber network in a ply. The fiber-contact-network brings electrical conductance even in the transverse direction. Therefore, an equivalent electric circuit is a simple network structure made from electrical resistances.

In the same way, the fiber-network produces non-zero electrical conductance in the thickness direction in a single ply. Electrical conductance in the transverse direction is much lower than that in the fiber direction. Abry and others(14) as well as the authors(15) have experimentally revealed that the electrical conductance ratio in the transverse direction ($\sigma_{90}$) to the fibre direction ($\sigma_0$) is approximately $\sigma_{90}/\sigma_0 = 10^{-3}$, and that the electrical conductivity ratio in the thickness direction ($\sigma_t$) to the fibre direction is approximately $\sigma_t/\sigma_0 = 10^{-4}$ for carbon/epoxy laminates.

Electrical conductance in the thickness direction ($\sigma_t$) is usually lower than that in the transverse direction ($\sigma_{90}$). Although the fibre-network structure in the thickness direction is almost similar to that of the transverse direction in a single ply, average conductance in the through-the-thickness direction ($\sigma_t$) of the multi-ply laminates is smaller than $\sigma_{90}$. That is due to the fact that a thin resin
rich interlamina exists between plies and the interlamina is insulator as shown in Fig. 1(b). For ideal regularly spacing carbon fiber/epoxy composites, $\sigma_1$ vanishes due to the resin rich interlamina. For actual carbon/epoxy composites, however, all plies curves just as the fiber in a single ply. The serpentine plies cause fiber contact through interlamina, and it causes positive electrical conductance in the thickness direction even for thick laminated carbon/epoxy composites. The fiber contact between plies causes positive electrical conductance in the thickness direction. Thus, $\sigma_1$ is usually smaller than $\sigma_{90}$.

Piezoresistivity is an electrical resistance change due to applied strain. The most popular sensor using piezoresistivity is a conventional strain gage. Electrical resistance $R$ of a wire is expressed as follows.

$$R = \frac{L}{A}$$  \hspace{1cm} (1)

where $\rho$ is electrical resistivity, $L$ is length of the wire and $A$ is a cross section area. When the wire deforms, fraction of electrical resistance change is expressed as follows.

$$\frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} + \frac{\Delta L}{L} - \frac{\Delta A}{A} = (1 + 2\nu)\varepsilon + \frac{\Delta \rho}{\rho}$$  \hspace{1cm} (2)

where $\varepsilon = \Delta L/L$, $\nu$ is Poisson’s ratio. Fraction of resistivity change ($\Delta \rho/\rho$) is proportional to fraction of volume change.

$$\frac{\Delta \rho}{\rho} = m \frac{\Delta V}{V}$$  \hspace{1cm} (3)

where $m$ is a material constant. Substituting Eq. (3) into Eq. (2), we can obtain a well-known relation.

$$\frac{\Delta R}{R} = K \varepsilon$$  \hspace{1cm} (4)

$$K = (1 + 2\nu) + m(1 - 2\nu)$$  \hspace{1cm} (5)

where $K$ is a proportionality constant called a gage factor.

For most of the metallic materials, $\nu = 0.3$ and $m = 1$. Although the gage factor varies depending on materials, the value is approximately around 2–4 for most of metallic materials and 80–170 or −95−110 for semiconductor strain gages.

Since the carbon fiber resembles the conventional strain gage, the gage factor in the fiber direction during tension loading in the fiber direction is expected to be near to 2. The gage factor in the transverse direction, however, is unclear because the fiber-contact network is the main cause of electrical conductivity.

### 3. Specimen and Test Method

#### 3.1 Materials

Material used here is prepreg Q-1111/2500 (carbon/epoxy, Tohotenax Inc). The prepreg is stacked to make laminates of $[0]_T$ (single-ply) and $[06]_T$ (multiply). The laminates were cured with a hot-press at $130^\circ$C × 90 min. From the laminates, rectangular plates of 200 mm × 200 mm were fabricated. Fiber volume fraction of the laminates is $V_t = 0.5$ here.

To measure the electrical resistance change during loading, the four-prove method is adopted in the present study. Electrodes of each specimen were produced using silver paste after polishing the specimen surface with sand paper. As a comparison, silver paste is painted on the specimen surface without polishing the specimen surface to investigate the effect of poor electric contact at electrodes.

#### 3.2 Single-ply tension specimen

Several types of tests were performed here. Using a single-ply, a specimen made from $[0]_T$, a $0^\circ$-tensile-0$^\circ$-charge specimen, a $0^\circ$-tensile-90$^\circ$-charge specimen, a 90$^\circ$-tensile-90$^\circ$-charge specimen and a shear specimen are fabricated: a $0^\circ$-tensile-0$^\circ$-charge specimen means tensile strain is loaded in the fiber direction and electric current for electrical resistance measurement is applied to the fiber direction; a $0^\circ$-tensile-90$^\circ$-charge specimen means tensile strain is loaded in the fiber direction and electric current is applied to the transverse direction; 90$^\circ$-tensile-90$^\circ$-charge specimen means that tensile strain is loaded in the transverse direction and electric current for the measurement of electrical resistance is applied to the fiber direction. These specimen configurations are shown in Figs. 2, 3 and 4 respectively.

These specimens are attached on the surface of a rectangular laminate (200 × 40 mm) of CFRP of $[0]_T$ with electrical insulation of epoxy adhesion on the specimen surface to load tensile strain in the small specimens as shown in Fig. 5. To prevent bending stress, the same size specimen is attached on the opposite side of the laminate. Electrical insulation of the base CFRP plate of $[0]_T$ is made by means of painting epoxy resin on the surface, and direct current is applied to measure the electrical resistance. The reason why these small specimens are adopted here is to prevent a poor electrical contact at the electrodes made from silver paste. Reduction of the size of the electrodes reduces possibility of poor electrical contact. After polishing the specimen surface with sand paper, silver...
paste is painted to make the electrodes of 2 mm × 12 mm. After painting the silver paste on the polished specimen surface, the silver paste is dried and conventional lead wire is placed on the electrodes. Silver paste is used here again for fixing the wire at the electrodes. After this, the electrodes are covered with epoxy resin to protect these electrodes.

3.3 Single-ply shear specimen

Similar specimen configuration to Fig. 2 is adopted as a shear test specimen. The small single-ply specimen is attached to the shear test jig shown in Fig. 6. The shear test jig is made from GFRP (Glass Fiber Reinforced Plastic) of five parts. The middle of the GFRP of the thickness of 0.5 mm has zigzag shape as shown in Fig. 6, and the stiffeners of the thickness of 2.5 mm are attached both ends and surfaces. When tension is loaded in the GFRP shear jig, shear stress is loaded in the middle of the jig where CFRP specimen is attached. To prevent bending of the specimen, the same size specimen is attached on the opposite side of the jig. The shear strain is monitored by means of a three-axis strain gage attached on the CFRP specimen surface. In the preliminary test conducted without attachment of CFRP, almost pure shear loading was confirmed in the small area at the middle of the shear jig. Several preliminary tests were performed to know loading range of perfect elastic deformation of the shear jig without buckling.

3.4 Multi-ply tension specimen

For the multi-ply specimen, a specimen made from the laminate of [06]T is used for the test. As the same as the previous tests, the four-prove method is adopted here to measure electrical resistance change during tensile loading. Figure 7 shows the specimen configuration of this multi-ply specimen. This test was performed to confirm the electrical resistance change in the fiber direction during tensile loading in the fiber direction. This test uses a similar type specimen to that with which Wang and Chung have performed.

In order to investigate the effect of poor electrical contacts at electrodes, two types of specimens were prepared using an identical specimen: silver paint was painted without polishing the specimen surface to make electrodes and...
the specimen surface was polished before painting silver paste. For CFRP laminates made from a hot-press, some carbon fibers are sparsely exposed on the surface, and electrical conductivity can be measured without polishing the surface. At first, electrodes were made without polishing surface with silver paste and the electrical resistance change was measured with the electrodes. This makes poor sparse electrical contact at the specimen surface. After the test, using the identical specimen, specimen surface was polished and the electrodes were made again to measure electrical resistance change during tensile loading.

4. Results and Discussion

4.1 Single-ply tension test

Measured electrical resistance change during the tensile loading of the single-ply tension test is shown in Fig. 8. In this figure, the abscissa is applied tensile strain measured by means of a conventional strain gage, which is attached on the specimen surface. The ordinate is the electrical resistance change of the 0°-tensile-0°-charge specimen: tensile strain is loaded in the fiber direction and the electric current is applied to the fiber direction in order to measure electrical resistance change.

As shown in this figure, the electrical resistance change rises with the increase of applied tensile strain almost linearly, and the slope of the relationship between the applied strain and the electrical resistance change is 2.0. This means the piezoresistivity of the CFRP is positive and the gage factor is 2.0. This gage factor is the same as that of a conventional strain gage. Several load-unload tests in the complete elastic deformation area of the CFRP (lower than maximum tensile strain of 350 μ) were performed and the results show that the gage factor is almost constant and no residual electrical resistance change is obtained here as shown in Fig. 8. This implies that the piezoresistivity of CFRP of the 0°-tensile-0°-charge test is equal to the conventional strain gage and that CFRP is a very reliable self-sensing system.

Electrical resistance change of the 0°-tensile-90°-charge specimen during tensile test is shown in Fig. 9. In this specimen, tensile strain is loaded in the fiber direction (90°) to measure the electrical resistance change in the transverse direction. The upper abscissa is the strain of applied load direction of 0°, and the lower abscissa is the transverse direction (90°) perpendicular to the applied load. The ordinate is the electrical resistance change. As shown in Fig. 9, the electrical resistance of the transverse direction rises with the increase of applied tensile strain in the fiber direction. The gage factor against applied strain is approximately 2, and the gage factor against transverse strain is −10. Several cyclic loading-unloading tests were also performed here.

Figure 10 shows the result of the 90°-tensile-90°-charge specimen. In this specimen, tensile strain is loaded in the transverse direction (90°-direction) and the electric current is also applied to the transverse direction. The abscissa is the strain in the loading direction (90°-direction) during tensile loading in the transverse direction, and the ordinate is the electrical resistance change in the transverse direction. The electrical resistance rises with the increase of applied tensile strain, but the gage factor is not 2.0 but 4.0. No residual electrical resistance is observed.
Fig. 10 Measured piezoresitivity of 90-tensile-90-charge small specimen made from single ply (Solid symbols represent loading and open symbols represent unloading)

Fig. 11 Fiber-contact separation model to explain positive piezoresistivity in the transverse direction and in the thickness direction of a single-ply

Fig. 12 Measured piezoresitivity of shear specimen made from single ply (Solid symbols represent loading and open symbols represent unloading)

Fig. 13 Measured piezoresitivity of 0-tensile-0-current laminated specimen (multi-ply) without polishing specimen surface (Solid symbols represent loading and open symbols represent unloading)

here too, and the relationship between the applied strain and the electrical resistance change is almost linear.

In both Figs. 9 and 10, however, electric current is applied to the transverse direction. In Fig. 9, tensile strain to the fiber direction is applied and compression strain to the fiber direction is applied in Fig. 10. Both results show the positive piezoresistivity as shown in Figs. 9 and 10. The fiber contact is the main electric current pass in the transverse direction. When the fibers are tensed, contacts between fibers are reduced as shown in Fig. 11. This caused increase of the electrical resistance of the 0-tensile-90-charge test.

4.2 Single-ply shear test

Figure 12 shows the result of the shear test. The abscissa is the applied shear strain calculated from the three-axis strain gage attached on the specimen surface. The ordinate is the electrical resistance change. As shown in this figure, shear strain has no effect on the electrical resistance change. This means that the piezoresistivity of CFRP is similar to the conventional metallic material at least for shear deformation.

4.3 Multi-ply tensile test

First a tensile test was performed with measuring electrical resistance change using the specimen of which electrodes were made without polishing specimen surface. Figure 13 shows the measured results. The abscissa is the applied strain in the fiber direction, and the ordinate is the measured electrical resistance. Figure 13 shows that the electrical resistance decreases with the increase of applied tensile load (negative gage factor) as the same as Wang and Chung(11) have reported. They have reported the negative gage factor of $-23$. In the present study, the negative gage factor is $-20$ and the value is almost the same as that of Wang and Chung(11) have reported.

Using the identical specimen of Fig. 13, the specimen surface was polished using sandpaper and the surface cleaning was performed. After that, silver paste is placed to make four electrodes on the specimen surface for the measurements of electrical resistance with the four-probe method. Tensile test was performed to measure the electrical resistance change of the specimen. Figure 14 shows the results of the identical polished specimen. Figure 14 shows that the electrical resistance increases with the increase of applied tensile strain in the fiber direction. The measured gage factor is positive value of 2.6, which is almost similar to the gage factor of the single-ply shown in Fig. 8. As the same as the single-ply specimen, the relationship between the applied strain and the electrical re-
Fig. 14  Measured piezoresistivity of 0-tensile-0-charge laminated specimen (multi-ply) (Solid symbols represent loading and open symbols represent unloading)

As mentioned before, this test using the specimen without polishing surface was performed to investigate the effect of poor electric contact at the electrodes. Since these two figures were obtained from the identical specimen, we can conclude that the negative piezoresistivity must be obtained owing to the poor electric contact at the electrodes. Usually the four-probe method is robust against electrical resistance change at the electrodes. However, the poor electrical contact makes sparse contacts to unidirectional CFRP, and this may make a complicated electric current path as the same as the model mentioned by Angelidis and others(6). This mechanism will be our next target to be confirmed.

The self-strain measurement system using piezoresistivity of CFRP is confirmed in this study with unidirectional CFRP. For most of practical applications of the CFRP structures, however, are multidirectional laminates. The application of this work for multidirectional CFRP is our future work.

5. Conclusions

The present study reveals the basic properties of piezoresistivity of CFRP. Several kinds of tests were performed to measure electrical resistance change during tensile and shear loading. Using the four-probe method and small specimens, the properties of piezoresistivity were carefully obtained here. The effect of poor electric contact at the electrodes was also investigated using specimens without polishing surface. The results obtained are as follows.

(1)  Piezoresistivity of CFRP in fiber direction has a positive gage factor and the value is 2.

(2)  Piezoresistivity of CFRP in transverse direction has a positive gage factor against applied tensile load. When the load is applied in the fiber direction, the gage factor is approximately 2, but the gage factor is 4 when the load is applied in the transverse direction.

(3)  Shear loading has no effect on the electrical resistance change.

(4)  Negative piezoresistivity is obtained when the specimen has poor electric contact even for the four-probe method. After polishing the surface, the identical specimen revealed positive piezoresistivity.

References


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