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Apparent negative piezoresistivity of single-ply CFRP due to poor electrical contact of four-probe method

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Abstract. A four-probe method has been an established reliable method to measure electrical resistance precisely for conventional homogeneous electrically conductive materials. A four-probe method is applied to measure electrical resistance change of carbon fiber reinforced plastics (CFRP), and decrease of the electrical resistance of CFRP under tensile loading to the fiber direction was obtained. On the other hand, increase of electrical resistance during tensile load is reported by means of a two-probe method. This paper deals with experiments of a single-ply CFRP and FEM analyses of the four-probe method of CFRP. The experimental results show that the electrical resistance of the single-ply CFRP increases with the increase of tensile loading. In small chance, the electrical resistance decreases with the increase of tensile load. The FEM analyses reveal that the four-probe method is not perfectly exact for a strongly orthotropic material such as a CFRP. For the CFRP electrical contact damage at the electrodes to apply electric current causes increase or decrease of the electric resistance when damaged probes for measuring voltage changes are used by chance. Even for the four-probe method, reliable electrodes are indispensable as the same as the two-probe method.

Introduction

Similar to conventional strain gages, piezoresistivity is a phenomenon in which electrical resistance of a material varies with applied strain. Many researchers have been reported a self-sensing system of unidirectional CFRP (Carbon Fiber Reinforced Plastic). They have utilized the piezoresistivity to measure applied strain of CFRP structures [1-14].

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

Wang and Chung [8-12] have revealed completely opposite results. They employed a four-probe method to measure precise electric 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 electric resistance in the fiber direction is reduced with the increase of applied tensile load in the fiber direction.

Wang and Chung [11] have already reported a paper 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-probe method and the two-probe method, and they concluded that the true piezoresistivity of a CFRP laminate in the fiber direction was negative and the apparent positive piezoresistivity was obtained due to the increase of electric resistance at the probes for the two-probe 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-probe method with electrodes made from silver paste and the negative piezoresistivity was obtained with electrodes made from carbon paste. They revealed that the low electrical contact at the electrodes made from carbon paste caused the negative piezoresistivity. They explained the apparent negative piezoresistivity by means of a model of irregularly placed electrodes of dot shape, and they showed the apparent negative piezoresistivity with the specimen on which electrodes are irregularly placed.

The objective of the present paper is to investigate the effectiveness of the four-probe method for strongly orthotropic CFRP when damaged electrodes are used. Wang and Chung [11] adopted simple electrodes made from painting silver paste without polishing surface of the CFRP specimens. Authors have experimentally revealed that the electrical contact at the electrodes was poor due to the thin resin layer on the surface of the CFRP specimen [13,14]. The poor electrical contact caused negative piezoresistivity while the identical specimen showed the positive piezoresistivity after polishing the surface [13]. To understand the mechanism of the effect of the poor electrical contact at the electrodes, the present report performed experiments and FEM analyses. For the experiments, single ply CFRP is used and electrical resistance change is measured. To simulate the damaged electrodes or the poor electrical contact at the electrodes, the area of electrodes for applying electric current is reduced to half of the specimen width. The effect of the reduction of the area of the electrode is compared with the experimental results.

Experimental method

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

For measurements of the electrical resistance change, the four-probe 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.

Using the single-ply, a specimen made from $[0]_T$, tensile strain is loaded in the fiber direction and electric current for electrical resistance measurement is applied to the fiber direction. The specimen configuration is shown in Fig.2.

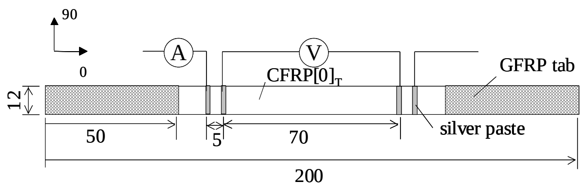


Fig. 1 Specimen configuration

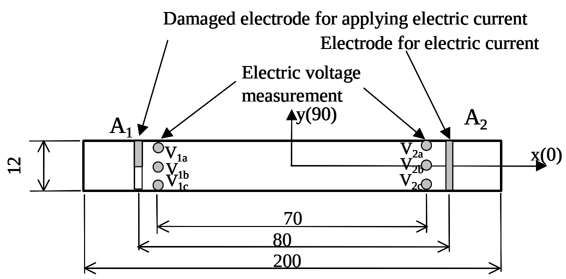


Fig.2 FEM model

FEM analytical method

The specimen used here is the same one shown in Fig.1. The length of the specimen is 200mm, and the width of the specimen is 12mm. Since the 2-D FEM analyses are performed here, the thickness of the specimen is equal to unit.

To simplify the problem, 2D-FEM analyses are performed here. The specimen surface of Fig.1 is analyzed using four-node quadratic elements (width 0.2mm and the length 0.5mm). The total number of nodes is 25681. The electrical conductivities used in the present analyses are σ_0=4600 [S/m], $\sigma_{90}/\sigma_0=1.1\times10^{-3}$ and $\sigma_t/\sigma_0=2.2\times10^{-4}$, which are the measured data in the reference [15].

Figure 2 shows the FEM model used here. To simulate the damaged electrode or the poor electrical contact at the electrode, two cases of the FEM analyses are performed. The first is the perfect electrical contact. The entire area of the electrode is used to apply the electric current at the electrode A1 and A2. The total sum of the distributed electric current is 50mA. At the electrode A2 the voltage is set to zero.

For the damaged electrode or the poor electric contact electrode, the area of the electrode (A1) to apply the electric current is reduced to half size as shown in Fig.2 (gray area at A1). The area of the electrode of the grand is kept at constant. This reduction of the electrode simulates the poor electrical contact at the electrode A1 due to the damage of the electrode or the impedance of the thin resin layer at the surface.

To simplify the problem, electrodes for measuring electric voltage are neglected here. Three patterns for measuring the electric voltage are investigated: a probe pattern of V1a-V2a (edge near the electric current path), a probe pattern of V1b-V2b (center) and a probe pattern of V1c-V2c (edge far from the electric current path).

Results and discussion

Experimental results. Fig. 3 shows the measured electrical resistance change of the specimen with surface polishing. The ordinate is fraction of electrical resistance change normalized by the initial electrical resistance and the abscissa is the applied strain measured by the conventional strain gage. As shown in this figure, electrical resistance increases with the increase of applied tensile strain: positive piezoresistivity. The relation ship between the fraction of the electrical resistance change and applied tensile strain is almost linear. This result shows that the positive piezoresistivity is intrinsic property of the CFRP.

Fig. 4 shows the measured electrical resistance change of the specimen without surface polishing. As shown in Fig.4, the fraction of the electrical resistance increases with the increase of applied tensile strain. The initial resistance R_0 is higher than the case shown in Fig.3. In our previous study [13], the fraction of electrical resistance decreases with the increase of the applied load for the multiple-ply unidirectional laminate without polishing. This implies that the electrical resistivity change in the thickness direction of multiple-ply laminate has large effect. This will be investigated in our future work. Six specimens were performed without surface polishing. Five specimens had the similar increase of the fraction with the increase of the applied strain. Only one case had the decrease of the fraction: negative piezoresistivity.

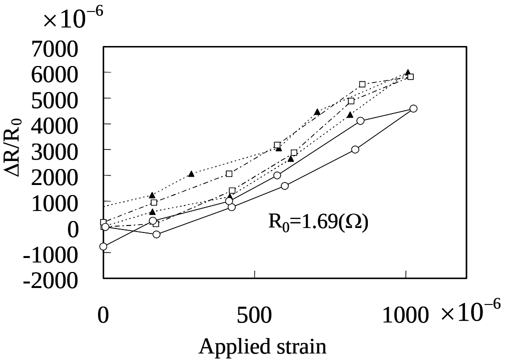


Fig.3 Measured piezoresistivity due to tensile strain
(with polishing specimen surface)

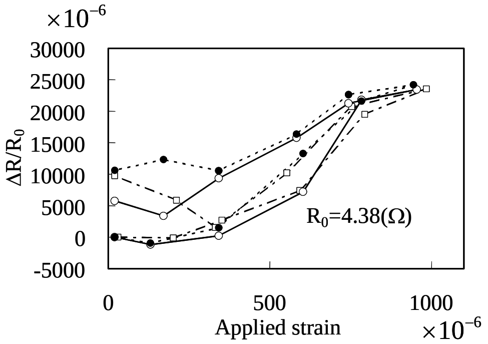


Fig.4 Measured piezoresistivity due to tensile strain
(without polishing specimen surface)

Fig. 5 shows the measured results of the negative piezoresistivity. The fraction of the resistance decreases with the increase of the applied strain. For the single-ply specimens, although most of the cases have positive piezoresistivity (increase of the fraction of the electrical resistance with the increase of applied strain), some cases have negative piezoresistivity. Fig. 6 shows the cross section of the electrodes of the both specimens. In these photos, white circles are the carbon fibers and the silver paste is shown as white areas. The gray area is the epoxy matrix. For the specimen with polishing, a lot of carbon fibers have electrical contacts with the silver paste. On the other hand, thin resin rich layer is observed in the specimen without polishing surface, and the sparse poor electrical contacts are recognized as shown in Fig.6.

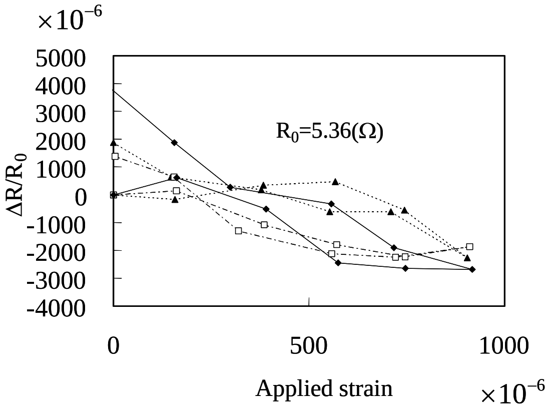


Fig.5 Measured piezoresistivity due to tensile strain (without polishing specimen surface)

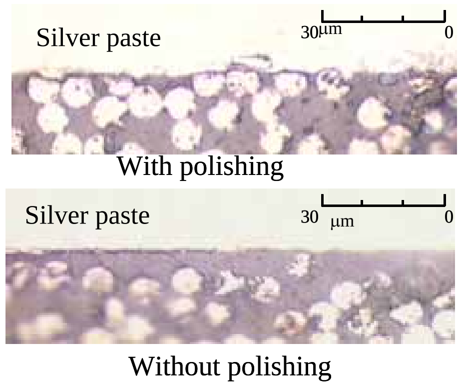
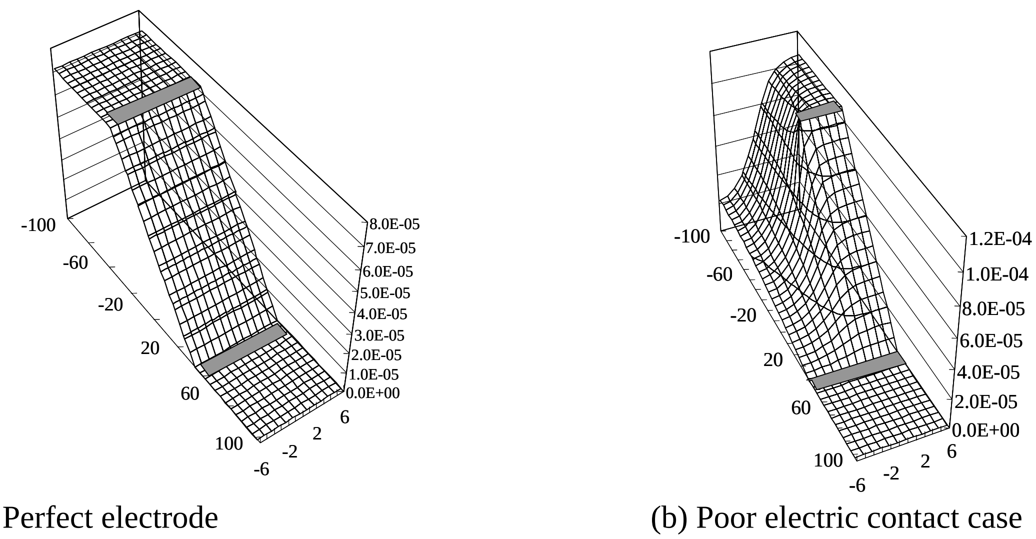


Fig.6 Cross section of the electrodes of both specimens.

FEM results. To investigate the effect of the poor electrical contact on the four-probe method of CFRP, FEM analyses were performed as previously mentioned. Fig. 7 (a) and (b) show the contour plot of the analytical results of surface voltage when electrical current is applied: electric voltage is plotted against the location on the specimen surface. Fig. 7(a) shows the contour plot of the voltage of the perfect electrodes and Fig. 7(b) shows the results of the damaged or poor sparse electrodes: half area of charging electrode is lost. The gray areas show the electrodes where electric current is applied. For the perfect electrodes, electric voltage is perfectly linear in the entire surface. However, for the poor electrical contact specimen, the linear relationship is only observed in the area between the intact electrodes. This means that the electric current flows only half area of the specimen.



(a) Perfect electrode (b) Poor electric contact case

Fig. 7 Contour plot of electrical voltage analyzed with FEM

This shrink of the electric current path is caused by the strong orthotropic electric conductivity of CFRP. As measured in our previous paper [15], the electric conductivity in the transverse direction is almost 1/1000 compared with the fiber direction for the CFRP of V_f=0.5. For the isotropic materials, even for the poor electric contact electrodes of half size, electric current flow in the transverse direction and the electric voltage distribution becomes almost linear except for around the electrode similar to the contour plot of Fig. 7 (a) when the two electrodes locate in fully enough spacing. This is why the four-probe method is considered to be very useful for precise measurement without including the electrical resistance at the probes. Even the system with the sparse dot like electrodes and probes measures exact electrical resistance for the isotropic materials. For the strong orthotropic conductivity materials like CFRP, however, the damage or the poor electrical contact at the electrodes where electrical current is applied has significant change of electric current path, and the change causes large error on the measurements.

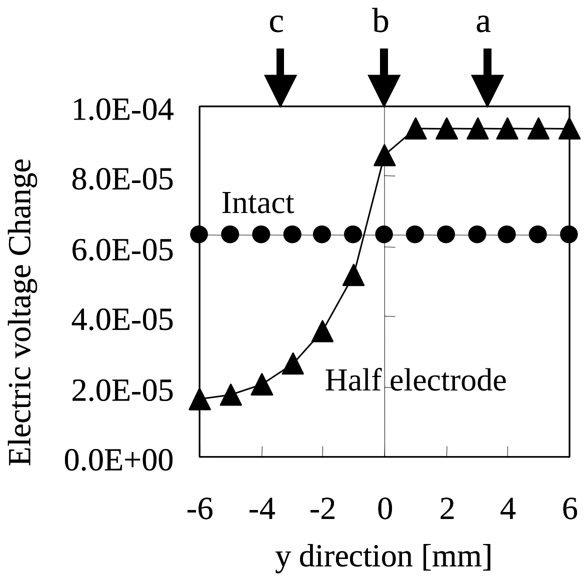


Fig. 8 Electric voltage change due to piezoresistivity

Fig. 8 shows the results of electrical voltage change at the probes to measure voltage in both cases: the case of intact electrodes (solid circle symbols) and the case of poor electric contact modeled by the half electrode (solid triangle symbols). For the FEM analyses, intrinsic piezoresistivity is considered to be positive and the electric resistivity change due to the positive piezoresistivity under the applied strain of 1000μ is added to the electric resistivity. The abscissa is the location of the probes and the ordinate is the electrical voltage difference between the two probes. Since the applied electrical current is constant, the electric voltage change means the change of electric resistance of the specimen if we do not pay attention to the change of the electric current path due to the poor electric contact. For the intact cases, the electric voltage is constant for every probe. This means poor contact at the probes has no effect. For the poor electric contact case (half electrode), the electric voltage change at the area where electric current flows (from 0 to 6mm) becomes higher than the values of the intact case, and the electric voltage change at the area where electric current does not flow (from –6 to 0 mm) becomes smaller than the values of the intact case. This means that positive piezoresistivity of higher gage factor is observed for the case that the probes locates at (a) and (b) in Fig.8, and the negative piezoresistivity is observed for the case that the probes locate at (c) in Fig.8: outside of the electric current path.

For the polished specimen, the positive gage factor is approximately 5 as shown in Fig.3 and the positive gage factor of the non-polished specimen is five times higher than the gage factor of the polished specimen (see Fig. 4). These results agree with the FEM analyses qualitatively.

Concluding Remarks

In the present study, single-ply unidirectional CFRP is used for measurement of electrical resistance change due to applied load (piezoresistivity). For the perfectly polished specimen, the resin rich layer at the surface is removed and perfect electric contact is obtained. The electrical resistance increases with the increase of the applied tensile strain. For the most of the non-polished specimen, electrical resistance increase is observed and the gage factor is higher than the polished specimen. A specimen without polishing surface shows the decrease of the electrical resistance with the increase of the applied tensile strain. FEM analyses reveal that the strong orthotropic electric conductivity causes the electric current path shrinkage when the electric contact at charging electrodes is poor (sparse dot like contact). The current path shrinkage brings apparent higher piezoresistivity or apparent negative piezoresistivity even for the single ply CFRP. We can conclude that the four-probe method is not always reliable for CFRP without perfect electrodes (without polishing surface).

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