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Residual strain relief effect on the electrical resistance measurement for delamination monitoring of carbon/PEEK laminates

Yusuke Samejima[1], Yoshiyasu Hirano[2], Akira Todoroki[3,*] and Ryosuke Matsuzaki[3]

[1] Department of Mechanical Sciences and Engineering, Graduate School, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro, Tokyo 152-8552, Japan
[2] Advanced Composite Group, Aerospace Research and Development Directorate, Japan Aerospace Exploration Agency (JAXA), 6-13-1 Osawa, Mitaka-shi, Tokyo 181-0015, Japan
[3] Department of Mechanical Sciences and Engineering, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro, Tokyo 152-8552, Japan,
e-mail: atodorok@ginza.mes.titech.ac.jp

*Corresponding author

Abstract

Damage, such as delamination and fiber breakages, to the carbon/epoxy laminates can be detected by measuring electrical resistance changes caused by the damage. The resistance changes result from the electrical current path being impeded and deformation of the composites relating to piezoresistivity. In the present study, the effect of the residual strain relief due to delamination is investigated analytically and experimentally for two different stacking sequences and it is confirmed that piezoresistivity has a significant effect on the measured electrical resistance change in the electrical resistance change method.

Keywords: composites; delamination; electrical resistance; piezoresistance; residual stress.

1. Introduction

Carbon fiber reinforced plastics (CFRPs) have electrical conductibility because their carbon fibers have high electrical conductance. Much research has adopted the method of measuring electrical resistance changes for CFRPs to detect damage to the composites [1–10]. The authors have proposed a damage identification method for CFRP structures using the electrical resistance change method (ERCM) [11–15]. In the ERCM, electrodes mounted on the surface of CFRP structures are used to measure electrical resistance changes for multiple segments, and damage, such as delamination and matrix cracking is identified from the measured changes. In the previous studies, thin laminated CFRP specimens were used, and this allows electric current to flow in the entire specimen. A delamination crack impedes the electric flow in the thickness direction, and the electrical resistance change is explained owing to the electrical resistance increase caused by the delamination crack. For a thick CFRP laminate, however, electric current will flow in many directions in multiple plies.

Usually, CFRP is cured at a high temperature, such as 180°C. This means the composite laminates usually have residual stress. A delamination crack causes residual strain relief, resulting in an electrical resistance change owing to the piezoresistivity of the CFRP. For thick CFRP laminates, the effect of the piezoresistivity on the measured electrical resistance change may be significant owing to the complicated residual strain relief. In the present study, therefore, the ERCM is applied to measure the residual strain relief caused by delamination and fiber breakages. As a first step, the piezoresistivity of CFRP is measured experimentally to obtain the gauge factor: electrical resistance change per unit applied strain. AS-4/polyetheretherketone (AS-4/PEEK) is adopted here because the process temperature is higher than the normal CFRP temperature; this means a large residual strain is produced in the AS-4/PEEK composites. Finite element method (FEM) analyses are performed to investigate the effect of residual strain produced during curing. Two types of cross-laminated beams are investigated here. Using the same specimen used in the analyses, experiments are performed. Comparing the analyses to the experimental results, the effect of the piezoresistivity caused by the residual strain relief on the electrical resistance changes is investigated.

2. Measurement of piezoresistivity for a single ply specimen

2.1. Specimens and procedure

The material used here is unidirectional prepreg APC-2, AS4/PEEK (carbon/PEEK). The prepreg is used to make a single-ply plate of $[0]_T$. Since PEEK is a thermoplastic polymer, the prepreg is directly used for measurements in the various tests. From the prepreg plate, four kinds of specimens are prepared for the measurements of piezoresistivity: (a) 0-tensile-0-charge, (b) 0-tensile-90-charge, (c) 90-tensile-90-charge and (d) 90-tensile-0-charge, where the first figure refers to the loading direction compared with the fiber direction and the second figure refers to the direction in which the electrical current is applied. For measurements of the electrical resistance change, the two-probe method is adopted. Electrodes of each specimen are produced using electric copper plating and leading wires are attached with silver paste. The electrode system has good electrical conductivity at the electrode. Specimens (a) and (b) are attached to the unidirectional laminate $[0_8]_T$ shown in Figure 1 and specimens (c) and (d) are attached to the unidirectional laminate $[90_8]_T$ shown in Figure 2 with normal epoxy adhesive. To prevent bending deformation, same sized specimens are attached to opposite sides. The tensile test is performed in the elastic deformation region with a tensile/compression testing machine (Shimadzu AG-1, Tokyo, Japan, 100 kN) up to 1000 μ strain. The applied strain is measured with a strain gage and the electrical resistance change is measured with an LCR meter (Hioki 3522, Nagano, Japan).

2.2. Results and discussion

The experimental results of electrical resistance change during tensile tests are shown in Figure 3. In the figures, the abscissa is the applied strain measured with the strain gage and the ordinate is the measured electrical resistance change normalized with the initial resistance. From the results for specimens (a) and (b), the gage factor is positive when the specimen is loaded in the electric charging direction and negative in the other direction. This means the biaxial effect is significant. Specimen (b) is under the tensile loading in the fiber direction and shrinks in the transverse direction owing to Poisson's ratio. However, pulling in the fiber direction results in less curvature in the carbon fibers, and this decreases the spacing between carbon fibers and increases the electrical resistance.

3. Residual strain relief effect

The effect of piezoresistivity caused by the residual strain relief on the electrical resistance changes is investigated analytically and experimentally. The effects of the insulation of the current path and the residual strain relief are compared.

3.1. Analytical investigation

3.1.1. Analysis model and procedure FEM analyses are performed using commercially available FEM code named ANSYS 11.0. A beam-type specimen, as shown in Figure 4, is adopted for the FEM analysis. Two 16-ply stacking sequences

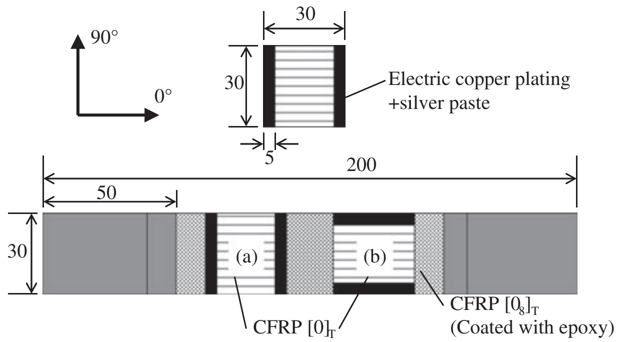

Figure 1 Configurations of specimens (a) and (b).

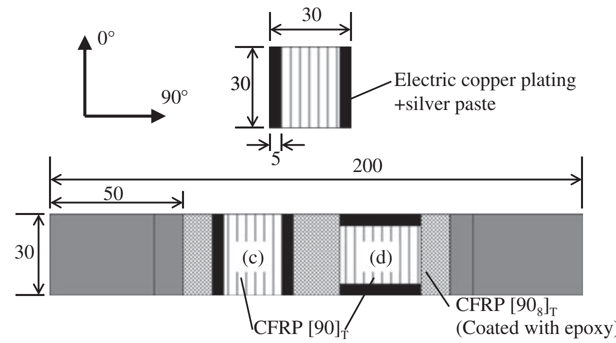

Figure 2 Configurations of specimens (c) and (d).

are computed to compare residual strains: (I) $[0_4/90_4]_S$ and (II) $[0_2/90_2]_{2S}$. The thickness of both specimens is 2.0 mm. The delamination crack configuration used here resembles the letter Z. The delamination location in the thickness direction is the interlamina that has a different fiber orientation angle. On the delamination crack surface lines, all nodes are doubly defined to represent the delamination crack surface. The delamination length is 10 mm in the x direction and 20 mm in the z direction. Two electrodes are mounted on one surface of the specimen. Their width and length is 4 mm and 20 mm. An electrode is modeled by coupling nodes on the electrode to give the same electric potential. In the analyses, a hexahedral eight-node element is adopted, the total number of nodes is 29333, and the total number of elements is 6400.

First, the analyses of the residual strain relief are performed. The residual strain analyses without delamination and with delamination are performed at 623 K, which is the processing temperature of AS4/PEEK prepreg, and the residual strain due to delamination is obtained by subtracting the strain at 300 K, which is the room temperature. The material properties used in the analyses are given in Table 1.

Analyses of the insulation of the current path are then performed. The electrical resistance changes are obtained by loading 15 mA of electric current on one electrode and fixing 0 V electric potential at the other electrode. The initial electrical resistance R_0 between the electrodes is obtained by performing FEM analysis with no delamination. An analysis is then performed with the delamination and the electrical resistance R' with delamination is obtained. The electrical resistance change ratio is expressed as

$$\frac{\Delta R}{R_0}=\frac{R'-R_0}{R_0} \tag{1}$$

where R_0 is the initial electrical resistance and R' is the electrical resistances after delamination creation. The measured electrical conductivity ratios of the specimen adopted in the analyses are given in Table 2.

3.1.2. Results and discussion The FEM analysis results of the residual strain relief effect are shown in Figure 5. From the results, the configurations of the residual strain relief due to the delamination are similar between stacking sequences

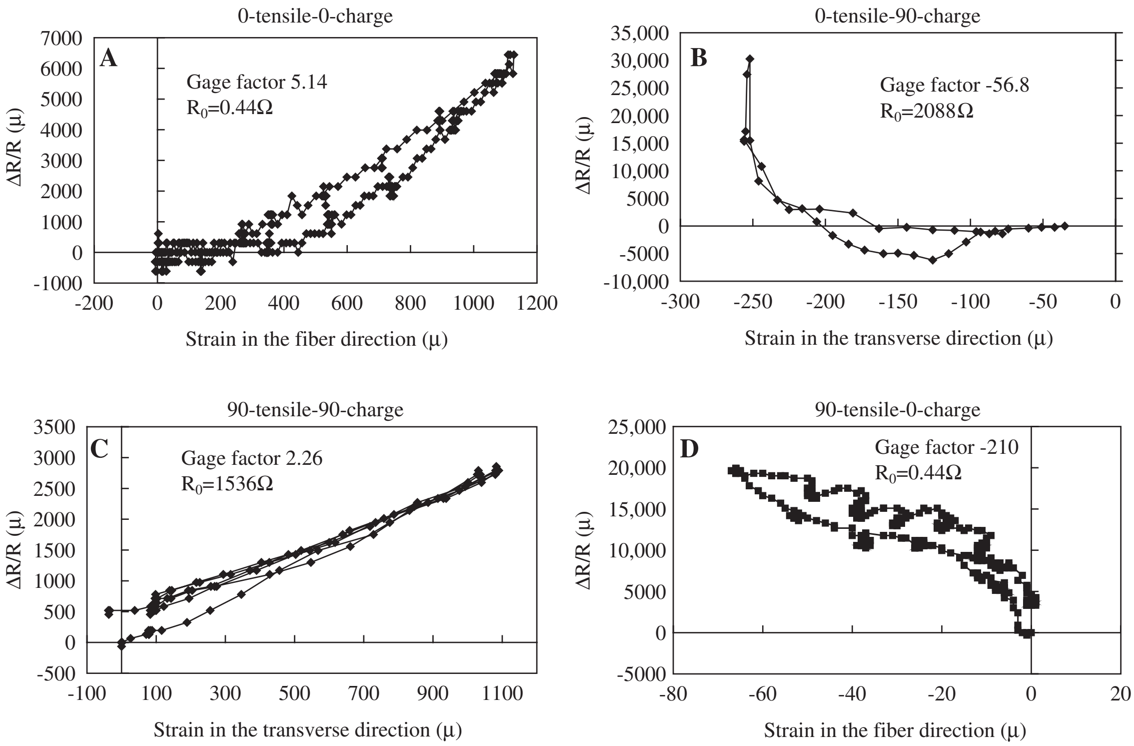

Figure 3 Measured piezoresistance of the single ply specimen from a tensile test in the elastic deformation region.

(I) and (II) but the residual strain magnitudes differ. It is shown that the smaller the number of zero degree layers close to the specimen surface, the larger the residual strain relief. As for the conventional strain gauge, the electrical resistance of CFRP is expressed as

$$R=\rho\frac{L}{A} \tag{2}$$

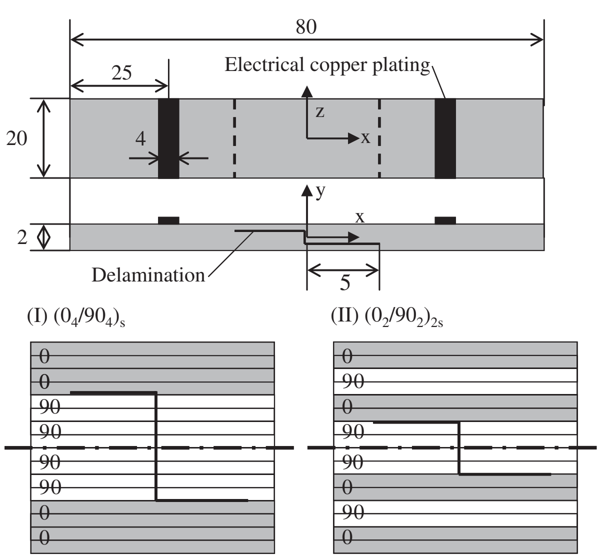

Figure 4 Analysis model and delamination crack configuration.

where ρ is resistivity, L is length and A is the cross-section area. When the carbon fiber is strained, the electrical resistance changes as

$$\frac{\Delta R}{R}=\frac{\Delta\rho}{\rho}+\frac{\Delta L}{L}-\frac{\Delta A}{A}=(1+2\nu)\varepsilon+\frac{\Delta\rho}{\rho} \tag{3}$$

where ν is Poisson's ratio. The change in ρ is proportional to the volume change:

$$\frac{\Delta R}{R}=\left\{(1+2\nu)+m(1-2\nu)\right\}\varepsilon=K\varepsilon \tag{4}$$

Table 1 Material properties of APC2.

Material Direction	AS4(carbon)/APC2(PEEK)		
	x (xy)	y (yz)	z (zx)
E (Gpa)	122	10.1	10.1
G (GPa)	5.5	3.7	5.5
ν	0.25	0.45	0.25
α (10^{-6}/K)	-0.2	24	24
K (W/mK)	3	0.2	0.2

Table 2 Measured electrical conductivity ratio of APC2.

σ_0 (S/m)	2196
σ_{90} (S/m)	33
σ_t (S/m)	33

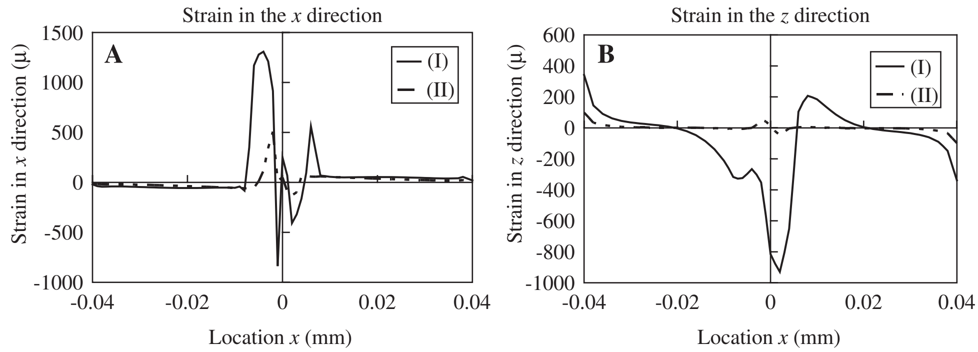

Figure 5 Residual strain distribution of the specimen surface along the x direction obtained by FEM analyses.

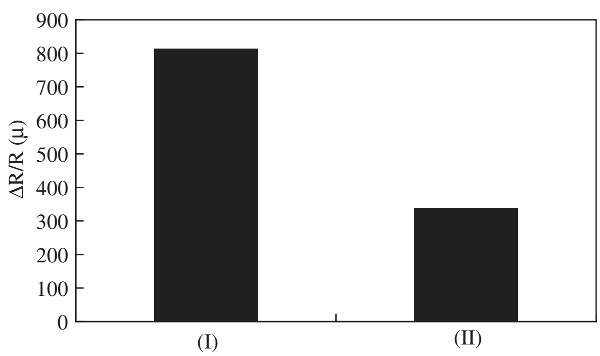

Figure 6 Electrical resistance change due to the insulation of the current path obtained by FEM analyses.

where the coefficient K is a gauge factor. In section 2, the piezoresistivity effect was experimentally measured along the zero degree direction of $(0)_T$ unidirectional specimens and the gauge factor was 5.14. Therefore, the electrical resistance change ΔR/R due to piezoresistivity of the CFRP is computed as about 6700 μ at the maximum point in the x-directional strain.

The analysis results of the insulation of the current path are shown in Figure 6. The electrical resistance change for specimen (I) is larger than that for specimen (II). This is because the insulation area in the thickness direction is large in specimen (I). The maximum electrical resistance change due to the insulation of the current path is about 800 μ for specimen (I).

From these results, the electrical resistance change for piezoresistivity is larger than that for insulation of the current path and it is confirmed that piezoresistivity significant affects the measured electrical resistance change in the ERCM. Residual strain in the z direction is also computed and its effect is also significant.

3.2. Experimental investigation

In section 3.1, we compared the residual strain relief effect and the insulation effect analytically. In this section, the residual strain relief effect is experimentally investigated.

3.2.1. Specimens and procedure The material is unidirectional prepreg APC-2, AS4/PEEK. Two 16-ply stacking sequences were manufactured to compare residual strains: (I) $[0_4/90_4]_s$ and (II) $[0_2/90_2]_{2s}$. The plate was cured with an autoclave at 623 K. From the laminates, rectangular plates of 80 mm×20 mm were fabricated as shown in Figure 7. The specimen thickness was about 2.3 mm. For measurements of the electrical resistance change, the two-probe method was adopted. Electrodes of each specimen were produced using electric copper plating and leading wire and by soldering. A three-point bending test was performed with a tensile/

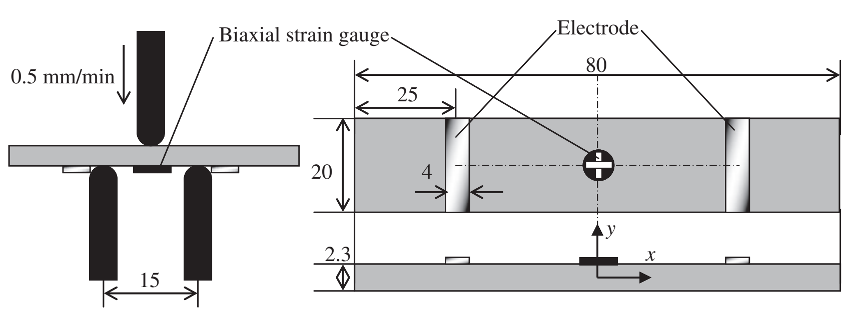

Figure 7 Experimental setup and specimen configuration for three-point bending test.

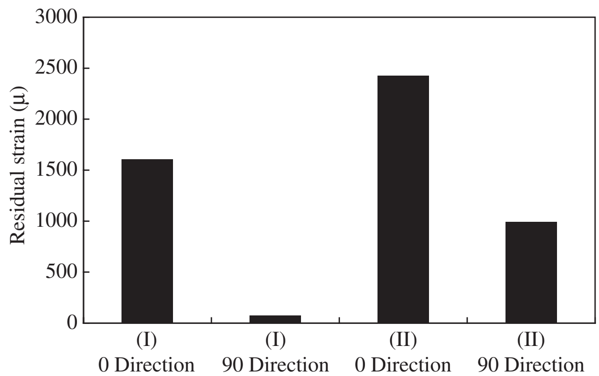

Figure 8 Measured residual strains in the 0 and 90° directions.

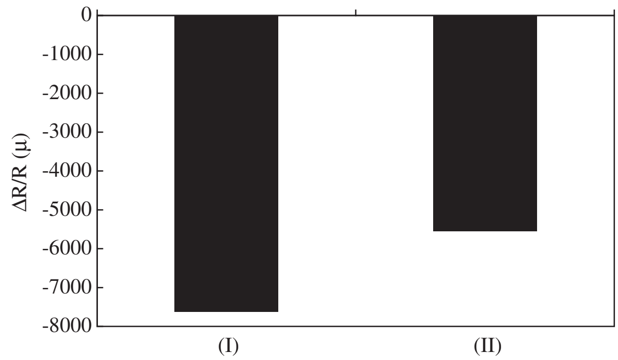

Figure 9 Measured electrical resistance changes for the two different stacking sequences.

compression testing machine (Shimadzu AG-1 100 kN) until delamination occurred. The crosshead speed was 0.5 mm/min and the spacing between supporting points was 15 mm. The residual strain was measured with a biaxial strain gauge attached to the jig side and the electrical resistance change was measured by an LCR meter (Hioki 3522) with a DC current.

3.2.2. Results and discussion The experimental results of residual strain and electrical resistance change are shown in Figures 8 and 9, respectively. Large residual strain was found in the experimental results, as in the analytical results, but the values were very different for both specimens. This is because plastic deformation occurs in specimen (I), while the fiber breakage occurs on the indentation side in specimen (II). APC2 prepreg contains PEEK resin, which has an impact resistance superior to that of a conventional epoxy resin. Therefore, the experimental results for the electrical resistance change also differ from the analytical results. Experimental results show a negative electrical resistance change, whereas the analytical results show a positive electrical resistance change. Therefore, the analytical electrical resistance change due only to the current path insulation does not simulate the experimental result sufficiently; thus piezoresistance relating to the residual strain relief effect should be investigated to clarify the negative electrical resistance change. An experiment without plastic deformation and fiber breakage is required.

4. Concluding remarks

In the present paper, the effect of piezoresistivity due to delamination occurrence was investigated using FEM analysis for beam-type specimens with two stacking sequences. It was analytically shown the piezoresistivity effect of CFRP is significant compared with the insulation effect of the current path. A three-point bending test was performed and the negative electrical resistance change measured experimentally. It was shown the analytical electrical resistance change only due to the current path insulation does not simulate the experimental result sufficiently. Further experimental investigation is required to investigate the negative electrical resistance change due to delamination occurrence.

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