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Electrical Resistance Change of Thick CFRP Laminate for Self-Sensing*

Akira TODOROKI**, Yuusuke SAMEJIMA***, Yoshiyasu HIRANO****, Ryosuke MATSUZAKI** and Yosihiro MIZUTANI**

** 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

*** Tokyo Institute of Technology

**** JAXA Supersonic transport team, Aviation Program Group, JAXA,
6-13-1 Osawa, Mitaka, Tokyo 181-0015, Japan

Abstract

This paper deals with the mechanism of electrical resistance change observed after delamination cracking of a thick Carbon Fiber Reinforced Polymer (CFRP) laminate. In a previous paper, the current shut-off caused by the delamination crack increased the electrical resistance for a thin laminate, and the effect of piezoresistance caused by the residual strain relief was small compared with the shut-off effect. For the thick CFRP, a dent is made because of the high indentation compression load at the loading point. The present paper measures the effect of the dent experimentally and estimates the electrical resistance increases caused by the shut-off effect and piezoresistance effect using Finite Element Method (FEM) analyses. The estimates are compared with the experimental results of the thick CFRP laminate. As a result, it is established that the effect of the dent (which causes a decrease of electrical resistance) is larger than the effect of the shut-off (which causes an increase of electrical resistance) for the thick CFRP laminate.

Key words: Composites, Carbon, Delamination, Piezoresistance, Dent

1. Introduction

Laminated Carbon Fiber Reinforced Polymer (CFRP) composites are widely adopted for aerospace structures because of their high strength, high stiffness and light weight. The CFRP laminates can easily have delamination cracks resulting from small impact loads such as from dropped tools. Since the delamination cracks are usually difficult to detect by visual inspection, the CFRP laminates must have high knockdown capabilities or require expensive non-destructive inspection tools to confirm their structural integrity.

A self-sensing method measures electrical resistance changes to detect damages in the CFRP laminates. The method uses carbon fibers as sensors, does not require expensive instruments, and can be used for existing structures. As the reinforcement fibers are used as sensors, the electrical resistance change method for CFRP laminates is called a self-sensing method. The method is a non-destructive and attractive inspection method that has been the subject of numerous experimental investigations [(1)-(10)]. Research on the use of the electrical resistance change method has been reported for monitoring applied strain [(11),(12)], matrix cracking [(13),(14)] and delamination crack monitoring [(15)-(23)].

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Multiple copper electrodes were implanted on a single surface of the laminated plate to monitor the delamination through the electrical resistance changes. The relationship between the delamination and the sets of the measured electrical resistance changes was obtained through artificial neural networks or response surfaces. For thin CFRP laminates the electrical resistance increased after delamination [(16)-(18)]. For thick CFRP laminates, however, the electrical resistance decreased after delamination cracking even though a two-probe method was used [(22)]. This work did not clarify the mechanism of the decrease of electrical resistance after delamination cracking, but residual strain relief is implicated in the mechanism. Residual strain relief may also affect a thin CFRP laminate.

The previous paper, dealt with the mechanism of electrical resistance change of a thin CFRP laminate [(24)]. Finite Element Method (FEM) analyses were performed to calculate the residual strain relief and the electrical resistance change caused by the piezoresistance of the relieved residual strain was estimated. The shut-off effect was also calculated using FEM analysis with multiple delamination cracks. The results revealed that the effect of piezoresistance is negligible compared with the effect of the shut-off for the thin CFRP laminate.

For a thick CFRP laminate, a dent deformation resulting from high compression loading was made at the indentation point, although the dent was not observed for the thin CFRP laminate. To investigate the effect of the dent, thick CFRP plates were adopted in the present study. The effect of the dent was experimentally investigated initially using the indentation tests on an elastic flat support. After making multiple delamination cracks using indentation tests on a metal ring support, ultrasonic C-scan images were taken by acoustic tomography to investigate the multiple delamination cracks. The multiple delamination cracks were modeled into complicated multiple square delamination cracks, and a FEM analysis was performed to investigate the effect of shut-off. The analytical results were compared with the experimental result to clarify the mechanism of electrical resistance change of the thick CFRP laminate.

2. Specimen and experimental method

The material used in the present study was unidirectional carbon/epoxy prepreg produced by Mitsubishi Rayon Co. Ltd. The prepreg production number was PYROFIL #380. As a thick CFRP laminate test piece, a simple sixteen-ply quasi-isotropic laminate with stacking sequence $[(0/90/45/-45)_2]s$ was used to compare the experimental results with the analytical results of the FEM. The CFRP laminates were cured at 130°C and 0.6 MPa for 90 min using an autoclave. Plate type specimens 80 mm long and 80 mm wide were made from the CFRP plate as shown in Fig.1. The thickness of the specimens was approximately 4 mm. and the fiber volume fraction, V_f, was 0.53. Two electrodes were mounted on the dual surface of the CFRP beam using an electrical copper plating method. The process used to make the electrodes was shown in the previous study [(24)]. In the previous paper, two electrodes were placed on a single surface of the beam type specimen. For a thick CFRP plate, electric current flows only in the surface layers when the two electrodes are placed on the single surface [(22)]. Thus, the two electrodes were placed on the opposite surface of the plate to produce an electric current in the thickness direction.

To make a delamination crack in the CFRP beam, an indentation test was used. The test jig is illustrated in Fig.2; the diameter of 60mm metal cylinder is used as a support. The multiple delamination cracks were observed by using ultrasonic C-scan SDS-5400R made by Krautkramer Japan Co. Ltd. At the indentation point, a piece of tire rubber (thickness=1 mm) was used to protect the CFRP laminated plate and to retain the electric insulation. At the cylinder support, a one millimeter thick Teflon filmwas inserted to prevent electrical contact between the specimen and the metallic jig. The loading speed of the indentation test was 0.5mm/min. Coordinates *x*-*y*-*z* were defined as shown in Fig.1.

The electrical resistance change was measured using a LCR meter (Type #3522-50) made by Hioki Co. Ltd. A two-probe method was used. Alternating current (1 kHz and 10 mA) was adopted for the measurements, because an alternating current gave more stable measurements than a direct current for this LCR meter. The CFRP laminates were modeled as simple orthotropic resistances up to 1 MHz. Thus, the CFRP laminate was treated as a simple electrical resistance for the low frequency alternating current.

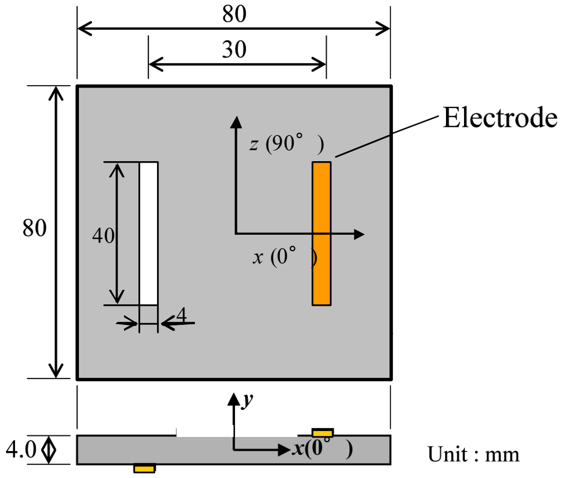

Fig.1 Specimen configuration of a thick CFRP plate

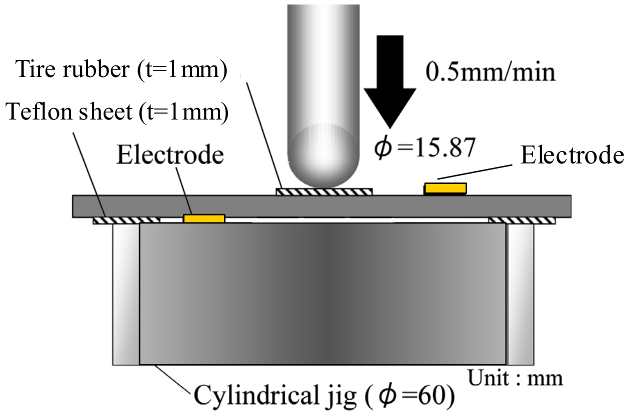

Fig.2 Jig to make delamination crack

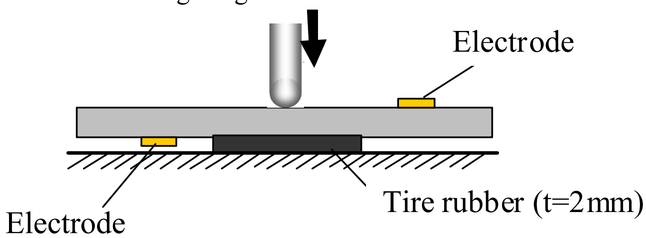

Fig.3 Test method to make a dent without delamination cracks

The indentation method shown in Fig.2 generates multiple delamination cracks with a dent. To measure only the effect of a dent, generation of the delamination cracks should be avoided. To make only a dent at the indentation point, an indentation test on a flat floor is adopted as shown in Fig. 3. The specimen shown in Fig.1 is placed on a rubber support on the floor, and the indentation test is performed to make a dent. After making the dent, the dent depth is measured using a three-dimensional LASER profilometer (Keyence, Type KS-1100), and the residual electrical resistance change is measured using the LCR meter.

3. FEM analytical method

To evaluate the effects of shut-off of the current path caused by the multiple delamination cracks, and piezoresistance effect caused by strain relief after delamination cracking, three dimensional (3-D) FEM analyses were performed. On the basis of the observed complicated multiple delamination cracks, a set of the similar multiple delamination cracks were prepared for the FEM analysis. The modeling of delamination and how to calculate the effect of effect of piezoresistance were shown in detail in the previous study [24].

For the FEM analyses exact conductivity is indispensable. Electric conductivity in the fiber direction (σ_0), transverse direction (σ_{90}) and thickness direction (σ_t) were measured with small sized specimens using the LCR meter in the previous study [24]. Delamination was modeled as the release of doubly defined nodes: electric current does not flow in the normal direction to the delamination crack surface. To calculate the residual strain relief, curing strain was calculated using the thermal properties shown in Table 1. In the actual delamination cracking, the delamination crack surfaces made partial contact with each other. The insulation between the delamination crack surfaces must be the overestimation of the shut-off effect. This means the FEM analyses of the present study were planned to roughly estimate the magnitude of each effect.

Table 1 Material properties used for FEM analyses

Material	PYROFIL #380 (Carbon/Epoxy)		
Direction	x (xy)	y (yz)	z (zx)
E [Gpa]	141	10	10
G [GPa]	5.0	0.15	5.0
ν	0.3	0.4	0.3
α [10^{-6}/K]	0.9	30	30
σ [S/m]	4100	3.3	3.3

Using the measured conductivities in the three directions, FEM analyses were performed with the commercially available FEM code ANSYS ver.11. For the 3D-FEM analyses, eight-node solid elements were adopted. At the electrodes, all surface nodes were coupled to have the same voltage, to simulate the copper electrodes. At the left electrode, an electric current of 10 mA was applied, and the voltage of the right electrode was kept at zero. From the calculated voltage at the left electrode, electrical resistance was calculated. The element dimension was 1.25 mm (long)×1.25 mm (wide)×0.125 mm (thick). For the 3-D FEM analyses of the plate type specimen, the total number of nodes was 146,595 and the total number of elements was 135,168.

The FEM analytical method used to estimate the residual strain relief was the same as used in the previous study [24]. Thermal deformation analyses of specimens with and without a delamination crack were performed. By subtracting the strain of the specimen with a delamination crack, from the strain of the specimen without a delamination crack, residual strain relief was calculated. By averaging the relieved residual strain between the two electrodes, the electrical resistance caused by the piezoresistance was estimated. The estimation method of the residual strain relief was confirmed with the experimental results measured by using strain gages in the previous paper [24]. In the present study, the FEM results were used to calculate the effect of residual strain relief. The averaged residual strain in the top and the bottom plies contributes to the relationship of the multi-axial piezoresistance effect [12]. Since it was quite difficult to measure the piezoresistance effect in the thickness direction, the effect of the residual strain relief only in the first and the bottom plies was considered. The relationship used for the multi-axial strain is as follows:

$$\begin{Bmatrix} \left(\dfrac{\Delta R}{R}\right)_L \\ \left(\dfrac{\Delta R}{R}\right)_T \end{Bmatrix} = \begin{bmatrix} 2.49 & 0.43 \\ -0.42 & 2.38 \end{bmatrix} \begin{Bmatrix} \varepsilon_L \\ \varepsilon_T \end{Bmatrix} \quad (1)$$

4. Results and discussion

4.1 Effect of dent

The dent effect was experimentally investigated using the square plates as shown in Fig.3. Figure 4 shows the measured results of the effect of the dent. The abscissa is the measured residual strain in the thickness direction: the maximum depth of the dent was measured using the three-dimensional LASER profilometer, and the maximum decrease of the thickness is divided by the initial thickness to calculate the residual strain in the thickness direction. The ordinate is the measured electrical resistance change.

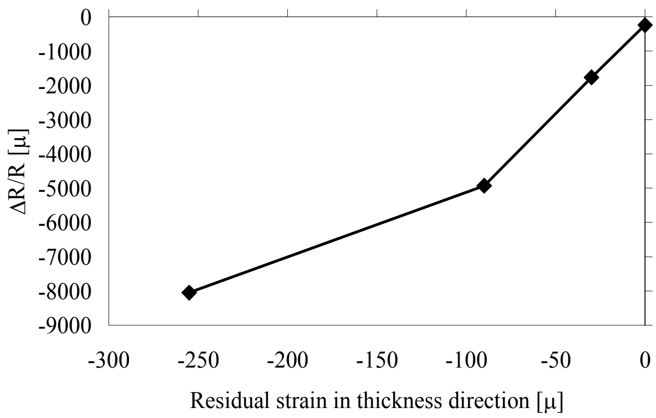

Fig. 4 Measured effect of a dent on the electrical resistance

As shown in Fig.4, the dent reduces the electrical resistance significantly. With the increase of the absolute value of the residual strain (decrease of the residual strain), the electrical resistance decreases almost linearly. This result is similar to the results reported by XS Yi, YM Hu and XL Tao [(25)]. The dent is the partial reduction of the thickness. In the dent area, the area of the fiber contact in the thickness direction increases with the plastic deformation of the resin. This may increase the electric conductivity in the thickness direction. The detail of this mechanism is our planned future work.

4.2 Delamination test

Figure 5 shows the typical result of the electrical resistance change during testing. The abscissa is the time from the start of loading. Since the test is a constant displacement rate test, the abscissa means the displacement of the indenter. The broken curve shows the results of the measured load, and the solid curve shows the measured electrical resistance change. In the initial loading up to 130 seconds, the electrical resistance does not show any change. In this region, the CFRP plate deforms elastically. Since the electrodes are mounted on both surfaces, the electric current flows in the tension ply and compression ply. These equal effects of tension and compression make no change in the elastic deformation region. Over the 130 seconds, plastic deformation of the resin starts and the electric current flows in the thickness direction. In the compression surface (indented surface), the electric conductivity decreases significantly with the plastic deformation in the thickness direction. Since there is no indentation in the tension side, the effect of the tensile stress has no change. This decreases the effect of the compression, and causes the increase of the electrical resistance.

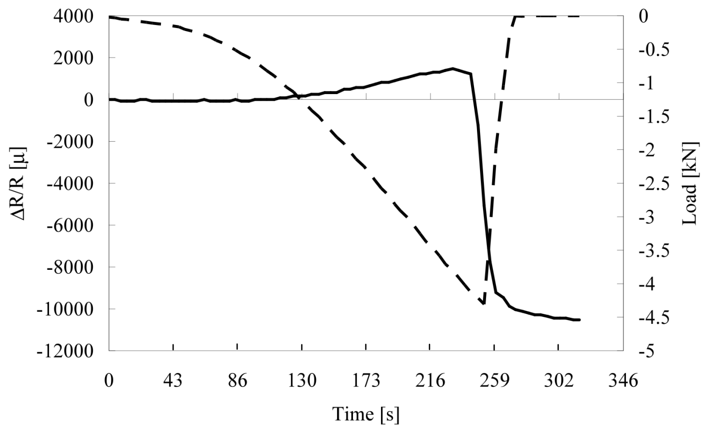

Fig.5 Measured load-displacement and electrical resistance change

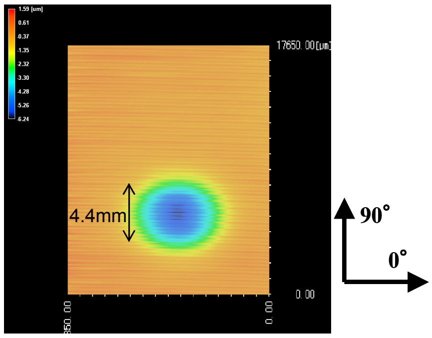

Fig.6 Typical dent configuration measured by using the LASER profilometer

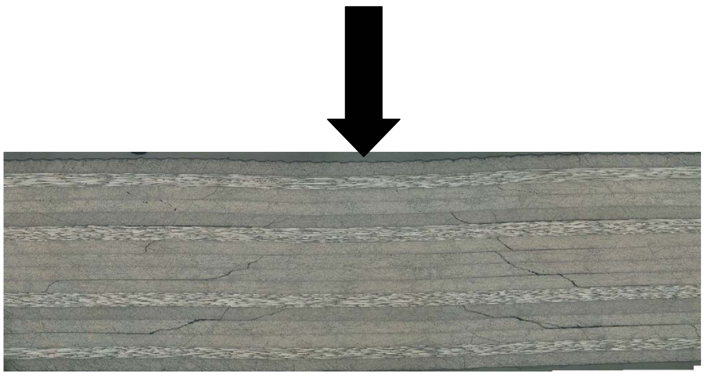

Fig.7 Cross section observation at the indentation point

Figure 6 shows the result of the typical dent configuration observed by using the LASER profilometer. Figure 7 shows the cross sectional view of the indentation point. As shown in Fig.7, there are multiple delamination cracks. Larger cracks exist in the bottom similar to the other research [26]. To confirm the delamination configuration, a phased array ultrasonic C-scan is used. Figure 8 shows the results of the delamination configurations for four typical interlaminae. A small number means the interlamina is located near the indentation surface. A large number means the interlamina is located near the back surface. As shown in Fig.8, the delamination size near the back surface is larger than that near the top surface. In the present study, the minimum size of the delamination near the top surface and the maximum size of the delamination near the back surface are measured exactly from each surface, and the middle delamination sizes are approximated using a linear interpolation to make a delamination model for the FEM analysis: 2 mm crack at the No.2 and 13mm crack at No.15.

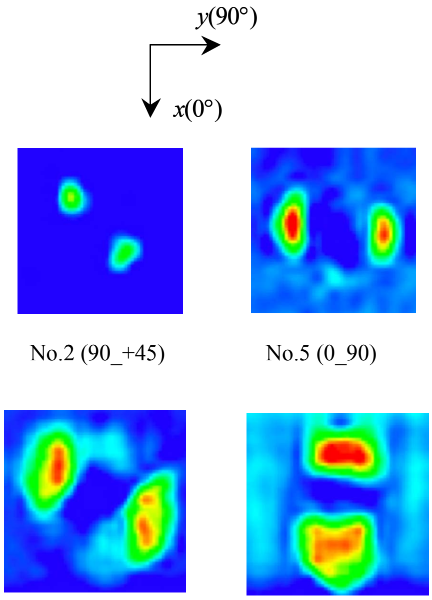

Fig.8 Typical observation using the phased array ultrasonic C-scan

Figures 7 and 8 show that there is no delamination crack in the area just under the indentation point. This non-delaminated area has high electric conductivity in the thickness direction because of the dent effect. To confirm the effect of the dent, the effect of the shut-off and the effect of the residual strain relief, FEM analyses were performed. For the FEM model, a delamination crack with matrix cracking at each interlamina was modeled as shown in Fig.9.

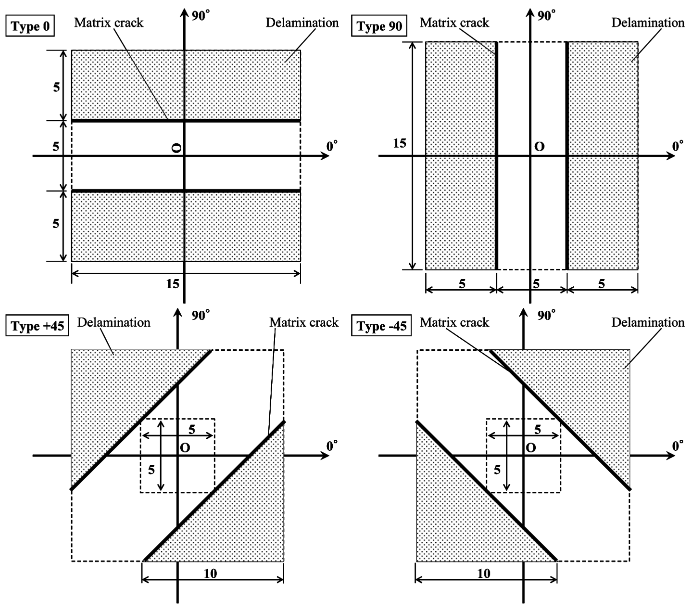

Fig.9 Delamination model used for FEM analyses

The delamination crack orientation is significantly affected by the next-ply fiber angle. Thus, the delamination crack is classified into four patterns as shown in Fig.9. Type 0 means the lower ply is 0°-ply. Since the lower ply is 0°-ply, a longer delamination is located in the 0°-direction. To simplify the FEM analyses, the configuration of the delamination is assumed to be a couple of rectangles or triangles.

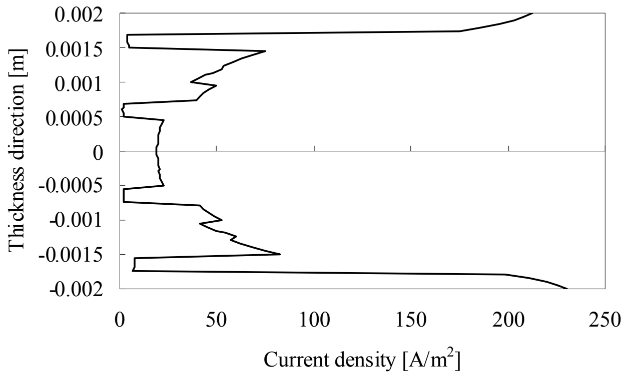

Fig.10 Electric current density in x-direction at the center

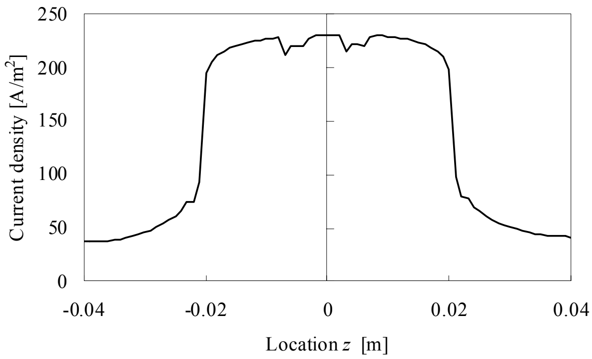

Fig.11 Electric current density in the thickness direction at the middle interlamina

Figure 10 shows the calculated electric current density with delamination cracks in the x-direction. The abscissa is the current density and the ordinate is the location in the thickness direction. As shown in Fig.10, most of the current flows in the top ply and the bottom ply. Figure 11 shows the electric current density at the middle interlamina. The abscissa is the location in the z-direction (the coordinates are shown in Fig.1). As shown in Fig.11, most of the electric current flows in the center area. This is because the multiple delamination cracks impede the electric current flow in the thickness direction, and there is a non-delaminated area under the indentation point.

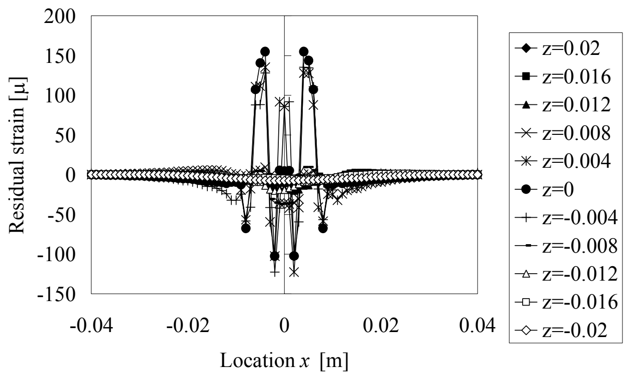

Fig. 12 Residual strain relief of x-direction strain in each ply

Figure 12 shows the residual strain relief of the x-direction strain in each ply at the center of the plate. The abscissa is the location of the x-direction, and the ordinate is the residual strain. As shown here, the residual strain distribution is very complicated because of the complicated multiple delamination cracks. The maximum magnitude of the residual strain is not large compared with the result of the beam type (600μ in the reference [24]).

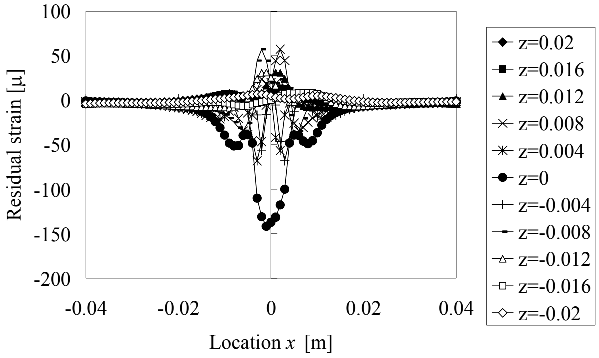

Fig.13 Residual strain relief of *z*-direction strain in each ply

Figure 13 shows the results of residual strain relief of the *z*-direction strain in each ply. In this direction, compression strain is relieved in the middle of the plate. In the other plies, the relieved residual strain is small.

Since the electric current density in the surface plies (the top ply and the bottom ply) is larger than that of other plies, electric current density in the top and bottom plies is averaged to evaluate the effect of the piezoresistance. The averaged result of the x-direction strain is -1.2μ, and the averaged result of the z-direction strain is -2.59μ. These values are quite small, and the electrical resistance change by the piezoresistance effect is negligible. This is the same result as the thin CFRP beam.

Electrical resistance caused by the electric path shut-off can be calculated from the FEM analyses of the intact plate and delamination cracking plate. The electrical resistance increases up to 10,654μ because of the shut-off effect.

The dent effect occurs just under the indentation point because of the decrease of the thickness. Figures 7 and 8 show that there is no delamination in the region. This means that the electric conductivity increase occurs similarly even when the delamination cracking occurs. Thus, the dent effect is estimated using Fig.4. The measured depth of dent is 3.0μm. -measured up to -260μ. From the result, the gage factor to the residual strain is 29. Although the estimation is extrapolated, the effect of the dent can be roughly estimated to be -21,968μ.

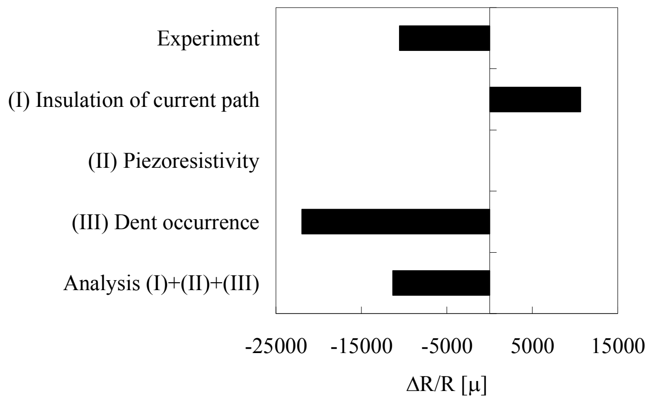

Fig.14 Calculation of the three effects

The result of the summing up of these effects in Fig.14 shows that the shut-off (I) and the dent (III) are the major effect for the CFRP plate. The decrease of the electrical resistance for the thick CFRP is caused by the dent. For the thin CFRP, high bending stress is made by the small indentation load. The high bending stress causes matrix cracking that precipitates the delamination cracking. For the thick CFRP plate, the matrix crack can be created by the higher indentation load. This higher indentation load causes compressive plastic deformation of the resin. The plastic deformation yields a dent. When a delamination cracking occurs in the thick CFRP, there is a non-delaminated area in the dent region, and the delamination cracks in the surrounding area impede the electric current in the thickness direction. Since the dent causes a significant decrease of electric resistance in the thickness direction, the effect is approximately twice as large as the shut-off effect. This is why an electrical resistance decrease is observed for the thick CFRP in reference [22]. For the delamination monitoring of the thick CFRP plate, further investigations must be performed to clarify the dents. This is planned for our future work.

5. Conclusions

The present paper deals with the mechanism of the electrical resistance change of thick CFRP. For the thick CFRP plate, dent is made with delamination cracking under the indentation point. This paper investigates the effect of the dent, the effect of the electric path shut-off caused by the delamination crack and the effect of the piezoresistance caused by the residual strain relief using FEM analyses and experiments. The results obtained are as follows.

(1) When a delamination crack is made, a dent is also made for a thick CFRP plate because of the high indentation loading, and the dent causes a large electrical resistance decrease in the thickness direction.
(2) Residual stress relief caused by the delamination cracking is very small for the thick CFRP plate. This is the reason why the piezoresistance effect is negligible.
(3) Although delamination cracking causes shut off of the electric current path, a non-delaminated area exists just under the indentation point for the thick CFRP plate, and the dent occurs in that area. The dent causes a twice larger electric current decrease compared with the electric current increase caused by the shut-off of the current path.

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