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Relationship between Delamination Growth and Electrical Characteristics in CFRP laminates

Yusuke Hirata, Jae Beom Park, Dong-Yeul Song* and Nobuo Takeda
The University of Tokyo, Takeda Lab. Komaba Open Laboratory, Univ. of Tokyo, 4-6-1, Komaba, Meguro-ku, Tokyo, Japan
*Gunma Technical Laboratory, Maebashi, Gunma, Japan
Tel/Fax: 81-03-5452-5216, e-mail: hirata@compmat.rcast.u-tokyo.ac.jp

In the present study, the electrical resistance change behavior of CFRP laminate [±25 /±25 /90]s under re/unload loading condition was investigated experimentally. Especially, the effect of the delamination on the electrical characteristics was evaluated using the internal and the surface electrical voltage distribution. From the experimental results, we identified that the residual resistance decreased along with the increase of the previously applied maximum strain and the internal voltage distribution in thickness direction did not change despite of the delamination. Voltage distribution of the bottom and the top surface indicated that the electrical current could flow through the region that had no delamination and this can explain the constant internal voltage distribution in thickness direction.
Key words: health monitoring, CFRP laminate, electrical resistance, edge delamination

1. INTRODUCTION

1.1 Health monitoring and smart materials

Because of low weight and high modulus and strength, composite materials have been used as structural materials in various applications, especially in aerospace applications where the weight restriction is severe. The damage induced under loading is quite complicated in composite materials compared with metals, the understanding of damage mechanism and the development of damage monitoring system is very important for wide applications of composites. In such circumstances, several structural health monitoring system of composite structures have been proposed recently. Although there are some other methods to detect damage such as using an optical fiber embedded in CFRP, we use a technique called "electrical resistance method" to detect damage of CFRP in the present study.

1.2 Electrical resistance method

CFRP is an electrically conductive material, especially in the fiber direction. When the load is applied to CFRP, the electrical resistance changes due to the change in the electrical conductivity of carbon fibers as well as breakages of fibers at further loading [1,2]. Fig.1 shows tensile test results of unidirectional CFRP. In this method, we can evaluate the damage state of CFRP from the change in electrical resistance.

These CFRP laminates can be adhered to conventional structures as sensing or repairing patches. In this research, we paid attention to the edge delamination progressed from the specimen edge in CFRP laminates, and examined the possibility of the use as a smart sensing patch, which is adhered on structures. From a practical view, the electrical characteristics were studied under repeated loadings, and related to the delamination growth.

2. EXPERIMENT

2.1 Experimental method

The specimen was [±25 /±25 /90]s CFRP laminate (T700S/2500). When a load was applied to this specimen, edge delamination easily occurred at the interface between 25 and 90 layers, and progressed in association with matrix cracks of the 90-degree layers in repeated loadings. The edge delamination was modeled as shown in Fig.2. Sequential X-ray photos of the edge delamination under fatigue loads at 40% of fracture stress are shown in Fig.3. The delaminated area was found to increase as a function of the number of cycles. This feature may be used as a sensor for memorizing the strain history.

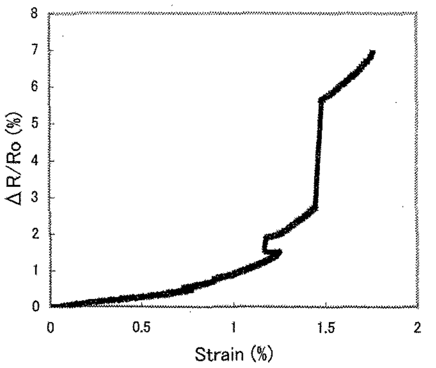

Fig.1 Electrical resistivity change of unidirectional CFRP under monotonic tensile test

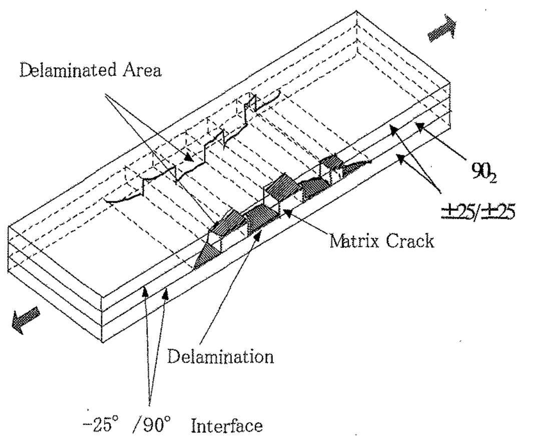

Fig.2 Model of edge delamination

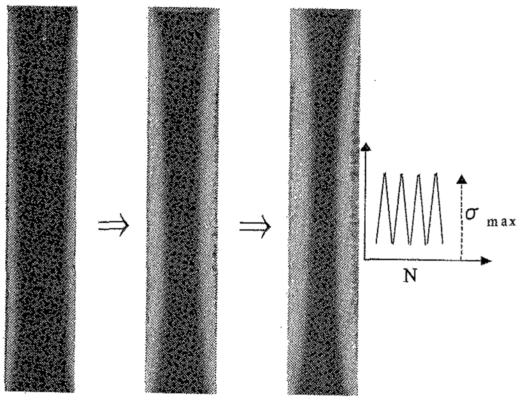

Fig.3 X-ray photos of edge delamination under repeated loads

(σ max=60MPa, Nf=61×10^4 cycles)

The specimen dimensions are shown in Fig.4. Electrical resistance was measured by the DC 4-probe method. In this method, current probes and electrical potential probes were independent. The added current was DC 1.0mA. We performed tensile, load/unload, and fatigue tests. The tensile test and load/unload test were performed at a crosshead speed of 0.5mm/min and the fatigue test was at 5Hz and 40% of the fracture stress.

2.2 Experimental results and discussions

The results of static and fatigue tests are shown in Fig.5. In both tests, the increase in electrical resistance showed similar tendency. Although delaminated area always increased, there was the portion, where the electrical resistivity reduced.

The result of the load/unload test is shown in Fig.6. This shows the resistivity change to the loaded time. In this test, the increase in residual resistivity (the resistivity increase from the initial value when unloaded) was not seen. To the contrary, the residual resistivity decreased as the maximum applied strain increases. It is considered that the fracture of carbon fibers hardly occurs before the fracture in this specimen, and 25-degree layers under the shear stress did not return to the original angle completely after unloaded. That is, the phenomenon of the increase in the residual resistivity by edge delamination was not seen. Based on these experimental findings, it is thought to be necessary to know the change of the voltage potential in each part of the specimen in detail.

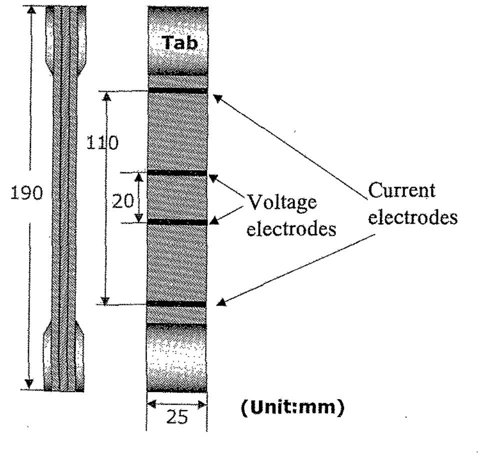

Fig.4 Specimen dimensions

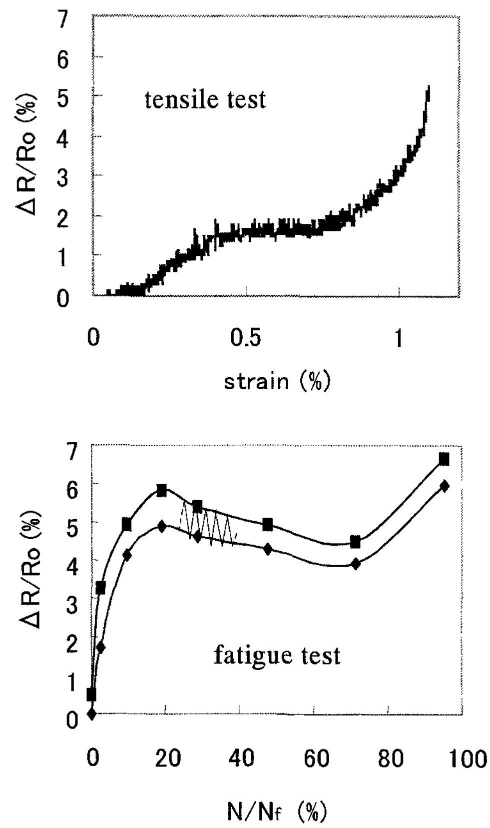

Fig.5 The result of the tensile and fatigue test

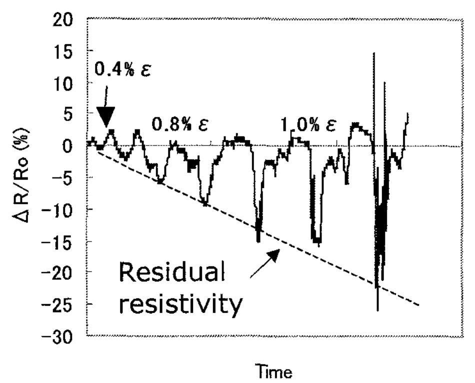

Fig.6 The electrical resistance change of load/unload test

3. ELECTRICAL POTENTIAL MODEL

3.1 Linear anisotropic resistivity model

In the quasi-static limit of the electrical current, the following differential equation for the voltage distribution $V(x,z)$ must be satisfied:

$$\operatorname{div} \cdot j = \frac{1}{\rho_x}\frac{\partial^2 V}{\partial x^2} + \frac{1}{\rho_z}\frac{\partial^2 V}{\partial z^2} = 0 \tag{1}$$

where ρ_x, ρ_z are the resistivities which correspond to the x and z coordinates, j is the electrical current density. The coordinate system is shown in Fig.7.

An approximate solution is given by the following equation:

$$V(x,z) \approx \frac{I}{b}(\rho_z \rho_x)^{1/2} \frac{\sin(\pi x / L)}{\sinh[(\pi t / L)(\rho_z / \rho_x)^{1/2}]} \times \cosh\left[\frac{\pi z}{L}\left(\frac{\rho_z}{\rho_x}\right)^{1/2}\right] \tag{2}$$

where L is the length of the specimen, and t is the thickness. From the ratio of the top and the bottom surface voltages, we obtain

$$\left(\frac{\rho_z}{\rho_x}\right)^{1/2} \approx \frac{L}{\pi z}\operatorname{arccos}h(V_{Top} / V_{Bot}) \tag{3}$$

and further from V_{Top}

$$(\rho_x \rho_z)^{1/2} \approx \frac{V_{Top} b}{2I \sin[\pi(x_2 - x_1) / 2L]} \times \tanh\left[\frac{\pi t}{L}\left(\frac{\rho_z}{\rho_x}\right)^{1/2}\right] \tag{4}$$

where x_1 and x_2 denote the coordinates of the voltage electrodes. Using the measured data of the top and the bottom voltage differences of the CFRP specimen, we can obtain the value of the Equations (3), (4). Then by substituting them into Equation (2), the voltage distribution $V(x,z)$ can be estimated and plotted as a function of the coordinate x and z.

3.2 Electrode configurations

In order to obtain the detailed voltage distribution inside the CFRP laminate using equations in Section 3.1, we measured the voltage of each part of the surface of the specimen during the load/unload test. The measurement position of electrical potential is shown in Fig.7. Voltages were measured at 30 lattice points (1A-10C per each surface) both on the front (surface with current probes) and rear surfaces. The added current to the probes was DC 1.0mA. Potential measurements during the load/unload test were performed when the specimen was at both the maximum loaded and unloaded states.

3.3 Results and discussions

Fig.8 shows the equipotential lines of C-plane (thickness direction) when the specimen was at the initial state(a) and at the unloaded state(b) after 0.8% strain was applied. In the latter state, the edge delamination reached to a position of about 4.7mm from the edge of the specimen (almost the middle point of A-plane and B-plane) that was estimated from experiment result. But noticeable change was not seen in the voltage distribution.

The equipotential distribution on the surface of material is shown in Fig.9. In the upper two figures (the initial state), the current flows almost in parallel with the direction of 0-degree layer. On the other hand, in the lower two figures (unloaded after 0.8% strain was applied), some current in the width direction is clearly seen. In the front surface, current flows from the edge to the center (the direction of A to C), but flows from the center to the edge (C to A) in the back surface. This shows the change in electrical flow due to the delamination. For this reason, even if the edge delamination grew, the residual resistance did not increase.

4. CONCLUSIONS

In the present study, the electrical resistance change behavior of CFRP laminate [±25 /±25 /90]s under re/unload loading condition was investigated experimentally. Especially, the effect of the delamination on the electrical characteristics was evaluated using the internal and the surface electrical voltage distribution. From the experimental results, we identified that the residual resistance decreased along with the increase of the previously applied maximum strain and the internal voltage distribution in thickness direction did not change despite of the delamination. Voltage distribution of the bottom and the top surface indicated that the electrical current could flow through the region that had no delamination. This can explain the constant internal voltage distribution in thickness direction.

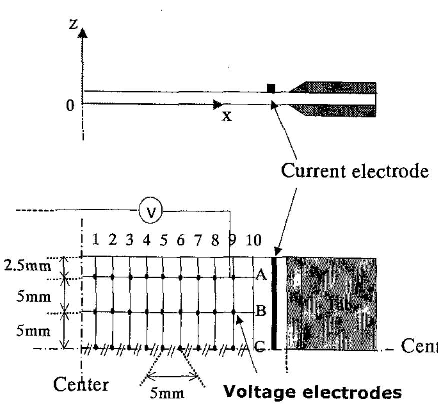

Fig.7 The coordinate systems and the positions of the probes

5. REFERENCES

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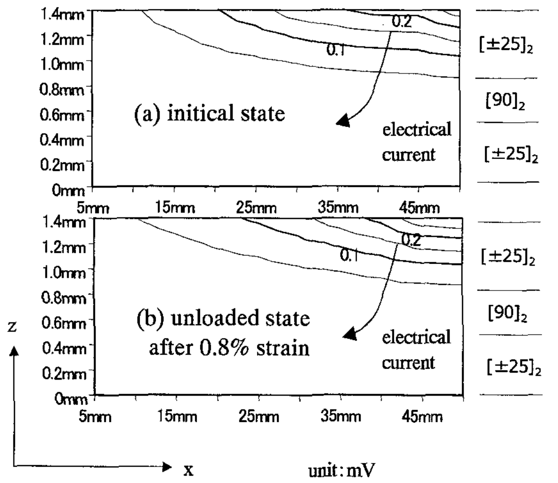

Fig.8 Equipotential lines of the C-plane

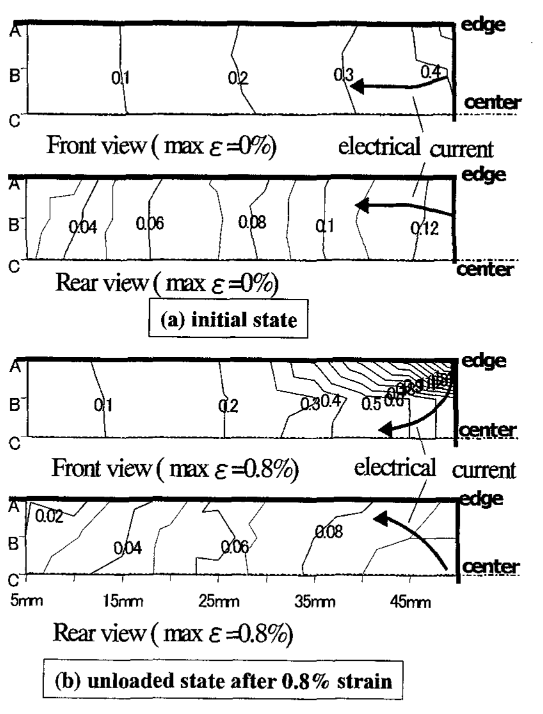

Fig.9 Equipotential line of front and rear surfaces

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