Key Engineering Materials. Vols. 321-323, p. 873-876
online at http://www.scientific.net

Matrix Crack Detection of CFRP Laminates In Cryogenic Temperature Using Electrical Resistance Change Method

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Keywords: Matrix, Crack, Electrical resistance, CFRP, Cryogenic Temperature

Abstract. For a cryogenic fuel tank of a next generation rocket, a Carbon Fiber Reinforced Plastic (CFRP) laminated composite tank is one of the key technologies. For the fuel tank made from the laminated composites, matrix cracks are significant problems that cause leak of the fuel. In the present paper, electrical resistance change method is adopted to monitor the matrix cracking of the CFRP laminate. Previous studies show that tension load in fiber direction causes electrical resistance increase due to the piezoresistivity of the carbon fibers, and fiber breakages also cause the electrical resistance increase of the CFRP laminates. In order to distinguish the electrical resistance changes due to matrix cracking from those due to the piezoresistivity and the fiber breakages, residual electrical resistance change under the complete unloading condition is employed in the present study. Experimental investigations were performed using cross-ply laminates in cryogenic temperature. As a result, it can be revealed that the residual electrical resistance change is a useful indicator for matrix crack monitoring of the cross-ply CFRP laminates.

Introduction

For a next generation rocket, a fuel tank made from Carbon Fiber Reinforced Plastics (CFRP) is one of the key technologies. For the CFRP composite fuel tank, matrix cracking causes fuel leak, and the detection of the matrix cracking without using additional sensors is desired. An electrical resistance change method is applied to detect damage of CFRP composites or strain of CFRP structures [1-11]. Schulte et al. have revealed [1] the electrical resistance increase of unidirectional CFRP due to piezoresistivity and fiber breakages before failure of tensile specimens. Todoroki [8,9] and others have applied the electrical resistance change method for identification of a delamination crack in laminated CFRP.

CFRP laminates have strong orthotropic electric conductivity [9]. Since the electric conductivity in the transverse direction is caused by fiber contact network of carbon fibers, matrix cracking in a CFRP ply causes increase of the electrical resistance. The electrical resistance change due to matrix cracking, however, is very small compared with the increase of the electrical resistance due to piezoresistivity, and it is very difficult to distinguish the electrical resistance increase due to matrix cracking from other electrical resistance changes.

In the present study, therefore, the electrical resistance change method is adopted and measurements of electrical resistance change properties of CFRP laminates are performed using a unidirectional CFRP single-ply specimen, a unidirectional CFRP multi-ply specimen and a cross-ply specimen. Tensile tests were conducted to measure electrical resistance change after matrix cracking in room temperature, and a bending test was performed in cryogenic temperature. A new method to distinguish electrical resistance change due to matrix cracking from other causes of the increase of electrical resistance change is proposed here.

Experimental Procedure

Specimen and test method for room temperature. Material used here is prepreg Q-1111/2500 (carbon/epoxy, Tohotenux). The prepreg is stacked to make laminates of $[0]_T$ and $[0/90/0]_T$. The laminates were cured at 130°C×90min. From the laminates, rectangular specimens of 15mm×210mm were fabricated. GFRP tabs were attached on both sides of ends of the specimen to protect the specimen surfaces from damages due to chucking.

To measure the electrical resistance change during loading, a four-probe method is adopted in the present study. Electrodes of each specimen were produced using lead wires and silver paste after polishing the specimen surface. The specimen for tensile test has length of 210mm and the width of 15mm.

The electrical resistance change was measured by means of a LCR meter produced by Hioki Co. Alternating current of 1kHz was used for the measurements for all specimens. Since the capacitance element of the CFRP in 1 kHz is very small (a phase angle is almost zero) compared with the resistance element, almost all measured impedance change is caused by the resistance change in this alternating current. Therefore, we focused on the electrical resistance change.

Using a material testing machine, displacement control tensile tests were conducted at the loading rate of 0.1mm/min. For every specimen, a strain gage was mounted on the center of the specimen, and a load-strain curve was monitored with measuring electrical resistance change. Loading and unloading tests were performed to measure the residual electrical resistance change and the electrical resistance change during reloading. For the cross-ply laminates, matrix crack density was measured using replica method from the specimen side surface.

Specimen and test method for cryogenic temperature. Since it is very difficult to perform tensile tests in cryogenic temperature, a four-point bending test of a sandwich plate was conducted in the present study. Materials used are the same kind of prepreg sheet and the stacking sequence is $[0/90/0]_T$. The length of the specimen is 200mm, and the width of the specimen is 15mm. To make a sandwich type specimen, the two CFRP specimens are bonded on both sides of a glass/epoxy plate of the thickness of 2.5mm. A jig of the four-point bending test and the sandwich specimen was cooled with liquid nitrogen. Four-point bending tests of outer span 120mm and inner span 40mm are performed in the liquid nitrogen in the cryogenic tests.

To make reliable electrodes for cryogenic temperature, copper plating with copper sulfate was performed on the specimen surface after polishing the surface with a sand paper. On the electrode made from the copper plating, a copper foil was placed and pressurized by means of a vice as shown in Fig. 1. A strain gage was mounted on the center of the specimen.

To measure the electrical resistance change, the same LCR meter was adopted, and alternating current of 1kHz was used for the measurements for all specimens similarly. The specimen was tested using the four-point bending method as shown in Fig. 2 in the liquid Nitrogen (-195.8ºC). Since the specimen is a sandwich specimen, tension load is applied to the lower surface CFRP plate. This tensile stress causes matrix cracking in the lower surface CFRP plate.

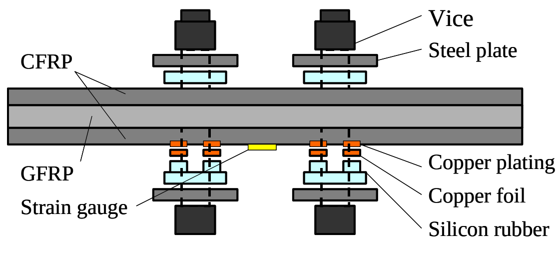

Fig.1 Specimen configuration of cryogenic test

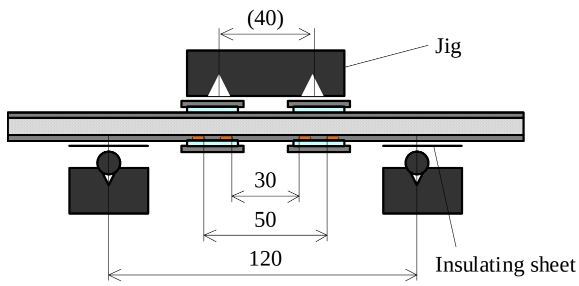

Fig.2 Four-point bending test for cryogenic test

Results and Discussion

Unidirectional specimens. K. Schulte et al. have measured electrical resistance change of unidirectional CFRP in the fiber direction [1]. They reported that that the electrical resistance increases with the increase of applied strain as the same as a strain gage during elastic deformation region, and rapid increase of the electrical resistance was also reported without any visually detectable damages. This rapid increase of the electrical resistance was caused by the carbon fiber breakages inside of the specimen. Chung et al. have, however, reported the decrease of the electrical resistance during tensile loading of unidirectional CFRP. In order to confirm the electrical resistance change due to elastic deformation and fiber breakage, we performed tensile tests using a single-ply unidirectional CFRP.

The results of electrical resistance change during tensile tests in the room temperature showed, the measured electric resistance rapidly increases with the increase of loading over the applied strain of 3500μ. This rapid increase of the electrical resistance during tensile loading is caused by carbon fiber breakages and debonding between carbon fibers and epoxy resin matrix inside of the specimens.

Cross-ply laminate. Measured results of cross-ply laminate of $[0/90/0]_T$ were performed. As a result, electrical resistance increases with the increase of applied tensile strain. Moreover, rapid increase of electrical resistance ($\Delta R/R$) is observed approximately over 2500μ, and residual electrical resistance is also recognized at the completely unloaded points.

Matrix crack density is also measured, and the results show the matrix cracking is observed over 2500μ strain for this type of specimen.

The strain level at the rapid increase of the electrical resistance is almost equal to the initiation of the matrix crack creation, and the strain level of the rapid increase of the electric resistance is much smaller than the fiber breakage level observed in the unidirectional tensile test. Therefore, it can be concluded that the rapid increase over 2500μ is caused by the generations of the matrix cracks.

Residual electrical resistances at complete unloading are also measured. As a result, the measured residual electric resistances at complete unloading increases with the increase of applied maximum strain exactly after applied strain of 2500m. This result reveals that the residual electrical resistance can be applied as a parameter to know the initiation of the matrix cracking.

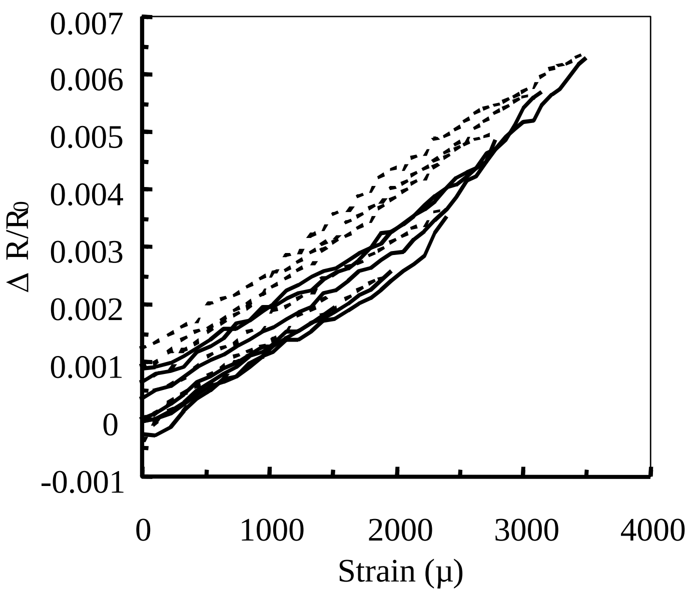

Fig.3 Electrical resistance change at cryogenic temperature

Cryogenic tests. Figure 3 shows the results of the cryogenic test of the four-point bending. The abscissa is the applied strain measured by means of the mounted strain gage on the tensile side of the CFRP plate. The ordinate is the electrical resistance change. This figure shows that the rapid increase of the electrical resistance is observed at approximately 2000μ.

Figure 4 shows the result of the residual electrical resistance at complete unloading in the cryogenic temperature. The abscissa is the applied maximum strain and the ordinate is the measured residual electrical resistance. This figure shows that the rapid increase starts at 2000μ. After finishing the test, matrix cracking was observed from the specimen side.

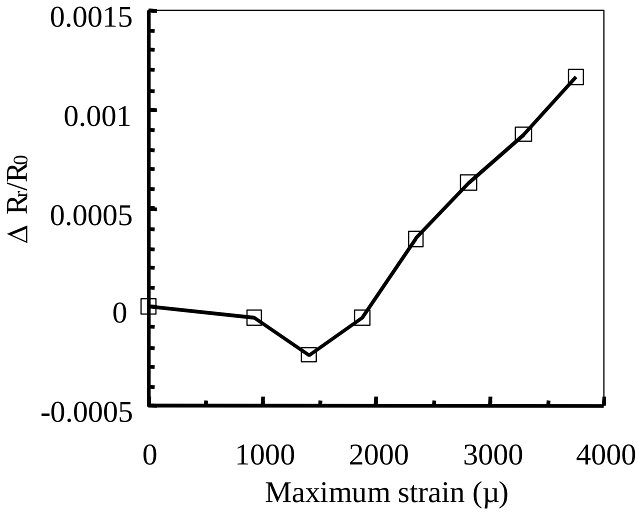

Fig.4 Residual electrical resistance by cyclic load at cryogenic temperature

Conclusions

(1)Electrical resistance change increases with the increase of applied tensile strain for both unidirectional CFRP specimens and a cross-ply specimen.
(2)Rapid increase of electrical resistance is observed after matrix cracking initiation.
(3)Residual electrical resistance increases with the increase of matrix cracking.
(4)Even in the cryogenic temperature, the electrical resistance change method detected the matrix cracking as an increase of the residual electrical resistance.

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