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Electric Resistance Change Method for Cure/strain/damage Monitoring of CFRP Laminates

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Abstract. This paper shows monitoring of Carbon Fiber Reinforced Polymer (CFRP) laminates by means of changes of electrical property of CFRP. Carbon fiber is electrical conductive materials and polymers are insulator. When electric current is applied to the CFRP laminates, many kinds of information are obtained such as degree of cure, applied strain and damages. For these monitoring, carbon fiber itself is adopted as a sensor. This paper shows the experimental results of the method to monitor the degree of cure, applied strain and damage. As a result, the method is shown to be effective for monitoring CFRP laminates of degree of cure, applied strain and damage.

Introduction

Carbon Fiber Reinforced Polymer (CFRP) laminates are applied to many aerospace structures. Several processing methods of the CFRP laminates have been adopted to fabricate the CFRP structures. Cure monitoring of composite structures is crucial for quality control and improvement of mechanical properties of structures. After curing, strain monitoring of the CFRP structures is very important to confirm integrities of processing, as well as vibration monitoring and applied stress monitoring to know the condition of the external loading. Since the delamination is invisible or difficult to detect by visually, the delamination causes low reliability for primary structures. To improve the low reliability, smart systems of delamination identifications in-service are desired. A structural health monitoring system to monitor the delaminations is one of the desired approaches. Matrix cracking simply causes fuel leak when a lot of matrix cracking occurs in a CFRP fuel tank. These damages of matrix cracking and delaminations are significant for aerospace applications.

Recently, an electrical resistance change method is employed to detect the internal damages of CFRP laminates by many researchers [1-18]. The electrical resistance change method does not require expensive instruments. Since the method adopts a reinforcement carbon fiber itself as a sensor, this method does not cause reduction of strength, and it is applicable to existing CFRP structures. Some researchers have published papers to monitor applied strain of the CFRP structures by means of electrical resistance change. Although Schulte and others [1-8] have reported the increase of electrical resistance when tensile load is applied to the CFRP laminates, Wang and Chung have reported the decrease of the electrical resistance when tensile loading is applied [9].

Author's group has already experimentally investigated the applicability of the electrical resistance change method for measurements of delamination crack length of the edge cracks of delamination resistance tests [19,20]. The embedded cracks of the beam type specimens have also been experimentally detected using the electrical resistance change method with carbon/PEEK composites [21]. In order to investigate the effect of orthotropic electric resistance on the delamination monitoring of cross-ply laminates, several FEM analyses have been also performed [22,23]. Beam type specimens were employed to monitor delamination creations experimentally [24], and plate type specimens were also adopted to monitor the delamination creations experimentally [25,26]. For these electrical resistance change measurements, copper foil electrodes are co-cured during curing process.

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Using the copper foil, changes of electrical capacitance of the CFRP laminates can be measured during cur process. Inada and Todoroki have proposed a new cure monitoring method without additional sensors [27].

Strain monitoring has also performed using the four-prove method by Todoroki and others [28] to clarify the cause of the discrepancy between the positive piezoresistivity and the negative resistivity.

In the present paper, therefore, these results performed in the previous papers are briefly explained. These successful results enable us to monitor a lot of information of the CFRP laminates by means of the electrical resistance and capacitance changes in many applications. Not only the individual successful results, a new united concept of the electrical resistance change method is proposed here.

Monitoring of CFRP laminates by means of electrical property change

Cure monitoring with capacitance change [27]. Carbon fibers have high electrical conductivity and polymer matrix like epoxy is electrical insulator. The polarization of an epoxy molecule changes with a progress of molecule linking (polymerization) during curing. Progress of the linking makes changes of dielectric constant of the epoxy resin. By charging alternating current to the target CFRP during curing, we can measure the dielectric constant of epoxy. Thus, we can monitor degree of cure by charging alternating current to the target CFRP.

A unidirectional CFRP laminate can be represented by parallel arrangement of a capacitance and resistance, because resin in composite materials has dielectric properties. Capacitance of a parallel plate capacitor is shown as

$$C = \varepsilon S / d \tag{1}$$

where ε is the dielectric constant; *S* and *d* represent parallel plates' area and distance, respectively. In actual CFRP laminates, the coefficient *S/d* is unknown and it may change owing to resin flow during the curing process. However, in a very short time, for instance, the measurement time of capacitances at several AC frequencies, *S/d* can be considered to be a constant value. In this case, frequency dependence of the dielectric constant is proportional to frequency dependence of capacitance.

The dielectric constant e of CFRP is approximately proportional to the small difference of frequency of applied alternating current.

$$\varepsilon \approx b_0 + b_1 \Delta \varpi \tag{2}$$

where b_0 and b_1 are the material constants. Using the linear relationship between the dielectric constant and degree of cure, the degree of cure is expressed as follows.

$$\beta = \int d\beta/dt\, dt = \int (db_1/dt) dt / A = \int b_1 dt/TA \tag{3}$$

where *A* is an integration result of coefficient b_1 from the start of curing to its end and *T* represents the total time for curing.

Thus, we can measure the degree of cure by measurement of frequency dependency of capacitance of actual carbon-fiber/epoxy laminates without considering movement of *S/d*. The detail of the theory is described in Ref [27].

To confirm the effectiveness of the method, the method was applied to unidirectional CFRP composites. Figure 1 shows a cure monitoring system for a unidirectional carbon-fiber/epoxy lamina. The specimen is made by aligning carbon fibers impregnated with Nikkatol VX-1315 epoxy resin in one direction on the glass-fiber/epoxy plate where two electrodes of thin copper film are attached. Capacitance change during curing is measured by applying AC between the electrodes.

The cure monitoring experiment was conducted in an electric furnace with retention temperature of 393 K; capacitance changes were measured with a 3522 LCR Hi-tester with five AC frequencies (0.8 kHz, 1 kHz, 1.2 kHz, 1.4 kHz, and 1.6 kHz). AC is applied perpendicular to the fiber direction. Measured capacitance changes showed large frequency dependency. Measured capacitance changes showed linear relationship between Δω and capacitance after the furnace temperature reached 393 K. Thus, the experimental result is regressed linearly.

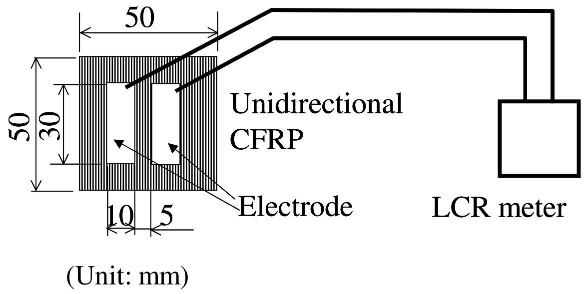

Fig. 1. Cure monitoring system for CFRP lamina

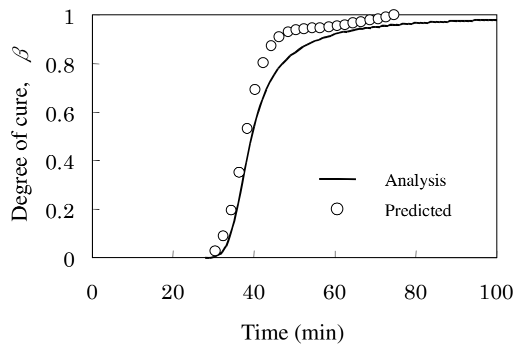

Fig. 2. Measured degree of cure of $[0]_T$

After integrating the slope of the linear relationship with subtracting the initial value at 393K, the partially integrated value is divided with the totally integrated value to the end of the cure, and the degree of cure β is obtained. Criteria of the cure-end time are obtained from the change of the slopes. The degree of cure obtained by the present method is shown in Fig. 2 with open circles. The degree of cure obtained from an analysis is also shown in the figure with a solid obtained by the analysis. The figure implies that the method is effective to estimate the degree of cure of CFRP.

Although the coefficient *S/d* changes owing to resin flow during curing, the method, using frequency dependency of the capacitance change of resin, is effective to estimate roughly the degree of cure. Moreover the co-cured electrodes can be used for strain and damage monitoring.

Strain monitoring with electrical resistance change. [28] The co-cured electrodes made from copper foil can be used for strain monitoring. Electrical resistance change with the change of applied strain is called piezoresistivity. As the same as the conventional strain gage, the fraction of the electrical resistance change ΔR/R is expressed as follows.

$$\frac{\Delta R}{R} = K\varepsilon \tag{4}$$

where the coefficient *K* is called a gage factor. Generally, the gage factor is positive and the value is between 2 and 4 for general metallic materials. Wang and Chung have reported the gage factor of CFRP is negative value when a four-probe method is adopted [9].

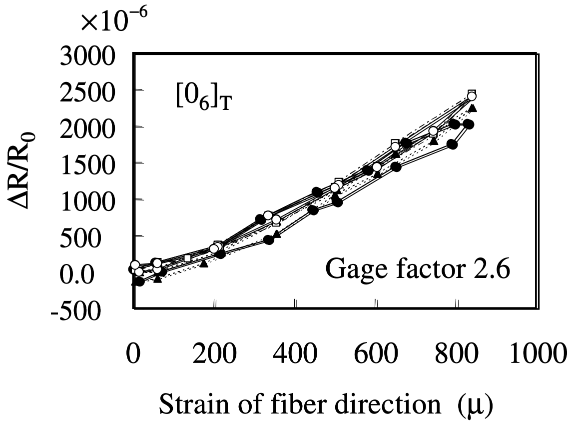

Fig. 3. Piezoresisitivity of 0°- specimen of CFRP ($[0_6]_T$). Electric current is charged in 0° direction

To investigate the true piezoresistivity, experimental investigations were performed with the four-probe method. Material used here is prepreg Q-1111/2500 (carbon/epoxy, Tohotenax Inc). The prepreg is stacked to make laminates of $[0_6]_T$. The laminates were cured with a hot-press at 130°C×90min. From the laminates, rectangular plates of 200mm×200mm were fabricated.

Electrodes of each specimen were made using silver paste after polishing the specimen surface with sand paper. The electrodes made from silver paste are adopted here to make the same experimental condition as published papers.

Tensile test was performed to measure the electrical resistance change, and the results are shown in Fig.3. Figure 3 shows that the electrical resistance increases with the increase of applied tensile strain. The measured gage factor is positive value of 2.6, which is almost similar to the gage factor of a conventional strain gage. As the same as the single-ply specimen, the relationship between the applied strain and the electric resistance change is linear.

Fiber breakage and matrix cracking detection with electrical resistance change. Electrical resistance change due to carbon fiber breakages have been reported [18]. It is no surprise that carbon-fiber breakages can be detected by means of measuring electrical resistance change in fiber direction during tensile loading because the carbon fiber is the only electrical conductive material in the CFRP composites. The electrical resistance change method, however, detects carbon fiber breakages highly sensitively. K. Schulte have already showed that the electrical resistance change method have detected the fiber breakages before macroscopic fracture of a unidirectional carbon-fiber/epoxy composite laminate [18].

The author has also performed a tension test of a unidirectional CFRP specimen with measuring electrical resistance change of the fiber direction. Material used here is prepreg Q-1111/2500 (carbon/epoxy, Tohotenux). The prepreg is stacked to make a laminate of $[0_4]_T$. The laminate was cured at 130°C×90min. From the laminate, rectangular specimens of 15mm×210mm were fabricated. To measure the electrical resistance change during loading, the four-probe method is adopted. Electrodes of each specimen were produced using lead wires and silver paste after polishing the specimen surface. The electrical resistance change was measured by means of a LCR meter. Alternating current of 1kHz was used for the measurements.

The results of electric resistance change during tensile tests are shown in Fig. 4. In the figures, the abscissa is applied strain measured with a strain gage, and the ordinate is the measured electrical resistance change normalized with initial electrical resistance. In smaller deformation region than approximately 3500μ, the electrical resistance change shows almost reversible reaction, and the electrical resistance increases with the increase of the applied tensile load. However, over 3500μ, the measured electrical resistance rapidly increases with the increase of loading. 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.

By using cross-ply specimens, similar tensile tests were performed with measuring electrical resistance change. In the cross-ply laminates, matrix cracking occurs before the fiber breakages. The matrix cracking causes electrical resistance changes as the same as fiber breakages.

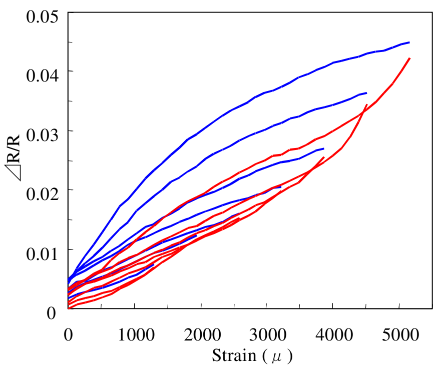

Fig. 4. Electric resistance change during tensile test of a unidirectional CFRP

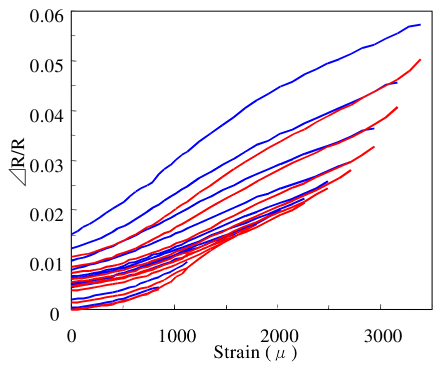

Fig. 5. Electric resistance change during tensile test of a cross-ply CFRP

A practical carbon fiber in a unidirectional ply is not straight. The curved carbon fiber contacts with each other, and that makes a large carbon-fiber network in a ply. The fiber-contact-network brings non-zero electric conductance even in the transverse direction. The authors group [23] have experimentally revealed that the electrical conductance.

When a matrix crack is created in a ply, the crack breaks the fiber-contact-network in the ply. Breakage of the fiber-contact network causes increased electric resistance of CFRP composites. Moreover, for the cross-ply laminates, the breakage of the matrix in 90°-ply causes stress redistribution near the adjacent 0°-ply ply. The local stress near the matrix crack increases due to the stress redistribution. The stress increase in the adjacent 0°-ply ply also causes electrical resistance increase in the 0°-ply due to piezoresistivity of 0°-ply. Therefore, matrix cracks can be detected by measuring electrical resistance change of a cross-ply laminate by charging electric current in fiber direction of the surface ply.

The prepreg is stacked to make laminates of $[0/90_2]$s. From the laminates, rectangular specimens of 15mm×210mm were fabricated.

Measured results of cross-ply laminate of $[0/90_2]$s are shown in Fig. 5. Electrical resistance increases with the increase of applied tensile strain. Rapid increase of electric resistance ($\Delta R/R$) is observed approximately over 2500μ. Using replica method, matrix cracking was observed over 2500μ strain in this type of specimen. The strain level at the rapid increase of the electrical resistance coincides with the initiation of the matrix crack creation, and the strain level of the rapid increase of the electrical 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 matrix crack creations. It can be concluded that matrix cracking can be detected by means of measuring electrical resistance change.

Delamination monitoring with electrical resistance change. Figure 6 reveals the schematic representation of the delamination-monitoring system with electrical resistance change method. Multiple electrodes are mounted on the specimen. All of these electrodes are placed on a single side of a plate. Usually it is impossible to place electrodes and lead wires outside of the aircraft structures. The location of the electrodes on the single side surface is representative the location of electrodes in the thin aircraft shell-type aircraft structures. Electrical resistance change of each segment between electrodes is measured for various cases of location and size of delaminations. Using the measured data, relations between electrical resistance change and location and size of delaminations are obtained using response surfaces. After the calculations of the response surfaces, location and size of a delamination can be estimated with the response surfaces from the measured electrical resistance changes.

Our previous FEM analyses of beam type specimens [23] revealed that electrical current has to be charged in the fiber direction on the surface ply. To identify delamination location and size precisely, more than four electrodes should be mounted on the beam type specimen. With increase of spacing between electrodes, estimation error of size of delamination increases [29].

Let us consider the case of a beam with five electrodes. Four electrical resistance changes are measured at four segments (electrical resistance change: E_1, E2, E_3 and E_4). To make the response surfaces, many experiments or calculations must be performed. From the experiments, several data sets of delamination location, length and electrical resistance changes are obtained. In the case where quadratic polynomials are adopted, the response surfaces to estimate the delamination length (a) are as follows.

$$
\begin{aligned}
a = {} & \beta^a_0 + \beta^a_1 E_1 + \beta^a_2 E_2 + \beta^a_3 E_3 + \beta^a_4 E_4 + \beta^a_5 E_1^2 + \beta^a_6 E_2^2 + \beta^a_7 E_3^2 + \beta^a_8 E_4^2 \\
& + \beta^a_9 E_1 E_2 + \beta^a_{10} E_1 E_3 + \beta^a_{11} E_1 E_4 + \beta^a_{12} E_2 E_3 + \beta^a_{13} E_2 E_4 + \beta^a_{14} E_3 E_4
\end{aligned} \tag{5}
$$

where all the coefficients (β^a_i, i=1…14) are obtained by the least square error method [30] . The lack of fit of the response surface can be evaluated with an adjusted coefficient of multiple determination R_{adj}^2 (see reference [30]). R_{adj}^2 is defined as follows.

$$R^2_{\mathrm{adj}} = 1 - \frac{SS_E/(n-k-1)}{S_{yy}/(n-1)} \tag{6}$$

where SS_E is the square sum of errors, S_{yy} is the total sum of squares, n is the number of data sets and k is the number of unknown coefficients. The R_{adj}^2 is equal to or lower than 1.0. Higher value of R_{adj}^2 implies a good fit.

The estimation of delamination locations with the similar response surface did not provide good estimations [24-26]. To improve the estimations, the measured electrical resistance changes were standardized with a norm as follows [31].

$$e_i = \frac{E_i}{\sqrt{E_1^2 + E_2^2 + E_3^2 + E_4^2}}, \quad (i = 1,2,3,4) \tag{7}$$

Using these standardized electrical resistance changes, the delamination location was estimated as follows.

$$\begin{aligned} x = \alpha^x_0 + \alpha^x_1 e_1 + \alpha^x_2 e_2 + \alpha^x_3 e_3 + \alpha^x_4 e_4 + \alpha^x_5 e_1^2 + \alpha^x_6 e_2^2 + \alpha^x_7 e_3^2 + \alpha^x_8 e_4^2 \\ + \alpha^x_9 e_1 e_2 + \alpha^x_{10} e_1 e_3 + \alpha^x_{11} e_1 e_4 + \alpha^x_{12} e_2 e_3 + \alpha^x_{13} e_2 e_4 + \alpha^x_{14} e_3 e_4 \end{aligned} \tag{8}$$

where all the coefficients (α^x_i , i=1…14) were obtained by the least square error method.

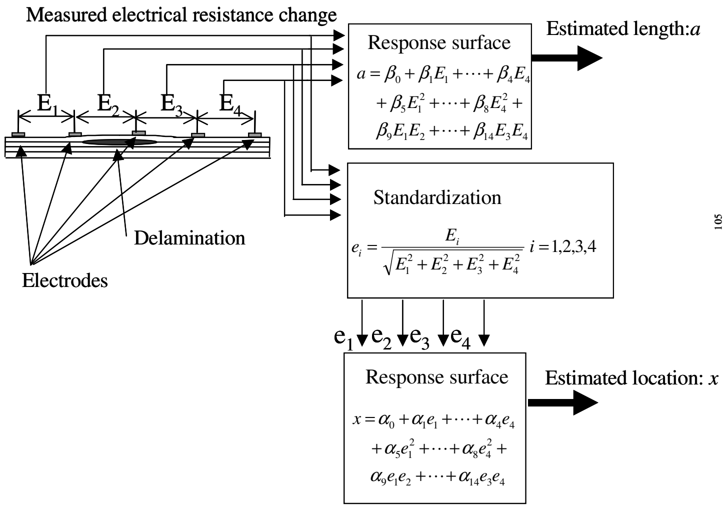

Fig. 6. Schematic image of delamination monitoring system using electrical resistance change method

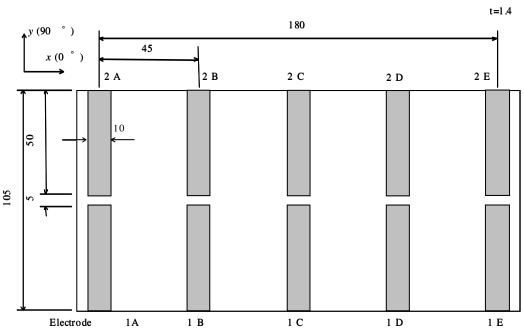

Fig. 7. Specimen configuration

This method was investigated for delamination identifications of cross-ply laminated plates. Material used is unidirectional CFRP prepreg. The type of the unidirectional prepreg sheet is TR340M150ST produced by Mitsubishi-Rayon Co. Ltd. Using the prepreg, cross-ply laminates of $[0_2/90_2]$s were fabricated. Thickness of the laminates is approximately t=1mm. Cure condition is 130°C×1.1MPa×1hr using a hot press. To make reliable electrodes, rectangle copper foil of 0.02mm thickness is mounted on the prepreg laminates, and these electrodes are co-cured with the laminates. From the laminates, rectangular plate type specimens of the length of 200mm and the width of 105mm were fabricated as shown in Fig. 7.

Since electrical resistance change due to a delamination crack creation is very small, the electrical resistance change is measured with the electric-resistance bridge circuit. In order to create a delamination crack in the plate-type specimen, an indentation test is employed. After making a delamination crack, electrical resistance changes of all segments between electrodes were measured using a conventional strain amplifier. Delamination location and size were measured using an ultrasonic C-scan image. Since the location in the plate type specimen has two directions, two directions of x-direction (0°-direction) and y-direction (90°-direction) are decided for the identification of the delamination location. The delamination size corresponds to the maximum diameter of a delamination crack.

Using the measured electric resistance data sets (number of the data sets is 64), response surfaces to estimate the delamination size from measured electric resistance changes are obtained. The adjusted coefficient of multiple determinations R_{adj}^2 is 0.816. Both response surfaces give good approximations. Results of estimations of delamination size are shown in Fig.8. The ordinate is the estimated delamination size with the response surface, and the abscissa is the measured delamination size. The figure shows that the response surface gives good predictions of the measured delamination size. Moreover, we can conclude that a delamination of larger than 10mm can be detected with the method.

To identify the location of delamination crack in a plate, two response surfaces are indispensable; x-direction and y-direction. The obtained R_{adj}^2 of the response surface of x-direction is 0.953 and the R_{adj}^2 of y-direction is 0.925. The approximations for the location of delamination are excellent compared to the estimations of the delamination size. The estimation results of x-direction are shown in Fig.9. The ordinate is the estimated location of delamination and the abscissa is the measured delamination location. The estimation results present excellent agreement with the measured results. The error band of the estimations of location is 15mm. From these results, we can conclude that the estimations of delamination location and size with the response surfaces are excellent.

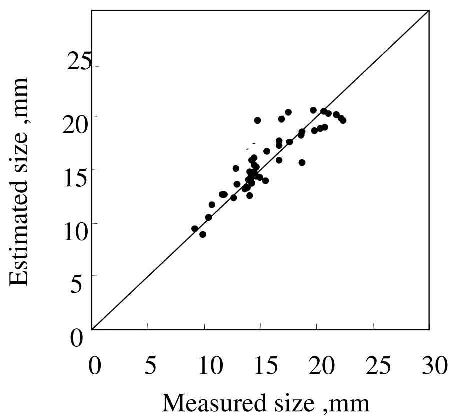

Fig. 8. Estimation results of delamination size for cross-ply laminate

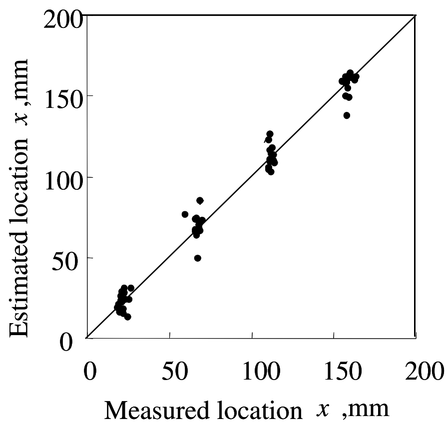

Fig. 9. Estimation results of delamination location for cross-ply laminate

A new united concept of individual record of electrical properties

On the basis of these results, a new united concept of individual record of electric properties is proposed. By means of co-cured electrodes, we can measure degree of cure during curing, applied strain, to monitor matrix cracking, to identify delamination location and size, and to detect fiber breakages. This means we can measure change of electrical property from fabrication to failure with the co-cured electrodes. If we can know the individual record of electrical properties from curing, we can predict current condition of CFRP structures and residual life.

Let us consider the ideal case, we can measure the degree of cure with the co-cured electrodes at several points of a target CFRP structure. This enables us to consider the effect of degree of cure on matrix cracking in the entire target structure. Stress monitoring enables us that the target structure is adequately fabricated without defects. Damage detection with the electrical change method enables us to know the damage stage of the target structures, and we can know the record of the electrical resistance change as well as electrical capacitance change of the target structures. All of these loading histories of the target CFRP structures are stored in the individual record of the target structures. This database of the loading history will enable us to predict precise residual life or requirement of repair. This is a target of my future research.

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