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Key words: CFRP, Composites, Electric Resistance, Delamination, Monitoring, Optimization

Introduction

Laminated Carbon Fiber Reinforced Polymer (CFRP) has been increasingly applied to the aerospace primary structures because of its high specific strength and stiffness. The CFRP laminate, however, delaminates easily by a slight impact load. That delamination crack reduces the compression strength and compression stiffness of the CFRP laminate. The delamination crack is, however, difficult to detect by a visual inspection. This causes the requirement of a monitoring method to maintain structural reliability and to reduce huge maintenance cost.

The CFRP laminate is composed of electrical conductive carbon fibers and insulating resin. Several structural health-monitoring methods utilize the electrical changes caused by applied load, temperature change, and fiber breakages have been studied [1-6]. Authors have proposed electrical resistance change method (ERCM) and electric potential change method to identify a delamination in the CFRP laminate [7-12]. In the ERCM, the delamination was estimated from the measured electrical resistances or electrical potential changes caused by a delamination using couples of electrodes mounted on the laminated CFRP plate surface.

For the ERCM, estimation performance is high although a lot of electric charges are required to measure electric resistances between all adjacent electrodes. Although the electric potential change method (EPCM) does not have high accuracy, the EPCM may enable to reduce the number of experiments. To improve the accuracy of the EPCM, a two-stage electric potential method (TS-EPCM) was proposed [11] [12] by authors. For the TS-EPCM, current electrodes and voltage electrodes are mounted separately to adopt a four-probe method. Only two charges of electric current are enough to monitor the delamination by measuring electric potentials at the voltage electrodes simultaneously.

The present study proposes a low cost method for a delamination monitoring of CFRP structures by means of measurements of the electrical resistance change with the help of an optimization method using

FEM analyses. As a first step, a low cost method that requires only several experiments is proposed here. From the several experiments, electrical conductivity of CFRP is obtained using optimization method. Electrical conductivities of CFRP laminates in all direction are obtained by means of an optimization method from the electrical voltages at the multiple points of the CFRP laminate. Delamination cracks usually have crack surface contacts. This contact is very difficult to deal with. In the present research, the effect is approximated using equivalent conductivity in the thickness direction. The equivalent conductivity is obtained using the optimization method to fit the electrical voltage in FEM analyses with the measured experimental results.

In the present study, a new asymmetrical dual charge electric potential change method (ADC-EPCM) is adopted. As electric potentials are measured by two separate times of electric charges using four-probe method, the number of electric charge is reduced compared to the normal ERCM. Although magnitude of the electric potential changes are small in the TS-EPCM when delamination locates at the center segment between current electrodes, ADC-EPCM is independent of the blind spot of the TS-EPCM. In the present study, the effect of the delamination shape (existence of the matrix crack) is investigated using FEM analyses, and the reduction of the number of experiments is performed using the ADC-EPCM in the present study.

Specimen configuration

Specimen used here is 180 mm long, 10mm wide, and 1mm thick (as shown in Fig.1). Stacking sequence is [0/90]s. Nine electrodes of 4mm long and 0.02mm thick are mounted on the single surface of a specimen. This means that electrodes are only mounted on the inside of a composite structure. Electrodes B, F and D, H are used to charge electric current, and A, C, E, G, and I are used to measure electric voltage change. Electric potentials are measured by a four-probe method. In the present study, delamination size is a projected length to the specimen surface, and delamination location is a distance from center of the specimen to center of the delamination. Delamination is assumed to be uniform to the y-direction (width direction).
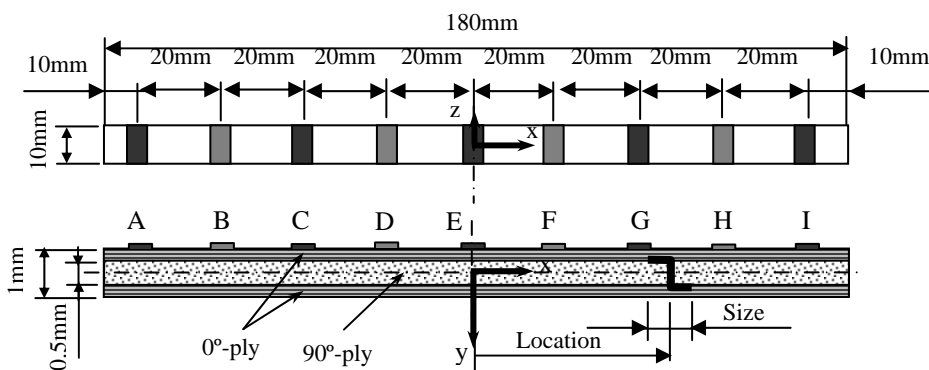

Fig.1 Configuration of specimen with nine electrodes

Numerical analysis

Analytical method. Numerical calculations are performed by commercially available FEM code ANSYS to investigate the effect of the delamination shape. Four-node quadrilateral elements of 0.25mm long and 0.0625mm in height are used for two-dimensional analyses. This implies that a delamination is

created uniformly in the y-direction. Electric potentials of the nodes at each electrode are coupled to have same electric potentials. A delamination is created by means of separating two nodes that are placed at same position. This means that electric current does not flow through the delamination in the FEM analyses. Three shapes of delamination are modeled in the FEM analyses: straight delamination, Z-type delamination crack, and inverse Z-type delamination crack (Fig.2). Z-type and inverse Z-type delamination cracks are straight delamination with a matrix crack, which had largest effect to electric potential changes compared to the straight delamination [9]. Electric conductivity components of fiber direction, transverse direction, and thickness direction were $\sigma_0=4600$, $\sigma_{90}=4.83$, $\sigma_t=1.03$[S/m]: these values were experimentally measured in the previous research [7]. Thickness direction component includes the effect of resin rich layers. The fiber volume fraction is assumed to be 47%.

Asymmetrical dual charge electric potential change method. No electric current flowes in the thickness direction at x=–20mm when electric current is charged from the electrode B to F (current path #1) [10]. When a delamination exists at x=–20mm, i.e. the center between current electrodes, the normalized electric potential changes are affected by the shape of delamination: by the existence of the matrix crack. Figure 3 shows normalized electric potential changes between electrodes AC, CE, EG, and GI obtained from the FEM analyses when the delamination of 5mm long locates around x=–20mm. As shown in Fig.3, the delamination shape affects significantly when the delamination locates at x--20mm. Estimation of delamination shows large errors dependent on the delamination shapes when it locates at the center between current electrodes [10].

(a) Straight-type   (b) Z-type   (c) Inverse Z-type
Fig 2. Delamination crack shapes used in the FEM analyses
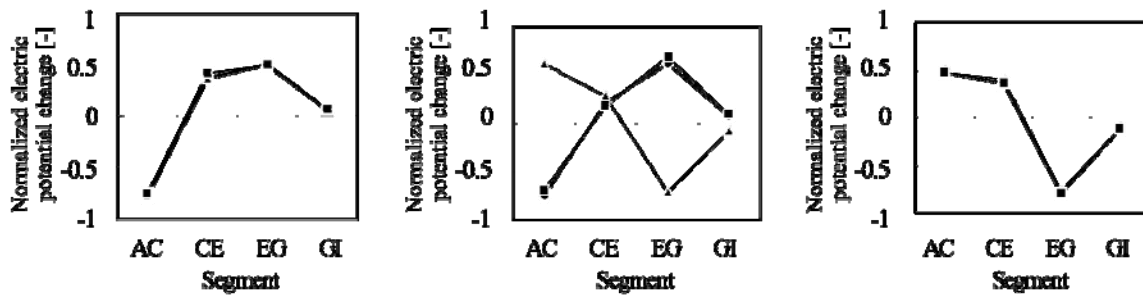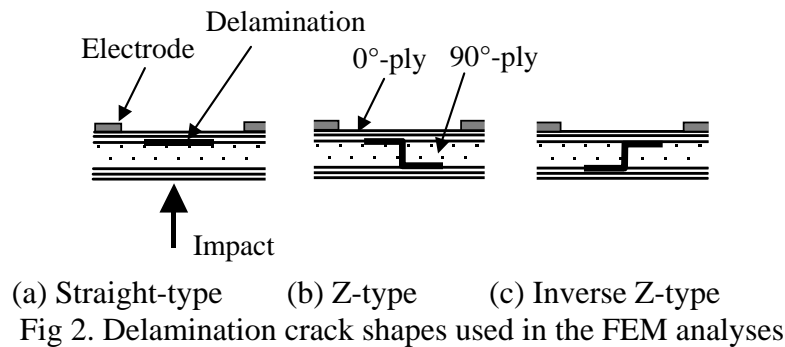
(a) Delaminations locate at x=-25mm (b) Delaminations locates at x=-20mm (c) Delaminations locates at x=-15mm

Fig.3 Normalized electric potential changes obtained from current path #1
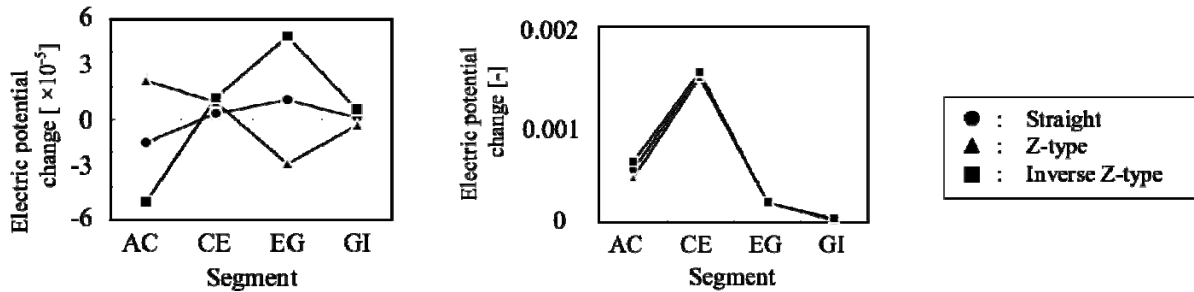
(a) Delaminations locate at x=-20mm   (b) Delaminations locate at x=-60mm

Fig.4 Electric potential changes before normalization

Figure 4 (a) and 4 (b) show the electric potential changes before normalization when delamination locates at x=–20mm and x=–60mm respectively. When a delamination locates at the center between current electrodes (Fig.4 (a)), the magnitude of the electric potential changes is small compared to the results of Fig.4 (b) due to delamination locates near the electric current electrodes (Fig.4 (b)). This is caused by the significantly small electric current in the thickness direction at the center between the couple of the electric current electrodes. Although the electric potential changes depended on the delamination shapes when the delamination locates at x=–20mm, it has negligible effect compared to those due to the delamination which locates at x=–60mm.

When the electric current is charged from the electrode D to the H (current path #2) and the delamination locates at x=–20mm, large electric potential changes can be obtained because it impedes the electric current in the thickness direction. These electric potential changes are not affected by the delamination shape (existence of the matrix crack).
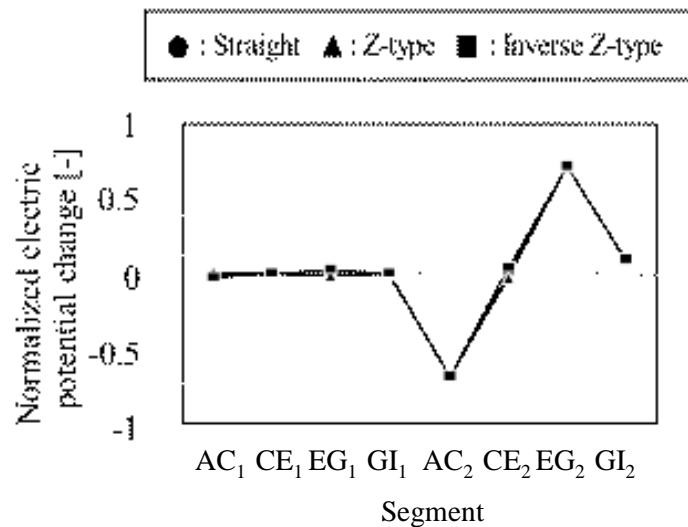

Fig.5 Normalized electric potential changes obtained from asymmetrical electric charge

Figure 5 shows normalized electric potential changes calculated from two sets of electric potential changes obtained by current paths #1 and #2 when delamination located at x=-20mm. In this figure, the subscript number indicates the current path number used to obtain the electric potential changes between the electrodes. Although the electric potential changes by current path #1 are different dependent on the delamination shapes because of the small electric current in the thickness direction, the magnitudes are small compared to those by the current path #2. The electric potential changes obtained using current

path #2 are not affected by the shapes of delamination because it locates near the electric current electrodes. Therefore, the normalized electric potential changes can be obtained independent on the delamination shape by using two sets of electric potential changes.

When a delamination locates outside the electric current electrodes, the electric potential change can be obtained. Figure 6 shows the contour plot of the electric potential in the CFRP laminate by the electric current path #2 calculated by the FEM. Electric current flows even in the outside of the couple of the electric current electrodes because of the strong anisotropy of the laminate. As delamination impeded the electric current, electric potential in the laminate changed. It is, therefore, possible to detect a delamination locates outside the current electrodes.
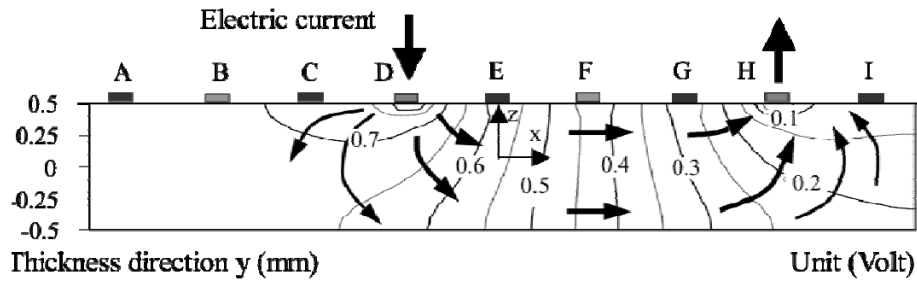

Fig.6 Contour plot of electric potential in CFRP laminate

Solver for inverse problem. In the present study, a response surface methodology is used to estimate delamination location and size from the measured electric potential changes [13]. The first electric current is charged from the electrode B to the electrode F (current path #1), and the second electric current is charged from the electrode D to the electrode H (current path #2) separately. Electric potential differences between electrodes AC, CE, EG, and GI are measured for each case before and after the creation of a delamination. Electric potential changes between electrodes are calculated from the electric potential difference between electrodes.

$$\begin{cases} \Delta P_{1i} = P_{1i} - P_{1i0} \\ \Delta P_{2i} = P_{2i} - P_{2i0} \end{cases} \quad (i = AC, CE, EG, and\,GI) \tag{1}$$

where P_{1i0}, P_{2i0} and P_{1i}, P_{2i} are the electric potential differences between the electrodes before and after the creation of a delamination by the current path #1 and #2, ΔP_{1i} and ΔP_{2i} are electric potential changes between the electrodes due to a delamination. ΔP_{1i} and ΔP_{2i} are normalized together.

$$\Delta p_{1i} = \frac{\Delta P_{1i}}{L}, \quad \Delta p_{2i} = \frac{\Delta P_{2i}}{L}, \quad L = \sqrt{\sum_{i=0}^{4} \left(\Delta P_{1i}^2 + \Delta P_{2i}^2 \right)} \tag{2}$$

where L is a norm of the all electric potential changes, and Δp_i is the normalized electric potential changes.

A response surface is obtained using the normalized electric potential changes as predictor variables, and delamination location as response variable. The norm is also used as a predictor variable when delamination size is a response variable. Quadratic polynomial is used as response surfaces here.

$$y = \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i{}^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \beta_{ji} x_j x \qquad (3)$$

Delamination location and size were estimated using the respective response surfaces. The significance of regression is estimated using the adjusted coefficient of multiple determination $R_{adj}{}^2$.

$$R_{adj}^2 = 1 - \frac{SS_E / (n - k + 1)}{SS_T (n - 1)} \qquad (4)$$

where SS_E is a square sum of errors, SS_T is a total sum of squares, n is a number of data and k is a number of unknown coefficients. The range of adjusted coefficient of multiple determination is $0 < R_{adj}{}^2 < 1$. The higher value of $R_{adj}{}^2$ implies a good regression of the model.

Response surfaces. FEM analyses are performed to examine the estimation accuracy of the proposed method. Straight delamination (no matrix crack) is supposed in FEM. FEM analyses are performed for multiple cases: delamination sizes of 5, 10, 20, 30, and 40mm, and delamination locations from –80mm to 80mm with spacing of 5mm. Total of 306 runs of FEM are performed to obtain learning data of the response surfaces. To investigate the robust property for delamination shape, Z-type and inverse Z-type delamination cracks are estimated using the response surfaces. Those delaminations of 7, 15, 25, and 35mm size are also estimated to investigate the accuracy of interpolation. The data includes artificially created errors are also used as learning data to make robust response surfaces for the experimental error. For normalized electric potential changes, less than 10% of errors of maximum values are added. For the norms, less than 10% errors are added. Above errors are created by random number.

Estimation results. Figure 7 shows estimation results of straight delamination, Z-type and inverse Z-type delamination cracks by the response surfaces obtained from results of FEM analyses of straight delamination. The adjusted coefficients of multiple determination are 0.991 for delamination location, and 0.996 for delamination size. The abscissas show delamination location or size, and ordinates show estimated location or size. The diagonal lines in the figures show exact estimation. The broken lines in Figure 7(a) and 7(b) show error bands of 10mm and 5mm. The degradation of estimation accuracy is not observed even if delamination locates at the center between current electrodes. Accuracy of estimation does not depend on the delamination shapes and shows a good performance of the method. The delaminations that are not used as learning data are also estimated accurately. The results shows that the applicability of the ADC-EPCM is shown analytically.
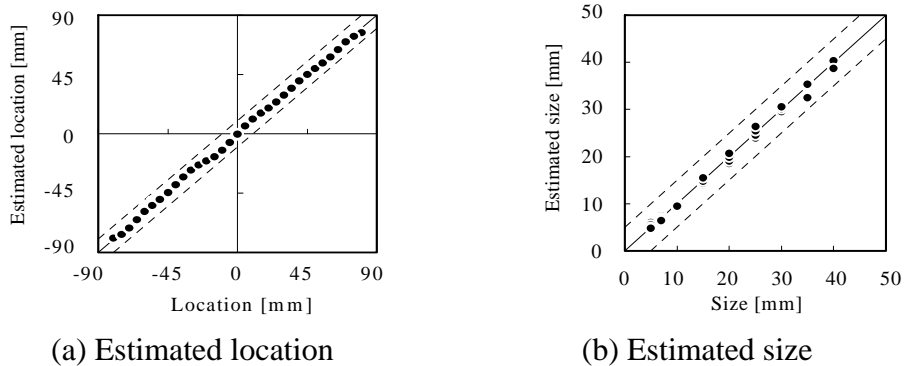

(a) Estimated location   (b) Estimated size

Fig.7 Estimation results of straight, Z-type, and inverse Z-type delamination cracks obtained by FEM

Experiments

Material. CFRP laminates are fabricated from unidirectional prepreg sheets PYLOFIL#380 (Mitsubishi Rayon Co., Ltd). The autoclave molding method is used to fabricate [0/90]s cross-ply laminate following the common manufacturer's instructions. Specimens (180mm long and 10mm wide) are cut from the CFRP laminated plate, with a thickness of approximately 1mm (Fig.1). Fiber volume fraction is 65.5%. Electrodes are mounted on the specimens by co-cured copper foil (4mm long and 0.02mm thick).

An inter-laminar shear test is performed to create a delamination. The load is applied to the outside surface opposite to the electrodes. Delamination location and size are measured using a microscope. The delamination is a straight delamination in an interlamina with a matrix crack in many specimens. It is observed by the ultrasonic C-scan image that delaminations were created uniformly along the y-direction.

Measurement of electric potential changes. A differential amplifier was used to measure the electric potential changes. Electric potential changes at voltage electrodes A, C, E, G, and I were amplified 1000 times. Amplified electric potential changes were measured by data logger PCD-320A (Kyowa Electronic Instruments Co., Ltd). Electric potential changes between electrodes were calculated from the data.
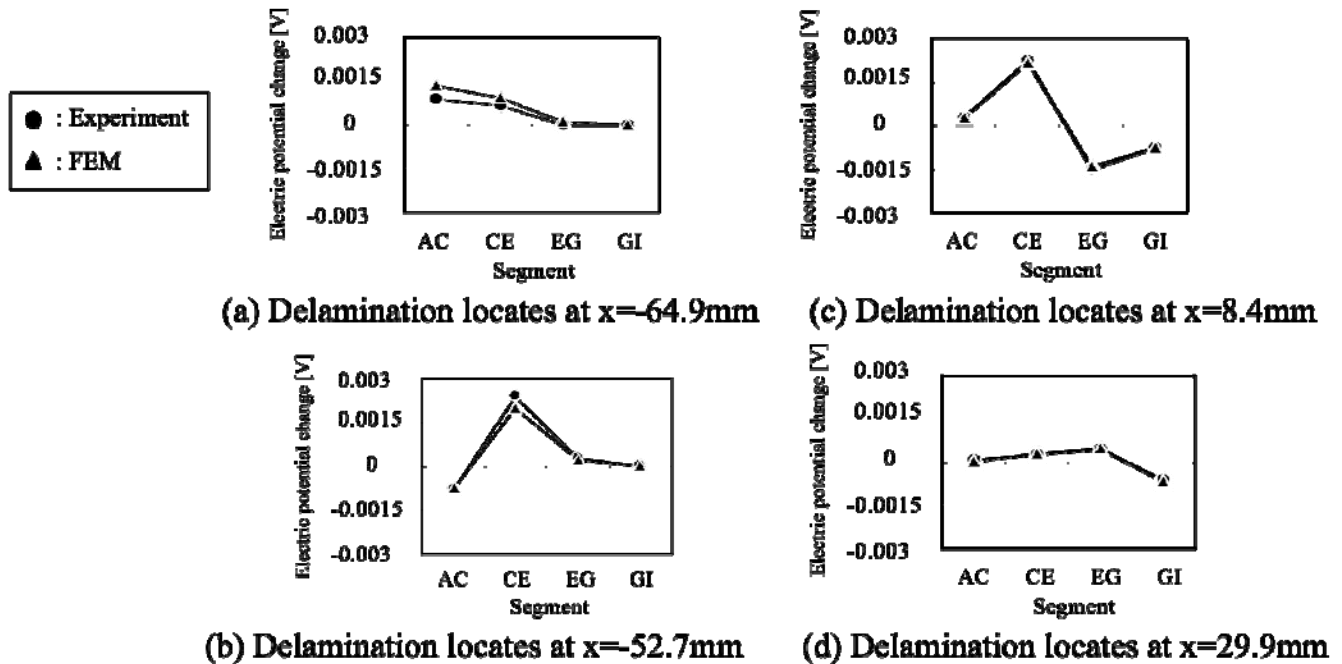

Fig.8 Comparison of the electric potential changes between FEM and experimental results

Search of equivalent electric conductivity using optimization method. To reduce the number of experiments, FEM analyses are the most adequate tool to produce a lot of data for making response surfaces. The measured electric conductivity, however, does not provide appropriate results because the actual experiments include the delamination crack surface contact. For the accurate estimation, equivalent electric conductivity that gives well agreement between FEM results and experimental results should be searched [12]. A total of 4 delamination tests are performed here. The delaminations are made as follows: the locations are between the electrodes A and B (x=–64.9mm, size is 17.8mm), B and C (x=–52.7mm, size was 20.7mm), E and F (x=8.4mm, size was 22.7mm), and F and G (x=29.9mm, size is 10.2mm). Electric potential changes are measured by current path #1. Equivalent electric conductivity is searched using the 4 sets of the measured electric potential changes, by minimizing the error sum of square of electric potential changes obtained from FEM and experimental results.

The searching step is shown as follows: Electric potential changes are measured experimentally using four specimens. Normalized electric potential changes are calculated from the measured electric potential changes Normalized electric potential changes are also calculated by means of FEM. The error sum of squares of these two normalized electric potential changes is calculated as follows:

$$Error = \sum_i \left(\Delta p_i^{Experiment} - \Delta p_i^{FEM} \right)^2 \qquad (5)$$

The equivalent electric conductivity ratios are those that minimize the errors defined by Eq. (5).

As the electric current in the longitudinal direction (x-direction) in the 90 degree-ply is quite small, the change of electric conductivity in the transverse direction is negligible on electric potential changes. Therefore, electric conductivity ratios σ_{90}/σ_0 and σ_t/σ_0 are approximately searched under the condition of $\sigma_{90}/\sigma_0 = \sigma_t/\sigma_0$. Subsequently, a closer search is conducted around the obtained minimum point. Total number of FEM calculations is 441.

The equivalent electric conductivity is obtained as $\sigma_0 = 32000$, $\sigma_{90} = 9.60$, $\sigma_t = 8.32$ [S/m]. Fig.8 shows comparison of electric potential changes between electrodes obtained from FEM and experimental results. The results of FEM analyses shows good agreement to the experimental results.

Response surfaces. FEM analyses are performed using the equivalent electric conductivity to obtain learning data of response surfaces. The straight delamination is assumed in the FEM analyses. A total of 306 runs of FEM analyses were performed by same conditions used in the previous chapter. The data that includes artificially created errors are also used as learning data.

Estimation results. A total of 70 delamination tests were performed, i.e. 70 sets of electric potential changes due to delaminations were measured. The delaminations were estimated using the response surfaces obtained from the results of FEM analyses. Figure 9 shows estimation results of all the delaminations. The estimation results shows good accuracy although the various shapes of delaminations were created. The delaminations that locates at the center between current electrodes are almost exactly estimated. The ADC-EPCM successfully estimated delaminations experimentally. This means that the significant reduction of the number of experiments is possible using the ADC-EPCM.
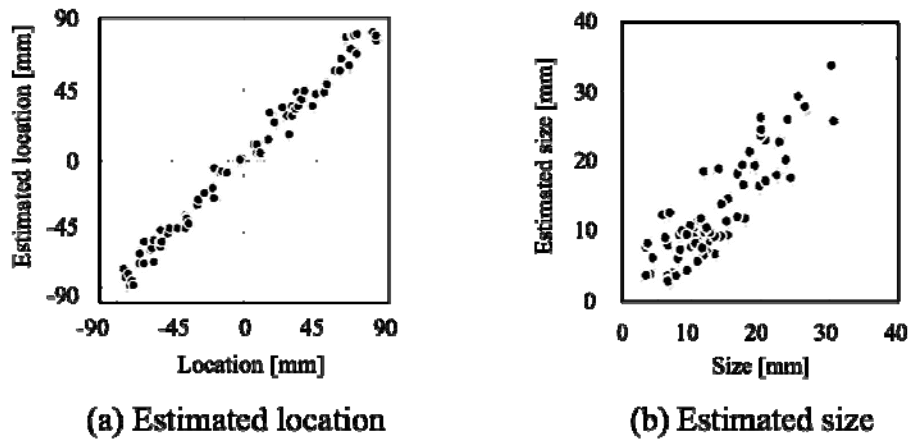

(a) Estimated location   (b) Estimated size

Fig.9 Estimation results of experimental data

Conclusions

ADC-EPCM is introduced to estimate delamination in the CFRP laminate. The applicability of the method is investigated analytically using FEM analyses before the experimental works. Delamination tests are also performed with beam type specimens. Optimization method is adopted to search the equivalent conductivity of the CFRP. 70 delamination tests are estimated by using response surfaces obtained from FEM results with the equivalent conductivity. Actual delaminations in the CFRP laminate are successfully identified. The present research indicates that the significant reduction of the number of experiments is possible using the ADC-EPCM. The FEM analyses on the basis of the small number of experiments enables us to monitor the delamination cracks.

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Published papers:

The part of the research (the optimization method to search the equivalent conductivity of CFRP laminates) is published in the reference [12].

Masahito Ueda and Akira Todoroki, "Delamination monitoring of CFRP laminate using the two-stage electric potential change method with equivalent electric conductivity", Engineering Fracture Mechanics, Vol.75, No. 9, (2008), p. 2737-2750.