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# Multi-probe electric potential change method for delamination monitoring of graphite/epoxy composite plates using normalized response surfaces

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**Abstract**

Delamination is a significant defect of laminated composites. The present study employs an electric potential change method in an attempt to identify internal delaminations experimentally. The method adopts reinforcing graphite fibres as sensors. In our previous paper, a two-probe method was adopted for the electric-resistance change measurements because of the simplicity. The two- probe method is not appropriate for a precise measurement, and it tends to include a large experimental error in the electric resistance change owing to the electric resistance change at the electrodes. Instead, the present paper employs a multiple-probe method for the measurements. In the present study, high precise measurement system of electric voltage change is developed, and the electric voltage measurement method is adopted for identification of embedded delamination location and size. Measured electric potential data are normalized for creations of response surface to identify the delamination. As a result, the new multi-probe electric potential method is shown to be effective for the identifications of embedded delamination cracks of graphite/epoxy composite laminates.


*Keywords:* Delamination

## 1. Introduction

Composite laminates have low delamination strength, and it causes a delamination by a slight impact. Since the delamination is invisible or difficult to detect 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 detect the delaminations is one of the desired approaches for practical laminated composite structures.

Recently, an electric resistance change method has been employed to identify the internal damages of CFRP (Carbon Fiber Reinforced Plastics) laminates by many researchers [1–18]. The electric resistance change method does not require expensive instruments. Since the method adopts reinforcement carbon fiber itself as sensors, this method does not cause reduction of strength, and it is applicable to existing structures.

Authors have already experimentally investigated the applicability of the electric resistance change method for measurements of delamination crack length of the edge cracks of delamination resistance tests [19,20]. For practical composite structures, however, delamination cracks are usually embedded cracks. The embedded cracks of the beam type specimens were also experimentally detected by the electric resistance change method by Todoroki using graphite/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 specimens, a two-probe method is employed to measure the electric resistance changes between two electrodes. Wang and Chung

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have, however, shown that the two-probe method gave misunderstanding because the method included the electric resistance change of electrodes [27]. The improved method is, therefore, required to obtain reliable information of the electric resistance change in graphite/epoxy composite laminates.

In the present study, a new multi-probe method is employed for delamination identifications of cross-ply laminates. An embedded delamination crack is created in a plate type specimen on which multiple electrodes are mounted. Electric potential changes at all of the electrodes are measured with a new amplifier circuit. Using response surfaces made from normalized sets of measured electric potential changes, delamination location and size is estimated as continuous values. Applicability of the method is experimentally investigated and compared to the previous electric resistance change method.

## 2. Principle of electric potential change method

Graphite fiber has a high electric conductivity, and the epoxy matrix is insulation resistance. For ideal graphite/plastics composites, electric conductance in fiber direction is very high. The ideal conductance can be easily calculated by multiplying fiber volume fraction to electric conductance of graphite fiber. On the other hand, the electric conductance of transverse direction vanishes for an ideal condition.

Practical graphite fiber in a unidirectional ply is serpentine as shown in Fig. 1(a). The curved graphite fibers contact with each other, and that makes a large graphite-fiber network in a ply. The contact-network brings non-zero electric conductance even in the transverse direction. In the same way, the fiber-network produces non-zero electric conductance in the thickness direction in a ply. The electric conductance in the transverse direction is much lower than the electric conductance of the fiber orientation. Abry et al. [11] and authors [28] have revealed experimentally that the electric conductance ratio of the transverse direction ($\sigma_{90}$) to the fiber direction ($\sigma_0$) is $\sigma_{90}/\sigma_0 = 3.7\times10^{-2}$, and the electric conductivity ratio of the thickness direction ($\sigma_t$) to the fiber direction is approximately $\sigma_t/\sigma_0 = 3.8\times10^{-3}$ for the laminates of the fiber volume fraction of 0.62 ($\sigma_0 = 5500$S/m). The result shows that the graphite/epoxy composite laminates have very strong orthotropic electric conductance.

The electric conductance of the thickness direction ($\sigma_t$) is also lower than the electric conductance of transverse direction ($\sigma_{90}$). Although the fiber-network structure in the thickness direction is almost similar to the structure of the transverse direction in a ply, through-the-thickness conductance $\sigma_t$ is smaller than the $\sigma_{90}$ for normal laminated composites. That is because thin resin rich interlamina exists and the interlamina is electrically insulating. For ideal graphite/epoxy composites, the $\sigma_t$ vanishes due to the resin rich interlamina. For practical graphite/plastics composites, however, prepreg plies are serpentine as the same as the fiber in a ply as shown in Fig. 1(b). The curve of plies causes fiber contact through plies and causes non-zero electric conductance in the thickness direction even for thick laminated graphite/epoxy composites. The contact between plies causes no-zero electric conductance in the thickness direction. Thus the $\sigma_{90}$ is usually larger than the $\sigma_t$. When a delamination crack grows in the interlamina, the crack breaks the fiber-contact-network between plies. The breakage of the contact network causes increase of the electric resistance of the graphite/epoxy composites. Therefore, delamination crack can be

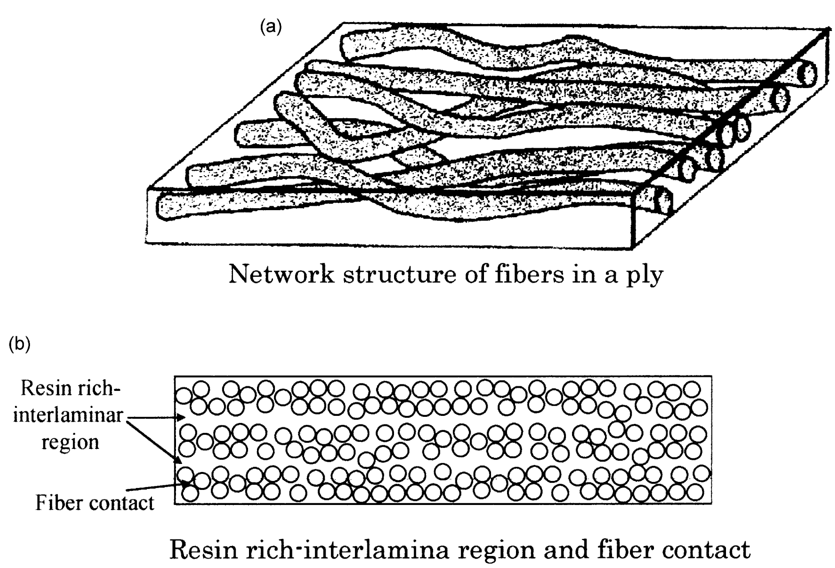


Fig. 1. Schema of practical structure of graphite/epoxy composite.

detected by the electric resistance change of graphite/epoxy composite laminates.

Fig. 2 reveals the schematic representation of the delamination-monitoring system with electric resistance change method proposed in the previous study. Multiple electrodes are mounted on the specimen surface as shown in Fig. 2. All of these electrodes are placed on a single side of a specimen. 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 of the location of electrodes in thin aircraft shell type aircraft structures. Electric-resistance change of each segment between electrodes is measured for various cases of location and size of delaminations. Using the measured data, relations between electric resistance change and location and size of delaminations are obtained using response surfaces. Since authors have revealed that the response surfaces are better than artificial neural networks for this inverse problem, the response surface method is employed here [29]. After the calculations of the response surfaces, location and size of a delamination can be estimated with the response surfaces from the measured electric-resistance changes. Our previous FEM analyses of beam type specimens [28] revealed that electric current has to be charged in the fiber direction on the surface ply. This electric resistance change method is a two-probe method. Wang and Chung [27] have already revealed that the two-probe method is signifcantly sensitive to electric resistance changes of the electrodes and a four-probe method should be employed for the electric resistance change monitoring. The multi-probe electric potential method is similar to the four-probe method, and it has high reliability for measurements of slight electric resistance changes of composite materials.

The principle of the multi-probe electric potential method is, however, quite similar to that of the electric resistance change method using the two-probe method. The schematic illustration of the multi-probe electric potential method is shown in Fig. 3. The only differences from the electric resistance method are the way to charge the electric current and the way to measure the electric potential using multiple probes as shown in Fig. 3. Electric current is charged between each electrode location at each end of the specimen surface as shown in Fig. 3(a). Electric potential is measured at each electrode to obtain several electric potential data. In Fig. 3(a), the electric potential value of eight probes is measured, and these measured data are input into the response surfaces to estimate delamination location and size. These measured electric potential data are normalized and response surfaces are created to estimate the delamination location $X$, $Y$ and size. The response surfaces are made from a large number of experiments using the least square error method.

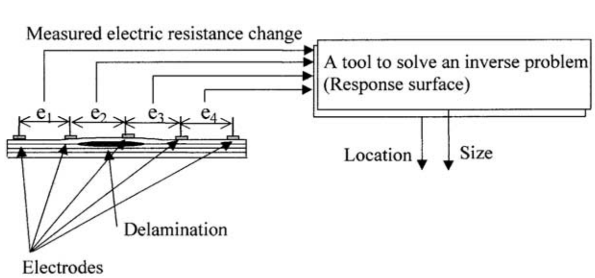


Fig. 2. Schematic representation of delamination identification method using electric resistance change method with response surfaces.

## 3. Experimental method

### 3.1. Specimens

The material used in the present paper is unidirectional graphite/epoxy prepreg. The type of the unidirectional prepreg sheet is TR340M150ST produced by

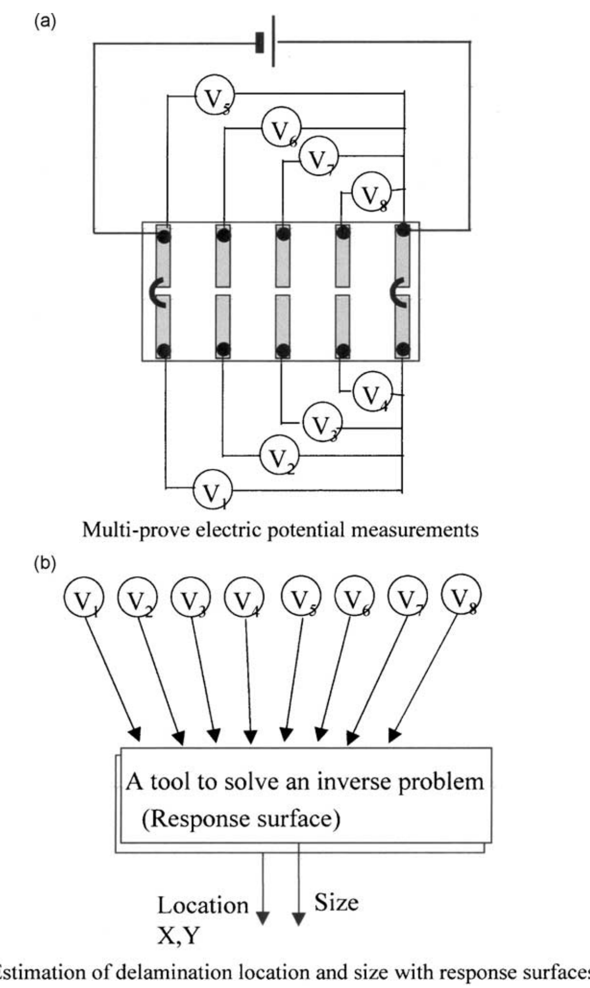


Fig. 3. Schematic representation of delamination identification method using multi-probe electric potential change method with response surfaces.

Mitsubishi-Rayon Co. Ltd. Using the prepreg, cross-ply laminates of $[0_2/90_2]$s were fabricated. The fiber volume fraction is approximately 0.5. Thickness of the laminates is approximately $t = 1$ mm. Cure condition is 130 °C×1.1Mpa×1h using a hot press. In order to measure electric-resistance changes using a two-probe method, reliable electrodes are indispensable. In order to produce the reliable electrodes, rectangle copper foil of 0.02 mm thickness is mounted on the prepreg laminates, and these electrodes are co-cured with the laminate. From the laminates, rectangular plate type specimens of the length of 200 mm and the width of 105 mm were produced as shown in Fig. 4. The multiple electrodes are mounted on a single surface of the specimen in the present study as previously mentioned.

### 3.2. Experimental procedures

To create a delamination crack in each plate-type specimen, an indentation test is employed here. An indentation type jig and cylindrical support is adopted here. By changing the diameter of the cylindrical support jig from 10 to 50 mm, different sizes of delamination cracks were created in the plate type specimen. The indentation point is loaded from the opposite side surface where the electrodes are mounted. This is to simulate the placements of electrodes inside the structures and the impact load that creates a delamination comes from the outside. Since the specimen is a thin laminate, the loading creates a large delamination crack in the 0–90° interface near the electrodes.

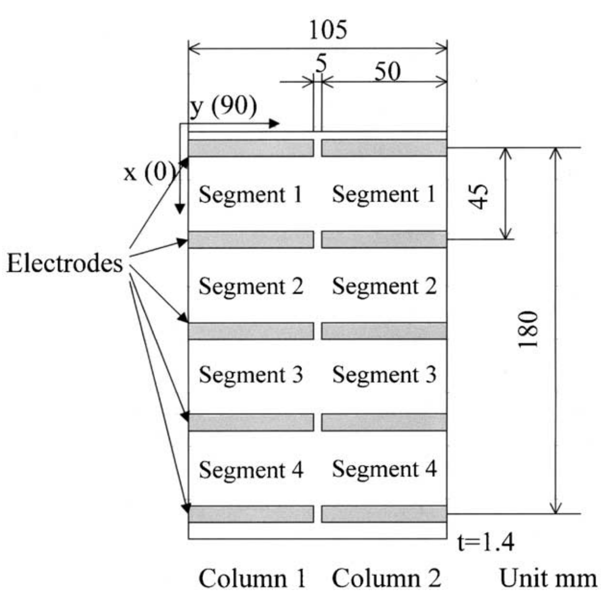


Fig. 4. Specimen configuration.

### 3.3. Electric potential change measurements

After creating a delamination crack, electric potential changes at all electrodes were measured using amplifier circuits. Usually, to obtain large electric potential change, high electric current must be charged: this may cause elevation of temperature. To prevent the elevation of the temperature, a new differential amplifier circuit is developed here as shown in Fig. 5. The circuit amplifies the voltage change without charging a large electric current. The circuit system comprises of a constant electric current circuit, several differential amplifier circuits and a data logger. Since the electrode 1A and 2A are connected together, electric current is supplied from the left edge (1A and 2A) to the right edge (1E and 2E) in Fig. 5. Electric potential changes are measured at each electrode using the amplifier circuits that amplify the potential change by the factor of 1000. Since the electric current in the amplifier circuits to measure the potential changes is negligible, the electric resistance changes at the electrodes can be neglected. This is the reason why the multi-probe method is appropriate for precise measurements of electric potential change.

Constant electric current of 250 mA is charged from the electric current supply circuit. This circuit adopts transistors of high thermal capacity (A814, 30 W) to prevent electric current fluctuation. Since the electric resistance of the specimen is approximately 0.6 Ω, the electric power consumption is only 0.0375 W. This electric power consumption is very small, and no temperature elevation was observed.

## 4. Response surface method using normalized data

### 4.1. Response surface method

The response surface is a widely adopted tool for quality engineering fields [30]. The response surface methodology comprises curve fitting with regression to obtain approximate responses, design of experiments to obtain minimum variances of the responses and optimizations using the approximated responses.

In the present study, the response surface methodology is adopted as a solver for inverse problems. For the present study, predictions of delamination locations and sizes from measured electric resistance changes are one of the inverse problems. The response surface methodology brings two advantages; the inverse problems can be approximately solved without consideration of modeling of functions, and the approximated response surfaces can be evaluated using powerful statistical tools. For most of the composites, it is very difficult to understand the precise model about electric-voltage change, and other tools like a back-propagation-neural-network

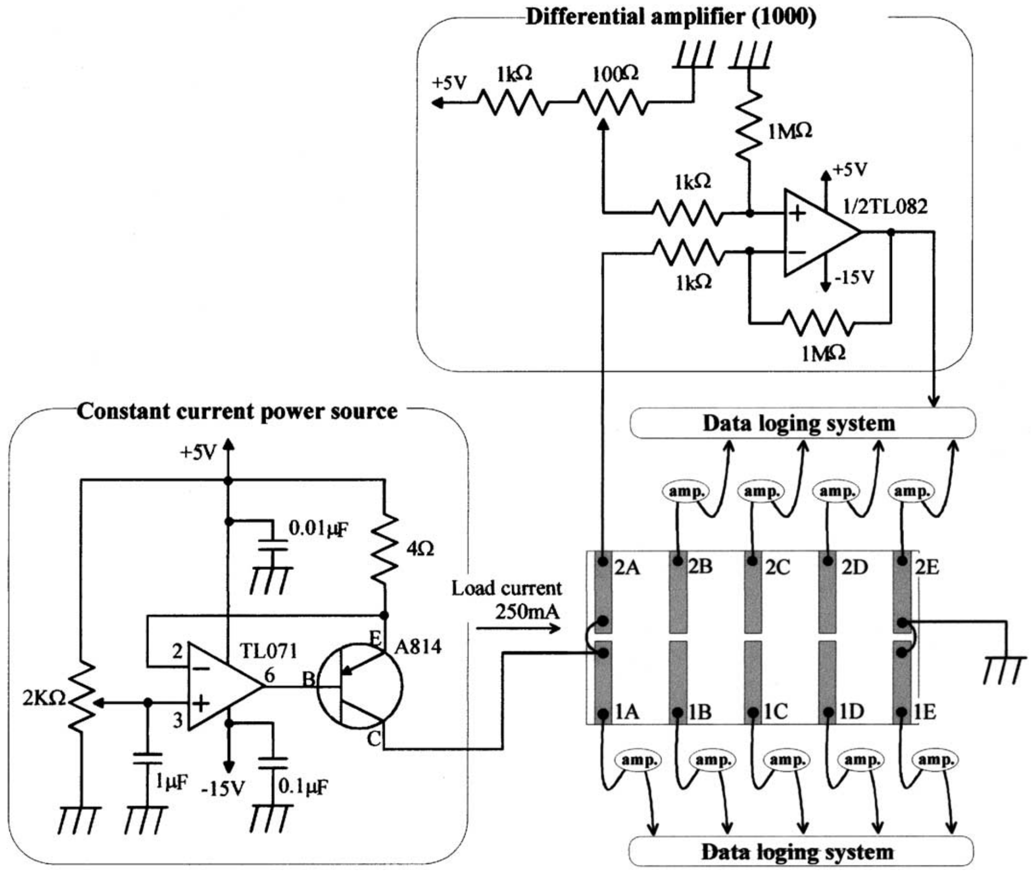


Fig. 5. Electric circuit used for voltage change method.

have difficulties for evaluations of curve fitness and of appropriateness of the network model.

For most of the response surfaces, the functions for the approximations are polynomials because of simplicity. For the cases of quadratic polynomials, the response surface is described as follows.

$$y = \beta_0 + \sum_{j=1}^{k}\beta_j x_j + \sum_{j=1}^{k}\beta_{jj}x_j^2 + \sum_{i=1}^{k-1}\sum_{j=i+1}^{k}\beta_{ij}x_i x_j \quad (1)$$

where $k$ is the number of variables. In the case of three-electrode type specimens, there are two electric voltage change variables; $v_1$ and $v_2$. The response surface for estimations of delamination location (p) is expressed as follow.

$$p = \beta_0 + \beta_1 v_1 + \beta_2 v_2 + \beta_3 v_1^2 + \beta_4 v_2^2 + \beta_5 v_1 v_2 \quad (2)$$

By replacements of $g = p$ $x_1 = v_1$,$x_2 = v_2$, $x_3 = v_1$, $x_4 = v_2$, $x_5 = v_1 v_2$ Eq. (2) becomes a linear regression model.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 \quad (3)$$

In the case that total number of experiments is $n$, the response surface can be expressed as follows using matrix expression.

$$\mathbf{Y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{e} \quad (4)$$

where

$$\mathbf{Y} = \begin{Bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{Bmatrix} \qquad \mathbf{X} = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1k} \\ 1 & x_{21} & x_{22} & \cdots & x_{2k} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_{n1} & x_{n2} & \cdots & x_{nk} \end{bmatrix}$$

$$\boldsymbol{\beta} = \begin{Bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_k \end{Bmatrix} \qquad \mathbf{e} = \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{Bmatrix}$$

where **e** is an error vector.

The unbiased estimator **b** of the coefficient vector **β** is obtained using the well known least square error method as follows.

$$\mathbf{b} = \left(\mathbf{X}^T\mathbf{X}\right)^{-1}\mathbf{X}^T\mathbf{Y} \quad (5)$$

The variance–covariance matrix of the b is obtained as follows.

$$\mathrm{cov}\left(b_i, b_j\right) = C_{ij} = \sigma^2\left(\mathbf{X}^T\mathbf{X}\right)^{-1} \quad (6)$$

where the $\sigma$ is the error of $\mathbf{Y}$. The estimated value of $\sigma$ is obtained as follows.

$$\sigma^2 = \frac{SS_E}{n-k-1} \tag{7}$$

$SS_E$ is a square sum of errors, and expressed as follows.

$$SS_E = \mathbf{Y}^T\mathbf{Y} - \mathbf{b}^T\mathbf{X}^T\mathbf{Y} \tag{8}$$

In order to judge the goodness of the approximation of the response surface, the adjusted coefficient of multiple-determination $R^2_{\mathrm{adj}}$ is used.

$$R^2_{\mathrm{adj}} = 1 - \frac{SS_E/(n-k-1)}{S_{yy}/(n-1)} \tag{9}$$

where $S_{yy}$ is the total sum of squares.

$$S_{yy} = \mathbf{Y}^T\mathbf{Y} - \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{n} \tag{10}$$

Each coefficient of the response surface can be tested by using $t$-statistic. The $t$-statistic of the coeficient $b_{\mathrm{j}}$ is expressed as follows.

$$t_0 = \frac{b_j}{\sqrt{\sigma^2 C_{jj}}} \tag{11}$$

where the $C_{\mathrm{jj}}$ is the element of number jj of variance–covariance matrix of Eq. (6). When the absolute value of the $t$-statistics is smaller than the threshold value of $t$-distribution ($t_{0.025,\mathrm{n-k-1}}$), the coefficient is eliminated from the response surface as a non-significant coefficient to obtain higher $R^2_{\mathrm{adj}}$.

The response surface (RS) is quite similar to the Artificial Neural Network (ANN) of the famous back propagation training system. The RS has advantages of low computational cost and the availability of the strong statistical tools in compensation for the decrease of fitness compared to the ANN. Our previous paper shows that the RS gives enough approximations for the inverse tool of electric resistance change method for delamination monitoring of graphite/epoxy laminates [29], and the ANN could give larger error for new data that are not used for training. On the other hand, the RS gives better estimations even for the new data. On the basis of the results, the RS is adopted as a tool for solving the inverse problem here.

Since the electrodes of 1E and 2E in Fig. 5 are connected to ground, total number of voltage changes is eight here: $V_1(=\Delta V_{1A}-\Delta V_{1E})$, $V_2$ $(=\Delta V_{1B}-\Delta V_{1E})$, $V_3$ $(=\Delta V_{1C}-\Delta V_{1E})$, $V_4$ $(=\Delta V_{1D}-\Delta V_{1E})$, $V_5$ $(=\Delta V_{2A}-\Delta V_{2E})$, $V_6$ $(=\Delta V_{2B}-\Delta V_{2E})$, $V_7$ $(=\Delta V_{2C}-\Delta V_{2E})$ and $V_8(=\Delta V_{2D}-\Delta V_{2E})$.

### 4.2. Normalized data

The authors' group [31] has revealed that the response surfaces may provide poor performance for estimations of delamination location for the case that a small delamination exists at the middle of the segments, and the poor estimations are caused due to the fact that the obtained configurations of the electric resistance change distributions contain both information of the delamination location and that of the delamination size. The authors' group [31] has proposed a new electric resistance change method with normalization of electric resistance changes. The normalizations make independent configurations of the electric resistance changes of the delamination size. The new method enables us to obtain significantly higher performance estimations of the delamination location. The new method is applied to the multi-probe electric potential method here.

In the case of Fig. 5, the measured electric resistance changes can be regarded as a vector of four elements: $V_1$, $V_2$, $V_3$ and $V_8$. The length of the vector $\eta$ is defined as follows.

$$\eta = \sqrt{V_1^2 + V_2^2 + V_3^2 + \cdots + V_8^2} \tag{12}$$

All of the elements are divided by the $\eta$ to obtain the normalized electric resistance changes vector (v) as follows.

$$\mathbf{v} = \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_8 \end{pmatrix} = \begin{pmatrix} V_1/\eta \\ V_2/\eta \\ \vdots \\ V_8/\eta \end{pmatrix} \tag{13}$$

With the normalized electric resistances, the response surface to estimate the delamination location $X$ and $Y$ are obtained as follows.

$$X = \beta_0 + \beta_1 v_1 + \beta_2 v_2 + \cdots + \beta_8 v_8 + \beta_9 v_1^2 + \beta_{10} v_2^2 + \cdots + \beta_{16} v_8^2 + \beta_{17} v_1 v_2 + \beta_{18} v_1 v_3 + \beta_{19} v_1 v_4 + \cdots + \beta_{44} v_7 v_8 \tag{14}$$

$$Y = \beta_0 + \beta_1 v_1 + \beta_2 v_2 + \cdots + \beta_8 v_8 + \beta_9 v_1^2 + \beta_{10} v_2^2 + \cdots + \beta_{16} v_8^2 + \beta_{17} v_1 v_2 + \beta_{18} v_1 v_3 + \beta_{19} v_1 v_4 + \cdots + \beta_{44} v_7 v_8 \tag{15}$$

For the estimations of the delamination size ($S$), the length of the vector is also a significant effect. Thus, the total number of variables of the response surface is increased by one as follows.

$$S = \beta_0 + \beta_1 v_1 + \beta_2 v_2 + \cdots + \beta_9 v_9 + \beta_{10} v_1^2 + \beta_{11} v_2^2 + \cdots + \beta_{18} v_9^2 + \beta_{19} v_1 v_2 + \beta_{20} v_1 v_3 + \cdots + \beta_{55} v_8 v_9 \quad (16)$$

where $v_9 = \eta$.

These new response surfaces for estimations are called the new method here. In the present paper, the terms of the response surfaces that reduce the value of $R^2_{adj}$ are deleted using *t*-statistics [30]. The total number of experiments is 74 in the present study.

## 5. Results and discussion

### 5.1. Measured potential changes

Fig. 6 shows the results of measured electric potential at 10 points. In this experiments, five additional electrodes are mounted on the bottom surface of the specimen as shown in Fig. 6. These extra electrodes are also co-cured here. Fiber direction of both of the surfaces is specimen longitudinal direction, and fiber direction of the middle ply is perpendicular to the specimen longitudinal direction. Electric current of 250 mA is charged between the electrode A and E. The electric voltage of the electrode E is set to 0 V. Electric voltages at other electrodes are shown in Fig. 6. As shown in Fig. 6, electric voltage at the charged surface (top surface) severely decreases from A to E. This means most of the electric current flows in the charged surface. Electric voltage of the charged surface (A), however, differs from that of the bottom surface (A′). This means that the electric current in the thickness direction exists. Even in the bottom surface, electric voltage decreases from A′ to E′, and this means that the electric current flows in the bottom surface from A′ to E′. The large difference of the electric voltage between A and A′ or E and E′ means that the large electric current exists between the charged surface and the bottom surface around the electrodes A–A′ and E–E′. This electric current in the thickness direction makes it possible to monitor delamination in graphite/epoxy-laminated composites. This electric current in the thickness direction is very small in the center point of the specimen. This small electric current means it is difficult to monitor a delamination location around the center of the specimen. The electric current is illustrated in Fig. 6 as marks of arrows.

Figs. 7 and 8 show the typical results of measured electric potential. The abscissa is the electrode number from A to D: electrode E is set to 0 V. The ordinate is the measured electric potential change using the amplifiers shown in Fig. 5. Column 1 means the left column of the electrodes and column 2 means the right column of the electrodes as shown in Fig. 5. In Fig. 7, a delamination exists in the first segment of the first

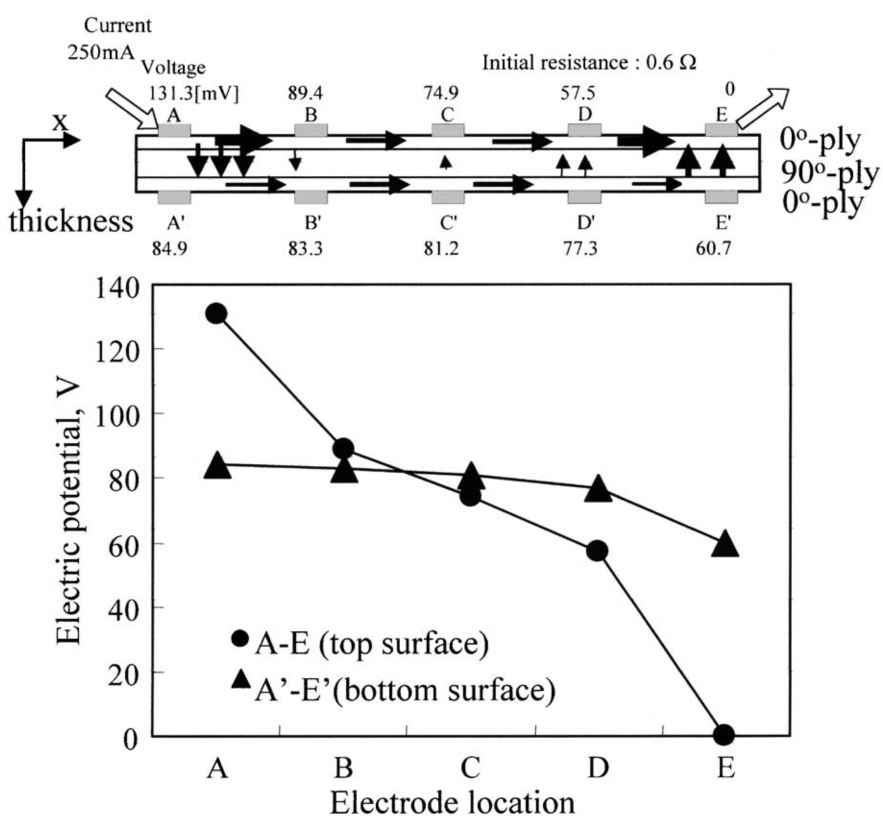


Fig. 6. Electric potential distribution and schema of electric current.

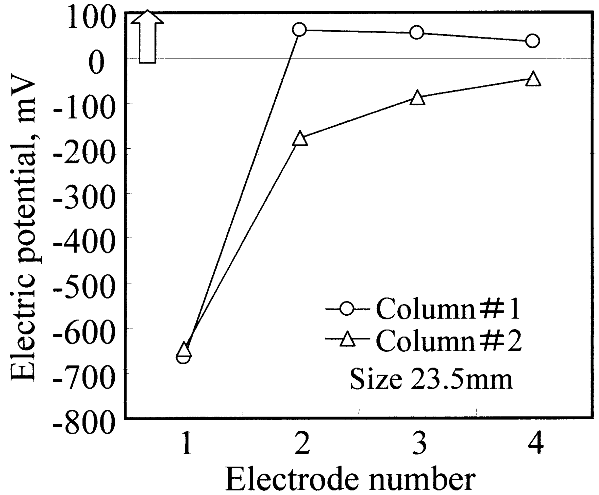


Fig. 7. Measured electric potential distribution at each electrode when the delamination exists at column #1 and line #1 ($x = 24.1$, $y = 21.2$).

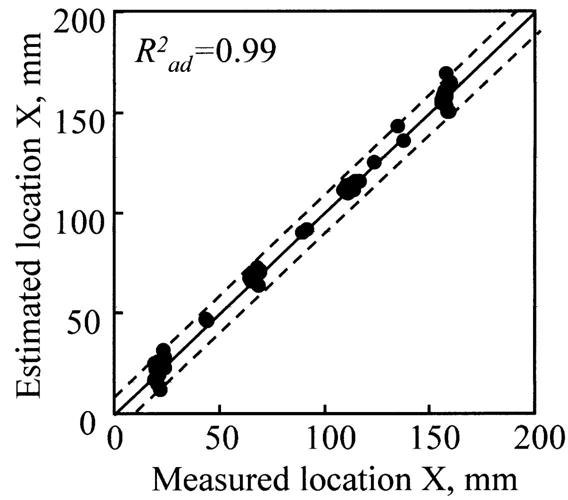


Fig. 9. Estimated delamination location of $X$ direction with error band of 10 mm.

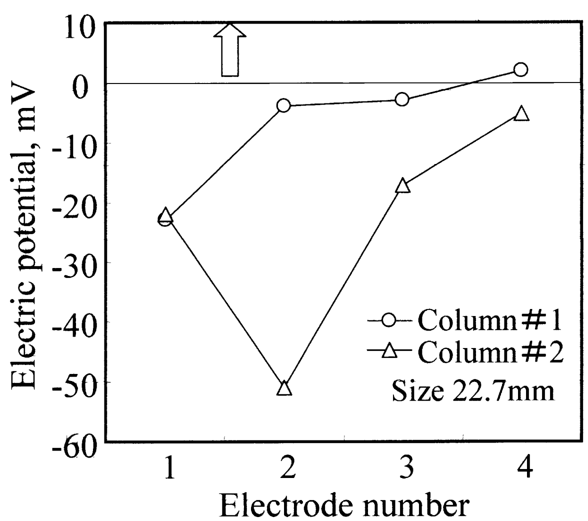


Fig. 8. Measured electric potential distribution at each electrode when the delamination exists at column #2 and line #2 ($x = 64.9$. $y = 82.9$).

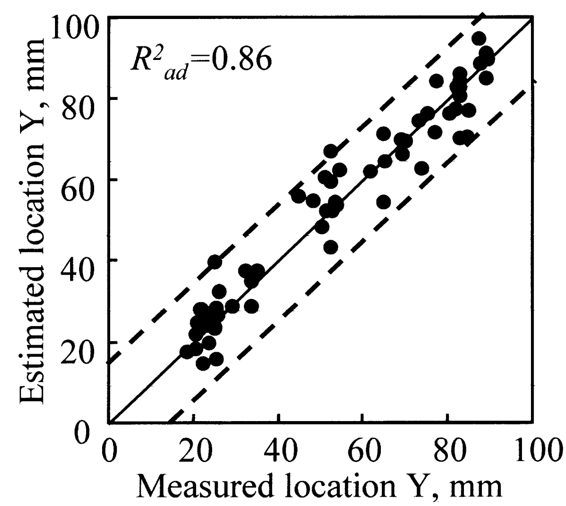


Fig. 10. Estimated delamination location of $Y$ direction with error band of 15 mm.

column. The arrow in Fig. 7 shows the point of the delamination location. Similarly, in Fig. 8, a delamination exists in the second segment in the second column.

The electric potential changes in Fig. 7 are significantly larger than those in Fig. 8. Although the sizes of delamination of both cases are quite similar to each other, the magnitude of the electric potential change is quite different. This corresponds to the small electric current in the thickness direction around the center of the specimen.

### 5.2. Delamination estimations

Seventy-four experiments were performed to measure the electric potential change after creating a delamination in the specimen. These 74 sets of measured results are normalized with Eq. (13), and the three response surfaces to estimate delamination location ($X$, $Y$) and size ($S$) are calculated using the least square error method. The estimation results are shown in Figs. 9–11. Figs. 9 and 10 show the estimation results of delamination location $X$ and $Y$ respectively. Fig. 11 shows the estimation results of delamination size $S$. For these figures, the abscissa is the measured value and the ordinate is the estimated value. The symbols plotted on the diagonal line mean that the estimation is quite exact. In these figures, error bandwidth is revealed with a pair of dashed lines.

Fig. 9 shows the estimation results of the delamination location $X$. The adjusted coefficient of multiple-determinant $R^2_{\mathrm{ad}}$ is 0.99 as shown in Fig. 9, and the error band is only 10 mm. These are quite excellent estimations. These delaminations have not only cracks at the interlamina but also matrix cracks, and these are

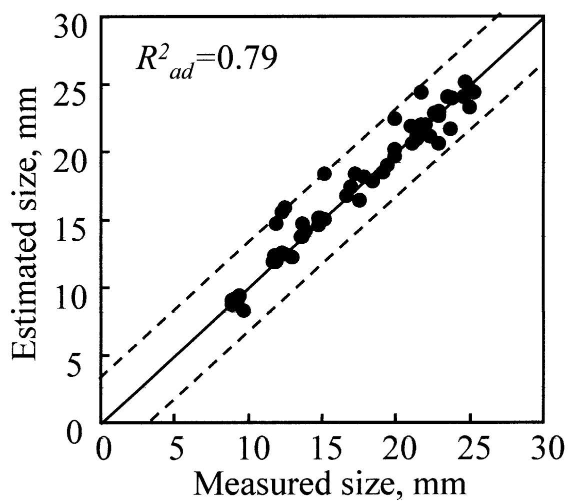


Fig. 11. Estimated delamination size error band of 3 mm.

Table 1
Comparison of adjusted multiple coefficients of determination ($R^2_{ad}$) of two methods ($R^2_{ad}$ of the resistance method is derived from [32])

| Method | $R^2_{ad}$ | |
|---|---|---|
| Resistance | $X$ | 0.95 |
| | $Y$ | 0.93 |
| | Size | 0.82 |
| Potential | $X$ | 0.99 |
| | $Y$ | 0.86 |
| | Size | 0.79 |

different from an ideal delamination adopted in FEM analyses [31]. Nevertheless, the estimation performance is quite excellent.

Fig. 10 shows the estimation results of the delamination location $Y$. The adjusted coefficient of multiple-determinant $R^2_{ad}$ is 0.86 as shown in Fig. 10, and the error band is only 15 mm although these results are affected by experimental errors. These small errors of estimations of delamination location experimentally show that the multi-probe method with normalized response surfaces is quite effective for monitoring of delamination location in practical use.

Fig. 11 shows the estimation results of the delamination size $S$. The adjusted coefficient of multiple-determinant $R^2_{ad}$ is 0.79 as shown in Fig. 11, and the error band is only 3 mm although these results are affected by experimental errors. This small error of estimations of delamination size experimentally shows that the multi-probe method with normalized response surfaces is also quite effective for monitoring of delamination size in practical use.

Table 1 shows the results of the adjusted coefficient of multiple-determinant of the electric resistance change method with the normalized response surfaces and the results of the adjusted coefficient of multiple-determinant of the multi-probe electric potential change method with the normalized response surfaces. These comparisons of the adjusted coefficient of multiple-determinant reveal that no difference of estimation performance is recognized between the two methods. Since the reliability of electrodes has significant impact on the electric resistance change method, it can be concluded that the multi-probe electric potential change method with the normalized response surfaces is the preferable method in practical use.

Damages of composite laminates include several types like delaminations, matrix cracking, fiber-matrix debonding and fiber breakages. The present study deals with damages caused by indentations. The indentation damages usually comprise delaminations and matrix cracking. Fiber-matrix debonding and fiber breakages may be included in the indentation damages. Since the present study uses the experimental method, the measured electric voltage change may include all of these effects. It is important to know the effect of each damage type on the measured electric voltage changes. Experimental method, however, is very difficult to distinguish these effects. Therefore, analytical research will be required in our future works.

## 6. Conclusions

In the present study, a multi-probe electric potential change method is adopted as a monitoring method of delamination location and size for graphite/epoxy laminated composites. The method has the advantage that the electric resistance changes at the electrodes do not affect the electric potentials measurements if the method is compared to the electric resistance change method. The results obtained are as follows.

1. Using the electric circuit adopted in the present study, the electric potential change method provides the same estimation performance as that of the electric resistance method.
2. Since the method is not affected by the electric resistance changes at the electrodes, this method is very effective in practical use for delamination monitoring.
3. The error band of the method is 10 mm in delamination location $X$, 15 mm in delamination location $Y$ and 3 mm in delamination size.

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