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Damage Identification of Woven Graphite/Epoxy Composite Beams using the Electrical Resistance Change Method

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ABSTRACT: This study examines the damage identification for woven graphite/epoxy composite beams by means of an electrical resistance change method. The method has been proposed by the authors and successfully applied to cross-ply and quasi-isotropic laminates; the method has yet to be applied to woven laminates. In many practical structures, woven plies are adopted to prevent peeling of the surface layer. Therefore, a woven graphite/epoxy composite is selected as the target material of the electrical resistance change method to identify the damage. Beam type specimens consisting of woven laminates are the focus of this article. For the purpose of identification, the response surface is adopted as a solving method for the inverse problem. As a result, the method shows an excellent performance for estimating delamination crack locations and sizes.

Key Words: composites, damage identification, electrical resistance change, response surface.

INTRODUCTION

LAMINATED composites have superior specific mechanical properties such as specific strength, specific stiffness, fatigue strength, etc. when compared to the conventional metallic materials. However, laminated composite structures usually have a low delamination resistance. This results in damage from any slight impact such as dropping a tool. Since delamination cracks are usually invisible and difficult to detect by means of visual inspections, delamination cracks result in low reliabilities for the primary structure of laminated composites.

In order to improve the low reliability of laminated composite structures, an in-service automatic system of delamination crack identification is desirable. Using a health monitoring system for detecting the delamination cracks is a promising approach for practical laminated composite structures.

A typical approach for identifying the delamination cracks in-service is by embedding fiber-optic strain sensors into the laminated composite structure for measuring the strain distributions (Badcock and Franklyn, 1995; Chang and Sirkis, 1997, 1998). This approach results in a precise measurement of strain distributions. However, the approach may cause a reduction in static and fatigue strengths, and the total weight of the laminated composite structure is increased (Seo and Lee, 1995; Seo et al., 1995). To prevent a reduction in static and fatigue strengths, a measurement method of strain distribution using bonded fiber-optic strain sensors to the surface of laminates has been developed (Tsuda et al., 1999; Murayama et al., 2003). This method results in reduced measurement accuracies when compared to the measurement method using embedded sensors. Those approaches are, moreover, very expensive due to the high cost of optical fiber sensors and sensing systems. Therefore, a new convenient technology is needed for smart structures to identify the delamination cracks in laminated composites.

In order to overcome these problems, many researchers have focused on smart composite structures that utilize the electrical conductivity of the reinforcement fiber, and also damage-monitoring methods have been investigated (Schulte and Baron, 1989; Chen and Chung, 1993; Irving and Thiagarajan, 1998; Abry et al., 1999; Seo and Lee, 1999; Weber and Schwarts, 2001; Muto et al., 2001; Kubo et al., 2002; Park et al., 2002). The authors, in their previous studies, proposed a cure monitoring method (Inada and Todoroki, 2004), the identification of an internal delamination (Todoroki and Tanaka 2002; Todoroki et al., 2002b; Iwasaki and Todoroki, 2005), the detections of matrix cracks (Omagari et al., 2005), and strain monitoring

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(Todoroki and Yoshida, 2004), using the electrical resistance change method, and confirmed the applicability of the method both analytically and experimentally.

In the electrical resistance change method, damage to laminates such as delamination cracks are identified from the electrical resistance changes in the laminates. Since the electrical resistance changes of a laminate can be measured using a conventional strain amplifier, the method does not require expensive instruments. Since the method adopts reinforcement carbon fibers as sensors for delamination crack identification, the method does not result in the reduction in either the static or fatigue strength. For the measurement of a change in electrical resistance, an electrical current is applied from electrodes that are mounted on the surface of a laminate. Therefore, the method is applicable to existing structures that have been fabricated without embedding sensors.

The authors have already investigated the applicability of damage identification by means of the electrical resistance change method for beam type (Todoroki and Tanaka, 2002) and plate type specimens (Todoroki et al., 2002b; Iwasaki and Todoroki, 2005) of cross-ply or quasi-isotropic laminates; the method has yet to be applied to woven graphite/epoxy laminates. In practical composite structures, a laminate whose surface layer is a woven ply, exists to prevent peeling of the surface layer. The electrical resistance change method positively utilizes the orthotropic electrical conductivity in the in-plane and thickness directions of graphite/epoxy laminates. The woven graphite/epoxy plies, however, have an in-plane isotropic electrical conductivity, and a low thickness directional electrical conductivity is expected due to the undulating boundary of the graphite fiber bundles. The different electrical property of the woven plies from the electrical property of the unidirectional (UD) plies may cause different reactions when an electrical current is applied to the woven graphite/epoxy laminates. Moreover, it may be expected that the woven ply of the surface layer does not result in good electrical contact. Since the electrical resistance change of the graphite/epoxy laminate due to damage such as delamination is very small, the reliability of the electrodes becomes a major issue for damage identification using the electrical resistance change method (Hirano et al., 2004). The possibility of poor electrical contacts at the electrodes, therefore, requires one to investigate the reliability of electrodes for the laminate whose surface layer is a woven ply.

In this study, therefore, the applicability of the electrical resistance change method is investigated using beam type specimens, whose surface layer is a woven ply. First, the effect of surface woven ply for the electrical resistance change method is investigated. The influence of an in-plane isotropic electrical conductivity of a surface woven layer upon the electrical resistance change is investigated both analytically and experimentally, and the condition of the electrical contact between electrode and specimen is investigated experimentally. Subsequently, the applicability of the electrical resistance change method for the beam type woven laminate specimen is confirmed experimentally by performing damage identification of the size and location of delamination cracks. A modified electric-bridge circuit for strain gages is employed to measure electrical resistance changes. The delamination crack is created by means of an interlamina shear test. For identifying damage location and size, the response surface, which provides the relationship between electrical resistance changes and damage size or location, is adopted.

SPECIMENS AND EXPERIMENTAL METHOD

Specimens

The configuration of the specimen for the identification of delamination crack location and size is shown schematically in Figure 1. The specimens are made of UD graphite/epoxy prepreg sheet PYROFIL #380G250S and woven graphite/epoxy prepreg sheet PYROFIL TR3110 #381 produced by Mitsubishi-Rayon Co., Ltd. An autoclave molding method was adopted to fabricate the laminates. The curing temperature is 130°C (±5°C), the curing time is 1.5 h, and the pressure is 0.7 MPa. The beam type specimens were cut from the cured laminates. The configuration is 190 mm in length and 10 mm in width, as shown in Figure 1. The thickness of the specimen is approximately 0.65 mm on average. The objective of this study is to investigate the effect of the surface woven ply for the electrical resistance change method and the influence of an in-plane isotropic electrical conductivity of a surface woven layer upon the electrical resistance change. The variance of the stacking sequence of the middle of the laminate comprises UD lamina that may cause the complex electrical resistance reaction against the creation of the delamination crack. Therefore, in order to avoid the influence of the difference in stacking

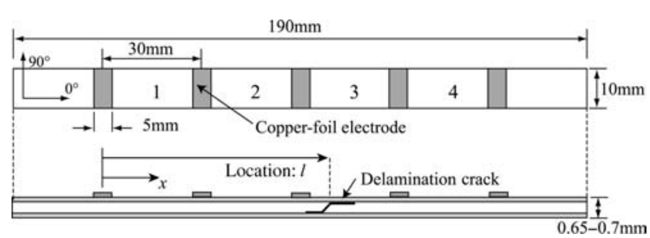

Figure 1. Configuration of specimen.

sequence, the stacking sequence of the specimens is fixed to $[(0,90)/90/(0,90)]_T$. Here, the stacking sequence code of (0,90) describes a woven CFRP ply consisting of 0° and 90° fibers.

In order to measure the electrical resistance changes due to a delamination crack, multiple electrodes are mounted on the single top surface of a specimen. Five electrodes are mounted in the 0° fiber direction. These electrodes are co-cured after mounting copper foils of 0.02 mm in thickness during the fabrication process. The coordinates of the specimen are defined as shown in Figure 1. In order to simulate the identification of damage to practical laminated composite structures such as the wing box, all of the electrodes are mounted on the top single surface of the specimen. Since the surfaces of a wing box must be smooth for good aerodynamic properties, all of the measurement devices for the health monitoring system must be located inside a wing box structure; damages can be detected by means of measurement devices mounted on one side of the structure. This is the reason for all of the electrodes being mounted on the top single surface of the specimen.

Creation of a Delamination Crack

An interlamina shear test, a kind of three-point bending test, is applied to create a delamination crack in each beam-type specimen. A tensile/compression testing machine (Shimano Auto Graph produced by Shimano Co. Ltd) is used for isostatic loading. The cross-head speed is 1 mm/min. In this test, delamination is generally created in the interlamina between the surface woven ply and middle 90° ply. The middle point is loaded from the bottom side of the specimen surface where electrodes are not mounted in order to make a large delamination at the interlamina near the electrodes. This is because a large delamination is generally created at the interlamina opposite to the impacted surface. Actual delaminations usually involve matrix cracking. As a result, delaminations are formed in zigzag shapes consisting of straight delaminations and a transverse crack. For simplification, damage is called a 'delamination crack' in this study. This test method and typical delamination crack shape are shown schematically in Figure 2.

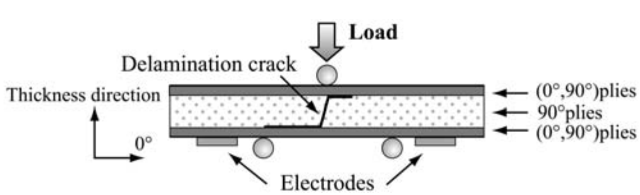

Figure 2. *Delamination creation method.*

Measurement of Electrical Resistance Changes

Since the changes in electrical resistance due to the creation of a delamination crack are very small, it is difficult to measure them directly using a resistance meter. Therefore, in order to obtain a large output signal, a modified resistance bridge circuit for a conventional strain gage is adopted, as shown in Figure 3. The only difference from the bridge circuit of the conventional strain gage is a connected electrical resistance. The initial electrical resistance of the specimen is approximately 0.7 Ω. Since the measurement method of the changes in electrical resistance is exactly the same as that of conventional strain gages, the conventional strain amplifier UCAM-1A (produced by Kyowa Electronic Instrument Co., Ltd) is adopted here. The amplifier of the conventional strain gage provides outputs of electric resistance as 'strain'. In this study, however, the output signal means an electrical resistance change, and does not mean specimen deformation. The electrical resistance change ratio is expressed using output 'strain' ε shown as follows:

$$\varepsilon = \frac{\Delta R}{R_0 k_s}, \tag{1}$$

where ε is the output signal 'strain', ΔR is the electrical resistance change due to a delamination crack, R_0 is the initial electrical resistance, and k_s is a gage factor of the strain amplifier system. The gage factor of the conventional strain gage amplifier adopted in this study is two. In this study, the output 'strain' data are regarded as electrical resistance changes without translations. After a delamination crack creation, electrical resistance changes are measured. The measured electrical resistance change is normalized by means of the norm

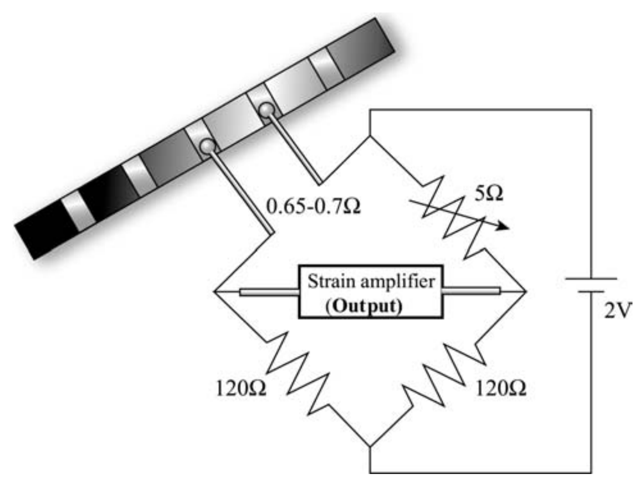

Figure 3. *Modified electrical resistance bridge circuit.*

of the measured electrical resistance change vector (Todoroki et al., 2004).

$$\frac{\Delta R_i}{R_{i0}} = \frac{\Delta R_i/R_{i0}}{L}$$
$$L = \sqrt{\sum_k \left(\frac{\Delta R_k}{R_{k0}}\right)^2} \quad (2)$$

After the measurement of electrical resistance changes, the size and location of created delamination cracks are measured using an ultrasonic C-scan testing machine AT5000 (produced by Hitachi Co., Ltd).

Application of Response Surfaces

A tool for solving inverse problems is indispensable for the identification of the delamination crack location and size from the measured electrical resistance changes. In this study, the relationship between measured electrical resistance changes and approximate delamination crack size and location are obtained by means of response surfaces. The response surfaces are usually adopted for process control optimizations (Myers and Montgomery, 1995). This method provides a moderate approximation function between predictor variables and a response. For this study, predictions of delamination crack location and size from measured electrical resistance changes are one of the inverse problems.

For simplicity, quadratic polynomials are usually adopted as approximation functions. For the case of quadratic polynomials, the response surface is described as follows:

$$y = \beta_0 \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j, \quad (3)$$

where k is the total number of predictor variables. For simplification, consider the case where the number of predictor variables is two. Equation (3) can be written as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1^2 + \beta_4 x_2^2 + \beta_5 x_1 x_2 \quad (4)$$

By the substitutions $x_3 = x_1^2$, $x_4 = x_2^2$, and $x_5 = x_1\ x_2$, Equation (3) can be transformed into a linear multiple regression:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 \quad (5)$$

Let the total number of experiments be n, the results of the total experiments can be written in a matrix form as follows:

$$\boldsymbol{Y} = \boldsymbol{X\beta} + \boldsymbol{e}, \quad (6)$$

where $\boldsymbol{Y}$ is the response vector, $\boldsymbol{X}$ is the coordinate of the experiments, $\boldsymbol{\beta}$ is the coefficient vector and $\boldsymbol{e}$ is the error vector.

The unbiased estimator $\boldsymbol{b}$ of $\boldsymbol{\beta}$ is obtained as follows:

$$\boldsymbol{b} = \left(\boldsymbol{X}^{\mathrm{T}}\boldsymbol{X}\right)^{-1}\boldsymbol{X}^{\mathrm{T}}\boldsymbol{Y} \quad (7)$$

The elimination of the coefficients that worsen regression accuracy is performed by the decreasing method based on F-statistics in order to obtain a better approximation function. The lack of fit of the approximation function can be estimated by means of the adjusted multiple determination R^2_{adj} as follows:

$$R^2_{\mathrm{adj}} = 1 - \frac{SS_{\mathrm{E}}/(n-k-1)}{S_{yy}/(n-1)}, \quad (8)$$

where SS_{E} is the error sum of squares and S_{yy} is the total sum of squares. See reference Myers and Montgomery (1995) for a detailed explanation.

RESULTS AND DISCUSSION

Influence of the Surface Woven Ply

As mentioned in the introduction, woven composites may be a difficult target for the application of the electrical resistance change method: the electrical conductivity of the surface woven ply is isotropic in the in-plane direction and is lower in the thickness direction, and has uneven surfaces due to the crimp texture of surface woven ply. These differences become major issues for the application of the electrical resistance change method to woven laminates. Therefore, the feasibility of the electrical resistance change method for woven composites is investigated.

First, the influence of electrical properties of surface woven plies is investigated analytically. In order to investigate the electrical current flow in the thickness direction of the laminates, an FEM analysis is performed. In this study, commercially available FEM code ANSYS is adopted. The analysis model is generated using a two-dimensional (2-D) rectangular solid element (SOLID 70) assuming the specimen (Figure 1) is a 2-D beam model. The size of an element is defined as 5.0×10^{-2} mm in the thickness direction and 0.25 mm in the longitudinal direction. The electrical properties of UD and woven plies are defined from experimental data measured in advance of FEM analysis. The conductivity of UD and woven plies is shown in Table 1, where σ_0, σ_{90}, and σ_t represent the conductivity in the longitudinal direction (0°), the transverse direction (90°), and the thickness direction, respectively. Todoroki et al. (2002a) described in detail the measurement method of conductivity. From Table 1, it is clear that woven plies have a higher electrical conductivity in the in-plane direction and a significantly lower electrical conductivity in the thickness direction when compared with UD plies.

Figure 4 shows the result of the FEM analysis schematically, when a normalized electrical voltage (1 V) is applied to the second segment (see Figure 1), i.e., from the electrode on the left-hand side to the electrode on the right-hand side. The electrical voltage distribution in the thickness direction is shown as contour plots in Figure 4(a) and the distribution of the electrical current density in the thickness direction is shown as contour plots in Figure 4(b). Although woven plies have low electrical conductivity in the thickness direction, electrical current flow can be seen in the thickness direction of the specimen. The electrical current flow in the thickness direction causes an electrical resistance change when a delamination has occurred, and the change enables one to detect the delamination crack. This is because the delamination impedes the path of electrical current flow in the thickness direction. A circular electrical current flow can be seen not only on the inside of the segment between the electrodes but also on the outside of the segment between the electrodes from the result of FEM analysis (Figure 4). The circular electrical current flow outside the electrodes is important for the identification of the delamination crack location or size using the electrical resistance change method. This electrical flow outside the charged segment results in electrical resistance changes, even when a delamination crack is located in an adjacent segment. This electrical resistance change makes it difficult to identify the delamination crack location without using the tool for solving the inverse problem, as in the case of UD laminated composites.

For the investigation of the effect of electrical contact between electrodes and undulating woven surface ply due to crimp texture, a micrograph of the interface between a co-cured copper foil electrode and a surface of a laminate, whose surface layer is a woven ply, is investigated as shown in Figure 5(a). For comparison, a micrograph of the interface between the co-cured copper foil electrode and the surface of the laminate, which consists only of UD plies, is also shown in Figure 5(b). The UD-laminate shows that many fibers have contact points with the copper foil (see Figure 5(b)). On the other hand, the copper foil and undulating carbon bundles have nonuniform contact points along the fiber bundle due to fiber undulation of the crimp texture. This fact compels to confirm experimentally the reliability of co-cured copper foil electrodes for woven laminate.

Table 1. Measured electrical conductance of woven ply ($V_f = 0.62$).

Prepreg sheet	σ_0(S/m)	σ_{90}/σ_0	σ_t/σ_0
TR3110 #381 (Woven ply)	9.7×10^3	1.0	2.3×10^{-4}
#380G250S (Unidirectional ply)	5.5×10^3	3.7×10^{-2}	3.8×10^{-3}

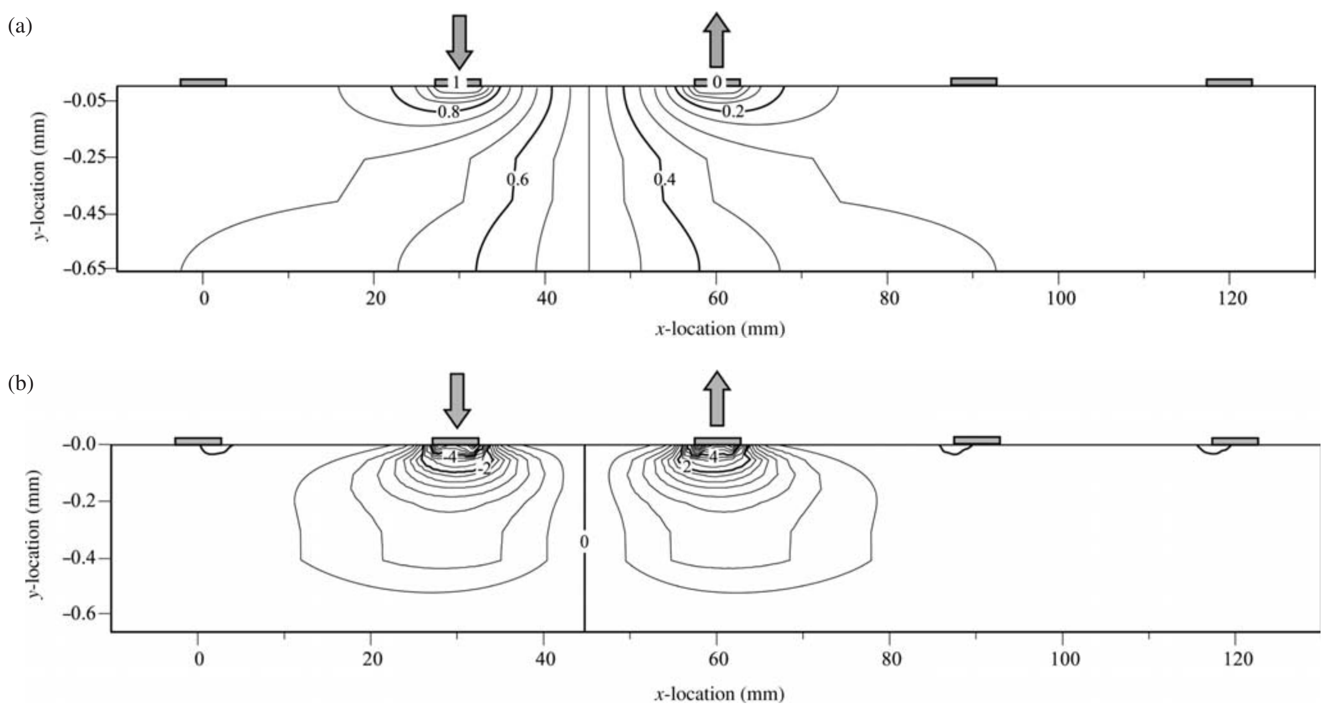

Figure 4. *Result of FEM analysis: (a) distribution of electrical voltage (V) and (b) distribution of electrical current density in the thickness direction (A/m^3).*

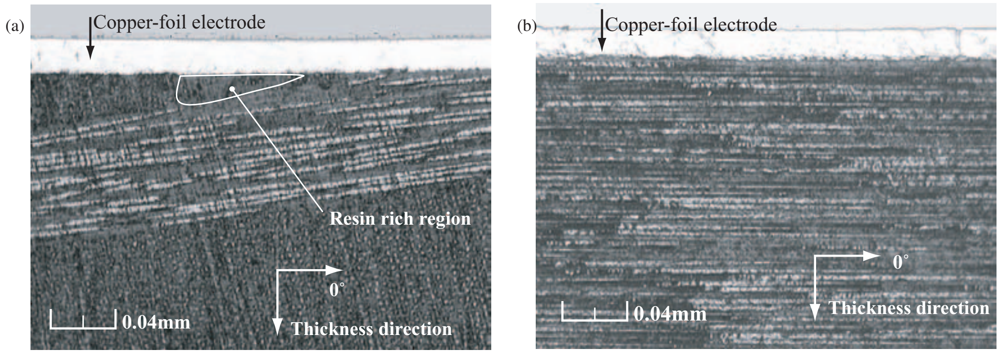

Figure 5. Micrograph of the interface between a co-cured copper foil electrode and the surface of the specimen: (a) co-cured electrode – woven ply and (b) co-cured electrode – UD ply.

In order to examine the validity of co-cured copper foil electrodes for surface woven plies, the initial inter-electrode resistances of all of the specimens are measured. It has been confirmed that the better electrode has a lower initial inter-electrode resistance when compared with that of the unreliable electrode in the previous study (Hirano et al., 2004) wherein the resistance was found to be about 1.0 Ω or less. In the case of this study, all of the measured initial resistances were $0.68 \sim 0.72\,\Omega$ on average. This fact indicates that the co-cured electrodes had good electrical conductivity with the surface woven ply. However, the effect of nonuniform electrical contacts remains to be investigated experimentally using a practical delamination crack.

The electrical resistance change method for woven laminates is confirmed experimentally using the specimen shown in Figure 1, with co-cured copper foil electrodes. Typical measured electrical resistance changes after creating a delamination crack are shown in Figure 6. The ordinate shows the measured electrical resistance changes and the abscissa shows the segment number of inter-electrodes of the specimen (see Figure 1). The output electrical resistance changes are sufficiently large for practical measurements. Although the delamination crack exists in the third segment, we can observe electrical resistance changes even in the second and fourth segments.

The electrical resistance changes in these adjacent segments where a delamination crack does not exist are due to the circular electrical current flow, as shown in Figure 4. Although surface plies are woven graphite/epoxy laminates, the measured electrical resistance change is similar to the electrical resistance change of the UD graphite/epoxy composites (Todoroki and Tanaka 2002). It is confirmed experimentally that the measured electrical resistance change is sufficiently large to measure by means of the conventional strain amplifier; the magnitude of the outputs are roughly the same as the magnitude of the outputs of the UD graphite/epoxy composites.

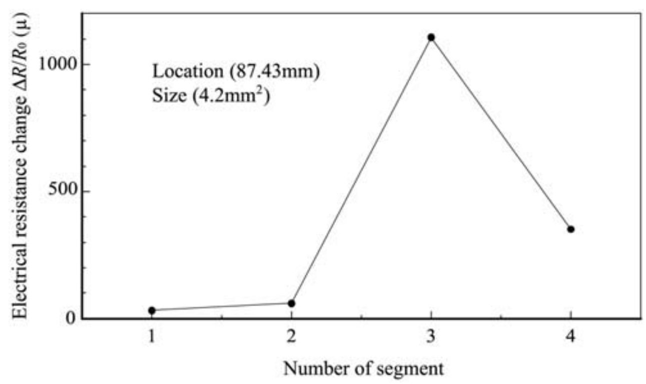

Figure 6. Typical measurement of electrical resistance change ratio.

Identification of Delamination Crack Locations

Using the measured electrical resistance data sets (the number of data points is 43), a response surface was created to identify the locations of the delamination cracks. The adjusted coefficient of multiple determination R^2_{adj} was 0.97; the obtained response surface agrees well with the relationship between the locations of the delamination cracks and the measured electrical resistance changes. Using the obtained response surface, delamination crack location was identified. In order to check the performance of the estimation for new data points, 10 new experimental data sets were prepared. These 10 new data points are not used for making the response surface. The identification result is shown in Figure 7. In this figure, the ordinate is the estimated delamination crack location, and the abscissa is the measured delamination crack location obtained with the ultrasonic C-scan image. The delamination crack location is defined as the distance from the origin to the center of the delamination crack (see Figure 1). In Figure 7, symbols plotted on the diagonal solid line represent the exact estimations. The solid circle symbols represent new experimental

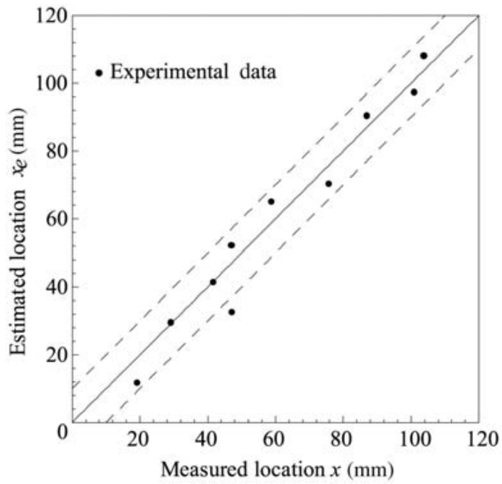

Figure 7. *Identification results of the delamination crack location.*

data sets that are not used for regression for creating the response surface.

As shown in Figure 7, the identification results are in good agreement with measured results. In order to evaluate the practical performances, it is necessary to decide on the tolerance error band of the delamination crack locations. The error band in this study is set to 10 mm, a smaller value than the length in the longitudinal direction of the electrode segment (30 mm). In Figure 7, the dotted lines show error bands of 10 mm and most of the estimated delamination crack locations are plotted inside the tolerance error band. This result means that delamination cracks can be identified with superior accuracy even up to the distance between the electrode segments. Therefore, it can easily be concluded that the identification of the delamination crack location is excellent.

Identification of the Delamination Crack Size

In order to identify the size of delamination cracks, an additional response surface has to be made, which gives the approximation of the relationship between the delamination crack sizes and measured electrical resistance changes using the measured electrical resistance data set (the number of data points in the set is 43). The adjusted coefficient of multiple determination R^2_{adj} is 0.82; the obtained response surface agrees well with the relationship between delamination crack size and measured electrical resistance change. Please note that the electrical resistance data set for the identification of the delamination crack size is the same as that used previously for the identification of the delamination crack locations. Using the obtained response surface, the identification of delamination crack sizes was performed. In order to verify the performance of the estimation, ten new data sets were prepared: these new data sets are the same data sets as those used in the response surface for monitoring delamination crack location.

As mentioned previously, the size of the delamination cracks are measured using ultrasonic C-scan imaging. Since the delamination of woven laminate progresses irregularly along the crimp of woven ply (see Figure. 8), for the sake of simplicity, the area of delamination is assumed to be trapezoidal, as shown in Figure 9. Here, the base of trapezoid (a_1), the upper base of trapezoid (a_2), and the height of trapezoid (h) are measured from the ultrasonic C-scan image. The area of trapezoidal shape is calculated from these measured results, and defined as the delamination area.

The identification results are shown in Figure 10. In this figure, the ordinate represents the estimated delamination crack size with the response surface and the abscissa represents the measured delamination crack size obtained with the ultrasonic C-scan image. The diagonal line (solid line) in Figure 10 shows the exact estimations and the solid circle symbols represent the new experimental data sets that are not used for the regression for creating the response surface.

As shown in Figure 10, identification of results is in good agreement with measured results. For the estimation of delamination crack size, the tolerance error band is chosen. The error band in this study is set to $\pm 5\,mm^2$. In Figure 10, dotted lines parallel to solid lines show error bands of $\pm 5\,mm^2$. Generally, damage tolerance design, which allows damage approximately 25–40 mm (1–1.5 in.) in diameter, is adopted for practical composite structures (Soderquist, 1987). Compared to the size of damage tolerance, the error band of $\pm 5\,mm^2$ is small enough for practical delamination crack identification. As shown in Figure 10, most of the estimated sizes are plotted inside the tolerance error band. Therefore, it can be concluded that the identification of the delamination crack size is excellent.

DISCUSSION

From the damage identification results, it is obviously confirmed that the electrical resistance change method is applicable to damage identification of the beam type woven graphite/epoxy specimens. The results also show the distinguished identification accuracy upon the estimation of delamination crack location and size as well as damage identification results of UD graphite/epoxy beam type specimens (Todoroki and Tanaka 2002), even though it is expected that woven composites may be a difficult target for the application of the electrical resistance change method.

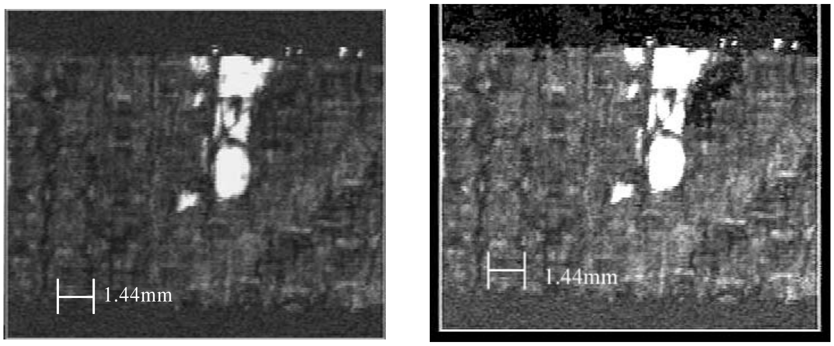

Figure 8. *Delamination crack image with ultrasonic C-scan.*

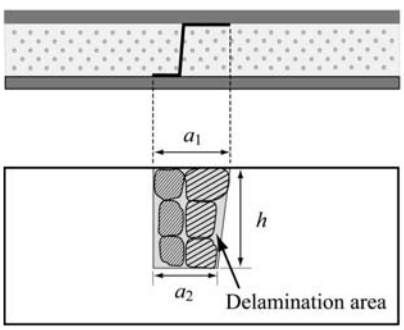

Figure 9. *Definition of delamination crack area.*

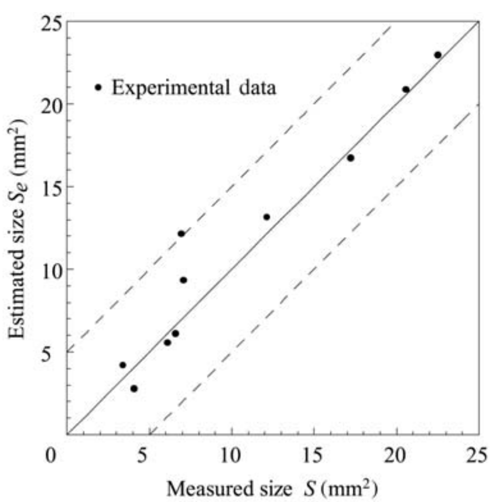

Figure 10. *Estimated results of the delamination crack size.*

It is clarified that the difference in electrical properties of the surface woven plies and UD plies hardly affects the electrical resistance change due to delamination crack creation. The results of FEM analysis (Figure 4) and experimentally measured electrical resistance change (Figure 6) are quite similar to the results of UD graphite/epoxy composites (Todoroki and Tanaka 2002; Todoroki et al., 2002a). For comparison and discussion, the results of the previous study are shown here.

Figure 11 represents the FEM analysis results of UD graphite/epoxy laminate (Todoroki et al., 2002a). The conditions of this analysis are as follows: the stacking sequence is [0/90]s, the thickness of laminate is 2.0 mm, and the electrical voltage (1.6 V) is added from $x=-70$ to $x=-35$. The electrical properties of the UD laminate are shown in Table 1. Though the stacking sequence, thickness of laminate, and the electrical property of the UD laminate are different from the woven laminate, the obtained electrical voltage distribution is similar to the result of woven laminate (Figure 4(a)); the circular electrical current flow can be observed not only on the inside of the segment between the electrodes but also on the outside of the segment. As shown in the Table 1, both woven ply and UD ply have a strong orthotropic electrical conductivity between the longitudinal direction and thickness direction, though a woven ply have an in-plane isotropic electrical conductivity. It is supposed that the FEM result of woven laminate shows a similar electrical voltage distribution to the result of UD laminate due to this strong orthotropic electrical conductivity in the thickness direction of woven laminate. As mentioned previously, the circular electrical current flow outside the electrodes is important for the identification of the delamination crack location or size using the electrical resistance change method. This electrical flow outside the charged segment results in electrical resistance changes, even when a delamination crack is located in an adjacent segment.

Figure 12 represents the experimentally measured electrical resistance change of UD laminate due to a delamination crack (Todoroki et al., 2002b). The abscissa shows the segment number of the inter-electrodes and the ordinate shows the measured electrical resistance changes. The experimental conditions are as follows: the length of the specimen is 270 mm, the width is 15 mm, the thickness is 1 mm, the stacking sequence is [0/90]s, the length of the electrode segment is 45 mm, and the number of the electrodes is 7. A delamination crack was created in

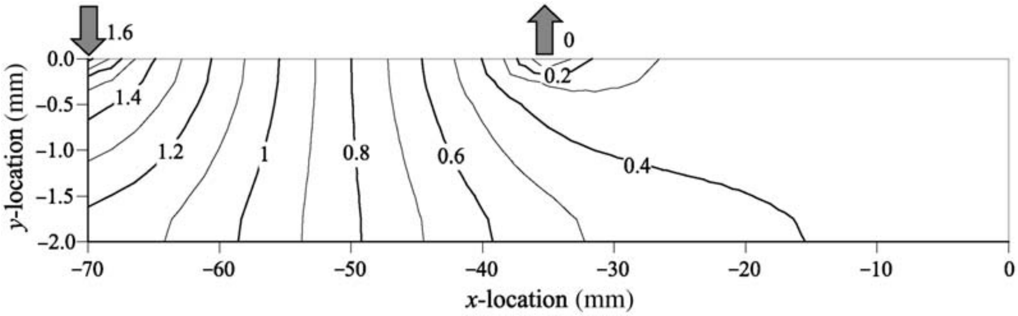

Figure 11. *Distribution of electrical voltage (V) of UD laminate (Todoroki et al., 2002a).*

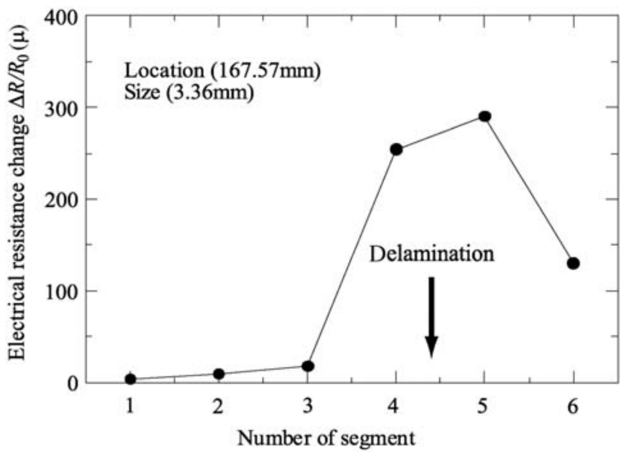

Figure 12. *Measured electrical resistance change of UD laminate (Todoroki and Tanaka 2002).*

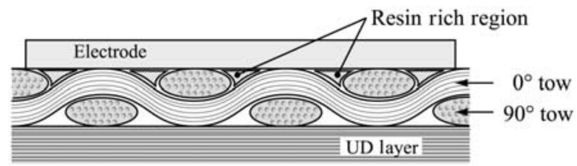

Figure 13. *Interface between the surface woven ply and the electrode.*

the fourth segment of the inter-electrodes. Similar to the typical results of woven laminate (Figure 6), the electrical resistance change can be observed not only on the segment of inter-electrodes where the delamination crack is created but also on the adjacent segment. Though the electrical properties and configuration of the specimen is different from the woven laminate, the obtained tendency of the distribution of electrical resistance change due to delamination crack is similar to the results of woven laminate (Figure 6). The difference in electrical properties and configuration of the specimen between UD laminate and woven laminate may affect the amplitude of the measured electrical resistance change ratio.

For the identification of the delamination crack location and size with the response surface method, the distribution of the electrical resistance change due to delamination crack is more important than the amplitude of electrical resistance change itself. This is because the response surface requires a variety in the distribution of the electrical resistance changes that correspond to the delamination crack location or size. From this point of view, it can be concluded that the difference in the electrical properties of surface woven plies and UD plies hardly affects the applicability of the electrical resistance change method and the tool for solving inverse problems using a response surface.

Though the surface woven ply is not entirely in electrical contact with the electrodes due to the crimp texture (see Figure 5(a)), it is confirmed that woven plies have good electrical contacts with the electrodes; the measured initial electrical resistances of each of the inter-electrodes are sufficiently small for the application of the electrical resistance change method, and the damage identification results show good performance. The reason why the crimp texture of surface woven ply achieves a good electrical contact with the electrodes is described as follows.

During the co-curing process of copper foil electrodes, surplus epoxy resin is oozed from tows that form the surface woven ply. The resin flows from the inner laminate toward the surface. The surplus epoxy resin usually forms a thin epoxy-rich layer, which impedes the path of electrical current flow between the surface ply and electrodes. The thin epoxy-rich layer acts as an insulator and increases the initial electrical resistances of each of the inter-electrodes of the specimen. In the woven laminate, however, the thin epoxy-rich layer between the surface layer and electrodes is barely there, due to the crimp texture of the surface layer. Instead of a continuous thin epoxy-rich layer, discrete resin rich regions are observed between the top of the wavy tow of the longitudinal direction and the tow of the transverse direction as shown in Figure 5(a). For clarity, the sectional illustration of woven laminate, which focused on the interface between the crimp texture of the surface woven ply and electrode, is shown in Figure 13. The figure is based on the sectional observation of Figure 5(a).

Most of the surplus epoxy resin may be condensed into each of the resin rich regions. As a result, a number of good electrical contact regions between woven surface ply and electrodes are achieved at the top of the wavy tow of the longitudinal and transverse directions, respectively. If the number in the electrical contact region is sufficient, a stable electrical contact between the surface woven layer and the electrodes is achieved.

CONCLUSIONS

In this study, the applicability of the electrical resistance change method for woven graphite/epoxy laminate was investigated. In order to confirm the applicability of the method, identification of the location and size of a delamination crack of a laminated graphite/epoxy beam type specimen whose surface layer is a woven ply, were performed using the electrical resistance change method. The influence of different electrical properties of surface woven plies on the electrical property of UD plies, and the influence of non-uniform contact between electrodes and surface woven ply was also investigated experimentally.

It is confirmed that the results of FEM analysis of electrical potential distribution and experimentally measured electrical resistance change are quite similar to the results of UD graphite/epoxy composites; the different electrical property of surface woven ply from UD ply is not critical for the application of the electrical resistance change method.

Although the surface woven ply does not ensure good electrical contact with the electrodes due to the crimp texture, the co-cured copper foil electrode is sufficiently reliable for the application of the electrical resistance change method; the partial resin rich regions due to the crimp texture of surface woven ply result in a number of good electrical contacts with the electrode at the top of the wavy tows.

As a result, the identification of the size and locations of delamination cracks using the electrical resistance change method can be carried out resulting in excellent performance. It is confirmed that the identification of delamination cracks with the electrical resistance change method is applicable.

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