# Electric Resistance Change Method for Identification of Embedded Delamination of CFRP Plates

Akira TODOROKI*, Yuuki TANAKA** and Yoshinobu SHIMAMURA*,
** Department Mechanics and Science, Tokyo Institute of Technology,*
*2-12-1, Ohokayama, Meguro, Tokyo, 1528552, Japan*
*** Graduate student of Tokyo Institute of Technology*

**Abstract**: In the present study, an electric resistance change method is employed for the identifications of location and size of the embedded delaminations. Indentation tests are conducted to make embedded delamination cracks in carbon fiber reinforced plastics (CFRP) plates. Two lines and eight columns of electrodes are mounted on the plate surface for measurements of electric resistance changes due to delamination. Response surface methodologies are applied to obtain the relation between the delaminations and measured electric resistance changes. The effect of temperature change is experimentally measured using the plate specimen. As a result, the method can successfully estimate the location and size of embedded delaminations, and the effect of the temperature change can be minimized using compensation for temperature change.

**Key Words**: *CFRP, Delamination, Electric Resistance Change, Smart Structure*

## 1.INTRODUCTION

Laminated composite plates fabricated by stacking unidirectional plies have superior specific mechanical properties to the mechanical properties of the conventional metallic materials. The laminated composite plates, however, have a weak point at the delamination resistance. The low delamination resistance causes a delamination crack by a slight impact such as a tool drop. Since the delamination crack is usually invisible or difficult to be inspected visually, the delamination causes low reliability for a primary structure of laminated composites. In order to improve the low reliability, an automatic detection system of a delamination crack in-service is required. A health monitoring system to detect the delamination crack is one of the desired approaches for a practical laminated composite structure.

An electric resistance change method is attempted to identify internal delamination cracks by authors [1,2]. The electric resistance change method does not require expensive instruments. Since the method adopts reinforcement carbon fiber as sensor for delamination detection, the method does not cause reduction of static strength or fatigue strength reduction, and the method is applicable to existing structures that have been fabricated without embedding sensors.

Authors have already investigated the applicability of the electric resistance change method for beam type specimens that have through the width delamination crack. The experimental results provided us that the method is applicable if it employs more than five electrodes on the specimen surface. The result also showed that the method is useful even for the quasi-isotropic laminates if the response surfaces [3] for the estimations are produced from the experimental data conducted with the quasi-isotropic laminates. For the practical components, however, the delamination crack is usually completely embedded cracks. The applicability of the method for the embedded delamination crack has not been confirmed yet. In the present study, therefore, the applicability of the electric resistance change method is experimentally investigated using a plate type specimen with an embedded delamination crack. The plate is a cross ply laminate that shows large electric resistance changes, and a modified electric bridge circuit is adopted here. The embedded delamination crack is made by a static indentation test method. In addition, an effect of high temperature was investigated experimentally.

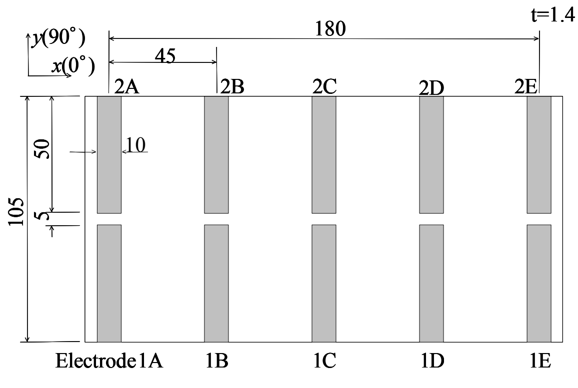



Fig. 1. Specimen configuration.

## 2. SPECIMENS AND EXPERIMENTAL METHOD

### 2.1 Specimens

The raw material used is unidirectional prepreg TR340M150ST produced by Mitsubishi Rayon Co. Limited. Laminates of staking sequence of $[0_2/90_2]$s were fabricated with a hot press process: The curing temperature is 130 °C, and the curing time is for one hour, and the pressure is 1.1MPa. The flat plate type specimens were cut from the cured laminates. The configuration is 180mm length and 105mm width as shown in Fig. 1. The thickness of the plate is about 1.4mm.

In order to measure the electric resistance change due to a delamination crack, multiple electrodes are mounted on the top surface of the specimen. Five electrodes are mounted in a column in 0-degree -fiber direction and the two electrodes are mounted in a line in 90-degree direction. The total number of electrodes is ten for each specimen. These electrodes are co-cured after mounting copper foil of the 0.02 mm thickness during fabrication process. In order to simulate the detections of delamination cracks from inside of the shell type structures, these electrodes are mounted on the specimen top surface. The coordinates of the specimen are defined as shown in Fig. 1.

**2.2 Delamination making**

In order to make an embedded delamination crack in the specimen, an indentation test method is adopted. The test method is schematically shown in Fig. 2. To obtain various size of delamination crack, four kinds of different size of supporting cylinders were prepared. The types of diameter of the cylinders are 10,15,30 and 50mm respectively. In general, when the low velocity impact is applied to a thin laminate, a larger delamination is made in the interlamina near the opposite surface [4]. In order to simulate the delaminations due to the low velocity impact, the indentation load is applied from the opposite surface of the specimen surface where the electrodes are mounted. For the indentation loading, a closed-loop hydrostatic material-testing machine produced by Shimazu Co. Limited is used. The loading was conducted under the deflection-controlled condition of the speed of 0.98mm/min.

**2.3 Measurement of electric resistance change**

Since the electric resistance due to a delamination changes only slightly, it is not easy to measure the change directly by using a resistance meter. For example, the electric resistance change due to the delamination for a bean type specimen was only 0.01Ω [1]. For the plate type specimen, electric current can flow outside of the delaminated area. This may cause smaller change of the electric resistance. In order to obtain large output signal, a modified resistance bridge circuit is developed as shown in Fig. 3. The difference from the bridge circuit of the conventional strain gage adopted for the plate type specimens is a connected electric resistance in Fig. 3. Before making a delamination crack, the electric resistance of the specimen is approximately 1Ω. Since the measurement method of the electric resistance change is completely the same as that of conventional strain gages, the conventional amplifier of the strain gage is adopted here. The amplifier of the conventional strain gage provides outputs of the electric resistance as "STRAIN". In the preset study, however, the output signal means electric resistance change, and does not mean specimen deformation. The relation between output signal STRAIN ε and the electric resistance change is shown as follows.

$$\varepsilon = \frac{\Delta R}{R k_s}, \qquad (1)$$

where $\varepsilon$ is the output signal STRAIN, $\Delta R$ is the electric resistance change due to delamination, $R$ is initial electric resistance, and $\boldsymbol{k_s}$ is an apparent gage factor of forty.

The apparent gage factor is not the real gage factor. The conventional amplifier that employs factor of two produces this apparent factor. The conventional amplifier usually employs electric resistances of 120Ω for the bridge circuit. The bridge circuit adopted here employs resistances of 22Ω. The difference causes the apparent gage factor. In the present study, the output signal STRAIN data are regarded as electric resistance change without translations.

Since the electric voltage of the bridge circuit is 2V, charged electric current is 87mA. To measure the eight electric resistance changes between electrodes (1A-1B, 1B-1C,., 2D-2E), the eight bridge circuits were prepared.

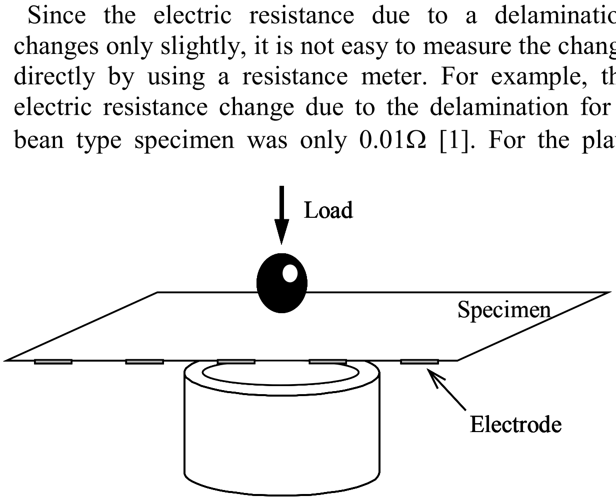



Fig. 2. Indentation loading.

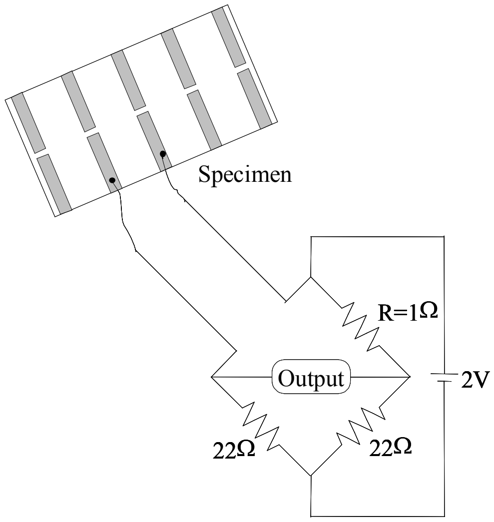



Fig.3. Bridge circuit.

For the measurement of the electric resistance change, a data-logger of UCAM10 produced by Kyowa-Dengyo Co. Limited was adopted here. After making the delamination, electric resistance is measured. After the electric resistance change measurement, the embedded delamination crack size and location was measured by using an ultrasonic C-scan AT5000 produced by Hitachi Construction Machinery Co. Limited.

## 3. APPLICATION OF RESPONSE SURFACES

### 3.1 Response surfaces

A tool for inverse problems is indispensable for estimations of the delamination location and size from measured electric resistance changes. In the present study, the relations between the measured electric resistance changes and delamination size and location are approximately obtained by response surfaces. The response surfaces are usually adopted for process control optimizations [3]. The method provides moderate approximation function between predictor variables and a response. The advantages for the employment of the response surface in the present study are as follows.

(1) Complicated fracture-process model is not necessary for the estimation of delamination. The statistical approach prevents the consideration of complicated fracture-process that caused by multiple matrix cracks and delamination transitions.
(2) Each unknown coefficients of the approximation function and fitness of the approximation function can be easily estimated by statistical methods.
(3) Minimum variance of the coefficient can be obtained by using design of experiments for the inverse problems.

For the simplicity, quadratic polynomials are usually adopted as approximation functions. The typical quadratic polynomial is shown as follows.

$$y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_j x_j^2 + \sum\sum_{i<j} \beta_{ij} x_i x_j \ , \qquad (2)$$

where k is total number of the predictor variables. In the case of two variables, Eq. (1) can be written as follows.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1^2 + \beta_4 x_2^2 + \beta_5 x_1 x_2 \ , \qquad (3)$$

Replacing $x_3=x_1^2$, $x_4=x_2^2$, $x_5=x_1x_2$, Eq. (3) can be transformed to a linear multiple regression.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 \ , \qquad (4)$$

Let the total number of experiments is n. The results of the total experiments can be written in a matrix form as follows.

$$\mathbf{Y} = \mathbf{X\beta} + \mathbf{e} \ , \qquad (5)$$

where **Y** is a response vector, **X** is a coordinate of the experiments, β is coefficient vector and **e** is the error vector.

The unbiased estimator **b** of the β is obtained as follows.

$$\mathbf{b} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{Y} , \qquad (6)$$

Eliminations of terms that worsen the regression by the decreasing method based on the F-statistics can give us the best approximation function. The lack of fit of the approximation function can be estimated by the adjusted multiple determination $R_{adj}^2$.

$$R_{adj}^2 = 1 - \frac{SSE/(n-k-1)}{SYY/(n-1)} ,$$

(7)

where $SS_E$ is the square sum of errors and $S_{yy}$ is the total sum of squares. See reference [3] for the explanation in detail.

From Eq.(6), it is easily recognized that the variance of the coefficients can be reduced by reducing $(\mathbf{X}^T\mathbf{X})^{-1}$. The reduction of $(\mathbf{X}^T\mathbf{X})^{-1}$ is the principle of design of experiments. In this process, the response **Y** is not required. In the present study, D-optimal design of experiments is adopted.

### 3.2 Application of response surfaces on inverse problem

Measurements of electric resistance change due to the delamination correspond to direct problems, and estimations of delamination size and location correspond to inverse problems. For an inverse problem, a large number of experiments or analyses are required. This causes high cost for solving an inverse problem. In order to reduce the cost, the present study adopts design of experiments for an inverse problem. The detail method is discussed in elsewhere [1].

(1) Do experiments at the selected patterns by the design of experiments for a direct problem. Measure the eight electric resistance changes between each electrode.
(2) Create the direct-problem response surface to predict resistance changes of the eight segments with the variables of delamination size and location using quadratic polynomials. This is abbreviated to direct-problem response surface (DRS).
(3) Create a large set of data of electric resistance changes with various delamination sizes and locations by calculating the DRS.
(4) Select a set for inverse-problem response surfaces using D-optimality (see ref.[1]) from the set comprising the calculated data and the experimental data. The selected data size must be threefold larger than the total number of experiments. The selected set must include the experimental data.
**(5)** Create the inverse-problem response surfaces to estimate delamination sizes and locations using quadratic polynomials. The response surfaces are

abbreviated to IRS (Inverse-problem Response Surface).

### 3.3. Levels

The delamination size and location are continuous amounts. These are rounded up to discrete levels to obtain robust estimations against experimental noise here.

In the present study, an exact estimate means that the estimated level is exactly the same as the measured level. The exact estimate performance means the ratio of the exact estimate against total number of estimates. Total number of levels of delamination location is eight that corresponds to the number of segments between the electrodes, and the total umber of levels of delamination size is three.

In the present study, the estimated laminate is quite thin. For the thin laminates, it is impossible and useless to estimate the delamination location in the thickness direction. From this reason, the delamination location of the thickness direction is completely ignored here, and the delamination plane transition due to matrix cracking is regarded as experimental errors.

## 4.EXPERIMENTAL RESULTS AND DISCUSSION

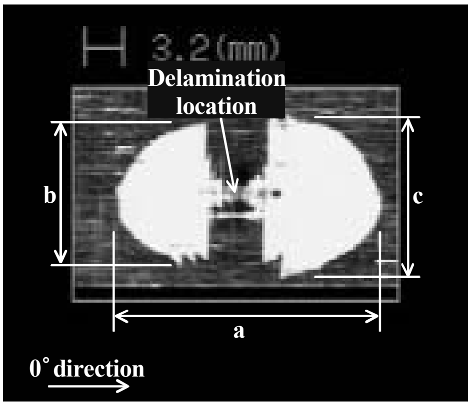
### 4.1. Delamination measurements

Typical ultrasonic C-scan image is shown in Fig. 4 (a). The delamination is a complete embedded crack as shown in Fig. 4 (a), and the delamination is similar to the practical delamination in practical components made by allow velocity impact. Since the stacking sequence is $[0_2/90_2]s$, the delamination is made in the interlamina between the 0-degree ply and the 90-degree ply, and provide the butterfly like configuration. The cross section of the delamination region is schematically shown in Fig. 4 (b). As shown in Fig. 4 (b), the larger delamination is created in the interlamina that locates near the specimen top surface where electrodes are mounted.

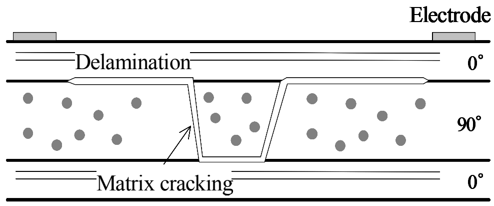
The delamination location is defined at the origin point of the butterfly like delamination configuration. The delamination size was decided from the C-scan image.

### 4.2. Electric resistance change

Typical examples of the measured electric resistance changes are shown in Fig. 5(a) and (b). Figure 5 (a) is the result of the case (A) that delamination exists between electrode number 2B and 2C. Figure 5 (b) is the result of the case (B) that the delamination exists between electrode columns (1A, 1B, 2A, 2B). The large change can be observed at the segment where delamination exists. In the case that the delamination exists between the electrode columns, the electric resistance change can be observed in both columns. As shown in Fig. 5, electric resistance change can be observed even in the segments where delamination does not exist. The strong orthotropic

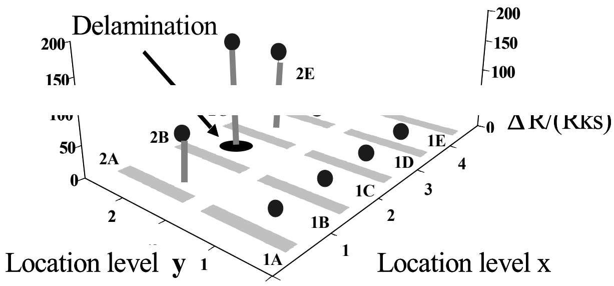



(a) C-Scan image

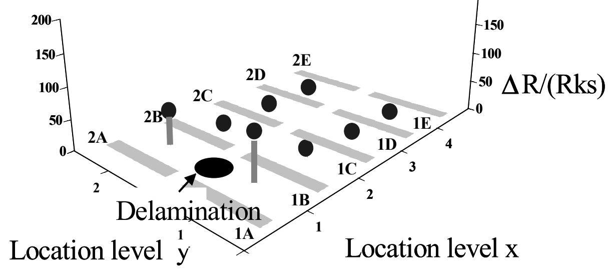



(b) Schematic image of cross section

Fig.4. Delamination configuration.




(a) Case A




(b) Case B

Fig. 5. Resistance ratio change.

electric resistance causes this electric resistance changes [5].

### 4.3. Estimation results

#### 4.3.1. Delamination size estimation

In order to decide the definition of delamination size, several definitions of delamination size are investigated. Since the delamination size corresponds to the electric resistance change, the definition that can provide the highest $R_{adj}^2$ of the IRS is employed here. The investigated definitions are (1) the maximum length in the 0-degree direction (definition "a" in Fig. 4), (2) the maximum length in the 90-degree direction (maximum value of "b" and "c" in Fig. 4), (3) the maximum value in all direction.

After the seventy-six experiments, the IRSs to estimate delamination size using the each definition of the delamination size are calculated. In this investigation, the design of experiments is not adopted for simplicity. The results are shown in Table 1. As shown in Table 1, there is little difference among the results of three definitions. For the conservative estimations, the maximum length in all direction is employed as the definition of the size. The delamination size $a$ is divided into three levels: level 1 $13 \le a \le 17\,(mm)$, level 2 $17 \le a \le 22\,(mm)$, level 3 $21 \le a \le 25\,(mm)$.

Table1. Mean error and $R_{adj}^2$ of each size level.

| Size level | Mean error [%] | $R_{adj}^2$ |
|---|---|---|
| (1) | 7.32 | 0.813 |
| (2) | 7.03 | 0.795 |
| (3) | 7.32 | 0.813 |

In order to obtain the IRS, eight DRSs that give estimations of electric resistance change in each segment were created from the sixty-four experimental data. The $R_{adj}^2$ of each DRS is, 0.671, 0.621, 0.628, 0.688, 0.747, 0.5930.619 and 0.739 respectively.

A large number of calculations were conducted using the DRSs by substitution of the cases of various delamination sizes and locations. In the x-coordinate direction, points from 20mm to 160 of spacing 5mm are selected and calculated. In the y-coordinate direction, points from 25mm to 80mm of spacing 5mm were selected and calculated. In the size coordinate, delamination size from 13mm to 25mm of spacing 0.5mm were selected and calculated. Total number of calculated data is approximately 8800 (see ref.[1]). 192 data were selected from the data using D-optimality. The selected data set includes sixty-four experimental data. After the classification of the size into the size-level, the IRS to estimate delamination size from the measured electric resistance change is produced. In the present study, the DRS and the IRS are all quadratic polynomials. After obtaining the IRS, the data used for the regression are substituted into the IRS to obtain an exact performance of the estimation for regressed data. In order to investigate the performance for the new data that are not used for regression, twelve data that are not used for regression are substituted into the IRS and the exact performance for the new data is obtained.

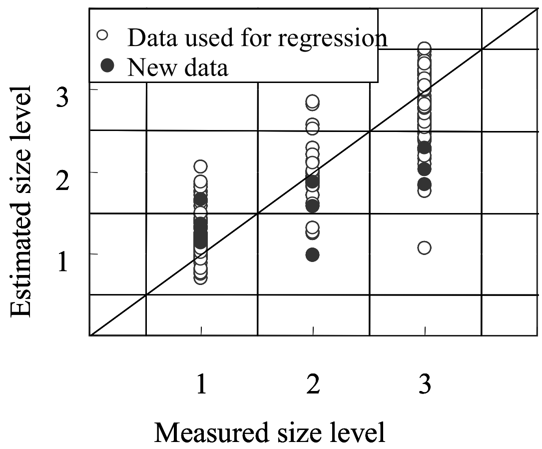



Fig.6. Estimated size by RS.

Table2. Estimation performance of size.

| | | |
|---|---|---|
| Number of experiments | | 64 |
| Number of selected data | | 192 (64 × 3) |
| $R_{adj}^2$ | | 0.753 |
| Exact performance | Used in RS | 81.3% |
| | Not used in RS | 58.3% |

The results of the $R_{adj}^2$ and the exact performances are shown in Table 2. The each estimated result is also shown in Fig. 6. In Fig. 6, the ordinate is the estimated size level, and the abscissa is the measured size level. The estimated size level is not shown as a discrete number to show the estimation distribution. The open symbols are the estimation results for the regressed data, and the solid symbols are the estimation results for the new data. The exact performance for the regressed data is 81.3 %, and the exact performance for the new data is 58.3 %. The most estimations locate at least within adjacent levels as shown in Fig. 6.

#### 4.3.2. Delamination location estimation

For the definition of an order of delamination location levels, several types can be considered. In the preset study, three types of the order of delamination location level are investigated to improve the $R_{adj}^2$. Three types of order of location levels are shown in Fig. 7. Type (a) has two kinds of levels of x-direction and y-direction. Type

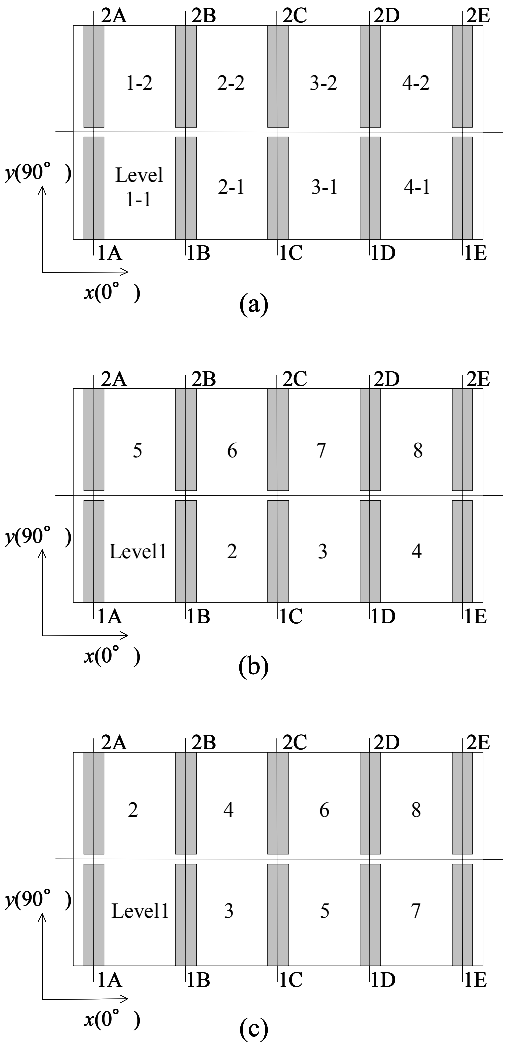



Fig.7. Types of location level.

Table3. Estimation performance of location.

| Definition of level | | (a) | (b) | (c) |
|---|---|---|---|---|
| Number of experiments | | 64 | | |
| Number of selected data | | 192 (64 × 3) | | |
| $R_{adj}^{2}$ | x | 0.920 | 0.864 | 0.913 |
| | y | 0.826 | | |
| Estimation performance | Used in RS | 86.5% | 59.2% | 63.0% |
| | Not used in RS | 66.7% | 58.3% | 33.3% |

(b) and (c) has one kind of level of eight levels. They are different order of the level. For the type (a), two IRSs are obtained to estimate the location level. For other types, an IRS was obtained to estimate the location level.

Similarly to the estimations of size, 192 data are selected and IRSs are obtained. Quadratic polynomials

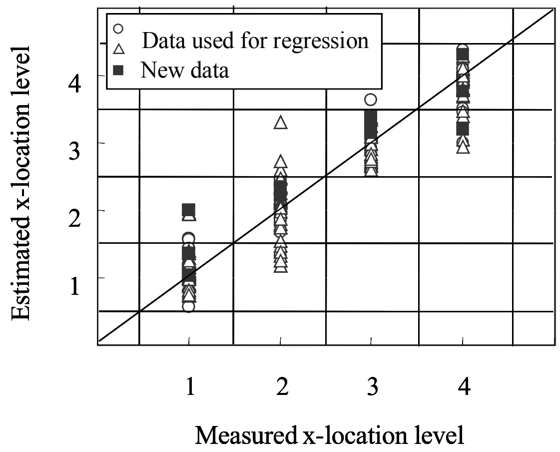



Fig.8 Estimated location level of x coordinate

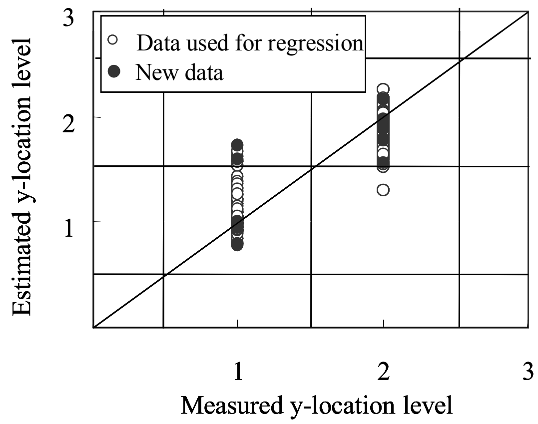



Fig.9 Estimated location level of y-coordinate

are employed here. The results of $R_{adj}^{2}$ of the all types are shown in Table 3. From the results in Table 3, type (a) gives the highest $R_{adj}^{2}$. The exact performance for the regressed data is 86.5% and 66.7% for the new data. This is caused by the continuity of the physical meaning of location level. For the type (b) and (c), the adjacent level is not always adjacent in the practical location in the specimen plate. In addition, fitness of the approximation functions $R_{adj}^{2}$ is improved for the type (a) as shown in Table 3. The improvement of the fitness also plays an important role for the better performance. From the results, the type (a) is employed here.

The each estimated result of the type (a) is shown in Fig. 8 and 9. The ordinate is estimated level and the abscissa is the measured level. As the same as Fig. 6, the ordinate is not discrete number. The open and solid symbols are the same as those of Fig.6.

Practically, we can admit small estimation error. The practical performance is defined as that the estimation misjudgments of location level to the adjacent levels is regarded as a practically tolerable estimation. The practical performance is up to 99.5% for the regressed

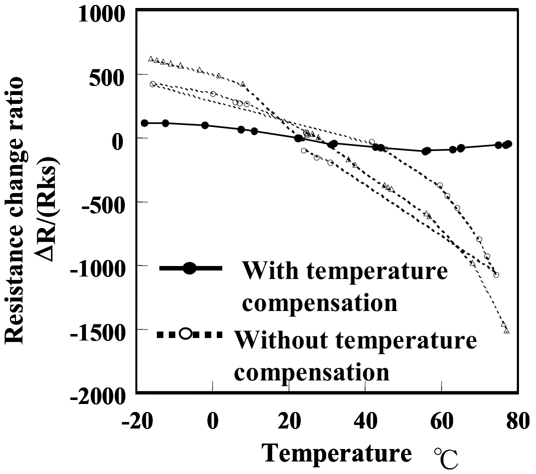



Fig.10. Effect of temperature on resistance change.

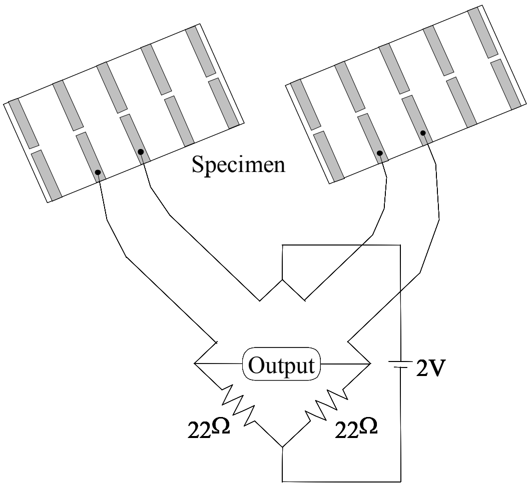



Fig.11. Temperature compensation bridge circuit.

data and the 100% for the new data. We can conclude that the embedded delaminations for the cross-ply laminates can be estimated by using the electric resistance change method.

### 4.3.3. Effect of temperature change

For the practical usage, environmental temperature change cannot be ignored. The temperature change may cause electric resistance change as the same as the conventional strain gage. The temperature change effect was experimentally investigated. Electric resistance change was measured under the various temperature conditions using a furnace and a refrigerator from –20 $^{o}$C to 80 $^{o}$C. Initializing of the electric resistance was conducted at 25$^{o}$C. The temperature was measured with a thermo couple. Typical result is shown as dotted curves in Fig.10. As the increase of the temperature, the electric resistance decreases, and the electric resistance increases as the decrease of the temperature. Hysterisis loop can be observed. When the temperature returns to the initial temperature, the resistance change approaches almost zero. While the maximum measured change due to the delamination is approximately $\Delta R/(Rk_s)$=300, the change due to the temperature change is up to 1500. Although the reason why the resistance changes due to the temperature change is not clear, the effect of the temperature change is clearly significant. From the results, we attempted a temperature compensation circuit as the same as that for a conventional strain gage.

The temperature compensated bridge circuit is shown in Fig. 11. Two specimens are connected similarly to a conventional two-gage method. The results are shown as a solid curve in Fig.10. As shown in Fig.10, the temperature change effect can drastically reduced, and hysterisis loop cannot be observed. From this result, the effect of the temperature change can be compensated using the conventional two-gage method.

On the basis of these results, we can conclude that the electric resistance change method is very effective for the estimation of embedded delamination size and location. Further researches are indispensable for the application of the electric resistance method to the practical components of laminated composites. Especially, the effect of stacking sequences and thickness must be clarified in our future work.

## 5. CONCLUSIONS

The electric resistance change method is applied to the plate type specimen made of a cross-ply laminate that has embedded delamination crack to estimate delamination size and location. The results obtained are as follows.

(1) The electric resistance change method is experimentally shown to be applicable for embedded delamination crack estimation.
(2) High performance estimations can be obtained by the response surface for the inverse problems.
(3) The electric resistance method is affected by the temperature change. The effect can be reduced using temperature compensation method.

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