Delamination Monitoring Analysis of CFRP Structures using Multi-Probe Electrical Method

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ABSTRACT: Since a delamination crack is invisible or difficult to detect visually, the delamination causes low reliability of Carbon-Fiber-Reinforced-Polymer (CFRP) for primary structures. To improve the low reliability, smart systems of delamination identifications in-service are desired. Recently, many researchers have employed an Electrical Resistance Change Method (ERCM) to detect the internal damages of CFRP laminates. The ERCM does not require expensive instruments. Author's group has already experimentally investigated the applicability of the ERCM for strain monitoring, delamination crack monitoring and matrix crack monitoring. In the present article, therefore, these results performed in the previous papers are briefly explained. These successful results enable us to monitor a lot of information of the CFRP laminates by means of the electrical resistance changes in many applications, although a lot of electrodes are required to be mounted. To reduce the number of electrodes, a new electrical potential method for the CFRP plate is proposed here, which enables us to reduce the number of electrodes. The present article compared the new method to the method proposed by Anderson. FEM analyses are performed to confirm the applicability of the new method.

Key Words: composites, CFRP, electrical resistance, delamination, monitoring.

INTRODUCTION

CARBON-FIBER-REINFORCED-POLYMER (CFRP) laminates are applied to many aerospace structures. Strain monitoring of the CFRP structures is very important to confirm integrities of the processing, as well as vibration monitoring and applied stress monitoring to know the condition of the external loading. Since the delamination is invisible or difficult to detect by visually, the delamination causes low reliability for primary structures. To improve the low reliability, smart systems of delamination identifications in-service are desired. A structural health monitoring system to monitor the delaminations is one of the desired approaches. A lot of papers have been investigated the delamination monitoring (Elvin et al., 1999; Krishnamurthy et al., 1999; Bois, 2004; Hu et al., 2006; Takeda et al., 2007)

Recently, an Electrical Resistance Change Method (ERCM) is employed to detect the internal damages of CFRP laminates by many researchers (Shulte and Baron, 1989; Chen and Chung, 1993; Kaddoour et al., 1994; Wang and Chung, 1997; Irving and Thiagarajan, 1998; Abryn et al., 1999; Seo and Lee, 1999; Weber and Schwartz, 2001; Park et al., 2002; Ogi and Takao, 2005). The ERCM does not require expensive instruments. Since the method adopts reinforcement carbon fibers themselves as sensors, this method does not cause reduction of strength, and it is applicable to existing CFRP structures. Although some researchers have published papers to monitor applied strain of the CFRP structures by means of electrical resistance change, they did not find the way to locate the damaged area for the practical CFRP laminates.

Author's group has already experimentally investigated the applicability of the ERCM for monitoring delamination crack and matrix cracks using a two-probe method (Todoroki et al., 1995; Todoroki, 2001; Todoroki et al., 2002a; Todoroki et al., 2002b; Todoroki et al., 2004a; Todoroki and Yoshida, 2004; Todoroki et al., 2004c; Shimamura et al., 2005; Omagari et al., 2005; Todoroki et al., 2006). Measurements of applied strain by means of the ERCM have been experimentally confirmed using a four-probe method.

In the present article, therefore, these results performed in the previous papers are briefly explained. These successful results enable us to monitor various information of the target CFRP laminate by means of the electrical resistance changes in many applications. Anderson et al. (2003) have proposed a new electrical potential change method using circularly placed multiple electrodes on the outer circumferential surface of the

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target CFRP plate. Ueda proposed a two-way electrical potential change method for CFRP beams (Ueda and Todoroki, 2006) using multi-probe electrical method. The present article deals with these two new electrical potential change methods. In the present article, the two-way electrical potential method is modified for a CFRP plate. FEM analyses were performed and the monitoring performances of the two methods of the multi-probe are compared with each other here.

PRINCIPLE OF ERCM FOR CFRP

Carbon fibers have high electric conductivity, and the epoxy matrix has insulation resistance. For ideal CFRP 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 carbon fiber. On the other hand, the electric conductance of transverse direction vanishes for an ideal condition.

A practical carbon fiber in a unidirectional ply is serpentine. The curved carbon fiber contacts with each other, and that makes a large carbon-fiber network in a ply. The contact-network brings nonzero electric conductance even in the transverse direction. In the same way, the fiber-network produces nonzero 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.

The electric conductance of the thickness direction (σ_t) is usually lower than the electric conductance of transverse direction (σ_{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 σ_t is smaller than the σ_{90} for normal laminated composites. The production process of prepreg causes the smaller electric conductivity in the thickness direction. Several fiber bundles are usually pressed by means of rollers to make unidirectional prepreg. This causes large number of fiber contact in the transverse direction but the roller press reduces the warping of fiber bundles in the thickness direction. This brings smaller electrical conductance in the thickness direction. The contact between plies causes no-zero electric conductance in the thickness direction. Thus the σ_{90} is usually larger than the σ_t. When a delamination crack or matrix crack grows in the matrix, the crack breaks the fiber-contact-network between plies. The breakage of the contact network causes increase of the electrical resistance of CFRP composites. Therefore, the delamination crack or the matrix crack can be detected by the electrical resistance change of CFRP composite laminates.

PREVIOUS RESULTS

Strain Monitoring

Carbon fibers have piezoresistivity like an electrical resistance strain gage. When the carbon fiber is under tension strain, the electrical resistance of the carbon fiber increases proportionally to the applied strain. We can utilize the piezoresistivity of the carbon fiber in the target CFRP as a sensor of applied strain without additional sensors.

An experiment was performed using a single-ply CFRP specimen (Todoroki and Yoshida, 2004). Using silver paste after polishing specimen surface with sand paper, four electrodes were made on the single surface of a rectangular CFRP specimen. Tensile strain is applied to the specimen, and the electrical resistance change was measured by means of the four-probe method with a LCR meter. As a result, the electrical resistance proportionally increases with the increase of applied tensile strain, and the gage factor is 2.6, which is almost the same as a conventional strain gage. Although the gage factor is slightly different from the value of 2, the gage factor of laminated CFRP is also positive using the four-probe method (Todoroki and Yoshida, 2004).

Damage Monitoring

Fiber breakages cause simply decrease of electric conductive cross sectional area. Schulte and Baron (1989) have already measured the electrical resistance change due to the fiber breakages. They showed that the electrical resistance increased over approximately 3000 μ strain due to the fiber breakages started from the weakest fibers.

Matrix cracking also causes the increase of electrical resistance. Author's group has already performed monitoring of the matrix cracks by means of the residual electrical resistance changes (Omagari et al., 2005; Todoroki et al., 2006). A cross-ply CFRP plate was fabricated and specimens of $[0/90/0]_T$ were made from the cross-ply CFRP plate. The four-probe method is adopted to measure the electrical resistance change; electric current was applied to the fiber direction of the surface ply.

Observations from specimen side revealed that the matrix cracking started from the applied maximum strain of 0.0025. The experimental results show that the residual electrical resistance at unloading is elevated just after the start of the matrix cracking.

For delamination monitoring, location and dimension of a delamination crack is necessary. For this objective, multiple electrodes are mounted on the single surface of the specimen as shown in Figure 1. Electrical resistance changes between adjacent electrodes were measured. From a large number of experiments, a relationship

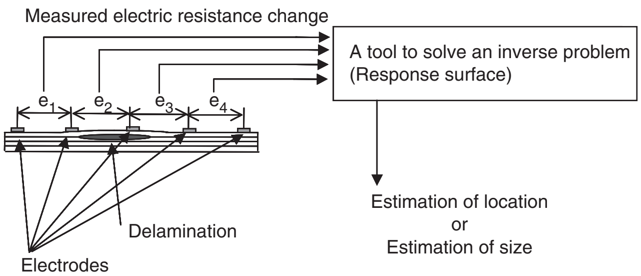

Figure 1. *Delamination monitoring system of ECRM.*

between measured electrical resistances and delamination locations or dimensions were obtained by means of response surfaces with the least square errors method. Once the relationship is obtained, the response surfaces estimate delamination location and dimension from the measured electrical resistance changes.

The experimental results showed that the monitoring system gave excellent estimations with small errors. Location error band was only 15 mm and dimension error band is 5 mm (Todoroki et al., 2002b). The system monitored practical delamination cracks that were made by means of indentation method in the target CFRP plates. These researches used a two-probe method. A four-probe method was also tried to monitor the delamination crack location and dimension (Todoroki et al., 2004b). The results told that the multi-probe method had large estimation errors when a delamination crack located near the middle of the target CFRP plate. Ueda and Todoroki have demonstrated a new multi-probe that uses dual electric current charges to improve the large error at the middle of the target CFRP beams (Ueda and Todoroki, 2006).

Anderson et al. (2003) have proposed a new multi-probe method that all of electrodes are placed circularly on the plate surface near the edges.

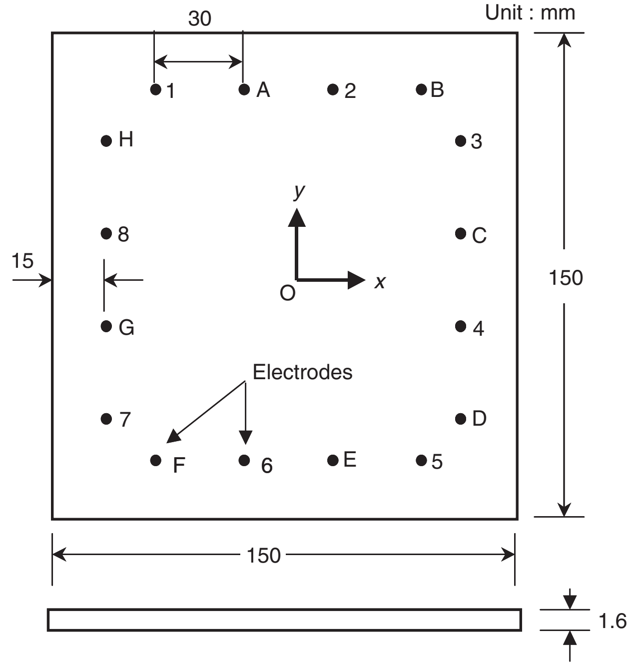

Figure 2. *Circular array method.*

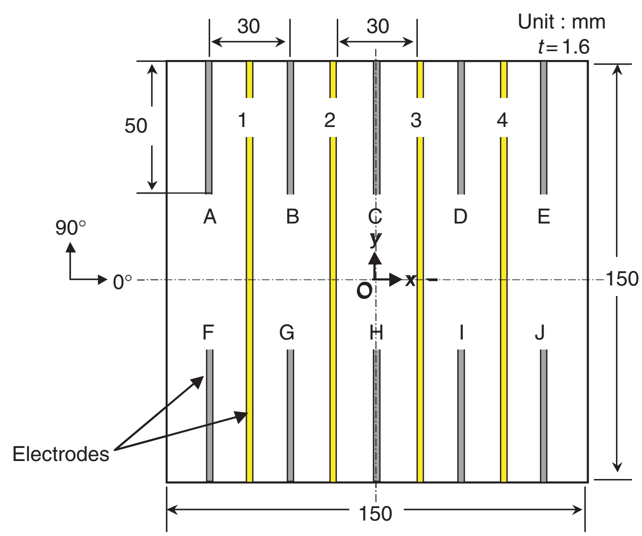

Figure 3. *Matrix array method.*

FEM ANALYSIS

FEM Model

In the present study, a modified two-way method (matrix array method) for CFRP plate and Anderson's method (circular array method) are investigated. Commercially available FEM code ANSYS ver5.6 is used for 3D FEM analyses. For both analyses, eight-node-octahedron elements of $2\,mm \times 2\,mm \times 0.1\,mm$ size are used. For the analysis of the circular array method, all electrodes are placed on the plate surface along with the edges as shown in Figure 2. Specimen configuration and dimensions are also shown in Figure 2. For the analysis of the matrix array method, all electrodes are placed on the specimen surface as shown in Figure 3 with specimen configuration and dimensions.

For each method, stacking sequence of the laminate is [0/45/−45/90]s. The x-coordinate is set to 0° of the fiber direction of the surface ply here. For the circular array method, the couples of numbered electrodes are used for applying electric current and all other electrodes named as A, B, C, . . . , H are used to measure the electric voltage changes. Therefore, 28 cases of applying electric current exist in the circular array method.

On the other hand, there are only two cases for the matrix array method: the two cases are case 1–3 and case 2–4 for applying electric current. Note that the two application patterns of the electric current are crossing with each other. The matrix array method requires placements of multiple electrode probes on the CFRP plate surface like a matrix array. All probes from A to J are used for measurements of voltage changes, and electrodes from 1 to 4 are used for applying electric current. Each application of electric current provides 10 V results at all probes. Total 20 results for each delamination case are obtained. From the obtained results, a relationship between the voltage changes and delamination location or size is calculated using the response surface. As shown in the reference of Ueda and Todoroki (2006), two cases of electric current charge are enough for monitoring delamination location and dimension in a beam type specimen.

For the FEM analysis, conductivity of CFRP are $\sigma_0 = 32{,}000$ S, $\sigma_{90} = 9.6$ S, and $\sigma_t = 8.3$ S. These values are obtained in the reference (Ueda and Todoroki, 2006). A rectangular delamination is adopted in the present study. All FEM nodes at the interlamina are doubly defined and jointed between the upper ply and the lower ply. This joint is released to represent no electrical current in the thickness direction at the delamination area. In the present study, dimension of the delamination is set to from 12 to 48 mm. The center of the delamination locates in the area from −50 to 50 mm in the x and y coordinates. Electric current of 0.1 A is applied at the cathode and the voltage of the anode is set to 0 V here.

Response Surface Method

To obtain the relationship between the calculated voltage change and the delamination location or the delamination dimension, responses surfaces of quadratic polynomials are adopted in the present study as the same as previous studies (Todoroki, 2001; Todoroki et al., 2002a; Todoroki et al., 2002b; Todoroki et al., 2004a; Todoroki et al., 2004c). The response surface has advantages of small requirement of computational resource and availability of statistical evaluations. The response surface is similar to an artificial neural network of a multi-layer back propagation type. For the circular array method, 4488 FEM analyses are performed and 922 FEM analyses are conduced for the matrix array method. The difference of the number of FEM analyses comes from the number of unknown coefficients in the each response surface. All these computed results are normalized using the norm of the set of voltage changes. The least square errors method is adopted to obtain the unknown coefficients of the quadratic polynomials.

RESULTS AND DISCUSSION

Circular Array Method

Figures 4 and 5 shows the estimation results of the delamination location of the circular array method.

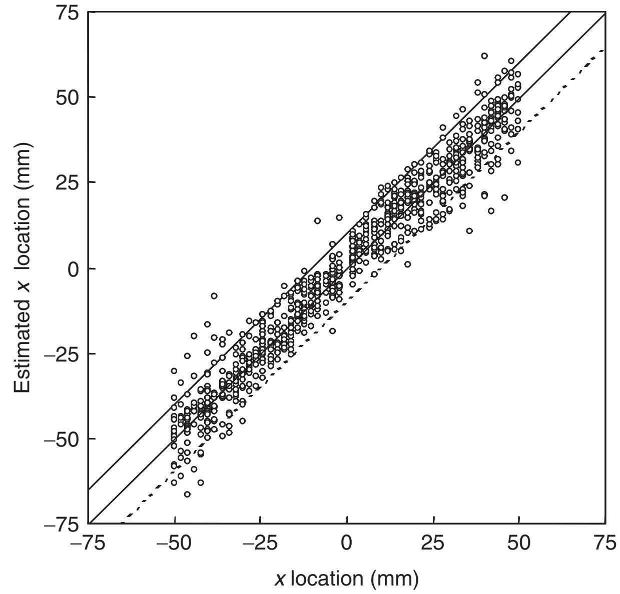

Figure 4. *Estimations of x-location for the circular array method.*

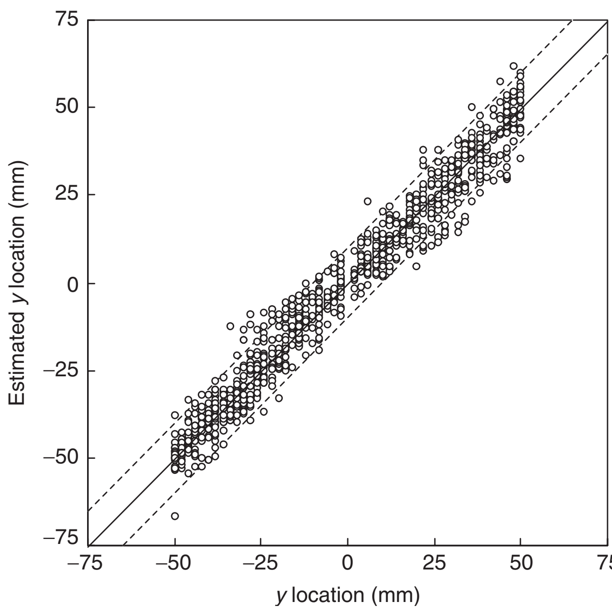

Figure 5. *Estimation s of y-location for the circular array method.*

The abscissa is the given location and the ordinate is estimated location. The plots on the diagonal line shows the estimations are exact. These figures show that they have large estimation error in the circular error method. The adjusted coefficient of determination R^2_{adj} of the x-location is 0.87 and that of y-location is 0.91. The values are not poor but there are large errors as shown in Figures 4 and 5 in some points.

Figure 6 shows the square sum of errors of the circular array method. The abscissa is the x-location of the delamination crack and the ordinate is the y-location of the delamination crack. The gray scale image plotted in the square area is the square sum error of x-location and y-location. The circles denote location of points that

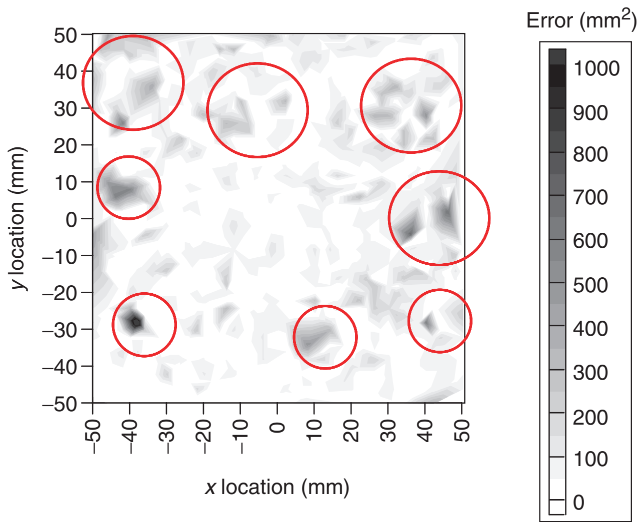

Figure 6. *Square sum of errors of delamination location of the circular array method. Circles denotes large error points.*

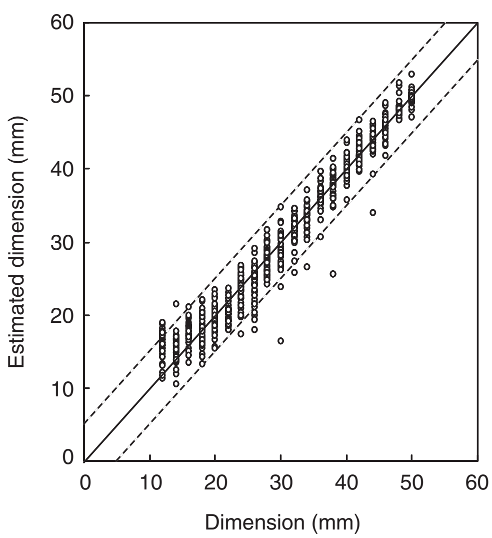

Figure 7. *Estimations of dimension for the circular array method.*

have large errors. These circles locate in the region near the edges of the square plate. This indicates that a large error of delamination location exists when the delamination crack locates near the edge of the square plate. This is because voltage change cannot be observed in the most of electrodes far from the delamination crack.

The estimations of delamination dimension are shown in Figure 7. The abscissa is the given delamination dimension of the square delamination crack and the ordinate is the estimated delamination dimension. The adjusted coefficient of determination R^2_{adj} is 0.94. The R^2_{adj} denotes the estimation is not poor for the delamination dimension. There are, however, some large error points in Figure 7.

Figure 8 shows the estimation error of each location. The abscissa is the x-location and the ordinate is the y-location. The gray scale image shows the absolute

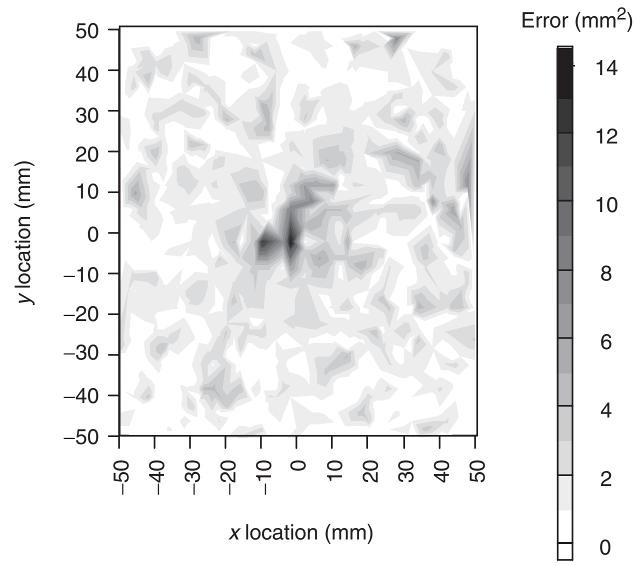

Figure 8. *Errors of delamination dimensions of the circular array method.*

error of the delamination dimension. The figure shows that there is large error in the middle of the square plate. This is because the voltage change is very small when a delamination locates in the middle of the square plate. When the delamination locates in the middle of the square plate, there is small change in voltage. Shape of distribution of the normalized voltage changes is important for the location monitoring. This, therefore, enables the monitoring of location of the delamination. The monitoring of delamination dimension, however, requires the norm of the voltage change data. When the norm is small, the error of the estimation becomes significant.

Matrix Array Method

Figures 9 and 10 show the results of the delamination location of the matrix array method. The abscissa is the given delamination location and the ordinate is the estimated delamination location using the response surfaces.

These figures show that the all data are plotted on the diagonal lines. The dashed lines are the error band of 10 mm. The error band is decided from the experimental results of the reference (Todoroki et al., 2002b). That has error band of 15 mm. Since this study uses FEM analyses, the error band is set to 10 mm instead. All data locate within these error bands. This means that the estimations of the delamination location are very exact.

The estimation result of the delamination dimension is shown in Figure 11. The abscissa is the given delamination dimension of a square delamination crack and the ordinate is the estimated dimension of the square delamination crack. Plots on the diagonal line mean that the estimations are quite exact. The dashed lines show

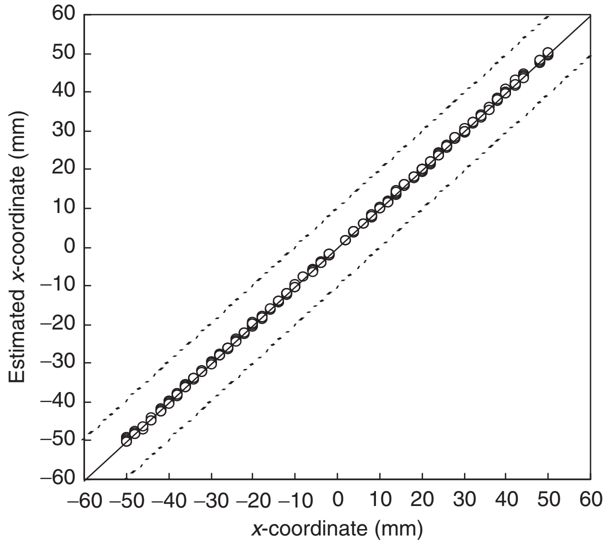

Figure 9. *Estimations of x-location for the matrix array method.*

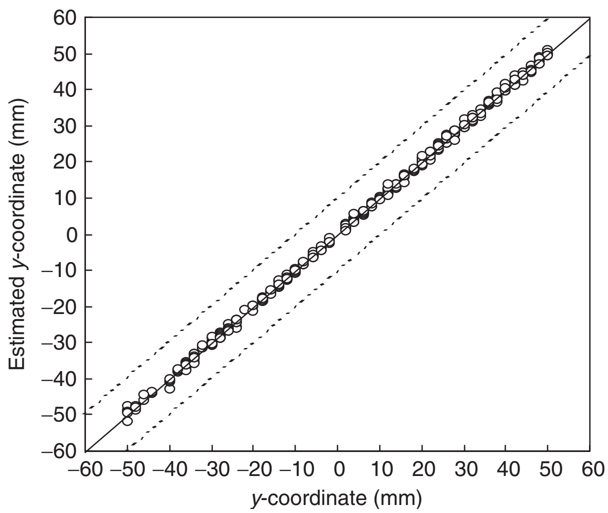

Figure 10. *Estimations of y-location for the matrix array method.*

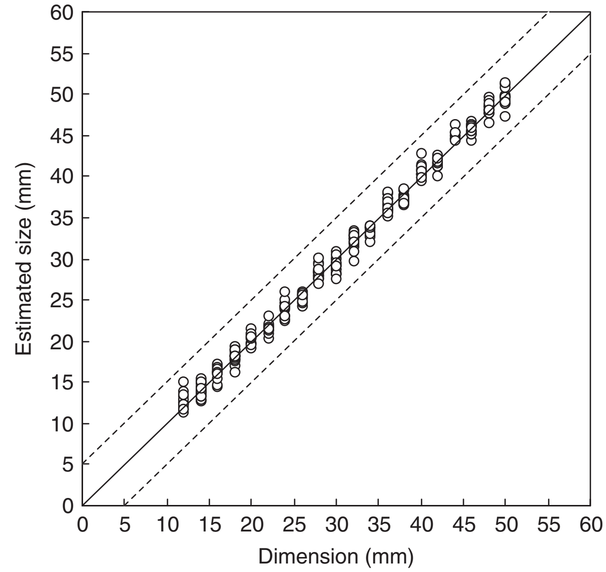

Figure 11. *Estimation s of dimension for the matrix array method.*

the error band of 5 mm. The error band is also decided from the experimental results of the reference (Todoroki et al., 2002b). Since the minimum delamination dimension that can be experientially made is approximately 5 mm, the error band is set to 5 mm here. Figure 11 shows that all of the plots locate within the error bands. This means that the matrix array method has excellent estimation performance.

DISCUSSION

These 3D FEM results show that the matrix array method has excellent performance for monitoring of delaminations but the circular array method has poor performance for monitoring of delaminations.

Anderson et al. (2003). have shown that the circular array method has high performance of monitoring damages of CFRP plates In the paper, they used 2D FEM analyses of isotropic square plate because they dealt with quasi-isotropic CFRP laminates. They simulated the damage as decrease of electric conductance of the FEM elements.

In a practical CFRP structures, a small delamination crack accompanies with a matrix cracking but not with fiber breakages. This means that the small delamination crack does not follow decrease of electric conductance in the fiber direction. Although the matrix cracking causes decrease of the electric conductivity in the transverse direction, the electric current in the transverse direction is very small compared to the electric current in the fiber direction. This indicates that the matrix cracking causes small difference and the difference can be measured when the spacing of the electrodes are smaller than approximately 30 mm as shown in the reference (Todoroki et al., 2002b). The circular array method used larger spacing between the electrodes to apply electric current and to measure electric voltage changes. This large spacing between electrodes of the circular array method causes larger estimation errors even though the number of available data is larger than that of the matrix array method.

The decrease of the electrical conductivity in the FEM analyses implies that the fiber breakages of the CFRP plate. Fiber breakages follow the significant decrease of the electric conductivity. These fiber breakages are caused by means of a large energy impact such as foreign objects like bullets. These damages are usually caused in service flights and are easily visible damages. We do not have to monitor these fiber breakages in high precision.

The matrix array method requires smaller number of FEM analyses compared to that of the circular array method. The matrix array method requires only two ways of electric current on the other hand the circular array method requires four ways. This means the electric circuit of the matrix method is smaller than the circular array method.

The estimation performance of the circular method is less effective than that of the matrix array method: the estimations have large errors in the edges of the square for the location monitoring and have large errors in the middle of the square for the dimension monitoring. This large error comes from the large spacing of the electrodes for the circular array method. We have to mount electrodes with smaller spacing than 45 mm as indicated in the reference (Todoroki et al., 2005) although the limit spacing changes with the fiber volume fraction.

When the estimation error of the circular array method must be reduced, the electrodes must be placed in the middle of the CFRP plate. That placement decreases the advantage of the circular array method.

The matrix array method, however, is affected by the severe impact following fiber breakages. The placement of large number of electrodes on the surface of the CFRP plate may follow significant damage of the electrodes at the severe impact by chance at higher probability than the circular array method. Although the matrix array method adopts the four-probe method to measure the electrical resistance change, the four-probe method is affected by the damage of the electric contact at the electrodes for the orthotropic materials like CFRP (Todoroki and Yoshida, 2005). This is a drawback of the matrix array method. The outer electrodes, however, can be used to measure the large-scale electrical resistance changes even for the matrix array method like the circular array method. This measurement enables us to know the fiber breakages with large spacing electrodes. This mixed type of the monitoring method may be the best one for the practical use.

CONCLUDING REMARKS

The present article deals with the electrical resistance change method for monitoring of delamination of CFRP structures. First of all, the results of the previous studies are briefly mentioned. A newly developed matrix array of electrodes to measure electrical voltage changes with two-way electrical application is mentioned in the present study and the estimation performance is compared to the results of circular array method that is proposed by Anderson et al. 3D FEM analyses were conducted and the estimations of the delamination crack location and dimension are performed by means of the response surfaces of quadratic polynomials. As a result, the matrix array method has excellent performance of monitoring of delamination and the circular array method is appropriate to monitor the fiber breakages.

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