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Monitoring delamination of laminated CFRP using the electric potential change method: Application of normalization method and the effect of the shape of a delamination crack

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Abstract—Monitoring for delamination is indispensable for carbon fiber reinforced plastic (CFRP) structures. The authors previously reported delamination monitoring using the electric resistance change method; which provides excellent estimations. However, the method requires complicated electric circuits and uses a two-probe method, in which electric resistance change at the electrodes has a significant effect. To overcome these problems, the present study adopted an electric potential change method. Since this method had poor estimation performance in our previous study, here we employed a normalization method that showed significant improvements in the estimations using the electric resistance change method. Moreover, the effect on the estimation performance of delamination with a zigzag shape caused by matrix cracking is investigated using FEM analyses. In the results, the electric potential change method shows good performance of estimations for delaminations located near the edges of the specimen but poor performance near the middle of the specimen. The zigzag shape has a large effect on the performance of the estimations when the delamination crack locates near the middle of the specimen. FEM analysis shows that a small electric current through the thickness direction near the middle of the specimen causes large effects on estimation performance.

Keywords: Delamination; smart structure; health monitoring; response surface; inverse problem; electric potential; matrix crack.

1. INTRODUCTION

Carbon fiber reinforced plastic (CFRP) laminate is widely used in aerospace structures because of its superior mechanical properties. However, CFRP laminates

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have delamination easily induced by a slight impact. Delamination causes large reductions in strength and stiffness of the CFRP laminate, bringing deterioration of the reliability of the CFRP structure. Therefore, monitoring for delamination is indispensable to maintain the reliability of the CFRP structure.

Damage detection and strain measuring methods for a CFRP structure using its electrical conductivity have been proposed by many researchers [1–10]. Carbon fibers, which are electroconductive materials, make an electrical network by contacting each other; after delamination, the electrical network of carbon fibers is partially broken causing a change in the electric potential distribution. The delamination location and size are estimated by means of the electric potential change as an inverse problem. In this method, CFRP laminates are themselves used as a sensor. Electrodes are mounted on the surface to measure the electric potential at the electrodes. The applicability of this method has so far been shown only for conventional metallic materials [11–13].

This method has some advantages for a CFRP structure. First, because no sensor is embedded in the CFRP laminate it never reduces the strength or stiffness. Second, the method is easily applied at low cost just by mounting electrodes on the surface of a CFRP structure. This enables easy repairs when a system malfunctions. The authors have already employed an electric resistance change method (two-probe method) for identification of delamination; the applicability of the method was investigated analytically and experimentally using beam-type specimens and plate-type specimens [14–20].

Studies with the two-probe method have shown the effectiveness of the electric resistance change method for monitoring delamination of CFRP laminates by measuring the electric resistance change between adjacent electrodes [14]. On the specimen surface, multiple electrodes were mounted by co-cured copper foil to measure the electric resistance changes. A response surface was employed as a solver of the inverse problem instead of an artificial neural network. The method successfully identified location and size of a delamination. The data-normalization method provided significant improvement in estimation performance [20]. This method, however, requires a lot of switching circuits to apply the electric current between all of the adjacent electrodes, and the accuracy of the estimation is strongly affected by the condition of the electric contacts between the copper electrodes and carbon fibers. To overcome the problem, the electric potential change method is introduced. In this method, the electric potentials at multiple points are measured by charging electric current at the two electrodes: two electrodes are made at each end of a beam type specimen. Our earlier studies showed that this electric potential change method provides poor performance of estimation analytically [15] and experimentally [16] when compared with the results of the electric resistance change method. The data-normalization method, however, is not applied to the electric potential change method; its applicability has not yet been examined.

It is expensive obtaining all the data from experiments to make response surfaces; hence FEM analyses should be conducted instead of experiments. Although the actual delamination cracks are generally zigzag shapes due to matrix cracking, it is impossible to make a response surface after considering all the shapes of the delaminations even for FEM analyses. Therefore, if the electric potential changes could be calculated using the FEM analyses without considering the zigzag cracks, it would greatly help to reduce the computational costs. That is, practical cracks with zigzag shapes can be estimated using the response surfaces made from the FEM analyses of straight delaminations. In an earlier study of ours, the difference of the electric resistance change between a straight delamination and a zigzag shape crack was demonstrated [17], clarifying that the difference is small and that it did not affect the estimation performance.

In this paper, the effectiveness of the data-normalization method for the electric potential change method is examined using FEM analyses of a cross-ply laminate. For its practical application, zigzag shape cracks are estimated using response surfaces made from the FEM analyses of straight delaminations. The influence on the estimation performance from the difference in the crack shape is examined in detail.

2. ANALYTICAL METHOD

2.1. Analytical model

In this study, FEM analyses are performed with the commercially available FEM code ANSYS. The specimen is a two-dimensional beam having a configuration of 200 mm length and 1 mm thickness as shown in Fig. 1. The stacking sequence of the specimen is [0/90]s and the thickness of a ply approximately 0.25 mm. Seven electrodes, of 5 mm width, are mounted on the one surface of the specimen spaced at 30 mm. It is assumed that electrodes are mounted only on the inside surface of CFRP structures. The nodes are coupled to be same electric potential at each electrode in the FEM analyses.

For the cross-ply composites, the electric current flows not only in the longitudinal direction, but also in the direction of the thickness throughout the specimen (Fig. 2). Since the electric current is impeded by the presence of a delamination, the

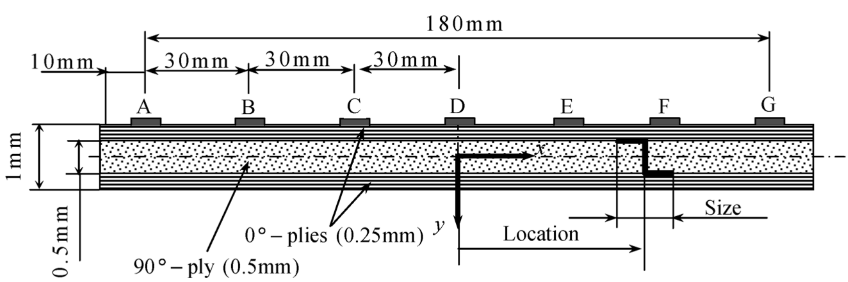


Figure 1. Analytical model of laminated CFRP.

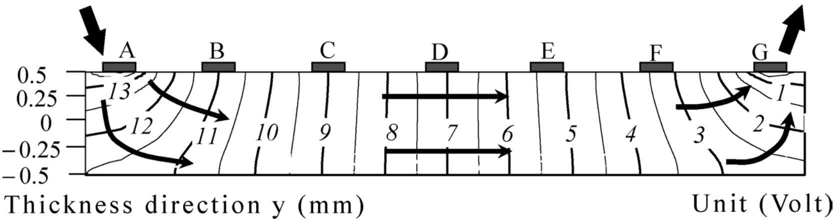


Figure 2. Contour plot of electric potential in cross-ply CFRP beam.

Table 1.
Conductivity ratio of CFRP ($V_f = 0.472$)

V_f (vol%)	σ_{90}/σ_0	σ_t/σ_0	σ_0 ($m^{-1}\Omega^{-1}$)
0.472	1.05×10^{-3}	2.24×10^{-4}	4.6×10^3

delamination can be detected by measuring the electric potential change between electrodes.

Quadratic four-node elements of 0.0625 mm in height and 0.25 mm in length are used for the FEM calculations. Electrical conductivity used in the FEM analyses is shown in Table 1. This electrical conductivity is obtained from the experimental results of a CFRP laminate which has a fiber volume fraction $V_f = 0.472$ [19]. σ_0, σ_{90}, σ_t are the conductivities in the longitudinal, transverse and thickness directions, respectively. The conductivity in the thickness direction includes the effect of the resin rich layers between plies.

2.2. Solver of inverse problem

Response surface methodology is applied to identify a delamination in a CFRP laminate. Details of the response surface methodology are shown in reference [21]. The following quadratic polynomial is adopted here:

$$y = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{j=1}^{n-1} \sum_{i=j+1}^{n} \beta_{ji} x_j x_i. \tag{1}$$

Our earlier studies demonstrated that a quadratic polynomial shows high estimation performances for this inverse problem [14–20]. An electric current of 50 mA is charged at the end-electrode A of the beam type specimen, and the other end-electrode G is set to be 0 V. The electric potentials at the electrodes are measured before and after creating a delamination. The electric potential differences P_i ($i = 1$ to 6) between electrodes AD, BD, CD, DE, DF, DG are calculated. FEM analyses are conducted for the multiple cases: delamination sizes of 5, 7, 10, 15, 20, 25, 30, 35 and 40 mm: delamination locations from –90 mm to 90 mm with spacings of 5 mm. FEM runs of 315 are performed.

From the electric potential differences between the electrodes, electric potential change ratios $\Delta P_i/P_{i0}$ are calculated, and normalized by the norm of the electric potential change vector [20]. The normalization transforms the electric potential change ratios of all electric potential differences to a unit vector by dividing them by the norm. The predictor variables of the response surfaces are normalized electric potential change ratios and the norm. The response variables are the delamination location and size.

$$\frac{\Delta p_i}{p_{i0}} = \frac{\Delta P_i/P_{i0}}{L} \quad (i = 1 - 6),$$
$$L = \sqrt{\sum_{k=0}^{6} (\Delta P_k/P_{k0})^2}. \tag{2}$$

When a regression coefficient has a low contribution to the regression, the coefficient is eliminated from the response surface to maximize the adjusted coefficient of multiple determination R^2_{adj}.

2.3. Shapes of delamination

Three delamination shapes are investigated in this paper: straight, Z-type and inverse Z-type delamination cracks (Fig. 3). The straight delamination is placed at the interlamina near the electrodes because a large delamination is generally created at the opposite interlamina to the impacted surface (the impacted surface is the opposite surface to the surface on which all electrodes are mounted). A Z-type delamination crack has two same-length delaminations, one at each end of the matrix crack as shown in Fig. 3. The inverse Z-type delamination crack is a symmetrical representation of the Z-type delamination crack. The delamination length of the upper and lower ends of the matrix crack is assumed to be the same length in this paper because the largest differences are expected in them compared with the straight delamination, as shown in an earlier study [17].

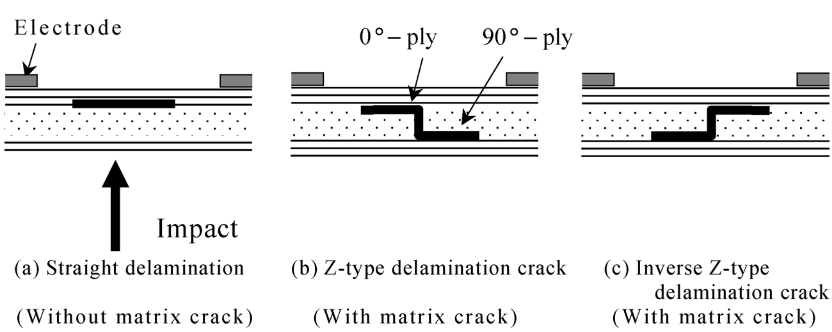


Figure 3. Types of delamination crack shape.

The coordinates are defined as shown in Fig. 1. The definition of the delamination location is the distance from the origin to the center of the delamination or the location of the matrix crack. The definition of the delamination size is a length projected onto the specimen surface. In the FEM analyses, delamination is created by means of separating two nodes that are placed at the same position. It is assumed in the FEM analyses that the electric current does not flow thorough the delamination.

As previously described, Z-type and inverse Z-type delamination cracks are analyzed to investigate the effect of the delamination shape on the estimation performance: for the estimation, response surfaces are made from FEM analyses of straight delaminations.

3. RESULTS OF THE ESTIMATION

3.1. Results of the estimation of a straight delamination using data-normalization

Two response surfaces for the estimation of the delamination location and size are made from the FEM analyses of straight delaminations. Figures 4 and 5 show estimated locations and sizes of the straight delaminations using the response surfaces. The abscissa shows the delamination location or size, and the ordinate shows the estimated location or size. Diagonal lines indicate an exact estimation. Broken lines in Fig. 5 show an error band of ±5 mm. The adjusted coefficients of multiple determination R^2_{adj} are 0.9988 for location and 0.9251 for size. Since the adjusted coefficients of multiple determination are close to 1, good regressions are indicated.

These results show that the data-normalization method also improves the accuracy of estimations with the electric potential change method. In our earlier study, the adjusted coefficient of multiple determination for estimation of location was 0.432

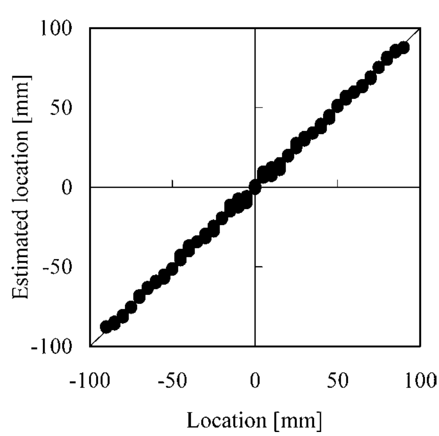


Figure 4. Estimated location of straight delamination using the response surface made from analyses of straight delaminations ($R^2_{adj} = 0.9988$).

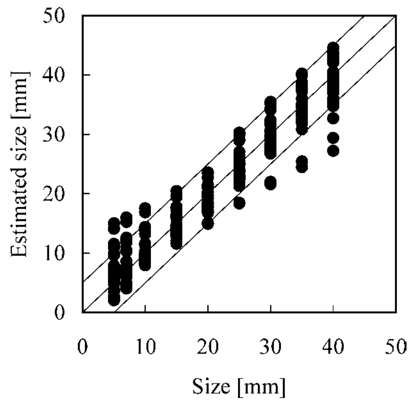


Figure 5. Estimated size of straight delamination using the response surface made from analyses of straight delaminations ($R^2_{adj} = 0.9251$).

without data-normalization [15]. The accuracy of the regression is remarkably increased by the data-normalization method, clarifying that the electric potential change method possesses sufficient accuracy for practical use with the data-normalization method.

3.2. The effect of matrix crack

Figures 6 and 7 show the estimated locations and sizes of the Z-type and the inverse Z-type delamination cracks using the response surface made from analyses of the straight delaminations. The abscissa and ordinate are the same as in Figs 4 and 5. The diagonal line in the figure shows an exact estimation. Broken lines in Fig. 7 show an error band of ±5 mm.

In this figure, delamination locations are estimated with good performance even though the response surface is made from analyses of the straight delaminations. However, some poor estimation results are observed at the center segment of the specimen. There are many poor estimation results of the estimated size, large errors being recognized when the delamination is located at the center segment of the specimen.

The differences of electric resistance changes caused by the delamination shapes did not affect the accuracy of the estimation using the electric resistance change method [17]. However, when using the electric potential change method, poor estimation results are caused by the difference of the delamination shape when the delamination is located at the center segment of the specimen.

Figure 8 shows the electric current density in the thickness direction at the interlamina between the surface 0°-ply and 90°-ply near the electrodes ($y = -0.25$ mm). The abscissa shows the longitudinal direction and the ordinate shows the electric current density in the thickness direction. The electric current density in the thickness direction vanishes at the center of the specimen. Figure 9 shows the normalized electric potential change ratios when a delamination is located near

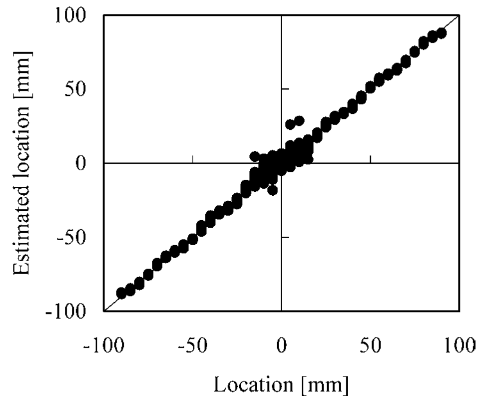


Figure 6. Estimated location of Z-type and inverse Z-type delamination cracks using the response surface made from analyses of straight delaminations.

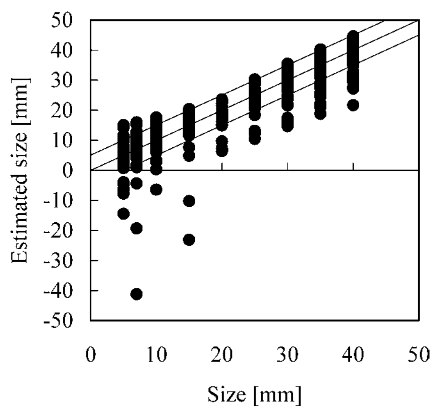


Figure 7. Estimated size of Z-type and inverse Z-type delamination cracks using the response surface made from analyses of straight delaminations.

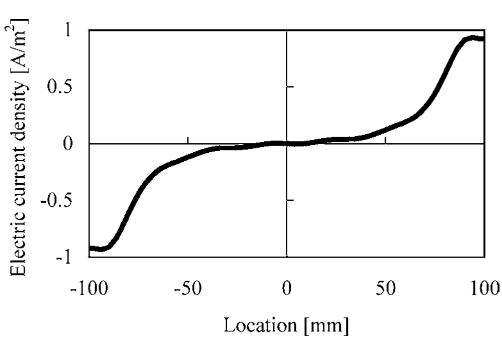


Figure 8. Electric current density in the thickness direction at the interlamina between the surface 0°-ply and 90°-ply near the surface of electrodes ($y = -0.25$ mm).

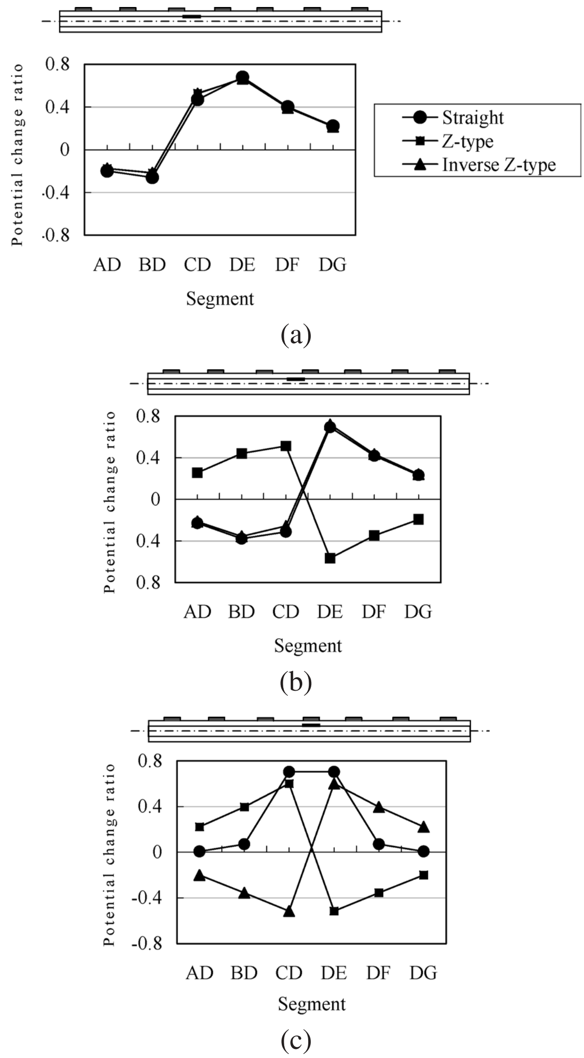
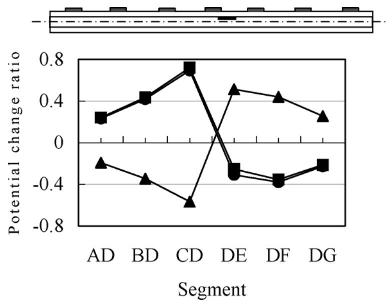
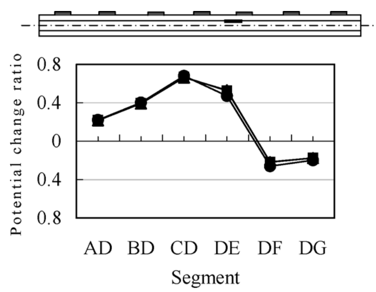


Figure 9. Normalized electric potential change ratios between electrodes (delamination size is 5 mm). (a) Delamination locates at $x = -20$ mm. (b) Delamination locates at $x = -10$ mm. (c) Delamination locates at $x = 0$ mm. (d) Delamination locates at $x = 10$ mm. (e) Delamination locates at $x = 20$ mm.

the center of the specimen. The abscissa shows the electrodes where electric potential differences are measured, and the ordinate shows the normalized electric potential change ratios. When a delamination is located outside $x = \pm 20$ mm, the electric potential change ratios are not affected by the delamination shape. However, when a delamination is located in the center segment of the charged electrode, the delamination shapes significantly affect the electric potential change ratios, as shown in Fig. 9. These results agree well with the experimental results in reference [18].



(d)



(e)

Figure 9. (Continued).

Figure 10 shows a contour plot of an electric potential inside a specimen when the delamination is located at the center of the specimen. Figure 11 is a zoomed schema of Fig. 10 around the delamination. The difference of the delamination shape caused little difference in the distribution of the electric potential, although a large difference is observed in the electric potential change ratios.

Electric potential change ratios before normalization are shown in Fig. 12, and are large when a delamination locates at $x = -50$ mm compared with the case of a delamination at $x = 0$ mm. This is because delamination at the interlamina impedes the electric current flow to the thickness direction when delamination is located near the charged electrodes. On the other hand, the electric potential change ratios are quite small when a delamination is located at the center of the specimen because of the low electric current in the thickness direction. These small differences due to the delamination shapes are magnified by applying data-normalization (Fig. 9).

The data-normalization method improves the estimation performance of the electric potential change method: data-normalization extracts important information about the delamination location from the electric potential change ratios. With the electric resistance change method, the delamination shape did not affect the estimation performance. Since the electric resistance change method uses adjacent electrodes for the charging electric current, the electric current density in the thickness direction is high enough because of the short spacing between the charged electrodes. However, the electric potential change method is affected by the

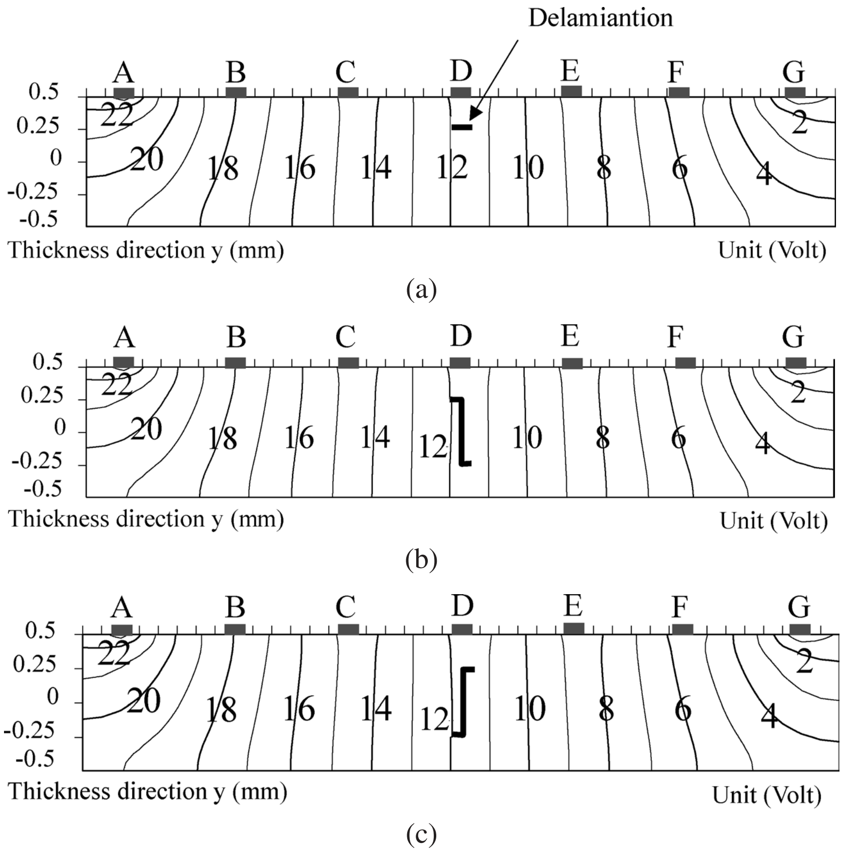


Figure 10. Contour plot of electric potential when the delamination is located at $x = 0$ mm and the delamination size is 5 mm. (a) Straight delamination. (b) Z-type delamination crack. (c) Inverse Z-type delamination crack.

delamination shape at the center segment of the charged electrodes. Electric current density in the thickness direction becomes significantly low at the center segment of the specimen because of the long spacing of the charged electrodes.

It can be seen from the above discussion that the reduction of electric current density in the thickness direction at the center segment of charged electrodes caused large estimation errors when a Z-type or an inverse Z-type delamination crack located in the center segment is estimated using the response surface made from analyses of straight delaminations. The accuracy of estimation at the center segment of the specimen must be improved for practical applications of the electric potential change method.

4. CONCLUSIONS

In this paper, the applicability of data-normalization to the electric potential change method was investigated using FEM analyses. In this method, electric potential

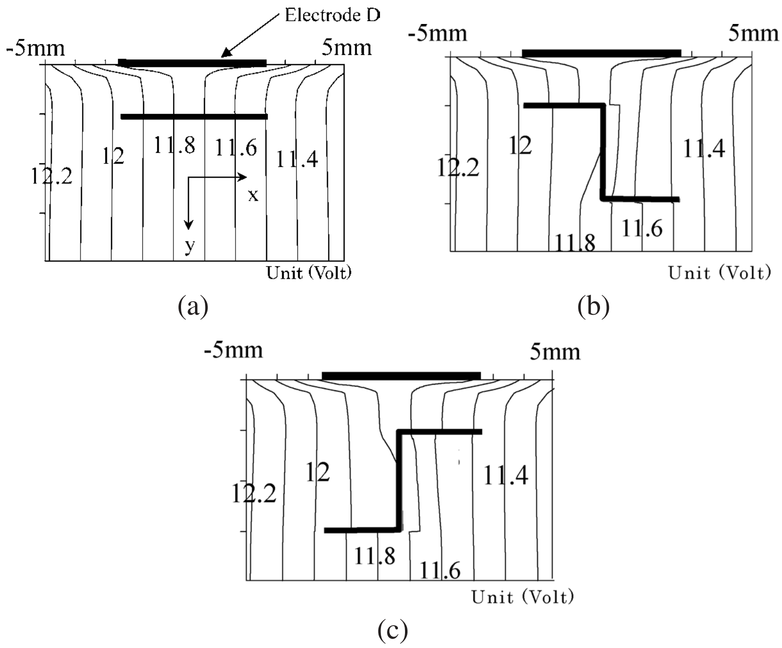


Figure 11. Contour plot of electric potential around the delamination when the delamination is located at $x = 0$ mm and delamination size is 5 mm. (a) Straight delamination. (b) Z-type delamination crack. (c) Inverse Z-type delamination crack.

differences were measured by charging electric current from the two electrodes made at the surface of each end of a beam type cross-ply laminate. The effect of the delamination crack shape (the existence of a matrix crack) on the accuracy of the estimations was examined using the response surfaces made from analyses of straight delaminations. The results obtained in this paper can be summarized as follows.

(1) The electric potential change method shows excellent estimation performance for straight delaminations by applying the data-normalization method.

(2) Except for the center segment of the specimen, actual delaminations such as Z-type or inverse Z-type delamination cracks can be estimated with excellent performance utilizing response surfaces made from analyses of straight delaminations.

(3) Large errors are created at the center segment of a specimen because of the low electric current in the thickness direction when a Z-type or an inverse Z-type delamination crack is estimated using response surfaces made from analyses of straight delaminations.

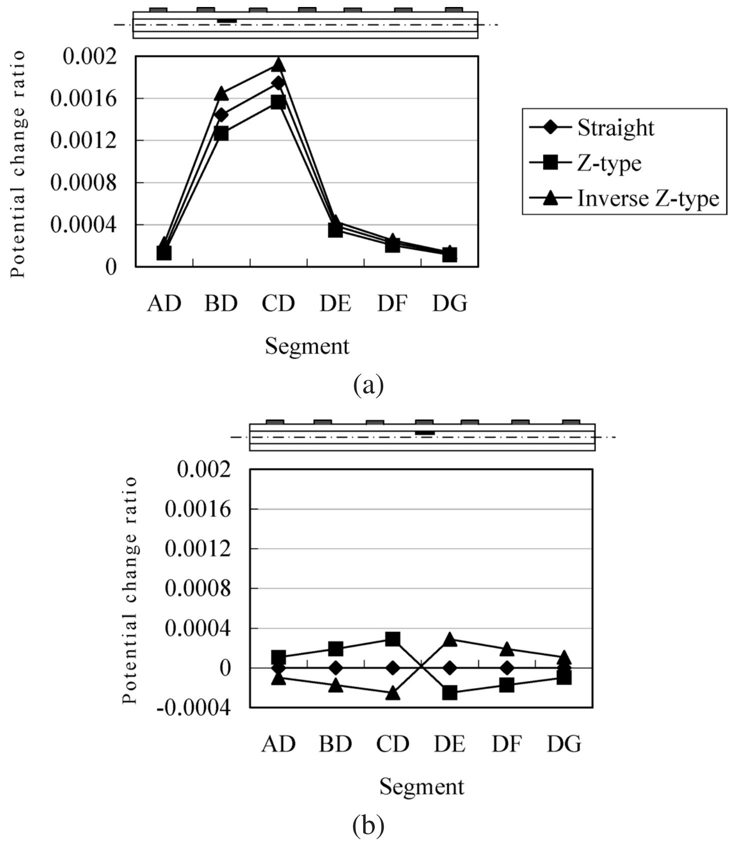


Figure 12. Electric potential change ratios without normalization (delamination size is 5 mm). (a) Delamination locates at $x = -50$ mm. (b) Delamination locates at $x = 0$ mm.

REFERENCES

1. K. Moriya and T. Endo, A study on flaw detection method for CFRP composite laminates (1st report), *J. Jpn. Soc. Aeronautical Space Sci.* **36** (410), 139–146 (1988).
2. K. Schulte and C. Baron, Load and failure analyses of CFRP laminates by means of electrical resistivity measurements, *Compos. Sci. Technol.* **36** (1), 63–76 (1989).
3. P. W. Chen and D. D. L. Chung, Carbon fiber reinforced concrete for smart structures capable of non-destructive flaw detection, *Smart Mater. Struct*. **2** (1), 22–30 (1993).
4. P. E. Irving and C. Thiagarajan, Fatigue damage characterization in carbon fibre composite materials using an electrical potential technique, *Smart Mater. Struct.* **7** (4), 456–466 (1998).
5. J. C. Abry, S. Bochard, A. Chateauminois, M. Salvia and G. Giraud, In situ detection of damage in CFRP laminates by electrical resistance measurements, *Compos. Sci. Technol.* **59** (6), 925–935 (1999).
6. D. C. Seo and J. J. Lee, Damage detection of CFRP laminates using electrical resistance measurement and neural network, *Composite Structures* **47** (1-4), 525–530 (1999).
7. I. Weber and P. Schwartz, Monitoring bending fatigue in carbon-fibre/epoxy composite strands: a comparison between mechanical and resistance techniques, *Compos. Sci. Technol.* **61** (6), 849–853, (2001).

8. N. Muto, Y. Arai, S. G. Shin, H. Matsubara, H. Yanagida, M. Sugita and T. Nakatsuji, Hybrid composites with self-diagnosing function for preventing fatal fracture, *Compos. Sci. Technol.* **61** (6), 875–883 (2001).
9. S. Kubo, M. Kuchinishi, T. Sakagami and S. Ioka, Identification of delamination in layered composite materials by the electric potential CT method, *Int. J. Jpn. Soc. Appl. Electromagn. Mech.* **15** (1/4), 261–267 (2001).
10. J. B. Park, T. Okabe, N. Takeda and W. A. Curtin, Electromechanical modeling of unidirectional CFRP composites under tensile loading condition, *Composites: Part A* **33** (2), 267–275 (2002).
11. C. N. Owston, Eddy current methods for the examination of carbon fibre reinforced epoxy resins, *Mater. Eval.* **34** (11), 237–244 (1976).
12. T. Sakagami, S. Kubo and K. Ohji, Crack identification by the electric potential CT inverse analyses incorporating optimization techniques, *Engineering Analysis with Boundary Elements* **7** (2), 59–65 (1990).
13. N. Tada, Y. Hayashi, T. Kitamura and R. Ohtani, Analysis on the applicability of direct current electrical potential method to the detection of damage by multiple small internal cracks, *Int. J. Fract.* **85** (1), 1–9 (1997).
14. Y. Tanaka, A. Todoroki and Y. Shimamura, Smart structure for delamination detection of CFRP using response surface of electric resistance change of multiple electrodes, *J. Jpn. Soc. Mech. Engng (A)* **65** (640), 2432–2438 (1999).
15. A. Todoroki, H. Suzuki and Y. Shimamura, Identification of delamination cracks of CFRP by electrical potential method, *J. Jpn. Soc. Mech. Engng (A)* **65** (634), 1330–1336 (1999).
16. A. Todoroki, Y. Tanaka, Y. Shimamura and H. Kobayashi, Smart structure for detection of embedded delamination of CFRP plates using multi-point potential change, *J. Jpn. Soc. Mech. Engn (A)* **67** (658), 1002–1008 (2001).
17. A. Todoroki, M. Tanaka, Y. Shimamura and H. Kobayashi, Analysis of the effect of the configuration of the delamination crack on delamination monitoring with electric resistance change method, *J. Japan Soc. Compos. Mater.* **29** (3), 113–119 (2003).
18. A. Todoroki and Y. Tanaka, Delamination identification of cross-ply graphite/epoxy composite beams using electric resistance change method, *Compos. Sci. Technol.* **62** (5), 629–639 (2002).
19. A. Todoroki, M. Tanaka and Y. Shimamura, Measurement of orthotropic electric conductance of CFRP laminates and analysis of the effect on delamination monitoring with an electric resistance change method, *Compos. Sci. Technol.* **62** (5), 619–628 (2002).
20. A. Todoroki, M. Tanaka and Y. Shimamura, High performance estimations of delamination of graphite/epoxy laminates with electric resistance change method, *Compos. Sci. Technol.* **63** (13), 1911–1920 (2003).
21. R. H. Myers and D. C. Montgomery, *Response Surface Methodology: Process and Product Optimization Using Designed Experiments*, 2nd edn. John Wiley, New York (2002).