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Finite Element Study on Delamination Identification in Quasi-Isotropic CFRP Laminate by Residual Stress Release Using the Electric Potential Change Method*

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Abstract

The electric potential change method (EPCM) was applied to identify delamination in quasi-isotropic carbon fiber reinforced plastic (CFRP) laminate. The authors have introduced EPCM previously to detect delamination in a cross-ply CFRP laminate although it was difficult to apply to quasi-isotropic CFRP laminate because of its complicated electric anisotropy. In this study, a new concept was introduced to resolve this problem. Residual stress that developed during the curing process in CFRP laminate fabrication was utilized. This residual stress was released locally by the creation of a delamination which resulted in a local strain variation on the laminate surface. Since the electric conductivity of CFRP may change with applied strain because of its piezoresistivity a CFRP cloth was used as a strain sensor. The release of residual stress was detected as an electric potential change of the CFRP cloth by applying electric current to the laminate. The delamination location and size were estimated from electric potential changes. A finite element study was performed to investigate the applicability of the method. Two steps of finite element analysis were performed to calculate the electric potential change due to delaminations and matrix cracks, structural analyses to calculate strain variation due to release of the residual stress by the delamination and then electric field analyses to calculate electric potential change due to strain variation. The delamination location and size were estimated from electric potential changes using a response surface methodology. A numerical simulation was successful in estimating delaminations in quasi-isotropic CFRP laminate.

Key words: CFRP, Delamination, Electric Potential Change Method, Residual Stress, Piezoresistivity, Structural Health Monitoring

1. Introduction

Carbon fiber reinforced plastic (CFRP) laminate has superior specific strength and stiffness compared to metallic materials. A disadvantage of the CFRP laminate, however, is its low interlaminar strength due to its laminated structure. Delamination is easily achieved by a relatively soft impact and delamination reduces the compression strength of the laminate (CAI strength) resulting in difficulty of visual inspection. Conventional nondestructive testing (NDT) methods such as ultrasonic inspection and X-ray inspection

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are costly and time-consuming and real-time monitoring is difficult. A simple and real-time structural health monitoring (SHM) method is required for the CFRP laminated structure to maintain structural reliability and to reduce huge periodic inspection costs.

Several SHM techniques have been proposed utilizing an optical fiber sensor [(1), (2)], piezoelectric sensor [(3), (4)], a frequency change [(5), (6)] and electric property changes [(7)] of CFRP. Embedding an optical fiber sensor into the laminate may cause damage and repair is difficult. A piezoelectric sensor can identify the impact force although it is difficult to estimate damage initiation or damage size from the impact force. In a frequency change measurement a small amount of damage is difficult to detect because of the low frequency applicable to the CFRP structure.

As CFRP laminate consists of electroconductive carbon fibers and insulative resin, which creates an electrical network in the laminate, electric current flows inside the laminate. Strain and damage monitoring can be done by measuring the change in an electric property of CFRP [(7)~(15)]. No additional sensor is, therefore, required for the method as CFRP is used as a sensor. Data acquisition systems for electric potential are low cost and real-time monitoring is possible.

The authors have applied the electric potential change method (EPCM) for delamination identification in CFRP laminate [(16)~(19)]. If a delamination is created in the laminate the electrical network is broken and the electric potential may change in the laminate because the delamination impedes electric current. Delamination locations and sizes were estimated by electric potential changes between electrodes which were mounted on the laminate surface. The applicability of the method was shown analytically and experimentally using a cross-ply laminated CFRP beam.

Quasi-isotropic CFRP laminate is often used in actual structures. In a previous study the applicability of the EPCM for quasi-isotropic CFRP laminate was investigated by means of the finite element method (FEM). Their results indicated the difficulty with delamination identification in quasi-isotropic CFRP laminate because of strong electric anisotropy [(20)]. Although electric current must be impeded by delamination to cause electric potential change in the laminate the effective electric current path, i.e. electric current in the thickness direction was difficult to generate in the quasi-isotropic CFRP laminate.

In this paper, a new concept in delamination identification using EPCM was proposed to resolve this problem. CFRP laminate has residual stresses resulting from the curing process during fabrication. The method utilizes the release of residual stress in the laminate due to creation of delaminations. CFRP cloth is often stacked onto quasi-isotropic CFRP laminate as a protective layer to prevent surface damage and it was thus used as a strain sensor for this method. The strain variation on the laminate surface, due to delamination, was measured as electric potential changes of the CFRP cloth. The delamination was estimated from the electric potential changes as an inverse problem using the response surface methodology. The applicability of the method for delamination identification in quasi-isotropic CFRP laminate was investigated by means of finite element analyses.

2. Analytical method

2.1 Finite element analyses

CFRP laminate is cured at elevated temperatures during its fabrication. After curing the laminate is cooled to room temperature. Residual stress develops in the laminate due to discrepancies in the coefficient of thermal expansion and the mold shrinkage factor between the carbon fiber and the epoxy matrix [(21), (22)]. When delaminations and matrix cracks are created the residual stress in the laminate is released locally. The electric conductivity of CFRP laminate may change in proportion to strain due to its piezoresistivity [(25)~(27)]. Electric conductivity of the laminate may, therefore, change locally due to the creation of delaminations and matrix cracks. When an electric current was applied to CFRP laminate and electric potentials were measured before and after the creation of delaminations and matrix cracks, the local electric potential change could be measured as the electric conductivity varied. Delamination locations and sizes were then estimated from electric potential changes as an inverse problem.

Finite element analyses were performed to obtain electric potential changes of CFRP laminate due to the creation of delaminations and matrix cracks. Finite element analyses were performed as follows.

A structural analysis was done first. The residual strain of a CFRP laminate due to cooling from the curing temperature to room temperature was calculated. Electric conductivities of the CFRP laminate were then calculated at all the finite elements in proportion to the strains at each element.

An electric field analysis was then performed. Revised electric conductivities which were obtained from the previous structural analyses were assigned to all the finite elements. An electric current was applied to a laminate and the electric potential of that laminate was calculated.

Finite element analyses were done for two models where in the first model the CFRP laminate was intact and in the other the laminate was delaminated locally. The difference in electric potentials of the two laminates was due to delaminations and matrix cracks. Electric potential changes due to the creation of delaminations and matrix cracks were, therefore, obtained from the results. Details of finite element analyses are given in the following sections.

2.2 Analytical model

The specimen was 100mm long, 50mm wide and 4mm thick as shown in Fig. 1 and this was regarded as a coupon specimen cut from a structural component.

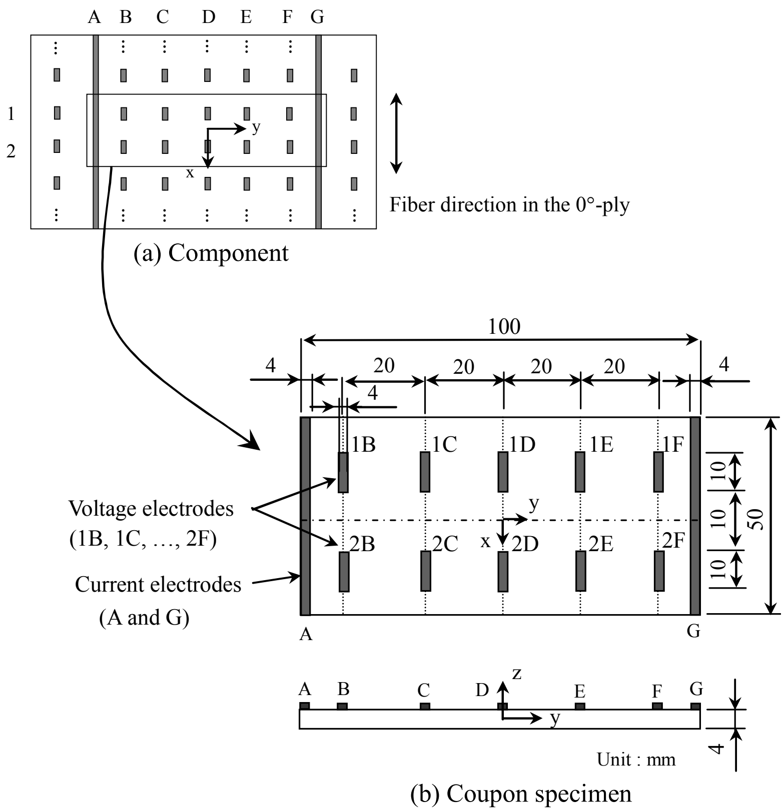


Fig. 1 Configuration of a laminate

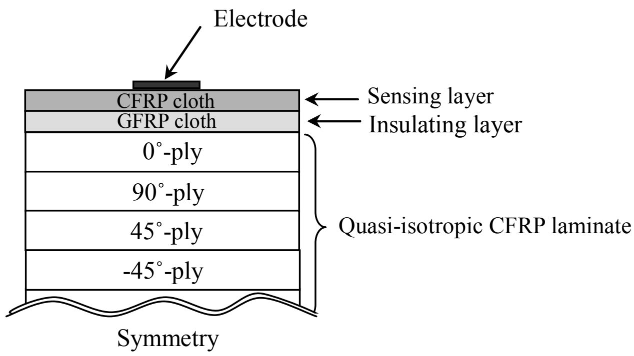


Fig. 2 The stacking sequence of a laminate

The stacking sequence of the specimen was quasi-isotropic as $[0_2/90_2/\pm45_2]_s$. CFRP cloth was stacked on both surfaces of the laminate. Glass fiber reinforced plastic (GFRP) cloth was inserted between the CFRP cloth and the quasi-isotropic CFRP laminate as shown in Fig. 2. GFRP cloth is an insulating layer and the electric current only flows in the CFRP cloth. A strain variation due to the creation of a delamination in a quasi-isotropic CFRP laminate was detected as an electric potential change of the CFRP cloth utilizing its piezoresistivity. In actual structures CFRP cloth is often used to protect laminate surfaces. Insertion of thin GFRP cloth as an insulating layer is easily done. Insulative coatings on carbon fibers in a unidirectional ply are an alternative way to insert GFRP.

Five voltage electrodes (electrodes 1B, 1C, 1D, 1E and 1F) were mounted on a surface of the laminate with a spacing of 20mm. Another set of voltage electrodes (2B, 2C, 2D, 2E and 2F) were mounted parallel with a spacing of 10mm. Two current electrodes (A and G) were mounted on the same surface of the laminate. All the electrodes were mounted on the inner surface of the structures. The voltage electrodes were 4mm long and 10mm wide. The current electrodes were 4mm long and the same width as the laminate. The electrodes were placed parallel to the fiber direction in the 0°-ply. In the finite element analysis electric potentials of nodes at each electrode were coupled and had the same electric potentials.

For the finite element analysis all the materials were assumed to be isotropic materials in the cross-sectional area. The material properties of the unidirectional CFRP lamina were as follows:

Unidirectional CFRP:

E_L=160GPa, E_T=8GPa, G_{LT}=3GPa, ν_{LT}=0.34, ν_{TZ}=0.4

Coefficients of thermal expansion (CTE) of the carbon fiber and epoxy matrix was $\alpha_f=-0.1\times10^{-6}$ and $\alpha_m=50\times10^{-6}$ from which the CTE of the lamina was calculated using the rule of mixtures. The fiber volume fraction was assumed to be V_f=0.6. The mold shrinkage factor (MSF) of the matrix α_{cure} was included with the CTE of the matrix α_m. MSF of the epoxy matrix was assumed to be α_{cure}=0.1%.

$$\alpha_m = \alpha'_m + \frac{\alpha_{cure}}{\Delta T} = 50\times10^{-6} \qquad (1)$$

Where $\alpha'_m=41\times10^{-6}$ is the CTE of the epoxy matrix in which the MSF is not included. CFRP laminate was assumed to have cooled ΔT=110°C from the curing temperature of 130°C to room temperature of 20°C. The discrepancies between the CTE and MSF of carbon fiber and epoxy matrix resulted in residual stress in the laminate after the curing process during fabrication [(21), (22)].

The material properties of the CFRP cloth and GFRP cloth were as follows:

CFRP cloth:

E_L=80GPa, E_T=10GPa, G_{LT}=5GPa, ν_{LT}=0.03, ν_{TZ}=0.05, $\alpha_L=2\times10^{-6}$, $\alpha_T=10\times10^{-6}$

GFRP cloth:

E_L=40GPa, E_T=10GPa, G_{LT}=2GPa, ν_{LT}=0.03, ν_{TZ}=0.05, $\alpha_L=6\times10^{-6}$, $\alpha_T=10\times10^{-6}$

The thickness of the unidirectional CFRP ply and the cloth ply was assumed to be 0.22mm and 0.12mm, respectively, from which the total thickness of the laminate was 4mm.

2.3 Delaminations and matrix cracks

In a quasi-isotropic CFRP laminate the delamination generally shows a complicated configuration with matrix cracks [(23),(24)]. For convenience in our numerical simulation square-shaped delaminations with matrix cracks were assumed for the finite element model (see Fig. 3). Surface strain variations due to delaminations and matrix cracks are usually different and dependent on the surface from where an indentation was applied because of the complicated shape of delaminations. Further study is required for detailed modeling of delaminations.

Square-shaped delaminations were made at all the interlaminars. The lengths and widths of delaminations were equal. Matrix cracks were made at the center of the delaminations along the fibers in each lamina. In the finite element analysis delaminations and matrix cracks were made by separating nodes that were placed in same position.

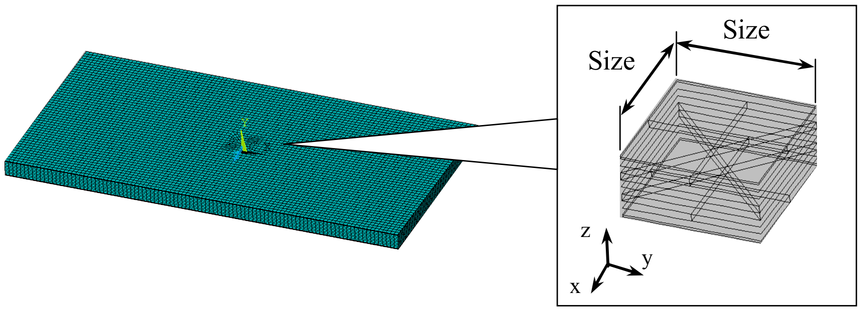


Fig. 3 Configuration of delaminations and matrix cracks as modeled in a finite element analysis

2.4 Piezoresistivity of CFRP cloth

Initial electric conductivities and gage factors of the CFRP cloth were σ_L=10000S/m, σ_T=20S/m and K_L=3, K_T=4, respectively. For structural analysis strain variations due to the creation of delaminations and matrix cracks were calculated for all finite elements. As electric conductivity may change proportionally to the strain [(25)~(27)] the electric conductivity was calculated at every finite element.

$$\sigma = \frac{\sigma_{int}}{(1+K\varepsilon)} \tag{2}$$

where σ_{int} is initial electric conductivity and ε is strain at each element.

For the electric field analysis, electric conductivities at every finite element in the CFRP cloth were replaced by revised electric conductivities that were proportional to the strain at each element. As GFRP cloth ply was an insulating layer a small electric conductivity was assigned.

3. Electric potential change method (EPCM)

Electric current was applied at the current electrode A and the other current electrode G was set to 0V. The electric potential of the laminate was measured with and without delaminations and matrix cracks. The electric potential changes between adjacent electrodes

1B-1C, 1C-1D, 1D-1E, 1E-1F and 2B-2C, 2C-2D, 2D-2E, 2E-2F due to delaminations and matrix cracks were obtained and normalized.

$$\Delta p_i = \frac{P_i - P_{i0}}{L},\ L = \sqrt{\sum_{i=1} \left(P_i - P_{i0}\right)^2} \qquad (i = 1 \sim 8) \tag{3}$$

where Δp_i (i =1~8) are normalized electric potential changes between electrodes, P_i and P_{i0} are electric potentials between electrodes with and without delaminations and matrix cracks and L is the norm of the electric potential changes between electrodes.

Delamination locations and sizes were estimated from normalized electric potential changes between electrodes and their norm. The response surface methodology was applied as a solver for the inverse problem [28]. The response surface methodology is a curve fitting technique of solution space to obtain approximate responses. Inverse problems can be approximately solved without considering the modeling of functions. The response surface is similar to the back-propagation artificial neural network (ANN). Advantages of the response surface are low computational cost and availability of strong statistical tools to compensate for the decrease of fitness compared to the ANN. Response surfaces can be evaluated statistically to maximize regression accuracy. Once the response surface is obtained the delamination can be estimated instantaneously from electric potential changes.

A polynomial expression is often used as an approximation function in the response surface methodology because of simplicity. In this study quadratic polynomials were used as response surfaces. Response surfaces were made using normalized electric potential changes between electrodes as predictor variables and x-location (or y-location) of the delamination as a response variable. The norm was also used as a predictor variable when delamination size was a response variable.

$$x - \text{Location} = \sum_{i=1}^{8} \alpha_i \Delta p_i + \sum_{i=1}^{8} \alpha_{ii} \Delta p^2{}_i + \sum_{i=1}^{7} \sum_{j=i+1}^{8} \alpha_{ij} \Delta p_i \Delta p_j \tag{4}$$

$$y - \text{Location} = \sum_{i=1}^{8} \beta_i \Delta p_i + \sum_{i=1}^{8} \beta_{ii} \Delta p^2{}_i + \sum_{i=1}^{7} \sum_{j=i+1}^{8} \beta_{ij} \Delta p_i \Delta p_j \tag{5}$$

$$\text{Size} = \sum_{i=1}^{9} \gamma_i \Delta p_i + \sum_{i=1}^{9} \gamma_{ii} \Delta p^2{}_i + \sum_{i=1}^{8} \sum_{j=i+1}^{9} \gamma_{ij} \Delta p_i \Delta p_j \qquad (\ \Delta p_9 = L\ ) \tag{6}$$

Training data of the response surfaces was obtained by FEM (see §4.3). Regression coefficients α, β, and γ were calculated by means of the least squares method using the training data. When response surfaces from Eqs. (4) and (5) are obtained, estimated x-locations and y-locations of delaminations can be obtained as response variables by substituting the normalized electric potential changes between electrodes into predictor variables. Delamination size can also be estimated by substituting normalized electric potential changes between electrodes and their norm into predictor variables of Eq. (6). In Eq. (6) norm L substituted Δp_9.

The significance of regression for response surfaces was evaluated using the adjusted coefficient of multiple determinations R^2_{adj} [28].

$$R^2_{adj} = 1 - \frac{SS_E/(n-k+1)}{SS_T(n-1)} \tag{7}$$

where SS_E is a sum of squares error, SS_T is the total sum of squares, n is the quantity of data and k is a number of unknown coefficients. The range of R^2_{adj} is $0 \le R^2_{adj} \le 1$ where a higher R^2_{adj} value implies a good regression of the supposed model. A statistical t-test was performed to investigate the contribution of the coefficients [28]. If a coefficient had a low contribution to the regression that coefficient was eliminated from the response surface to maximize R^2_{adj}.

4. Results and discussion

4.1 Strain variation on laminate surface due to delaminations and matrix cracks

Finite element analyses were done to calculate strain variations in laminates due to delaminations and matrix cracks. Residual strains were calculated under a cooling condition of ΔT=110°C with and without delaminations and matrix cracks. By subtracting the results local strain variations in laminate due to delaminations and matrix cracks were calculated.

Figure 4 shows a contour plot of a y-directional strain variation on a laminate surface due to delaminations and matrix cracks. The delamination location was at the center of the laminate i.e. x=y=0mm. The size of the delamination was 8mm. Compressive strain was observed on the laminate surface at the delaminated area and tensile strain was observed around the area. A local strain variation on the laminate surface which was due to the creation of delaminations and matrix cracks was recognized.

CFRP laminate contain residual stress from the curing process during fabrication [21], [22]. Discrepancies of the CTE and MSF between the fiber and matrix result in residual stress within the laminate. A local strain variation due to the release of residual stress by delaminations and matrix cracks can, therefore, be observed on the laminate. Delaminations and matrix cracks may be detected by measuring the local strain variation on the laminate surface.

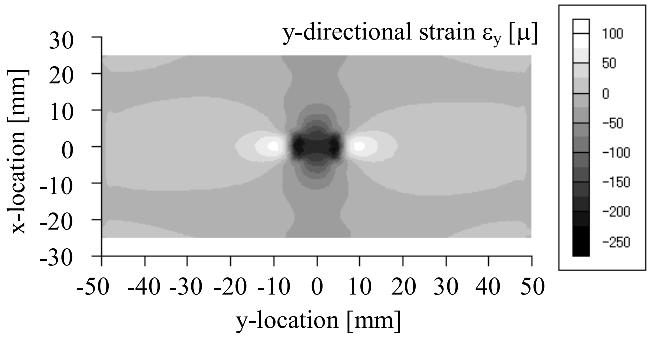


Fig. 4 Contour plot of y-directional strain variation on the laminate surface due to delaminations and matrix cracks

(Delamination located at x=0 and y=0mm. Delamination size was 8mm)

4.2 Electric potential change due to the surface strain variation

Finite element analyses were performed to calculate the electric potential change of the CFRP cloth due to delaminations and matrix cracks. An electric current of 100mA was applied at current electrode A and the other current electrode G was set to 0V. Electric conductivities at every finite element in the CFRP cloth were revised electric conductivities and were proportional to the residual strain at each element. The electric potential of the laminate was calculated with and without delaminations and matrix cracks. The electric potential change due to the surface strain variation by the delaminations and matrix cracks was obtained by subtracting the electric potentials.

Figure 5 shows a contour plot of electric potential change on laminate surface due to a surface strain variation. The delamination location was at the center of the laminate. The size of the delamination was 8mm. The electric potential change was measured on the laminate surface using the piezoresistivity of the CFRP cloth and this change was due to the release of residual stress by delaminations and matrix cracks.

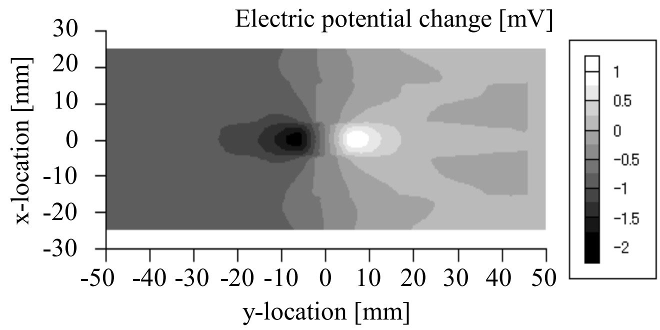


Fig. 5 Contour plot of electric potential change on the laminate surface due to surface strain variation

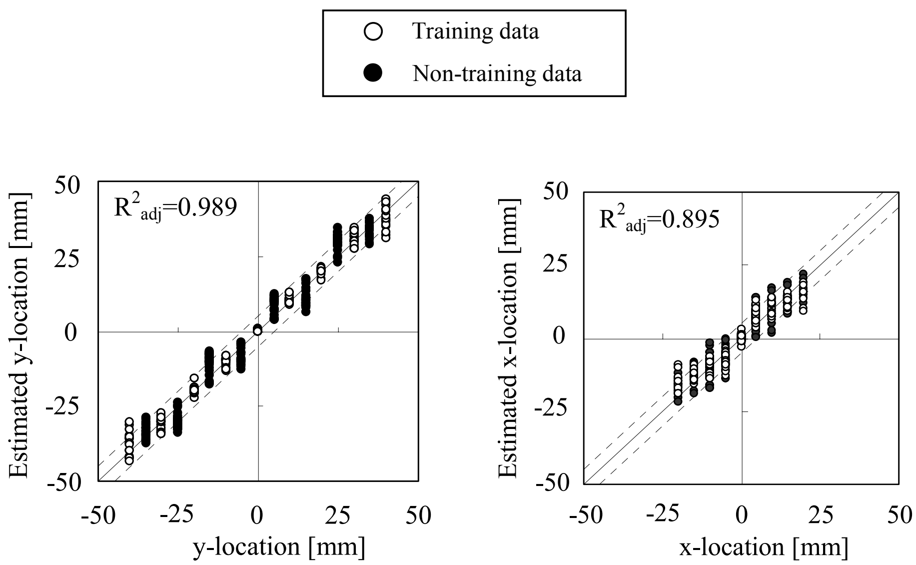
(Delamination located at x=0 and y=0mm. Delamination size was 8mm)

4.3 Estimation of delaminations

Response surfaces for the estimation of delamination locations and sizes were made using the training data that was obtained by FEM analyses. FEM analyses were performed for multiple cases: delamination locations of $-20 \leq x \leq 20$mm with a spacing of 5mm and $-40 \leq y \leq 40$mm with a spacing of 10mm. Delamination sizes were 8, 16, 24 and 32mm. Some FEM analyses were omitted in cases where delaminations made an open crack at the edge of the laminate. A total of 200 runs of FEM analyses, therefore, were performed to obtain training data for response surfaces.

FEM analyses were also performed using different conditions at delamination locations of $-20 \leq x \leq 20$mm with a spacing of 5mm and $-35 \leq y \leq 35$mm with a spacing of 10mm. Delamination sizes were 8, 16, 24 and 32mm. These 186 delaminations were not used as training data but were also estimated using the response surfaces to examine the robustness of the method.

Figures 6 (a) and (b) show estimation results of y- and x-locations of the 386 delaminations investigated. The abscissas show delamination locations and ordinates show estimated locations. The diagonal lines show the exact estimation. Broken lines in the figures show error bands of ± 5mm. The adjusted coefficients of multiple determinations of



(a) Estimated y-location (b) Estimated x-location

Fig. 6 Results of estimation for delamination location

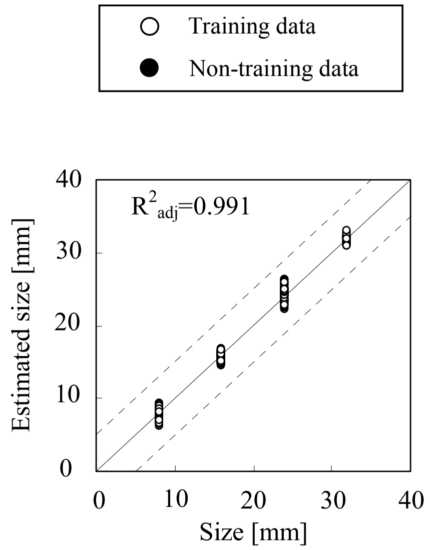


Fig. 7 Results of estimation for delamination size

the response surfaces for the estimation of y-locations was R^2_{adj}=0.989 and x-locations was R^2_{adj}=0.895. The response surfaces for estimation of delamination locations showed good accuracy of regression. Delaminations which were not used as training data could also be estimated accurately.

Figure 7 shows estimation results for sizes of the 386 delaminations investigated. The abscissas and ordinates show delamination sizes and estimated sizes, respectively. The diagonal line shows exact estimation. The broken lines show error bands of ± 5mm. The adjusted coefficient of multiple determinations of the response surface for estimation of delamination size was R^2_{adj}=0.991. The response surface for the estimation of delamination size showed good accuracy for the regression. Delaminations which were not used as training data could also be estimated accurately. The results showed that various sizes of delamination which were located throughout the laminate could be identified successfully by the proposed method.

5. Conclusions

A new concept for delamination identification in quasi-isotropic CFRP laminate was proposed to resolve a problem previously introduced by EPCM. In this method, CFRP cloth which is generally used as a protection layer for laminate surfaces was used as a strain sensor using its piezoresistivity. GFRP cloth was inserted as an insulating layer between CFRP cloth and quasi-isotropic CFRP laminate to prevent electric current flow in the quasi-isotropic CFRP laminate.

The applicability of the method was investigated by means of finite element analyses. Delaminations with matrix cracks resulted in strain variations on the laminate surface due to the release of residual stress which was produced during the fabrication process of the laminate. The electric potential change which resulted from a surface strain variation was observed utilizing the piezoresistivity of the CFRP cloth. Delamination locations and sizes were estimated from normalized electric potential changes between electrodes using the response surface methodology. A numerical simulation was successful in estimating delaminations in quasi-isotropic CFRP laminate.

References

(1) Takeda, S. Okabe, Y. and Takeda, N., Delamination detection in CFRP laminates with embedded small-diameter fiber bragg grating sensors, *Composite Part A*, Vol.33, No.7 (2002), pp.971-980.
(2) Okabe, Y. Tsuji, R. and Takeda, N., Application of chirped fiber bragg grating sensors for identification of crack locations in composites, *Composite Part A*, Vol.35, No.1 (2004), pp.59-65.
(3) Seydel, R. and Chang, F.K., Impact identification of stiffened composite panels: I. system development, Smart Materials and Structures, Vol. 10, No.2 (2001), pp. 354-369.
(4) Seydel, R. and Chang, F.K., Impact identification of stiffened composite panels: II. Implementations studies, *Smart Materials and Structures*, Vol. 10, No. 2 (2001), pp. 370-379.
(5) Okafor, A.O. Chandrashekhara, K.C. and Jiang, Y.P., Delamination prediction in composites beams with built-in piezoelectric devices using modal analysis and neural network, *Smart Materials and Structures*, Vol. 5, No. 3 (1996), pp. 338-347.
(6) Inada, T. Shimamura, Y. Todoroki, A. and Kobayashi, H., Development of the two-step delamination identification method by resonant and anti-resonant frequency changes, *Key Engineering Materials*, Vol.270-273 (2004), pp. 1852-1858.
(7) Todoroki, A. Ueda, M. and Hirano, Y., Strain and damage monitoring of CFRP laminates by means of electrical resistance measurement, *Journal of Solid Mechanics and Materials Engineering*, Vol. 1 (2007), No. 8, pp.947-974.
(8) Owston, C.N., Eddy current methods for the examination of carbon fibre reinforced epoxy resins, *Materials evaluation*, Vol. 34, No. 11 (1976), pp. 237-244.
(9) Schulte, K. and Baron, Ch., Load and failure analyses of CFRP laminates by means of electrical resistivity measurement, *Composites Science and Technology*, Vol. 36, No. 1 (1989), pp. 63-76.
(10) Prabhakaran, P., Damage assessment through electrical resistance measurement in graphite fiber-reinforced composites, *Experimental Techniques*, Vol. 14 (1990), pp. 16-20.
(11) Wang, X. and Chung, D.D.L., Continuous carbon fibre epoxy-matrix composite as a sensor of its own strain, *Smart Materials and Structures*, Vol. 5 (1996), pp. 796-800.
(12) Kupke M., Schulte K. and Schuler R., Non-destructive testing of FRP by d.c. and a.c. electrical methods, *Composites Science and Technology*, Vol. 61, No. 6 (2001), pp. 837-847.
(13) Anderson, T.A., Lemoine, G.I., and Ambur, D.R., An artificial neural network based damage detection scheme for electrically conductive composite structures, *44th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials conference* (2003), pp.1-9.
(14) Wang, D. and Chung, D.D.L., Comparative evaluation of the electrical configurations for the two-dimensional electric potential method of damage monitoring in carbon fiber polymer-matrix composite, *Smart Materials and Structures*, Vol. 15, No. 5 (2006), pp. 1332-1344.
(15) Angelidis, N. and Irving P.E., Detection of impact damage in CFRP laminates by means of electrical potential techniques, *Composites Science and Technology*, Vol. 67, No. 3-4 (2007), pp. 594-604.
(16) Ueda, M. Todoroki, A. Shimamura, Y. and Kobayashi, H., 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), *Advanced Composite Materials*, Vol.13, No.3-4 (2004), pp.311-324.
(17) Ueda, M. Todoroki, A. Shimamura, Y. and Kobayashi, H., Monitoring delamination of laminated CFRP using the electric potential change method (Two-stage monitoring for robust estimation), *Advanced Composite Materials*, Vol.14, No.1 (2005), pp.83-97.

(18) Ueda, M. and Todoroki, A., Asymmetrical dual charge EPCM for delamination monitoring of CFRP laminate, *Key Engineering Materials*, Vol. 321-323 (2006), pp.1309-1315.

(19) Ueda, M. and Todoroki, A., Delamination monitoring of CFRP laminate using the two-stage electric potential change method with equivalent electric conductivity, *Engineering fracture mechanics*, Vol. 75, No. 9 (2008), pp. 2737-2750.

(20) Ueda, M. and Todoroki, A., Delamination monitoring of quasi-isotropic CFRP plate by electric potential change method, *Proceeding of the 12th US-Japan conference on composite materials*, (2006), pp.269-278.

(21) Kugler, D and Moon, T. J., Identification of the most significant processing parameters on the development of fiber waviness in thin laminates, *Journal of Composite Materials*, Vol. 36, No. 12 (2002), 1451-1479.

(22) Hahn, H.T., Residual stresses in polymer matrix composite laminates, *Journal of Composite Materials*, Vol. 10, No. 4 (1976), pp. 266-278.

(23) Ishikawa, T. Sugimoto, S. Matsushima, M. and Hayashi, Y., Some experimental findings in compression-after-impact (CAI) tests of CF/PEEK (APC-2) and conventional CF/EPOXY flat plates, *Composites Science and Technology*, Vol. 55, No. 3-4 (1995), pp. 349-363.

(24) Soutis, C. and Curtis, P.T., Prediction of the post-impact compressive strength of CFRP laminated composite, *Composite Science and Technology*, Vol. 56, No. 6 (1996), pp. 677-684.

(25) Wang, S and Chung, D.D.L., Piezoresistivity in continuous carbon fiber polymer-matrix composite , *Polymer Composite*, Vol. 21, No.1 (2000), 13-19.

(26) Todoroki, A. and Yoshida, J., Electrical resistance change of unidirectional CFRP due to applied load, *JSME International Journal*, Vol. 47, No. 3 (2004), pp. 357-364.

(27) Angelidis, N. Wei, C.Y. and Irving, P.E., The electrical resistance response of continuous carbon fibre composite laminates to mechanical strain, *Composites Part A*, Vol. 35, No. 10 (2004), pp. 1135-1147.

(28) Myers, R.H. and Montgomery, D.C., *Response surface methodology*, (2002), John Wiley & Sons, Inc.