

Asymmetrical dual charge EPCM for delamination monitoring of CFRP laminate

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Abstract. CFRP laminate is sensitive to impacts. Even a low impact creates delamination, bringing deterioration of the structural reliability. Monitoring for delamination is, therefore, indispensable to maintain the reliability of a CFRP structure. In this study, asymmetrical dual charge electric potential change method was introduced to estimate a delamination in the CFRP laminate. Delaminations were estimated using response surfaces as solver of the inverse problem. Learning data of response surfaces were calculated by FEM analyses. Actual delaminations in the CFRP laminate were successfully identified.

Introduction

Carbon fiber reinforced plastic (CFRP) has been increasingly applied to the primary structure because of its high specific strength and stiffness. CFRP laminate, however, delaminates easily by an impact, reducing strength and stiffness of the laminate promoting overall failure of the structure. The simple monitoring method is required to maintain structural reliability and to reduce huge maintenance cost.

CFRP laminate is composed of electro-conductive carbon fibers and insulating resin. Health monitoring methods which utilize electrical change by applied load, temperature change, and fiber breakage have been studied [1-6]. Authors have proposed electric resistance change method (ERCM) and two-stage electric potential change method (TS-EPCM) to identify a delamination in the CFRP laminate [7-12]. Delamination was estimated from electric resistance or potential changes due to a delamination which were measured at electrodes mounted on the laminate surface.

For the ERCM, accuracy of estimation is high because a lot of electric charges are required to measure electric resistances between all neighboring electrodes. ERCM is, therefore, suited to be applied to parts of structure which requires high accuracy of estimation. For the TS-EPCM, current electrodes and voltage electrodes are mounted separately to adopt a four-probe method. Only a charge of electric current is enough to monitor the delamination by measuring electric potentials at voltage electrodes simultaneously. TS-EPCM is, therefore, suited to be applied to the large structure.

In this study, asymmetrical dual charge electric potential change method (ADC-EPCM) is newly proposed. As electric potentials are measured by two separate times of electric charges using four-probe method, the number of electric charge is reduced compared to ERCM. Although magnitude of electric potential changes are small in the TS-EPCM when delamination locates at center segment between current electrodes, which means high susceptibleness to experimental error, ADC-EPCM has no such a segment. The ADC-EPCM, therefore, has advantages of above two methods, overcoming the disadvantages. In this paper, ADC-EPCM is examined; delaminations in the CFRP laminate are estimated.

Specimen configuration

The specimen was 180mm long, 10mm wide, and 1mm thick (Fig.1). Stacking sequence was [0/90]s. Nine electrodes of 4mm long and 0.02mm thick were mounted on the surface of a specimen. It was assumed that electrodes were only mounted on the inside of a structure. Electrodes B, F and D, H were current electrodes, and A, C, E, G, and I were voltage electrodes. Electric potentials were measured by four-probe method. Delamination size was a projected length to the specimen surface, and delamination location was a distance from center of the specimen to center of the delamination. Delamination was assumed to be uniform to the y-direction (width direction).

Numerical analysis

Analytical method. Numerical calculations were performed by commercially available FEM code ANSYS. Four-node quadrilateral elements of 0.25mm long and 0.0625mm in height were used for two-dimensional analyses. This supposed that delaminations were created uniformly in the y-direction. Electric potentials of the nodes at each electrode were coupled to have same electric potentials. A delamination was created by means of separating two nodes that were placed at same position. This means that electric current does not flow through the delamination in the FEM analyses. Three shapes of delamination were supposed in FEM: straight delamination, Z-type delamination crack, and inverse Z-type delamination crack (Fig.2). Z-type and inverse Z-type delamination crack were straight delamination with matrix crack, which had largest effect to electric potential changes compared to the straight delamination [9]. Electric conductivity components of fiber direction, transverse direction, and thickness direction were $\sigma_0=4600$, $\sigma_{90}=4.83$, $\sigma_t=1.03$ [S/m], which were measured experimentally [7]. Thickness direction component included the effect of resin rich layers. The fiber volume fraction was 47.2%.

Asymmetrical dual charge electric potential change method. No electric current flowed to the thickness direction at $x=-20$ mm when electric current was charged from electrode B to F (current path 1) [10]. If delamination existed at $x=-20$ mm, i.e. the center between current electrodes, normalized electric potential changes were affected by the shape of delamination. Fig.3 shows normalized electric potential changes between electrodes AC, CE, EG, and GI obtained from FEM analyses when delamination of 5mm long located around $x=-20$ mm. Normalized electric potential changes were different dependent on the shapes of delamination when it located at $x=-20$ mm. Estimation of delamination showed large errors dependent on the delamination shapes when it located at center between current electrodes [10].

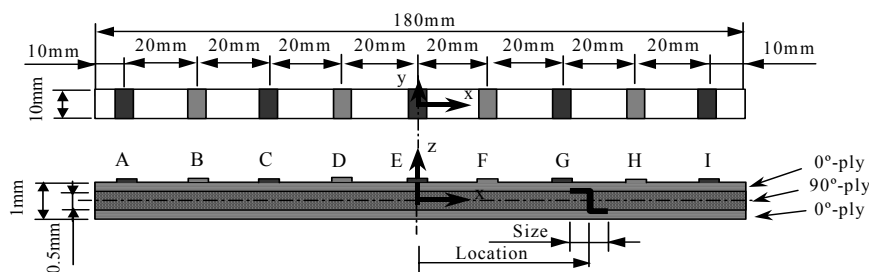


Fig.1 Configuration of specimen with nine electrodes

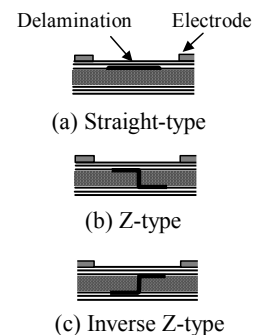
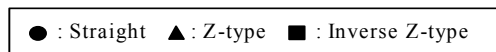
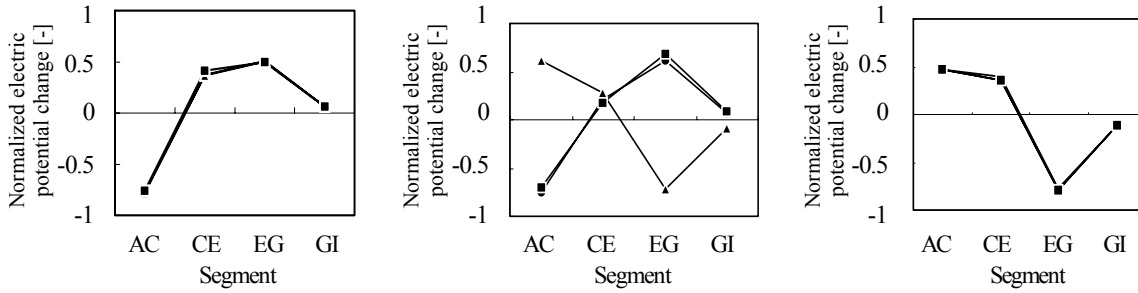


Fig.2 Delamination crack shapes used in the FEM analyses



(a) Delaminations locate at $x=-25\text{mm}$ (b) Delaminations locates at $x=-20\text{mm}$ (c) Delaminations locates at $x=-15\text{mm}$

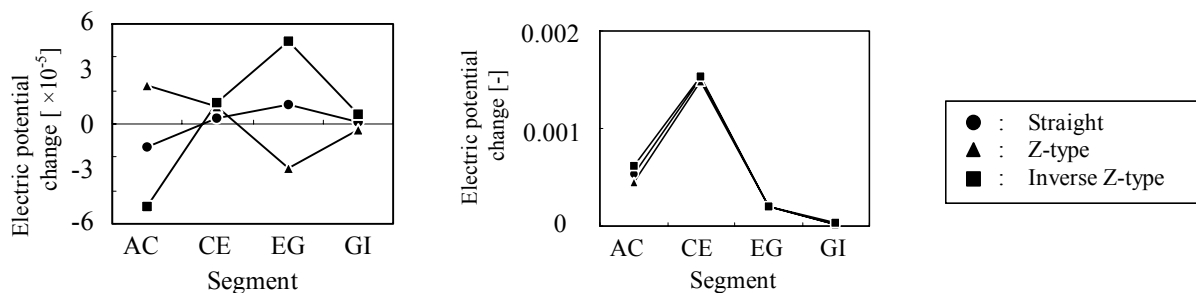
Fig.3 Normalized electric potential changes obtained from current path 1

Fig.4a and 4b show electric potential changes before normalization when delamination located at $x=-20\text{mm}$ and $x=-60\text{mm}$ respectively. If delamination located at the center between current electrodes (Fig.4a), the magnitude of electric potential changes was small compared to those due to delamination which located near current electrodes (Fig.4b). This was because of low electric current to the thickness direction at the center between current electrodes. Although the electric potential changes depended on the delamination shapes when it located at $x=-20\text{mm}$, it was negligible effect compared to those due to the delamination which located at $x=-60\text{mm}$.

Next, if electric current is charged from electrode D to H (current path 2) and delamination locates at $x=-20\text{mm}$, large electric potential changes can be obtained because it impedes the electric current to the thickness direction. The electric potential changes are not affected by the delamination shape.

Fig.5 shows normalized electric potential changes calculated from two sets of electric potential changes obtained by current paths 1 and 2 when delamination located at $x=-20\text{mm}$. In the figure, subscript indicates current path used to obtain the electric potential changes between electrodes. Although the electric potential changes by current path 1 were different dependent on the delamination shapes because of low electric current to the thickness direction, the magnitudes were small compared to those by current path 2. The electric potential changes obtained using current path 2 were not affected by the shapes of delamination because it located near the current electrodes. Therefore, normalized electric potential changes could be obtained independent on the delamination shape by using two sets of electric potential changes which were measured in two separate times of asymmetrical electric charge.

It is possible to locate delamination outside the current electrodes if electric current is charged asymmetrically as stated above. Fig.6 shows contour plot of electric potential in the CFRP laminate by current path 2 calculated by the FEM. Electric current flowed roundabout routes which were outside of the current electrodes because of strong anisotropy of the laminate. As delamination impeded the electric current, electric potential in the laminate changed. It is, therefore, possible to detect a delamination which locates outside the current electrodes.



(a) Delaminations locate at $x=-20\text{mm}$ (b) Delaminations locate at $x=-60\text{mm}$

Fig.4 Electric potential changes before normalization

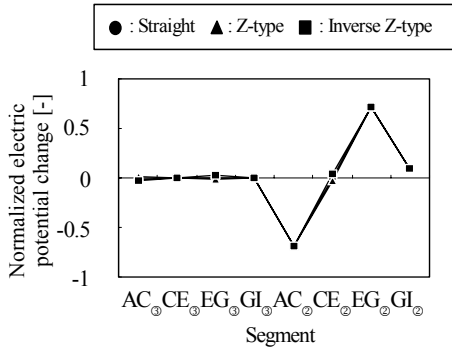


Fig.5 Normalized electric potential changes obtained from asymmetrical electric charges

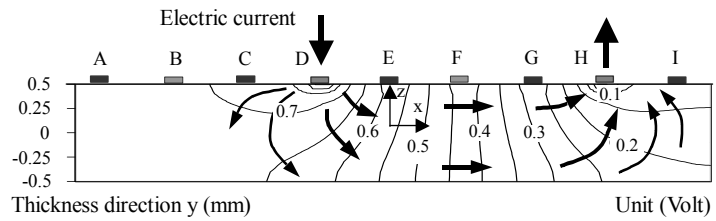


Fig.6 Contour plot of electric potential in CFRP laminate

Solver of inverse problem. In this study, response surface methodology was used to estimate delamination location and size from electric potential changes [13]. Electric current was charged from electrode B to F (current path 1), and electrode D to H (current path 2) separately. Electric potential differences between electrodes AC, CE, EG, and GI were measured for each case before and after creation of a delamination. Electric potential changes between electrodes were calculated from the electric potential difference between electrodes.

$$(i = AC, CE, EG, \text{ and } GI) \quad (1)$$

where $P_{\odot i0}$, $P_{\ominus i0}$ and $P_{\odot i}$, $P_{\ominus i}$ are electric potential differences between electrodes before and after creation of a delamination by current path 1 and 2, $\Delta P_{\odot i}$ and $\Delta P_{\ominus i}$ are electric potential changes between electrodes due to a delamination. $\Delta P_{\odot i}$ and $\Delta P_{\ominus i}$ were normalized together.

$$(2)$$

where L is a norm of electric potential changes, and Δp_i is the normalized electric potential changes.

The response surface was obtained using normalized electric potential changes as predictor variable, and delamination location as response variable. Norm was also used as a predictor variable when delamination size was a response variable. Quadratic equations were used as response surfaces.

$$(3)$$

Delamination location and size were estimated using the respective response surfaces. The significance of regression was estimated using the adjusted coefficient of multiple determination R_{adj}^2 .

$$(4)$$

where SS_E is a error sum of squares, SS_T is a total sum of squares, n is a number of data and k is a number of unknown coefficients. The range of adjusted coefficient of multiple determination is $0 \leq R_{adj}^2 \leq 1$. The higher value of R_{adj}^2 implies a good regression of supposed model.

Response surfaces. FEM analyses were performed to examine the estimation accuracy of the proposed method. Straight delamination (no matrix crack) was supposed in FEM. FEM analyses were performed for multiple cases: delamination sizes of 5, 10, 20, 30, and 40mm, and delamination locations from -80mm to 80mm with spacing of 5mm. Delaminations were located as not to create an open crack at the edge of the specimen. A total of 306 runs of FEM were performed to obtain learning data of response surfaces. To investigate the robust property for delamination shape, Z-type and inverse Z-type delamination cracks were estimated using the response surfaces. Those delaminations of 7, 15, 25, and 35mm size were also estimated to investigate the accuracy of interpolation. The data which included artificially created errors were also used as learning data to make robust response

surfaces for the experimental error. For normalized electric potential changes, less than 10% of errors of maximum values 1 were added. For norms, less than 10% errors were added. Above errors were created by random number.

Estimation results. Fig.7 shows estimation results of straight delamination, Z-type and inverse Z-type delamination cracks by the response surfaces obtained from results of FEM analyses of straight delamination. The adjusted coefficients of multiple determination were 0.991 for delamination location, and 0.996 for delamination size. The abscissas show delamination location or size, and ordinates show estimated location or size. The diagonal lines in the figures show exact estimation. The broken lines in Fig.7a and 7b show error bands of 10mm and 5mm. The degradation of estimation accuracy did not observed even if delamination located at center between current electrodes. Accuracy of estimation did not depend on the delamination shapes and showed a good performance of the method. The delaminations which were not used as learning data were also estimated accurately. The applicability of the ADC-EPCM was shown analytically.

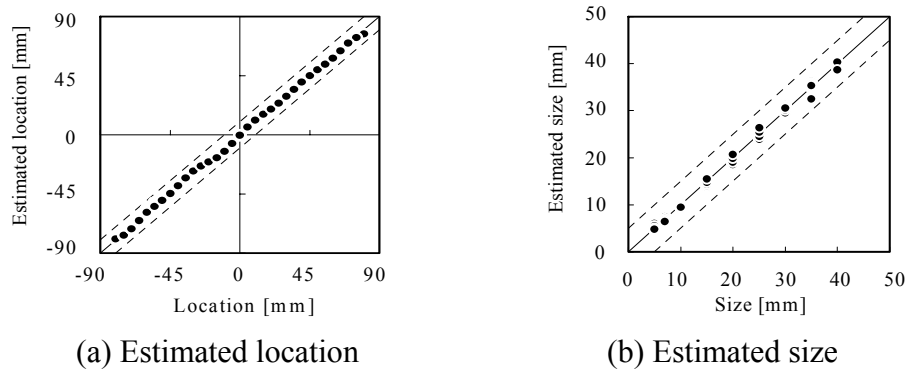


Fig.7 Estimation results of straight, Z-type, and inverse Z-type delamination cracks obtained by FEM

Experiments

Material. Laminates were fabricated from unidirectional prepreg sheets PYLOFIL#380 (Mitsubishi Rayon Co., Ltd). The autoclave molding method was used to fabricate [0/90]_s cross-ply laminate following the manufacturer's instructions. Specimens (180mm long and 10mm wide) were cut from the laminate plate, with a thickness of approximately 1mm (Fig.1). Fiber volume fraction was 65.5%. Electrodes were mounted on the specimens by co-cured copper foil (4mm long and 0.02mm thick).

An inter-laminar shear test was performed to create a delamination. The load was applied to the outside surface opposite to the electrodes. Delamination location and size were measured using a microscope. Delaminations were straight delaminations in the interlamina and matrix crack. It is observed by the ultrasonic C-scan image that delaminations were created uniformly along the y-direction.

Measurement of electric potential changes. A differential amplifier was used to measure the electric potential changes. Electric potential changes at voltage electrodes A, C, E, G, and I were amplified 1000 times. Amplified electric potential changes were measured by data logger PCD-320A (Kyowa Electronic Instruments Co., Ltd). Electric potential changes between electrodes were calculated from the data.

Search of equivalent electric conductivity. For the accurate estimation, equivalent electric conductivity which gives well agreement between FEM and experimental results was searched [12]. A total of 4 delamination tests were performed here. Delaminations were created in 4 specimens, whose locations were between electrodes A and B ($x=-64.9\text{mm}$, size was 17.8mm), B and C ($x=-52.7\text{mm}$, size was 20.7mm), E and F ($x=8.4\text{mm}$, size was 22.7mm), and F and G ($x=29.9\text{mm}$, size was 10.2mm). Electric potential changes were measured by current path 1. Equivalent electric conductivity was searched using the 4 sets of measured electric potential changes, by minimizing the error sum of square of electric potential changes obtained from FEM and experimental results. The equivalent electric conductivity was obtained as $\sigma_0=32000$, $\sigma_{90}=9.60$, $\sigma_t=8.32$ [S/m]. Fig.8 shows

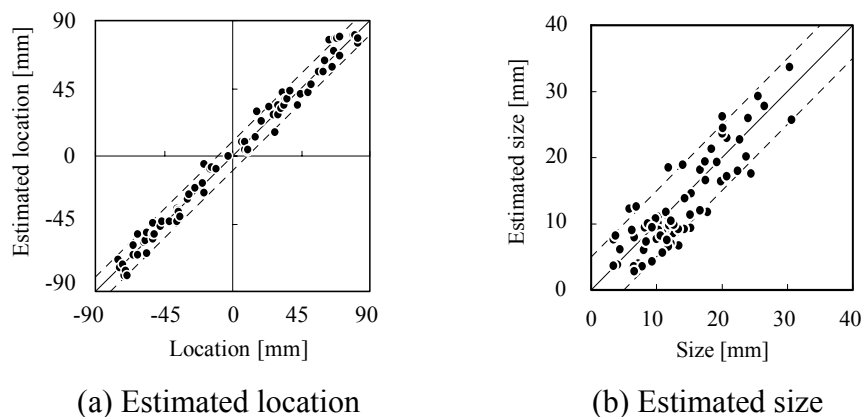
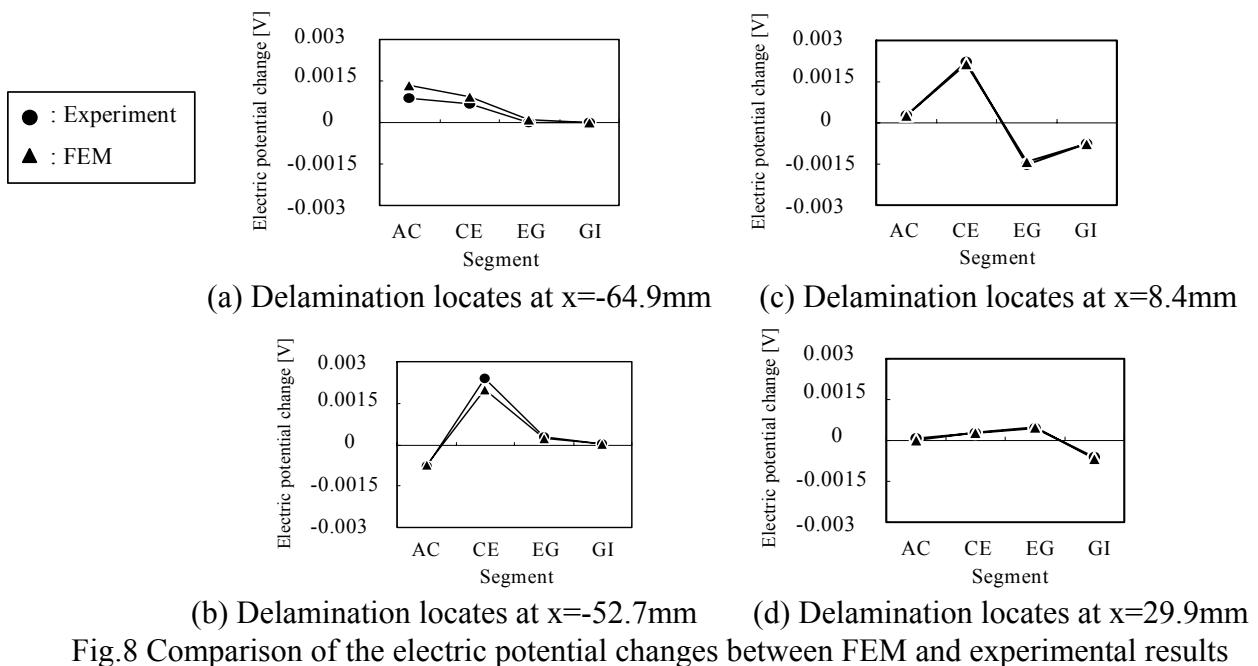
comparison of electric potential changes between electrodes obtained from FEM and experimental results. The results of FEM analyses showed good agreement to the experimental results.

Response surfaces. FEM analyses were performed using the equivalent electric conductivity to obtain learning data of response surfaces. Straight delamination was supposed in the FEM analyses. A total of 306 runs of FEM analyses were performed by same conditions used in the previous chapter. The data which included artificially created errors were also used as learning data.

Estimation results. A total of 70 delamination tests were performed, i.e. 70 sets of electric potential changes due to delaminations were measured. The delaminations were estimated using the response surfaces obtained from the results of FEM analyses. Fig.9 shows estimation results of all the delaminations. The estimation results showed good accuracy although the various shapes of delaminations were created. The delaminations which located at the center between current electrodes were also well estimated. ADC-EPCM successfully estimated delaminations experimentally.

Conclusions

ADC-EPCM was introduced to estimate delamination in the CFRP laminate. The applicability of the method was investigated analytically. Delamination tests were also performed. A total of 70 delaminations were estimated by using response surfaces obtained from FEM results. Actual delaminations in the CFRP laminate were successfully identified.



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