An Application of the Passive Electric Potential CT Method for Identification of Plural Delaminations in a Composite Material

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Abstract: The passive electric potential CT method was applied to the identification of plural delaminations in a composite material. The piezoelectric film was pasted on the surface of CFRP composite material subjected to three-point bending. The effect of the location of delaminations on electric potential on piezoelectric film was investigated. A hierarchical inversion scheme was proposed for identification of plural delaminations. For the estimation of the number of delaminations the Akaike information criterion was used. Numerical simulations were made to investigate the applicability of the passive electric potential CT method for the identification of plural delaminations from electric potential observed on the piezoelectric film. It was found that the present method was useful for the identification of the plural delaminations in the composite material.

1. Introduction

Non-destructive and real-time damage monitoring technique is important for maintenance of structures such as power plants, chemical plants, aircrafts, space structures and bridges. Non-destructive crack identification is recognized as a domain/boundary inverse problem [1,2], which deals with the estimation of an unknown boundary. Conventional NDT (non-destructive testing) methods such as ultrasonic method, radiation method, electric potential method and magnetic method may not be applied for the purpose, since they have some limitations in their applications for automatic inspection, non-contact inspection or remote inspection in severe environment. The intelligent structures [3] provide us continuous and real-time signals concerning damage initiation and propagation. They have a function of self-damage detection and monitoring and contribute to prevention of catastrophic failure of the structure.

Piezoelectric film is a sensing device that generates an electrical charge proportional to a change in mechanical strain. Several investigations have been conducted on the development of intelligent structures using piezoelectric materials. Galea et al. [4] showed the possibility of the use of piezoelectric PVDF (poly vinylidene fluoride) film as a sensing device for detecting and monitoring damages in composite materials. Yin et al. [5] carried out numerical analyses to demonstrate the feasibility of applying PVDF film for damage detection in composites. Li and some of the present authors [6] conducted theoretical and numerical investigation on the development of crack identification technique for the structures on which piezoelectric material was installed.

Some of the present authors [7-9] proposed the active electric potential CT (computed tomography) method for quantitative identification of two- and three-dimensional cracks, by applying inverse analyses to electric potential distributions observed on the surface of the cracked body under electric current application. The passive electric potential CT method, which did not require the application of electric current, was also proposed by gluing piezoelectric film on a cracked body subjected to mechanical load [10]. In this method the quantitative crack identification was made from the distribution of electric potential observed on the surface of piezoelectric film. Numerical simulations and experiments showed the applicability of the method to the identification of a single crack and plural cracks in a homogeneous body [11-13]. The method was applied to the identification of delamination in a composite material also [14, 15].

In this paper, the applicability of the method to the identification of plural delaminations is examined. Numerical simulations are carried out on the estimation of location, size and the number of delaminations, based on the inverse analyses.

2. Passive Electric Potential CT Method

On piezoelectric material electrical charge proportional to a change in mechanical strain is incurred. When the piezoelectric film is glued on cracked body or plate with delaminations, which undergoes mechanical load, electric potential distribution is incurred due to the piezoelectric effect without applying the electric current on the cracked body or the plate with delaminations. Some of the present authors [10] made theoretical and numerical investigation on the development of crack identification technique for the structures on which piezoelectric material was installed.

In piezoelectric material mechanical and electrical effects are coupled. Finite element method can be applied to calculate the electric field on the piezoelectric film as well as the deformation field.

3. Analysis Model

Delaminations in a carbon-fiber reinforce plastics (CFRP) composite material are investigated in this study. Quasi-isotropic laminate plate examined in this paper is shown in Fig. 1. The laminate plate has $[(0/90)_4]_s$ laminate configurations with 17 unidirectional laminates, where the number in the parentheses indicates the azimuthal angle of the fiber orientation with respect to the longitudinal axis *x*; the subscript “s” denotes that the lamina are symmetrically stacked about the neutral plane. The laminate is 160 (mm) in length, 20 (mm) in width, and 0.2 (mm) in thickness. The laminate plate has plural interlaminar delaminations throughout the width of the plate. For simplicity, it is assumed that the leading edges of delamination are straight and are perpendicular to the longitudinal direction of the laminate. On the top of the laminate plate piezoelectric film with thickness of 0.052 (mm) is glued. The laminate plate is subjected to three-point bending. Left edge of upper surface is sliding-supported and right edge of upper surface is pin-supported to prevent rigid body displacement. The load of 49 (N) is applied upward on the center-line.

Under these assumptions, j-th delamination can be represented by three delamination parameters, i.e. half length of delamination a_j, lengthwise location of left delamination tip x_{cj}, and the depth of delamination d_j. When a delamination exists between the i-th layer and the (i+1)-th layer, the depth of delamination is expressed as $d_j = i$.

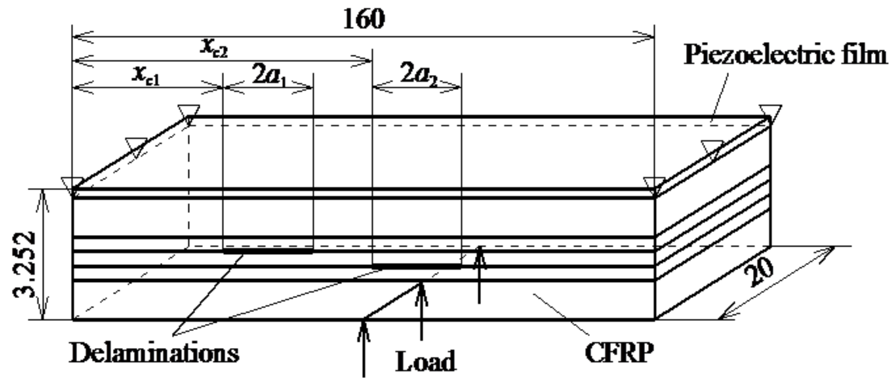

Fig.1 CFRP quasi-isotropic laminate plate with two delaminations used for analysis

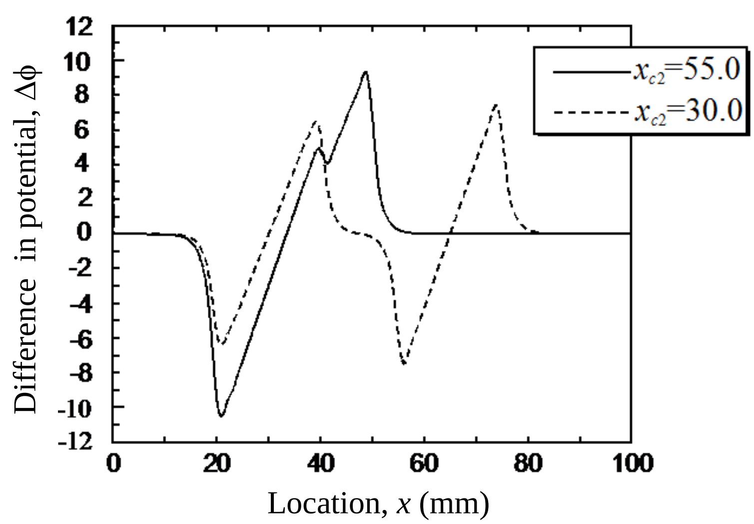

Fig. 2 Difference between electric potential with delamination and that without delamination (d_1=8, d_2=10, a_1=a_2=10.0, x_{c1}=20.0)

Figure 2 shows difference between the electric potential distribution with delaminations and that without delaminations. The difference is calculated using the finite element method for a_1=10.0, a_2 =10.0, d_1=8, d_2 =10 and x_{c1} =20.0. The value of x_{c2} is selected as x_{c2} =30.0 or x_{c2} =55.0.

From Fig. 2 it is seen that when the locations of delminations do not overlap in the longitudinal direction x, two local maxima and two local minima, and therefore four peaks, can be found. The locations of the peaks in the x-direction coincides with that of the leading edges of delaminations. On the other hand when the locations of delminations overlap in the longitudinal direction x, only 2 major peaks can be found. The effect of the delamination edge which locates below the other delemination is minimal. From these findings it is seen that the left end and the right end of all the delaminations can be easily estimated from the location of the peaks.

4. Inverse Analysis Scheme for Identification of Delaminations

As the inverse analysis method for the identification of delaminations, the least residual method [7] was applied. In this method, computed values $\phi^{(c)}$ are compared with the measured values $\phi^{(m)}$ to determine the most plausible delamination location and size. As a criterion for the identification of delaminations, the following square sum R_s of residuals is calculated.

$$R_s\,(d_1, d_2, a_1, a_2, x_{c1}, x_{c2}) = \sum_{i}^{M} \left(\phi_i^{(c)}(d_1, d_2, a_1, a_2, x_{c1}, x_{c2}) - \phi_i^{(m)} \right)^2 \quad (1)$$

Here $\phi_i^{(m)}$ denotes measured electric potential value at the i-th measuring point, and $\phi_i^{(c)}(d_1, d_2, a_1, a_2, x_{c1}, x_{c2})$ denotes the electric potential values at the i-th measuring point computed by the FEM, in which delamination parameters are assumed to be d_1, d_2, a_1, a_2, x_{c1} and x_{c2}. The values of a_1, a_2, x_{c1}, and x_{c2} are denoted in mm. M is the total number of measuring points. The combination of delamination length, depth and location, which minimized R_s, was employed as the most plausible one among all the assumed combinations of the delamination length, depth and location.

For effective inverse analysis, the following hierarchical calculation steps were introduced.

(a) In the first step, delamination depth d_1 and d_2 are roughly estimated. From the peaks of the difference in electric potential with delamination and that without delamination, the location in the x-direction of the left end and the right end of all the delmainations are roughly estimated.

(b) In the second step, the R_s value is calculated for the combinations of five values of delamination lengths a_1, a_2. It is assumed that R_s is approximated by a quadratic function of a_1 and a_2. The coefficients in the function is determined from the calculated R_s values. The combination of a_1 and a_2, which minimizes this approximate function for R_s, is employed as the plausible combination in the rough estimation of a_1 and a_2.

(c) In the third step, the combination of delamination parameters, which gives the minimum R_s, is searched by using the modified Powell optimization method [16]. The delamination parameters obtained in the above rough estimation are used as the initial values of the delamination parameters for the modified Powell method.

(d) In the forth step, for estimating the number of delaminations the Akaike information criterion (AIC) [17] is evaluated [18], which is defined by the following equation for the present problem.

$$\mathrm{AIC} = N\ \mathrm{loge}(R_s / N) + 2P \qquad (2)$$

Here N denotes the total number of measurements and P is the number of delamination parameters. The number of delaminations giving the smallest value of AIC is taken as the plausible one.

5. Results of Identification

5.1 Identification from Data without Noise

Numerical simulations are made for two types of plural delaminations, whose parameters are shown in Table 1. In the table the results of the rough estimates and the detailed estimates are also shown. Artificial noise is not introduced in the potential data used in this simulations. As can be seen from Table 1 the rough estimates give reasonable estimation of the delamination parameters. The delamination parameters are estimated with good accuracies when detailed estimation is made.

Table 1 Result of identification of two delaminations from potential data without noise

	$(d_1, d_2, a_1, a_2, x_{c1}, x_{c2})$	$(d_1, d_2, a_1, a_2, x_{c1}, x_{c2})$
Actual	(9,11,6.95,8.75,30.6,43.7)	(14,7,13.9,10.25,28.9,39.
Rough Estimate	(9,11,7.0,8.5,30.0,43.0)	(14,7,13.0,11.0,30.0,38.0)
Detailed Estimate	(9,11,7.0,8.8,30.6,43.6)	(14,7,13.9,10.3,28.9,38.9)

5.2 Identification from Noisy Data

The applicability of the proposed method to the identification of the delmaination from noisy data is examined. To simulate the experimental acquisition of potential $\phi_i^{(m)}$, artificial noise was added to the computed values obtained by the FEM. As the noise levels, 0.5%, 1.0% and 3.0% were selected. On the surface of PVDF film, electric potential was measured at points placed with an interval of 0.5 (mm). The total number of measurements N is equal to 239.

The delamination parameters were estimated using the least residual method with the modified Powell method assuming that the delaminations were single or plural. The number of delaminations was estimated using the AIC criterion. The number of delmination parameters P=3 for a single delamination, and P=6 for the plural delaminations. The estimated delamination parameters when the delaminations are assumed to be single and plural are shown with the values of residual R_s and AIC in Table 2.

For the plural delaminations, the value of AIC assuming the cracks are plural is smaller than that assuming the crack is single for all the noise level, indicating that the estimated number of cracks is 2. It is seen from Table 2 that the delamination parameters are estimated with good accuracies, even when the measurement noise level is 3%.

Table 2 Result of identification of two delaminations and AIC from noisy potential data

		$(d_1, d_2, a_1, a_2, x_{c1}, x_{c2})$	R_s	AIC with two delam.	AIC with single delam.
	Actual	(9,11,6.95,8.75,30.6,43.7)			
	0.50%	(9,11,7.0,9.1,30.4,43.2)	4.7	-924.8	-45.9
Noise	1.00%	(9,11,7.0,8.8,30.6,43.5)	10.7	-730.7	-32.3
	3.00%	(9,11,7.0,8.9,30.4,43.2)	91.8	-216.7	49.6

6. Conclusions

The passive electric potential CT method was applied to the identification of plural delaminations in a composite material. The piezoelectric film was pasted on the surface of CFRP composite material subjected to three-point bending. Numerical simulations were made to investigate the applicability of the passive electric potential CT method for the identification of plural delaminations from electric potential observed on the piezoelectric film. It was found that the inverse analysis using the least residual method and AIC criterion was useful for the estimation of the location and size of plural delaminations in the composite material. The number of delaminations can be estimated by applying the AIC criterion.

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