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Crack swarm inspection for estimation of crack location in carbon fiber reinforced plastics: A numerical study

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ABSTRACT

The present study proposes crack swarm inspection (CSI) for estimating crack location and size in carbon composite laminates from the surface voltage distribution. This technique generates a large number of virtual microscopic cracks, and calculates the surface voltage distribution of the composites using anisotropic electric potential functions and doublet strings. Using genetic algorithms, the virtual microscopic cracks formed a swarm to coincide with the measured surface voltage; thereby, the crack sizes and locations are estimated from the position of the crack swarm. The CSI was applied to crack detection in carbon laminated composite plates; it was confirmed that the existence of cracks in each partitioned section was detected with >80% probability, in reference to the crack location and size information. Furthermore, we also confirmed that the estimation accuracy was affected by the electric current density in the thickness direction, and addressed the recommended electrode interval based on the minimum size of the estimated crack.

1. Introduction

The applications of carbon fiber reinforced plastics (CFRPs) have expanded, particularly in the field of aeronautics, because of its outstanding specific strength and stiffness as compared with metals [1,2]. However, when CFRP laminated plates are used as a structural component, even small impacts can easily lead to delamination, considerably reducing strength [3]. To ensure the structural integrity (and to reduce the high costs incurred by periodic inspections), there is an urgent need for a health monitoring system for CFRP laminated plates. Previously, the following nondestructive inspection techniques have been used: ultrasonic inspection [4–6], X-ray inspection [7,8], acoustic emission (AE) [9,10], optical fiber inspection [11–13], and visual inspection. However, these methods are costly and time-consuming, or may decrease the structural strength by requiring an embedded sensor. Against this backdrop, there is a demand for a simple, non-destructive health monitoring process that detects delamination during periodic inspections or during operation. The monitoring method must be suitable for existing structures, and must not cause a reduction in strength by requiring sensors to be embedded.

As a useful health monitoring technique that can be applied during operation, the electrical resistance change method [14,15] has been proposed for monitoring fiber fractures [16,17], strain [18], and fatigue [19]. In this technique, the electrical resistances that arise because of delamination are measured using electrodes attached to the structural surface, so as not to cause a reduction in strength. The suggested technique was applied to monitoring the occurrence of delamination in CFRP laminated plates based on changes in the electrical resistance between a number of electrodes on the CFRP surface [20–23]. However, this method does present complex challenges for measurement systems because it is necessary to measure the electrical resistance of every current in all of the spaces between adjacent electrodes to measure the delamination-dependent changes in electrical resistance between electrodes. To address this problem, the electric potential difference technique is used; it involves installing a pair of electric current electrodes and a large number of voltage electrodes, making it possible to identify cracks using a single electric current [24–27]. However, these techniques require multiple tests and expensive numerical analyses; thus, there is a need to develop a technique that is simpler to implement.

A simple technique has been proposed for analyzing electric current density in CFRP, in which changes in voltage due to delamination are analyzed by installing a string of anisotropic doublets at separation points [28,29]. This technique makes it possible to

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analyze the electric current density of a CFRP laminated plate using a mirror image relationship. However, even though it is possible to calculate voltage changes with this technique in situations where delamination is known to have occurred, it is difficult to estimate the location and size of delamination from the voltage change.

Therefore, in this research, crack swarm inspection (CSI) is proposed, which estimates crack size and location based on a large number of virtual microscopic cracks in the inner layers of the CFRP using anisotropic electric potential functions and doublet strings. A genetic algorithm (GA) is used to minimize the difference with the voltage true value distribution and voltage distribution with virtual microscopic cracks in CFRP by changing the virtual crack position; thereby, the virtual cracks form a swarm, and the crack location and size are estimated from the crack swarm. CSI is applied to crack detection in unidirectional laminated plates, and its validity is investigated.

2. Crack estimation with crack swarm inspection

2.1. Overview of CSI

Fig. 1(a) shows a schematic diagram of the CSI method. CSI is a technique for estimating cracks by simulating many virtual cracks, which approximate the voltage distribution of damaged CFRP. One benefit is that this method allows estimation of internal cracks using only the surface voltage distribution data. The analysis process involves calculating the electric current density distribution in CFRP using an anisotropic potential function, and producing a large number of virtual microscopic cracks (unit cracks) by installing doublets [30] to oppose the electric current density in the thickness direction at the crack locations. This technique allows the position and size of cracks to be estimated using a genetic algorithm, which treats the position of cracks as a design variable, to minimize the difference between the surface voltage distribution of a CFRP that has crack swarm, and the real-world value of the voltage distribution measured in a cracked CFRP. This approach is shown in Fig. 1(b). In the present study, the aim is to investigate the delaminations in a unidirectional CFRP; as such, the virtual cracks modeled by doublets are placed in parallel to the specimen surface. To extend this to the estimation of transverse cracks in the multidirectional laminates, the directions of the doublets should be arbitrary and treated as variables.

2.2. Analysis of electrical current density using anisotropic electrical potential function

The electric potential function ϕ is calculated using the Cartesian coordinate system: the direction that the fibers are arranged into is labeled x, the transverse direction is labeled y, the thickness direction is labeled z; the current densities i_x, i_y, i_z are calculated using the following equations [31].

$$\begin{aligned} i_x &= -\sigma_x \tfrac{\partial \phi}{\partial x} \\ i_y &= -\sigma_y \tfrac{\partial \phi}{\partial y} \\ i_z &= -\sigma_z \tfrac{\partial \phi}{\partial z} \end{aligned} \tag{1}$$

Here, σ_x, σ_y, σ_z refer to the electric conductivity of the CFRP in the direction of the fiber, the transverse direction, and the thickness direction, respectively. If there is no electrical current source, the following equation can be derived from the equation of continuity.

$$\frac{\partial}{\partial x} i_x + \frac{\partial}{\partial y} i_y + \frac{\partial}{\partial z} i_z = 0 \tag{2}$$

If σ_x, σ_y, σ_z are constant regardless of location, then the following equation can be derived by substituting equation (2) into Eq. (1).

$$\sigma_x \frac{\partial^2 \phi}{\partial x^2} + \sigma_y \frac{\partial^2 \phi}{\partial y^2} + \sigma_z \frac{\partial^2 \phi}{\partial z^2} = 0 \tag{3}$$

Here, two dimensions, the fiber direction and the thickness direction, are considered. When a coordinate axis affine transformation is carried out as in Eq. (4), the Laplace equation shown in Eq. (5) is obtained.

$$\xi = \frac{x}{\sqrt{\sigma_x}}, \quad \eta = \frac{z}{\sqrt{\sigma_z}} \tag{4}$$

$$\frac{\partial^2 \phi}{\partial \xi^2} + \frac{\partial^2 \phi}{\partial \eta^2} = 0 \tag{5}$$

Eq. (5) resembles the velocity potential of an irrotational ideal fluid. Fig. 2(a) shows a schematic drawing of a CFRP beam with thickness t, which is the object of the anisotropic electric potential function. If there are current and earth electrodes on the same side of the CFRP beam, the electric current density analysis can be carried out on the CFRP using the velocity potential of an ideal fluid by setting the current electrode as a source point and the earth electrodes as a sink point. Assuming that the source (electric current load point) coordinates are $(-a, 0)$, and the sink (ground point) coordinates are $(a, 0)$ where $a > 0$, the electric current density is given by [28]

$$\begin{aligned} i_x &= \frac{I}{\pi\sqrt{\sigma_x \sigma_z}} \left\{ \frac{x+a}{\frac{(x+a)^2}{\sigma_x} + \frac{z^2}{\sigma_z}} - \frac{x-a}{\frac{(x-a)^2}{\sigma_x} + \frac{z^2}{\sigma_z}} \right\} \\ i_z &= \frac{I}{\pi\sqrt{\sigma_x \sigma_z}} \left\{ \frac{z}{\frac{(x+a)^2}{\sigma_x} + \frac{z^2}{\sigma_z}} - \frac{z}{\frac{(x-a)^2}{\sigma_x} + \frac{z^2}{\sigma_z}} \right\} \end{aligned} \tag{6}$$

Furthermore, when analyzing thin laminates, an affine-transformed ξ-η coordinate system contains an isotropic space; therefore, it is

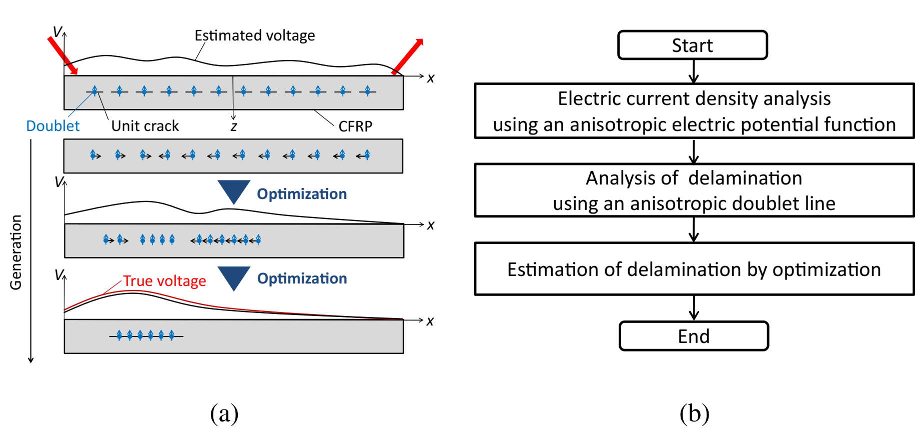

Fig. 1. Schematic of crack swarm inspection. (a) Basic concept for detection of cracks inside CFRP. (b) Flowchart of CSI.