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Test Method

A simple inverse analysis method for eddy current-based measurement of through-thickness conductivity of carbon fiber composites

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ABSTRACT

A simple inverse analysis method is proposed to measure the through-thickness conductivity of carbon fiber reinforced plastic (CFRP) laminates using eddy current testing. Finite element analyses were performed to investigate the relationship between the eddy current sensor signal and the anisotropic conductivity of a cross-ply CFRP. It was found that the resistive component of the impedance of the eddy current sensor changed with the through-thickness conductivity of CFRP, while the conductivity in the transverse direction had almost no influence on the sensor impedance. Using this characteristic and the conductivity in the fiber direction determined by fiber volume fraction, the through-thickness conductivity of a CFRP laminate was estimated from the resistive component of the impedance of the eddy current sensor. Experimental studies showed that the through-thickness conductivity estimated by the proposed eddy current testing method was in good agreement with that measured by the four-probe method. The proposed eddy current method enables fast and non-contact measurement of the through-thickness conductivity of CFRP laminates.

1. Introduction

Carbon fiber reinforced plastics (CFRPs) are lightweight materials with high strength and stiffness. They have been increasingly used as structural materials for aircraft and wind turbine blades. Generally, a CFRP is composed of straight continuous carbon fibers and a matrix resin. Layers with unidirectional carbon fibers are stacked such that fibers are oriented in multiple directions to increase the strength and stiffness in various directions.

Because carbon fiber is electrically conductive, CFRPs are conductive materials. Conductivity in the fiber direction of a unidirectional CFRP is approximately 1/1000 of the conductivity of metals [1]. Conductivities in the transverse and thickness directions are much smaller than conductivity in the fiber direction. Because more Joule heat is generated in a material with lower conductivity, CFRP structures are more severely damaged by lightning strikes than metals [2]. There have been attempts to improve electrical conductivity of CFRP for lightning protection by using conductive fillers in the matrix [3] or conductive polymer [4,5].

For assurance of sufficient electrical conductivity of the fabricated CFRP components, a method to measure electrical conductivity of CFRP is required. In particular, the through-thickness conductivity of CFRP depends on contacts between fibers, and is susceptible to manufacturing conditions such as the molding pressure [6]. Large variations have been observed when the through-thickness conductivity of different CFRP samples or at different locations in the CFRP was measured. Hence, measurement of the through-thickness conductivity is important for quality assurance of manufactured CFRP parts. Conventionally, conductivity of CFRP is measured by two-probe and four-probe methods that use electrodes mounted on the CFRP surface [1,7]. However, it is difficult to use these methods on CFRP parts manufactured for aircraft and wind turbine blades because small sample pieces must be cut from the parts and polished to apply the electrodes.

In this study, an eddy current testing method was developed to measure the through-thickness conductivity of CFRP. Because eddy current testing is a contactless nondestructive method that uses electromagnetic induction, it is potentially a fast and efficient way of measuring the conductivity of a CFRP. The present study numerically investigated the relationship between the anisotropic conductivity of CFRP and impedance of an eddy current probe. A new inverse analysis method is proposed to measure the through-thickness conductivity of CFRP using the obtained relationship. Experiments of eddy current testing were performed to measure the through-thickness conductivity of a cross-ply CFRP sample using the proposed inverse analysis method. The through-thickness conductivity measured by the eddy current testing method was compared with that measured by the four-probe method.

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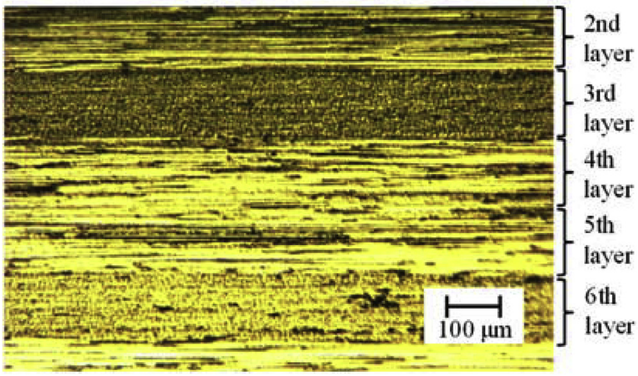

Fig. 1. Photograph of the cross section of an eight-layer cross-ply CFRP.

2. Materials

A unidirectional CFRP laminate and a cross-ply CFRP laminate were fabricated. The unidirectional CFRP was fabricated by press molding of prepregs (Toray Industries, Inc., T700SC/2592) and had a stacking sequence of $[0_{30}]$. The length, width and thickness of this laminate were 120 mm, 18.8 mm and 3.65 mm, respectively. This unidirectional CFRP was used to obtain a material property that was necessary for performing finite element method (FEM) analyses of eddy current sensor response. The cross-ply CFRP was an eight-layer laminate with a stacking sequence of [0/90/0/90]s. This laminate was also fabricated by stacking prepregs (Toray Industries, Inc., T700SC/2592) and curing them in a press forming machine. The length, width and thickness of this laminate were 60 mm, 60 mm and 1.15 mm, respectively. Fig. 1 shows a photograph of the cross section of the eight-layer cross-ply CFRP. Because no resin rich layer was observed between plies in this laminate, through-thickness conductivity of this laminate can be assumed to be through-thickness conductivity of the unidirectional ply. This cross-ply CFRP was used for eddy current testing to measure its through-thickness conductivity.

A unidirectional CFRP ply is an orthotropic material defined by three independent conductivities [8]: conductivity in the fiber direction σ_0, conductivity in the transverse direction σ_{90} and conductivity in the thickness direction σ_t. σ_0 is expressed as follows [9].

$$\sigma_0 = \sigma_f V_f + \sigma_m (1 - V_f), \tag{1}$$

where σ_f is the conductivity of the carbon fiber, σ_m is the conductivity of the matrix, and V_f is the volume fraction of fiber. The value of V_f is approximately 0.6 for commonly used CFRPs. When the matrix is an insulating resin, the second term in Eq. (1) is almost zero. The conductive polymer studied for lightning protection had a conductivity of approximately 100 S/m [4]. σ_f is still two orders of magnitude larger than the conductivity of the conductive polymer. Hence, σ_0 is approximated by the following equation.

$$\sigma_0 \approx \sigma_f V_f. \tag{2}$$

Eq. (2) shows that σ_0 is determined by V_f. Because the scatter of V_f is small in general CFRP, it has been reported that variation of σ_0 is much smaller compared with variation of σ_{90} and σ_t [7]. Values of σ_{90} and σ_t have large scatter even if V_f is identical because these properties depend on contacts between carbon fibers.

To investigate the effect of variation of σ_{90} and σ_t by numerical analyses, it is necessary to obtain the conductivity in the fiber direction σ_0. σ_0 was measured by a four-probe method for the unidirectional CFRP laminate. The four-probe method was chosen because this method can reduce the effect of contact resistance included in the measurement of low resistance samples [7]. Fig. 2 shows a schematic illustration of the four-probe method to measure the conductivity in the fiber direction. Silver paste was mounted on four locations to produce

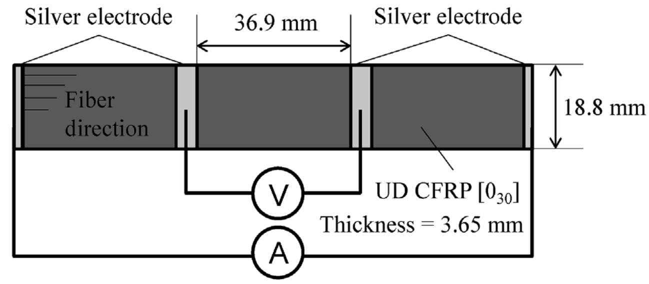

Fig. 2. Schematic illustration of the four-probe method to measure conductivity in the fiber direction.

electrodes as shown in Fig. 2. The electrodes on the edges of the sample were used to supply electric current. The inner electrodes were used for measurement of voltage. The four-probe method was performed by an LCR meter (HIOKI E. E. Corporation, IM3536). Impedance of the unidirectional CFRP was measured by the LCR meter at 100 Hz, and conductivity in the fiber direction was calculated. The impedance at this frequency was assumed to be the sample resistance because the phase angle of the impedance was almost zero. The calculated conductivity was 28,400 S/m. This value was input into σ_0 in the numerical analyses.

3. Numerical analysis

3.1. Analytical model

The relationship between the anisotropic conductivity of CFRP and the eddy current sensor signal was investigated using FEM analyses. The general-purpose FEM software ANSYS was used for the analyses.

The effect of the change of σ_{90} and σ_t on the eddy current sensor signal was investigated using FEM analyses. Fig. 3 shows the analytical model of eddy current testing for CFRP. A circular coil was used as an eddy current sensor and was placed above an eight-layer cross-ply CFRP plate with a stacking sequence of [0/90/0/90]s. The length, width and thickness of the plate were 60 mm, 60 mm and 1.15 mm, respectively. The stacking sequence and dimensions of the laminate were the same as those of the fabricated cross-ply CFRP sample. Each layer of the CFRP was modeled as a homogeneous orthotropic material defined by σ_0, σ_{90} and σ_t. It was assumed that each layer had complete electrical contacts at the interface because no resin rich layer was observed at the interfaces in Fig. 1. The modeled eddy current sensor was a coil with a number of turns n of 20, outer diameter d_o of 3.2 mm and height h of 2.8 mm. The distance between the bottom of the coil and the CFRP plate was 1 mm. It was assumed that the drive frequency of the coil was 1 MHz. Calculations were performed based on the *A*-φ formulation, which is commonly used to numerically solve eddy current problems. Number of elements in the model of the CFRP plate was 48,600. The impedance of the coil was calculated varying σ_{90} and σ_t from 1 S/m to 5 S/m. The value of σ_0 (28,400 S/m) measured by the four-probe method for the unidirectional CFRP was input into σ_0 in the FEM

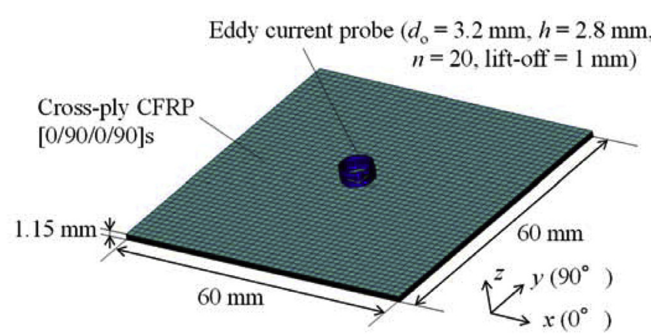

Fig. 3. Analytical model of eddy current testing for CFRP.