論文

브리지 회로 개념이 적용된 전기 전위법을 이용한 탄소섬유복합재료의 균열검출

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Crack Detection of Carbon Fiber Reinforced Composites by Electric Potential Method with Bridge Circuit Concept

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ABSTRACT

This paper suggested the electric potential method with a bridge circuit concept for the detection of the location and crack growth of carbon fiber reinforced composites to reduce the measurement numbers. 2 pairs of electrodes were fabricated on the center cracked thin composite plates, and potential changes at one pair of adjacent electrodes were observed while external voltage input was applied to the other pair of adjacent electrodes. The effects of the size and interval of electrodes, location and propagating direction of center cracks were investigated by experiments and finite element analyses. Detectable crack size was influenced by the electrode interval rather than the electrode size, and crack detection was enhanced as the size and interval of electrodes were smaller. Besides, output potential changes were larger as the crack grew and was nearer the voltage input electrodes.

초 록

본 논문에서는 탄소섬유 복합재료의 균열의 위치 및 성장을 감지하기 위하여 브리지 회로 개념이 적용된 전기 전위법을 제안하였다. 중앙 관통 균열을 가진 복합재료 박판 시험편에 두 쌍의 전극을 생성하였으며, 브리지 회로 개념을 적용하여 한 쌍의 전극에 외부 전압을 인가하고 다른 한 쌍의 전극으로부터 출력 전압 변화를 관찰하였다. 실험과 유한요소해석을 통하여 전극의 크기와 간격, 균열의 위치와 크기 및 성장 방향의 영향을 고찰하였다. 검출 가능한 균열의 크기는 전극의 크기 보다는 전극의 간격에 의한 영향이 더 컸으며, 전극의 크기와 간격이 작을수록 균열의 검출 능력이 우수하였다. 또한, 균열 크기가 증가할 수록, 입력 전극과 가까울수록 출력 전압의 변화가 큼을 관찰할 수 있었다.

Key Words : 전기 전위법(electric potential method), 브리지 회로 (bridge circuit), 탄소섬유 복합재료(carbon fiber reinforced composites), 균열 검출(crack detection)

1. Introduction

For the damage detection of carbon fiber reinforced composites, carbon fibers may be used as the sensors embedded in an insulating matrix because the resistivities of carbon fibers and polymeric matrix are of the order of 10^{-8} and 10^{20} Ωm, respectively. The changes in the electrical resistance of the composite can be expected when the conducting paths are modified by virtue of damage development in the carbon composites. Therefore, the non-destructive testing method based on the measurements maybe an effective way to detect damages in carbon fiber

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reinforced composites without strength reduction and special equipment [1]. The electrical resistance and potential methods have been validated by the several investigations of laminated carbon fiber reinforced composites subjected to tensile or flexural loading [2-5], in which it was concluded that the detection of macroscopic damage during monotonic loading was possible by means of the electrical resistance measurements and their relationships between the changes in the resistance and the information provided by damage indicators such as stiffness or microscopic observations [1]. However, most researches on the electric resistance and potential method of carbon fiber composites have been concentrated on the delamination cracks.

For the measurement of changes of resistance or potential difference between two electrodes, all the pairs of electrodes are requiring for locating cracks or damages. For example, we can assume a composite plate with 4 electrodes (2 pairs of electrodes). By the electrical resistance method, electrical resistance changes should be measured continuously twice and two sets of measuring equipment are required. If a bridge circuit, which consists of 6 resistors between 4 electrodes, is adopted, only one successive measurement of electric potential changes is necessary.

In this study, therefore, the electrical potential method with the bridge circuit concept was introduced for crack detection of unidirectional carbon fiber epoxy composites. The center cracked and single edge cracked thin composite plates were used to investigate the possibility of the electric potential method. Experiments and finite element analyses were conducted in order to investigate the effect of the location and propagating direction of center cracks as well as the effect of the size and interval of electrodes on the crack detection of unidirectional carbon fiber composites.

2. Experimental

2.1 Materials

The material used in this study is a unidirectional carbon fiber epoxy composite (USN150, SK Chemicals, Korea). Carbon fiber epoxy composite specimens, with the $[0]_{10T}$ stacking sequence were fabricated using vacuum bag degassing molding process under the recommended cure cycle. The mechanical properties of the composite materials are listed in Table 1.

For the reliable electrical measurement, an electrical conductive adhesive (Silver paste 3350C, ThreeBond, Korea)

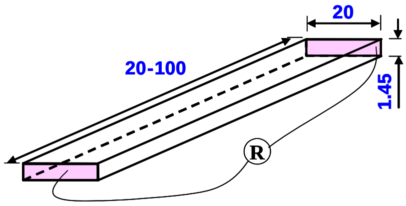

Fig. 1 Configuration of composite specimen for the resistivity measurement (unit in mm).

Table 1 Mechanical properties of USN 150

Longitudinal elastic modulus (GPa)	131.6
Transverse elastic modulus (GPa)	8.2
Shear modulus (GPa)	4.5
Poisson's ratio	0.28
Fiber volume fraction	0.62
Density (kg/m^3)	1560

Table 2 Electrical properties of silver paste

Composition	Silver powder and acrylic resin
Viscosity (Pa s)	3.01
Density (kg/m^3)	1.99
Volume resistivity (Ωm)	1.5x10^{-6}
Curing Condition	24 hours at ambient temperature

was used for creating electrodes and connecting the electrodes and electrical wires. Table 2 represents composition and electrical properties of the electric conductive adhesive used in this study.

2.2 Resistive Measurement

The basic electrical resistivities of composites were measured using the specimens of length of 100mm, width of 20mm and thickness of 1.45mm in the longitudinal, transverse, and thickness direction as shown in Fig. 1.

The resistance R of the composite can be expressed as follows:

$$R = \rho \frac{l}{A} + R_C \tag{1}$$

where ρ, l, A, and R_C represent the resistivity of the composite, length and area of the composite specimen, and the contact resistance between the electrodes and the composite, respectively. The resistivities of the composite were measured with the composite specimens with different dimension, from which the slope of resistance versus length or resistance versus area curves were drawn.

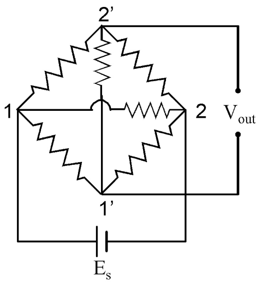

Fig. 2 Schematic diagram of the bridge circuit for modeling the internal resistance of composite specimens.

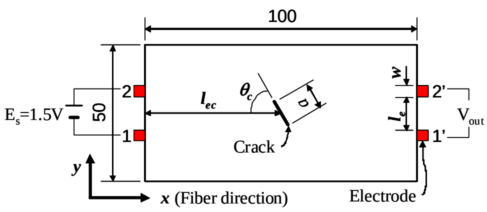

Fig. 3 Composite specimens for the crack detection by the electric potential method with the bridge circuit concept(unit in mm).

2.3 Electrical Potential Method

Six resistors (between electrodes 1-1', 2-2', 1-2, 1'-2', 1-2', and 2-1') may be considered for the composite specimens with the four electrodes as shown in Fig. 3. The position of the crack in the *x* and *y* coordinates can be determined with the measured electric resistance or potential changes between the electrodes 1-1', 2-2', 1-2 and 1'-2'. For this method, electric resistance or potential should be measured at least four pairs of electrodes.

For the bridge circuit concept of Fig. 2, similar to strain measuring circuit, after a constant external voltage is applied between the electrodes 1 and 2, the output voltage between the electrodes 1' and 2' is measured. The crack growth and location can be determined by measuring the electric potential changes between one pair of electrodes. Therefore, the electric potential method with the bridge circuit concept was also used in this work and validated for locating the crack and estimating the crack growth of the carbon fiber epoxy composites.

In order to investigate effects of position and propagating direction of center cracks, and size and interval of electrodes on the crack detection of unidirectional carbon fiber composites, four types of plate composite specimens with the center crack as shown in Fig. 3 were prepared. The electrical potential changes were measured between the electrodes 1' and 2', applying a constant electric voltage of 1.5V between the electrodes 1 and 2.

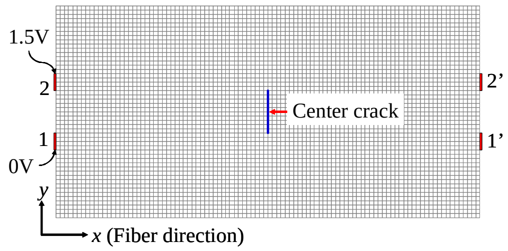

Fig. 4 Finite element model for analyses of electric potential changes with the bridge circuit concept.

3. Finite Element Analysis

3.1 Numerical Model

In company with the experimental approach, finite element analyses for the crack detection method were also performed. Since the diameter of carbon fiber is 7μm, which was smaller than the mesh size of finite elements adopted here, the homogeneous orthotropic properties of carbon fiber reinforced composites was assumed for the analysis. The resistivity measurement results were used for the electric resistivity in each direction for finite element analyses.

In an orthotropic electric resistance field, the direct electric current field is governed by the equation as follows:

$$J=\left(\sigma_x,\sigma_y,\sigma_z\right)\left(\frac{\partial\varphi}{\partial x}\quad\frac{\partial\varphi}{\partial y}\quad\frac{\partial\varphi}{\partial z}\right)^T \tag{2}$$

$$\nabla\cdot J=0 \tag{3}$$

where J, σ_x, σ_y, σ_z, and φ are electric current density (A/m^2), electric conductance in the *x*-, *y*-, and *z*-axis directions (A/m), and electric potential (V). Eqs. (2) and (3) are similar to the thermal conduction equations for orthotropic thermal conductance field. Therefore, orthotropic electric resistance field is considered as the thermal conduction equation analysis of commercial finite element software [3]. In this study, all finite element analyses were conducted with ABAQUS 6.4 (Hibbitt, Karlsson & Sorensen, USA).

3.2 Electrical Potential Changes

Fig. 4 shows the finite element model for analyses of electric potential changes with the bridge circuit in composite specimens. 5,000 two-dimensional elements with 8 nodes (CD2DE) of ABAQUS were used for finite element model and all the nodes on the crack surface were doubly defined to model the crack surface. When the crack grew, the doubly defined nodes were released with each other to give conditions for the electric current insulation [3, 6].

Using the bridge circuit concept, the electric voltages at electrodes 1 and 2 were set to 0V and 1.5V respectively, and the electric potential changes between the electrodes 1’ and 2’ were calculated by the equation as below:

$$\Delta\varphi = \left(J_{2'} - J_{1'}\right) \cdot A_e \qquad (4)$$

where $J_{1'}$ and $J_{2'}$ are the electric current density (A/m^2) through electrodes 1’ and 2’, respectively.

4. Results and Discussion

4.1 Resistivity of Carbon Fiber Epoxy Composites

Fig. 5shows the measured resistance of the unidirectional carbon fiber epoxy composite with respect to the length-to-area ratio of specimens, where the electric resistances of composite specimens increased linearly as expected as the length-to-area ratio (*l*/A) was increased. The resistivities in the longitudinal, transverse and thickness directions were 2.64x10^{-5} Ωm, 1.79x10^{-1} Ωm and 1.83x10^{-1} Ωm, respectively. The measured resistivities had the similar order of magnitude to the other data reported [1, 7].

4.2 Crack Detection by Electric Potential Changes with the Bridge Circuit Concept

In this study, the bridge circuit concept as mentioned above was introduced in order to overcome the disadvantages of conventional electric resistance and potential measurements. For the bridge circuit method, electric potential changes between a pair of electrodes were measured, and the finite element analyses were performed with respect to size and interval of electrodes, and location and propagation direction of cracks.

In order to study the effect of electrode size, the electrodes of width (*w*) of 2, 4, 6, and 10 with 10 mm gap (l_e) between the electrodes were prepared as shown in Fig. 3. The Center cracks were assumed to propagate along the transverse direction, that is, perpendicular to the fiber direction. Fig. 6 shows the experiment and finite element analysis results. The finite element analysis results were in good agreement with the experimental results even though there were differences of absolute values due to small changes

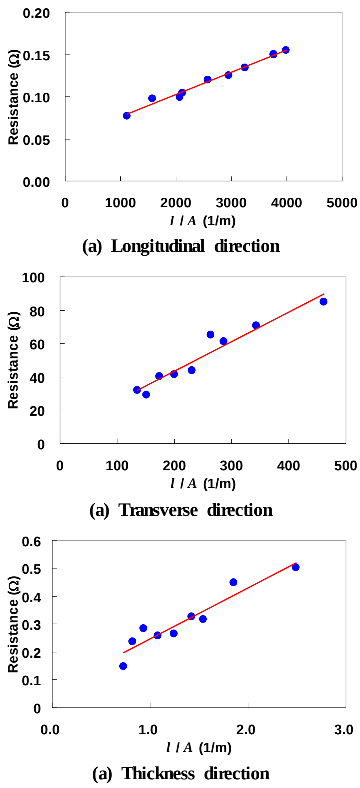

Fig. 5 Measured data of resistances of unidirectional carbon fiber epoxy composites with respect to the length-to-area ratio(*l*/*A*).

of contact resistance and external voltage. The voltage output was constant until the crack passed over the line connecting the opposite electrodes. From Fig. 6, it was found that the initial voltage output and the detectable crack size increased, and the difference of voltage output decreased as the electrode size increased. Therefore, it was concluded that small electrodes gave more effective and sensitive measurements because the difference of the voltage output was large when the electrode size was small.

For the effect of gap (l_e) of electrodes, the gaps (l_e) of 6, 10, 20, and 30 mm between the electrodes of 2 mm width (*w*) were fabricated on the composite plate specimens as shown in Fig. 3. The center cracks were assumed to propagate along the transverse direction, that is, perpendicular to the fiber direction. Fig. 7 shows that finite element analysis results were also in good agreement with the trend of experiment results. The tendency of the voltage output was similar to that of Fig. 6. From Fig. 7, it was found that the initial voltage output and the detectable crack size increased, and the difference of the voltage output decreased as the gap

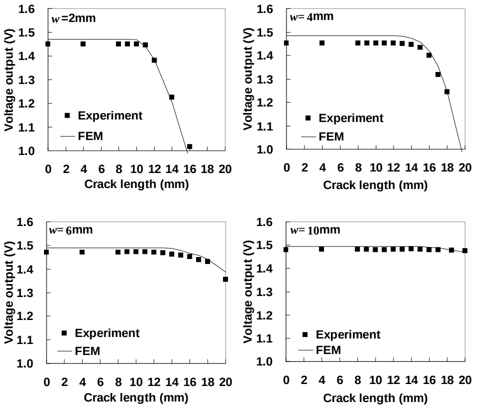

Fig. 6 Measured and calculated electric voltage output of unidirectional carbon fiber epoxy composites by the electric potential method with the bridge circuit concept with respect to the electrode size(w).

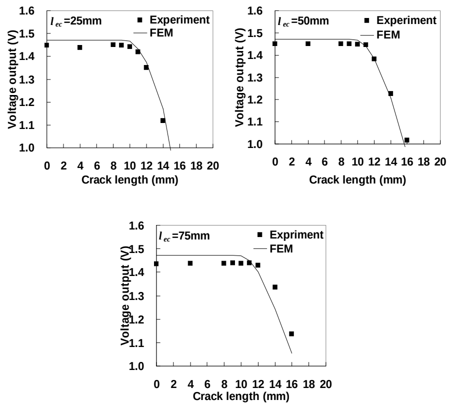

Fig. 8 Measured and calculated electric voltage output of unidirectional carbon fiber epoxy composites by the electric potential method with the bridge circuit concept with respect to the distance (l_{ec}) between the electrode and crack.

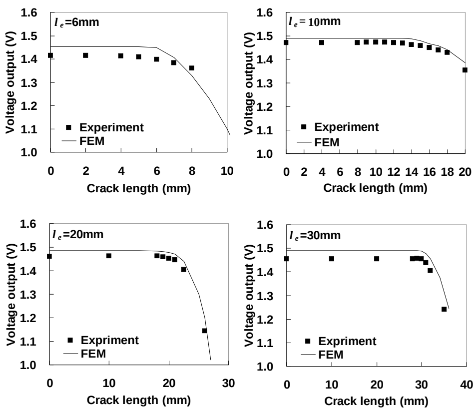

Fig. 7 Measured and calculated electric voltage output of unidirectional carbon fiber epoxy composites by the electric potential method with the bridge circuit concept with respect to the gap (le) between the electrodes.

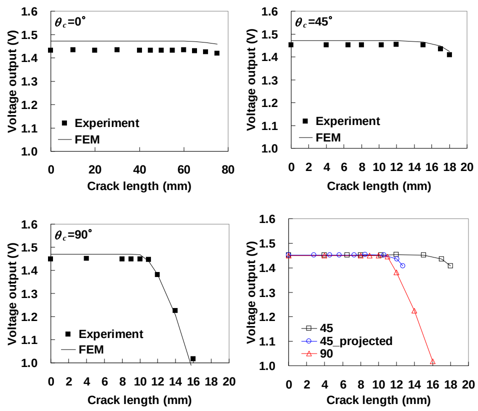

Fig. 9 Measured and calculated electric voltage output of unidirectional carbon fiber epoxy composites by the electric potential method with the bridge circuit concept with respect to the inclined angle(θ_c) to the fiber direction.

between the electrodes increased. The detectable crack size was about the same as the electrode interval and electric voltage began to vary after the crack passed over the line connecting the opposite electrodes. Therefore, it was concluded that small gap between the electrodes was more effective and sensitive.

In order to investigate the effect of the crack location, the cracks on the composite specimens were created with the distance between the electrode and crack (l_{ec}) of 25, 50, and 75 mm. In this case, the size (w) and gap (l_e) of electrodes were fixed to be 2 mm and 10 mm, respectively, as shown in Fig. 3. Cracks were assumed to propagate along the transverse direction, that is, perpendicular to the fiber direction. The finite element analysis results as shown in Fig. 8 gave similar results to the experiment results. The tendency of the voltage output was similar to that of Fig. 6. Since the size and electrode interval were same for this case, the detectable crack size was same regardless of the crack location. However, the difference of the voltage output was larger as the cracks were closer the electrodes for the external voltage input. So, it was concluded that the crack location influenced the voltage output.

For the propagation of the successive cracks in the inclined direction of fibers, the cracks were created with the inclined angle (θ_c) to the fiber direction of 0, 45, and 90 degree. The size (w) and gap (l_e) of electrodes were 2 mm and 10 mm, respectively. From Fig. 9, when the angle was 0 degree, that is, the crack propagated parallel to the fiber direction, the electric voltage change was 5mV at the crack length of 60 mm, which was very small compared to other cases. On the other hands, when the angle was 90 degree, that is, the crack propagated perpendicular to the fiber direction, the electric voltage changed 0.54V at the crack length of 10mm (same as the electrode interval) as shown in Fig. 9. This result was caused from the anisotropic electric properties of unidirectional carbon fiber epoxy composites. Therefore, the accuracy and sensitivity of the crack detection was different with respect to the direction of the crack propagation since the crack propagated the transverse direction reduces the current flow through the carbon fibers.

When the angle between the crack propagation and fiber direction was 45 degree, the crack lengths a_{cx} and a_{cy} in the *x*- and *y*-axis, respectively, are expressed as follows:

$$a_{cx} = a_c \cos\theta_c = \frac{a_c}{\sqrt{2}} \quad (5)$$

$$a_{cy} = a_c \sin\theta_c = \frac{a_c}{\sqrt{2}} \quad (6)$$

Using Eq. (6), the voltage output of the angle of 45 degree was replotted with respect to the projected crack length to the *y*-axis in last graph of Fig. 9. The voltage output change was observed when the crack grew 10 mm based on the projected length to the *y*-axis, which was the same as the 90 degree case. But the difference of the voltage output for the 45 degree case was smaller than that of the 90 degree case. From the results, it was concluded that the crack detection by the electric potential method with the bridge circuit was influenced on the projected crack length to the transverse direction rather than the real crack length, and the sensitivity was higher as the direction of the crack propagation was closer to the transverse direction.

6. Conclusion

In this work, the crack detection of unidirectional carbon fiber epoxy composites was measured by the electric potential method and simulated by the finite element analyses. With the electric resistance or potential methods, the *x* and *y* location of the crack could be determined by electric resistance or potential changes between the all the pairs of electrodes. In order to reduce the measurements, the electrical potential method with the bridge circuit concept was introduced. From the results of experiments and finite element analyses, it was concluded that the suggested method could detect the location of the crack and crack growth in carbon fiber epoxy composites, and as the size and gap of electrodes were smaller the sensitivity was better.

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