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Electrical impedance change method for moisture absorption monitoring of CFRP

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Abstract—Health monitoring techniques for CFRP composite structures have been developed to assure structural integrity. An electric impedance method is cost-effective and easy to apply to various structures. In an actual environment, moisture absorption may affect the electric impedance change of CFRP. In this paper, the influence of moisture absorption is investigated experimentally. The electric impedances both in the fiber direction and the transverse direction were measured during moisture absorption. For both directions, it was found that the electric impedance increased with moisture absorption. Furthermore, a monitoring method of moisture content near the surface is proposed and experimentally investigated. As a result, it is shown that the change of the electric impedance is relevant to the moisture content near the surface.

Keywords: CFRP; moisture content; electrical impedance; health monitoring.

1. INTRODUCTION

Structural health monitoring techniques to detect damage in CFRP integral structures have been developed to assure structural integrity. For example, techniques using optical fiber sensors [1–4], dynamic properties [5–8], electric properties [9–15] and acoustic emission [16] have been proposed. The health monitoring technique based on the electric resistance or impedance change of CFRP, which is generically named ‘the electric impedance change method’, is the focus of this study. The electric impedance change method does not need embedded sensors and expensive measurement instruments; so the application of the method does not induce structural degradation and it is also possible to apply the method to existent structures.

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The electric impedance change method has been applied to detect fiber breakage [9–12], delamination [13, 14], and matrix cracking [15]. The method is also applied to measure or monitor strain [17], degree of cure [18], and post-cure [19].

Banks *et al.* [20] report that the permittivity of CFRP at high frequency range (300 kHz to 3 GHz) increases according to moisture absorption. This implies that the influence of moisture absorption on the electric properties of CFRP cannot be neglected. In practice, DC or low-frequency AC measurement have been conducted in the electric impedance change method, but the influence of moisture absorption for low-frequency AC measurement has not been reported. In this study, the electrical impedance change on CFRP due to moisture absorption was experimentally investigated for low-frequency AC measurement. Acceleration tests of moisture absorption were carried out by immersing specimens into a water bath.

Moisture absorption of CFRP may affect the structural properties such as compressive strength, and thus moisture absorption is not negligible for CFRP structures of aerospace vehicles [21]. Based on the results, a health monitoring method of moisture absorption was proposed and the feasibility was demonstrated.

2. MEASUREMENT OF MOISTURE ABSORPTION

2.1. Specimen and experimental method

Moisture absorption tests were conducted based on JIS 7209. The specimen shape was a square plate of $50 \times 50 \times 3.3$ mm^3. CFRP prepreg used in this study was TOHO TENAX BESFIGHT Q-1112. $[0_{15}]_T$ laminates were cured by hot-press at 130°C for 1.5 hours. Specimens were cut from the laminates, and 2-axis strain gauges were mounted on both surfaces. After specimens were dried at 50°C for 24 h, the specimens were immersed into a water bath at 50°C to accelerate moisture absorption. The weight of each specimen was measured periodically by using an electronic balance, and the longitudinal and transverse strains were monitored during moisture absorption. Moisture content M (%) is described as

$$M = \frac{W_2 - W_1}{W_2} \times 100, \tag{1}$$

where W_1 is the weight of a dried specimen and W_2 is the weight of a moisture absorbed specimen.

2.2. Theory of moisture absorption

It is well known that moisture absorption of CFRP obeys Fickian diffusion theory. The total mass m of water in the plate at time t is expressed as follows [22].

$$m = \frac{4m_\infty}{\sqrt{\pi}}\sqrt{t}\left(\frac{1}{L}\sqrt{D_L} + \frac{1}{W}\sqrt{D_W} + \frac{1}{e}\sqrt{D_e}\right), \tag{2}$$

where m_∞ are the total mass of water in the plate at saturation, L, W, e are respectively the length, width and thickness of the specimen, and D_i is the diffusion coefficient in the i direction. Equation (2) can be applied until the moisture absorption decelerates due to saturation. Equation (2) means that the total mass of water in the plate is linearly proportional to the square root of time.

2.3. Results and discussion

Figure 1 shows the results of the moisture absorption test. In Figs 1a and 1b, the vertical axis is moisture content, and the horizontal axis is (a) time and (b) square root of time. The test was conducted for 120 days. The moisture content is linearly proportional to the square root of time up to 1.0% (55 days). This result means that equation (2) holds for the specimen.

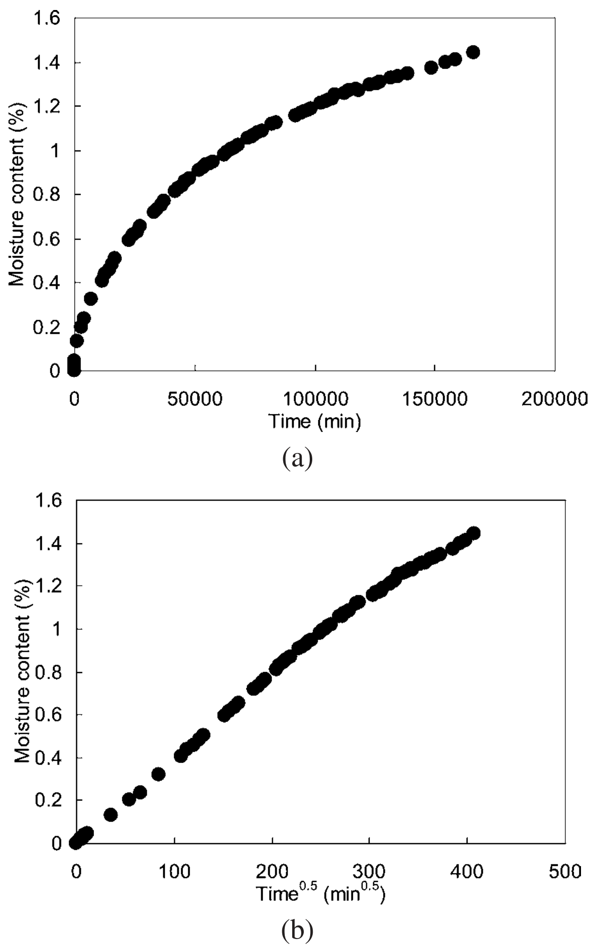


Figure 1. Moisture content.

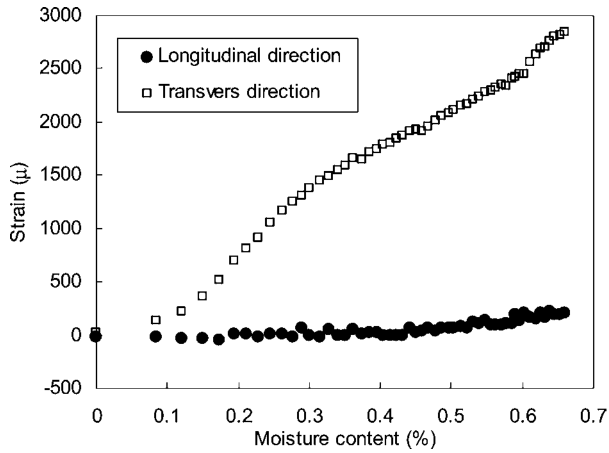


Figure 2. Strain due to water absorption.

Figure 2 shows longitudinal and transverse strains as a function of moisture content. When the moisture content reached 0.7%, a strain gauge debonded. The figure reveals that the change of the longitudinal strain is negligible, but the transverse strain increases significantly with moisture absorption. The reason is that carbon fiber does not absorb water but epoxy absorbs water and swells. In addition, the longitudinal elastic modulus of carbon fiber is considerably larger than that of epoxy. Note that, at the earliest stage of moisture absorption, the transverse strain does not increase until voids in the matrix are filled with water.

3. ELECTRICAL IMPEDANCE CHANGE

3.1. Specimen and experimental method

The electrical impedance during moisture absorption was measured by the four-electrode method shown in Fig. 3. Two current flow directions were chosen. The first one is a longitudinal direction, i.e. current flows through carbon fibers. The second one is a transverse direction, i.e. current flows perpendicular to carbon fibers. The measurement was conducted for 2 days in a water bath at 50°C. The experimental method is almost the same as mentioned before. The specimen configuration is shown in Fig. 3. The specimen was a rectangular plate of $80 \times 12 \times 3.3$ mm^3. Silver-paste electrodes were mounted after polishing the appropriate locations on the plate. After the silver-paste cured, the electrodes were coated by chloroprene rubber (Tokyo Sokki Kenkyujo N-1) to prevent debonding of the silver paste. An LCR meter (HIOKI E.E. 3532-50) was used to measure the electrical impedance and the phase of the specimen. The moisture content of each specimen was measured because the specimen shape was different from the experiments in Section 2.

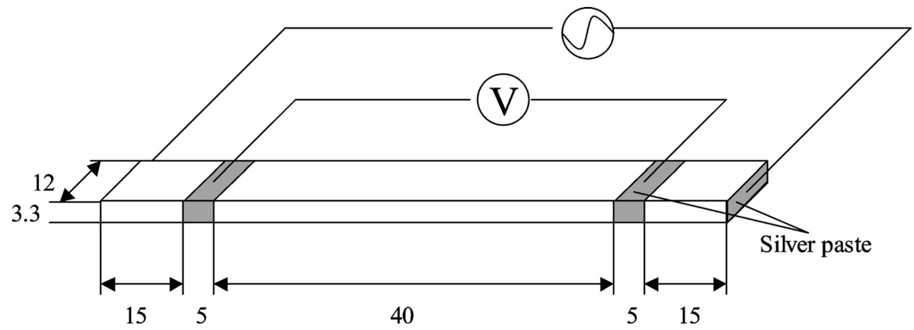


Figure 3. Specimen configuration for electric impedance measurement.

3.2. Frequency response

Frequency responses of the dried specimens are shown in Fig. 4. Figure 4a shows the results of the longitudinal current flow, and Fig. 4b shows the results of the transverse current flow. The phase is almost 0 up to 10^4 Hz for the longitudinal direction and at least 10^5 for the transverse direction. This means that the specimen is a resistor up to each frequency.

It is reasonable that the longitudinal direction is a resistor. The model of the current flow network in the longitudinal direction is shown in Fig. 5a. Carbon fibers have contacts among them in the specimen; thus it is supposed that not a simple parallel circuit but a current flow network is constructed in the specimen. An RC circuit is often used as an equivalent circuit for the transverse direction. However, results in Fig. 4b mean that the capacitive component is negligible up to at least 10^5 Hz because of the fiber contacts.

3.3. Electrical impedance change of longitudinal direction

The electrical impedance change was measured at 1 kHz because stable measurements were possible at that frequency. The electrical impedance and the phase change in the longitudinal direction as a function of moisture content are shown in Fig. 6a. The electrical impedance increased with moisture absorption. The phase change was small and negligible. The change of the electrical impedance in the longitudinal direction is about 5% for 0.1% of moisture content. It is shown that the electrical impedance is sensitive to moisture absorption. It is considered that there are several reasons for the increase of the electrical impedance. Swelling of the matrix increases the contact resistance between fibers, so some parts of the current flow network are virtually cut off and the network turns into a simple parallel circuit. Moisture absorption may increase the mutual inductance between carbon fibers and the matrix, so that the total electrical impedance may increase. The reason for the electrical impedance increase needs further and more detailed research.

In addition, the longitudinal tensile strain of CFRP unidirectional laminates increases the electric resistance on the order of 10^{-3} to 10^{-2} [17]. The electrical

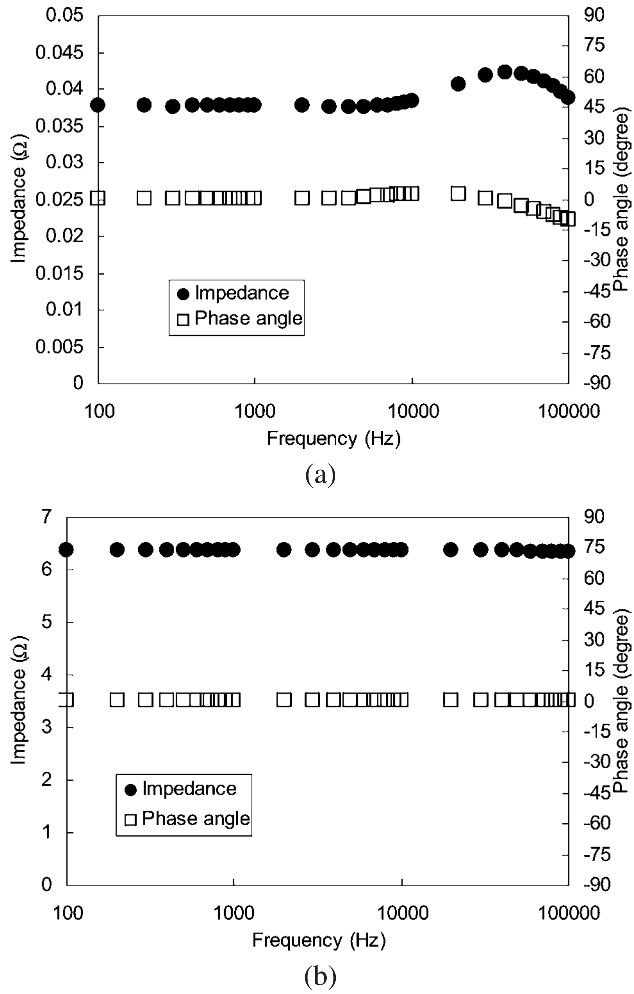


Figure 4. Frequency response of electric impedance and phase angle. (a) Longitudinal specimen. (b) Transverse specimen.

impedance change due to moisture absorption is larger than the electrical impedance change due to tensile strain corresponding to swelling.

3.4. Electrical impedance change of transverse direction

The electrical impedance and the phase change in the transverse direction as a function of moisture content are shown in Fig. 6b. The electrical impedance increased but the change of the phase was negligible, which was similar to the result in the longitudinal direction. The increase of the electrical impedance change is 0.4% for 0.1% of moisture content. This is less than 10% of the electrical impedance change in the longitudinal direction. It is presumed that swelling of matrix increases the contact resistance between fibers. The transverse tensile strain

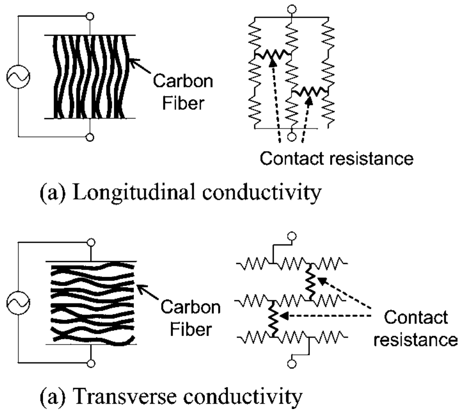


Figure 5. Model of electric conductivity.

of CFRP unidirectional laminates increases the electric resistance on the order of 10^{-3} to 10^{-2} as well as the electrical impedance change in the longitudinal direction [17]. The electrical impedance change due to moisture absorption is of the same order as the electrical impedance change due to tensile strain corresponding to swelling.

As a result, it is experimentally shown that a CFRP unidirectional laminate is a resistor regardless of the direction of current flow. Also, the electrical impedance increases with moisture absorption but the phase change is negligible. The electrical impedance change in the longitudinal direction is larger than the electrical impedance change due to tensile strain corresponding to swelling. On the other hand, the electrical impedance change in the transverse direction is of the same order as the electrical impedance change due to tensile strain corresponding to swelling.

4. APPLICATION TO MONITORING

4.1. Monitoring of moisture content of CFRP structure

The experimental results indicate that the electrical impedance of CFRP laminates increases with moisture absorption. The longitudinal electric conductivity of CFRP is 10^2 to 10^3 times larger than electric conductivities in the transverse and the through-thickness direction. This implies that the electrical impedance in the fiber direction of the outmost layer of composite laminated structures is not affected by the internal layers, except for the existence of delamination near the electrodes [13–15]. In other words, monitoring of moisture content of composite laminated structures is possible by mounting electrodes on a single surface of composite laminates to flow current in the fiber direction. In this study, the feasibility of the monitoring method is experimentally demonstrated

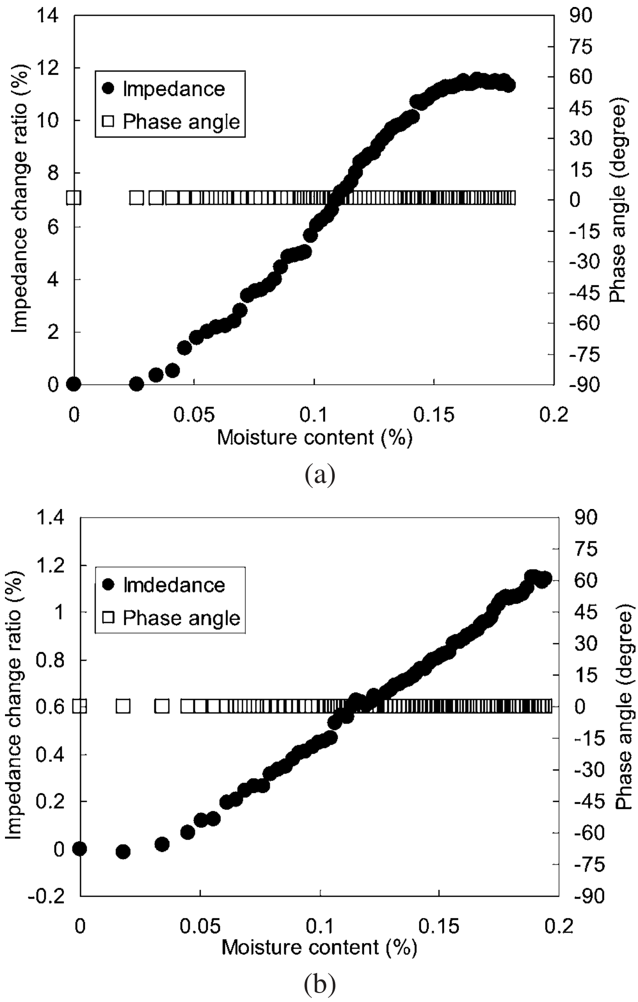


Figure 6. Impedance change ratio. (a) Longitudinal specimen. (b) Transverse specimen.

by a monotonous moisture absorption test and an iterative moisture absorption–desorption test.

4.2. Specimen and experimental result

The specimen configuration is shown in Fig. 7. It is a square plate with four co-cured copper electrodes. The size is the same as that used for the moisture absorption test in Section 2. After curing the specimen, the electrodes were coated with chloroprene rubber (Tokyo Sokki Kenkyujo N-1) to prevent debonding of electrodes. An LCR meter (HIOKI E.E. 3532-50) was used to measure the electrical impedance and the phase of the specimen. For desorption, the specimen was placed in a furnace at 50°C, which was the same temperature as the water bath.

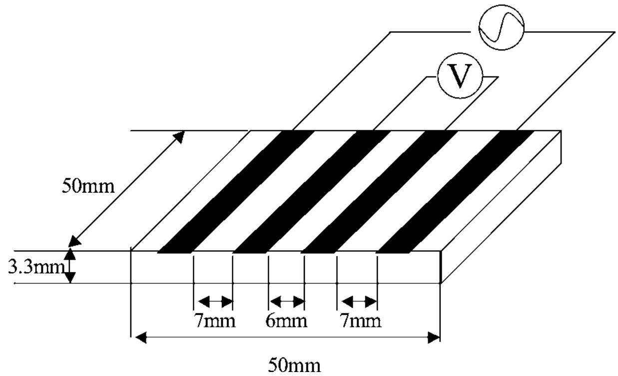


Figure 7. Specimen configuration for water absorption monitoring.

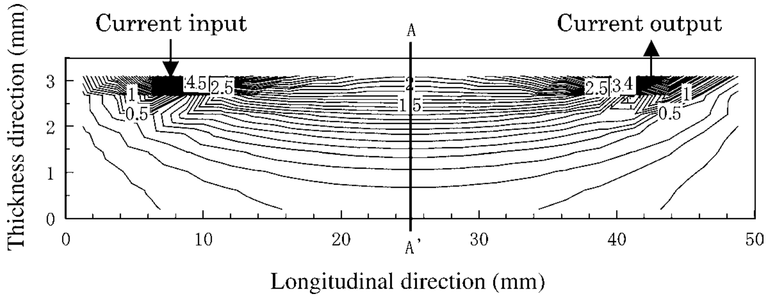
4.3. Current density in the specimen

In order to estimate the depth of current flow in case the electrodes were mounted on a single surface, and the distribution of current density was analyzed by a commercial FEM code, ANSYS. Figure 8 shows the distribution of current density. For simplicity of analysis, the electrodes are point-sources, and a DC current of 3 mA was applied instead of AC. The electric conductivity of CFRP in Ref. [13] was used for the analysis. Figure 8a shows the distribution of the current density in the cross-section of the specimen, and Fig. 8b shows the current density in the through-thickness direction of the center of the specimen, which corresponds to A-A′ in Fig. 8a. The vertical axis is the coordinate of the thickness direction, and the horizontal axis is the current density. Since the electric conductivity of CFRP is significantly anisotropic, current mainly flows through the outmost layer even if DC is applied. In the case of AC, it is supposed that more current flows through the outmost layer because of the surface effect of AC. This implies that it is possible to measure the moisture content of the outmost layer of CFRP laminated structures by mounting electrodes on a single surface.

4.4. Electrical impedance change of monotonous moisture absorption

The electrical impedance change as a function of average moisture content in the case of monotonous moisture absorption is shown in Fig. 9. The period of moisture absorption was 120 days. As well as the rectangular specimens in section 3, the electrical impedance increased with moisture absorption. Also, the relationship between the electrical impedance and the moisture content is linear until moisture absorption decelerates due to saturation. After 1% of moisture absorption, the electrical impedance dramatically increased. It is supposed that the contact resistance between fibers significantly increases because high moisture content induces debonding between fiber and matrix [23, 24].

The electrical impedance change of the square specimen whose electrodes are mounted on the single surface is half as much as the electrical impedance change of



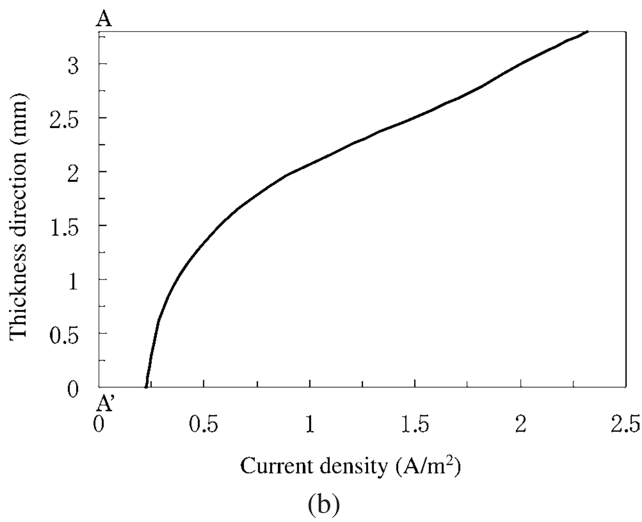


Figure 8. Current density distribution. (a) Contour of current density. (b) Current density on A-A′ section.

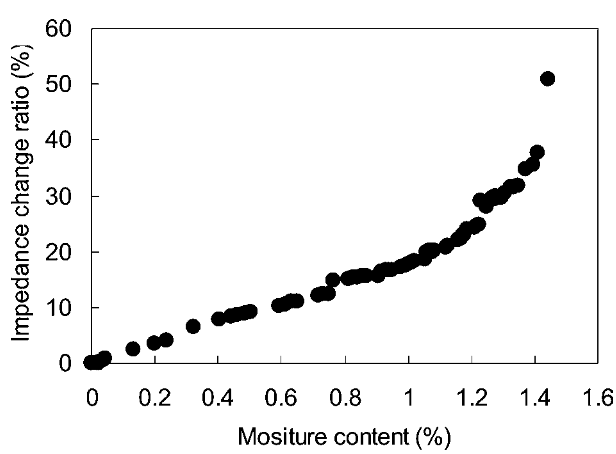
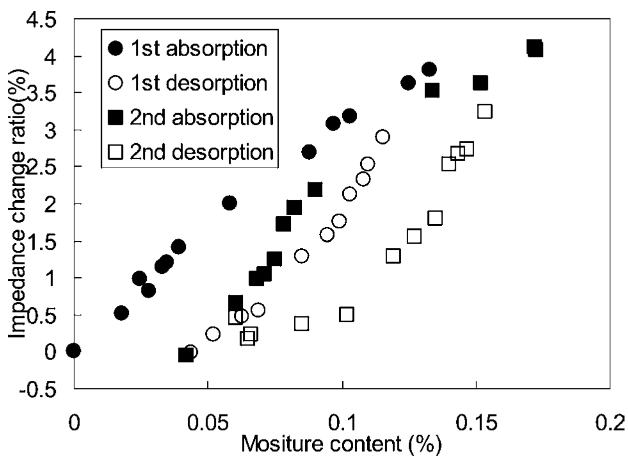


Figure 9. Impedance change ratio for long term water absorption.

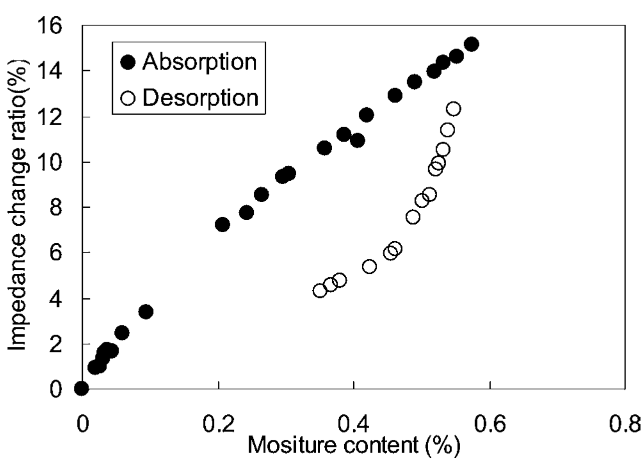
the rectangular specimen for the longitudinal current flow. The current in the square specimen flows not only in the fiber direction, but also in the through-thickness direction of the outmost layer. Since the electrical impedance change in the through-thickness direction is much smaller than that in the fiber direction, the total change is presumed to be smaller. Nevertheless, the electrical impedance change for 0.1% of moisture absorption is about 2%. This is large enough compared to the electrical impedance change due to tensile strain corresponding to swelling.

4.5. Electrical impedance change of iterative moisture absorption and desorption

The electrical impedance change as a function of average moisture content in the case of iterative moisture absorption and desorption is shown in Fig. 10a. Two cycles of moisture absorption for 2 days and desorption for 2 days were carried



(a)



(b)

Figure 10. Impedance change ratio for absorption and desorption. (a) 2 days. (b) 30 days.

out with a total time of 8 days. The maximum moisture content in the test was 0.15%, which corresponds to about 10% of saturation. Hysteresis was observed during moisture absorption and desorption. The curve is slightly convex during moisture absorption, and slightly concave during moisture desorption. The moisture content near the surface is higher than the average moisture content during moisture absorption, and is lower during moisture desorption. Thus, the experimental results mean that the moisture content near the surface can be measured by the proposed method.

The electrical impedance change as a function of average moisture content in the case of moisture absorption and desorption for a long term is shown in Fig. 10b. Moisture absorption for 30 days and desorption for 10 days was carried out with a total time of 40 days. The maximum moisture content in the test was 0.6%, which corresponds to about 40% of saturation. The hysteresis was larger than that for the short term iteration, but this is reasonable as mentioned before.

These experimental results show that electrodes mounted on the single surface is applicable to measure the impedance change due to moisture content. They also show that the measured electrical impedance change is relevant to the moisture content near surface.

5. CONCLUSIONS

The influence of moisture absorption on the electrical impedance of CFRP was investigated experimentally. Specimens were immersed into a water bath and the electrical impedances were measured during moisture absorption. As a result, it is shown that the specimen is a resistor regardless of the current flow direction: the electrical impedance increases with moisture absorption, and the electrical impedance change in the fiber direction is much larger than the electrical impedance change due to tensile strain corresponding to swelling.

In addition, monitoring of moisture content by mounting electrodes on the single surface of a composite laminate is demonstrated by moisture absorption and desorption tests. It is shown that the electrical impedance change is relevant to the moisture content near surface.

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