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ELECTROMECHANICAL MODELING OF UNIDIRECTIONAL CFRP COMPOSITES

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ABSTRACT

The electrical resistance behavior of conductive carbon fiber reinforced composites under the loading/unloading process is investigated experimentally and analytically. The well-known recovery of the conductivity in a multi-fiber composite during the unloading process is investigated using the single fiber composite, consisting of a single fiber in a polymer. Based on the experimental hysteresis curve of conductivity for a fragmented single fiber, the authors modify our previous discrete network model. Predictions for the electrical resistance behavior have good agreements with the experimental results.

KEYWORDS

Composite, Fiber break, Electrical sensing technique, Nondestructive inspection

INTRODUCTION

In the use of conductive carbon fiber reinforced composites, the insitu and nondestructive inspection should be clearly established. However, since fiber damages occur at the microscopic level (Fig. 1), the monitoring technique considering the micro-damages are required. As argued by some studies[1-6], the measurement of the electrical resistance change for the engineering application has been expected to be one of the promising techniques. Although experimental results imply that the electrical resistance change has a correlation with fiber breaks, the micro-mechanism and theoretical modeling have not been well discussed. The main reason is the lack of understanding of the internal contacts between carbon fibers. Recently, we proposed a new theoretical model to account for the conducting path formed by the fiber contacts [7]. The present theoretical model assumes the concept of an electrical ineffective length as the finite length δ_{ec} over which a broken carbon fiber loses its current-carrying capacity. Therefore, as shown in Fig. 2, the conductive composite can be modeled as a series array of parallel fiber resistors of length δ_{ec} such that fiber damage within one length δ_{ec} does not affect the resistance of other sections of the composite.

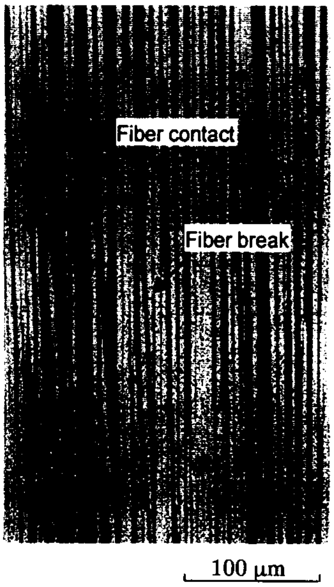

Figure 1: Photograph of CFRP composite

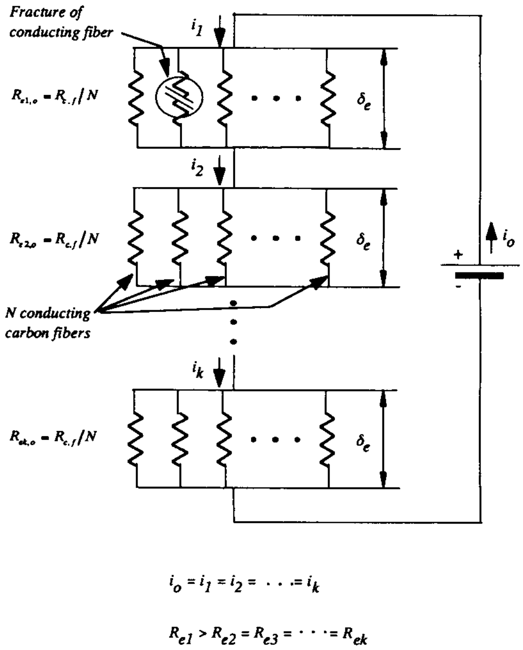

Figure 2: Schematic figure of discrete network model

Then, taking into account the linear dependence of fiber resistance as a function of the strain and the Weibull strength distribution over the length δ_{ec}, we have derived an expression for the resistance change ΔR_{total} normalized by the initial composite resistance $R_{total,o}$ as

$$\frac{\Delta R_{total}}{R_{0,total}} = \frac{(1+\alpha\varepsilon)}{1-P_f(\varepsilon)} - 1 \qquad (1)$$

$$P_f(\varepsilon) = 1 - \exp[-(\frac{\delta_{ec}}{L_0})(\frac{E_f\varepsilon}{\sigma_0})^m] \qquad (2)$$

where E_f is the fiber Young's modulus, α is the proportionality constant between single fiber strain and resistance, σ_o is the stress for one break to occur in Length L_o and m describes the statistical scatter. The above model can predict the resistance change during the tensile load. The δ_{ec} is also found to be the average distance between fiber contacts by the application of the percolation theory [8]. The insitu monitoring of cumulative microdamages during the cyclic load is also important. Some researchers [3,5] have pointed out that the residual electrical resistance is a useful parameter to detect the loading history of the composite. However, as argued by Arby et al.[5], the residual electrical resistance is remarkably reduced during unloading. In the present study, we measure the electrical resistance of a single fiber composite to investigate the basic mechanism for the recovery of an electrical conductivity in a multifiber-reinforced composite during the unloading process. Based on the hysteresis curve of the single fiber composite after a first fiber break, we modify our previous theoretical model to explain the electrical resistance change of multifiber-reinforced composites under the cyclic load. Although the model requires further development and verification, comparisons with experimental results show good agreements.

EXPERIMENT

We measured the electrical resistance in T700S type carbon fiber/ 2500 epoxy matrix CFRP composites under the gradually increasing loading/unloading cycles. Using the applied maximum strain ε^{max}, the electrical resistance change is given as

$$\frac{\Delta R_{total}}{R_{0,total}} = \frac{(1+\alpha\varepsilon)}{1-P_f(\varepsilon^{\max})} - 1 \qquad (3)$$

As shown in Fig. 3, although the theoretical line has a reasonable agreement with the experimental results, the difference increases as the strain approaches to the perfectly unloading process.

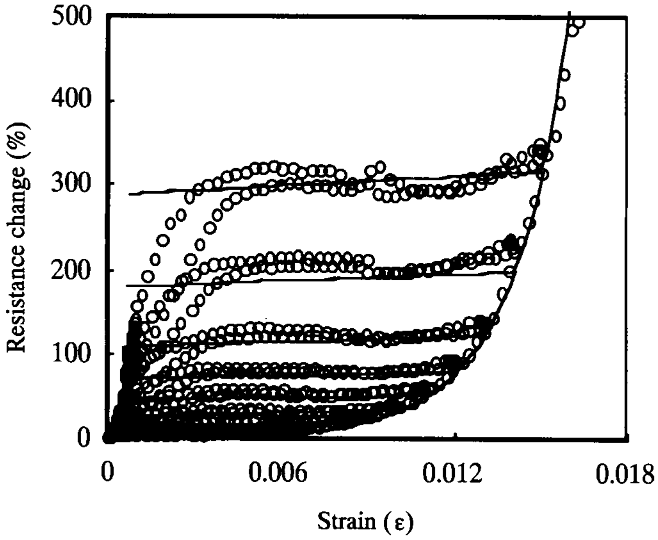

Figure 3: Resistance change curves of loading/unloading cycles

To investigate the mechanism of this difference between our model and experimental results, we measured the electrical resistance of a single fiber composite with the same specimen configuration to as multifiber-reinforced composites. Figure 4 shows the electrical resistance versus test time. As shown in Fig. 4, before a first break, the electrical resistance increases linearly. After that, the fiber becomes nonconductive. However, the electrical conductivity recovers during an unloading process. This behavior is also seen after the 2nd cycle. Therefore, the recovery of an electric conductivity in a multifiber-reinforced composite is originated from this recovery in a fragmented single fiber . This is the first main result of the present paper.

Figure 5 shows the relation between current i versus voltage V during the unloading process. The relation i-V is linear. Therefore, the conductivity in a broken part of the embedded single fiber is found to be ohmic. The fiber strain is still positive when the conductivity of a fragmented single fiber recovers, as shown in Fig. 6. Herein after, to remove the thermal residual strain in a single fiber, the fiber strain ε is used as

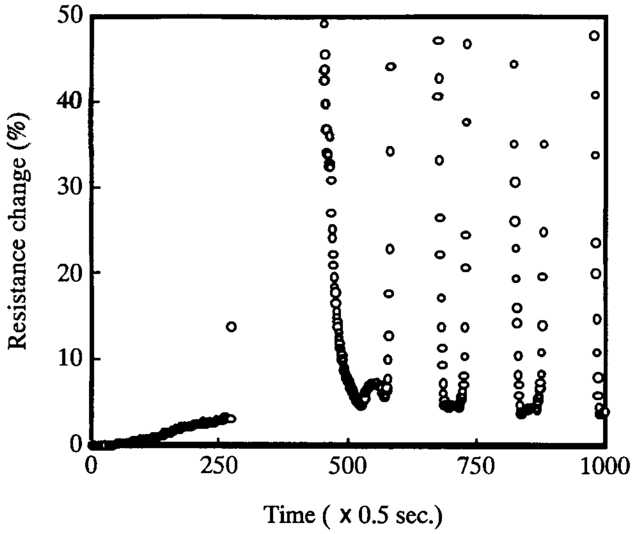

Figure 4: Electrical resistance change of a fragmented single fiber

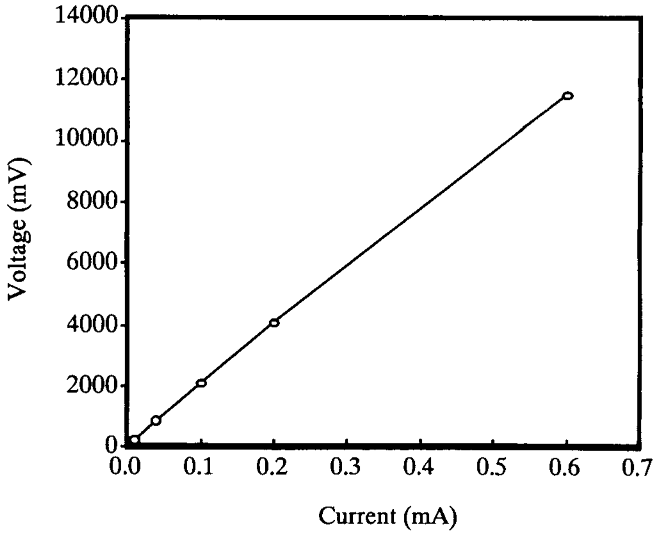

Figure 5: Experimental results for the relationship between current versus voltage

$$\varepsilon = \varepsilon_{comp} - \varepsilon_{thermal} \qquad (4)$$

Since the direct contact of neighboring fractured planes is unrealistic, this conductive path in the fractured region is considered to be formed by carbon fiber flakes as shown in Fig. 7. These experimental results are very similar to the electrical response of the conductive thin film reported by Cairns et al.[9]. In their analytical model, the bridging block is assumed as a conductive path. However, we proceed below to analyze with the experimental relation between electrical resistance and strain and will address the mechanism for future study.

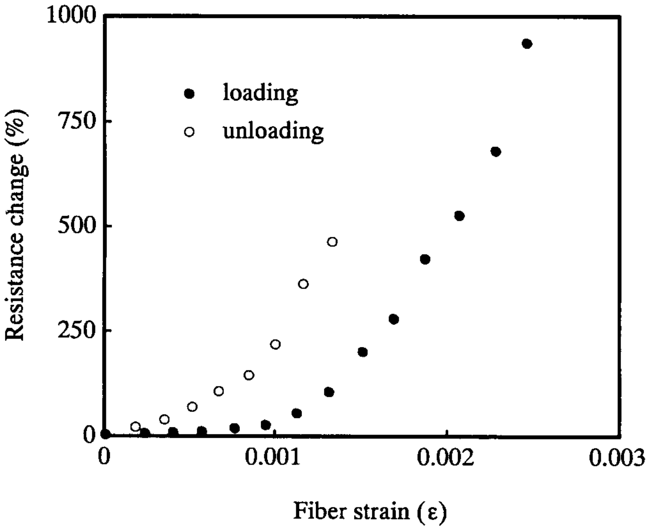

Figure 6: Electrical resistance change of a fragmented single fiber

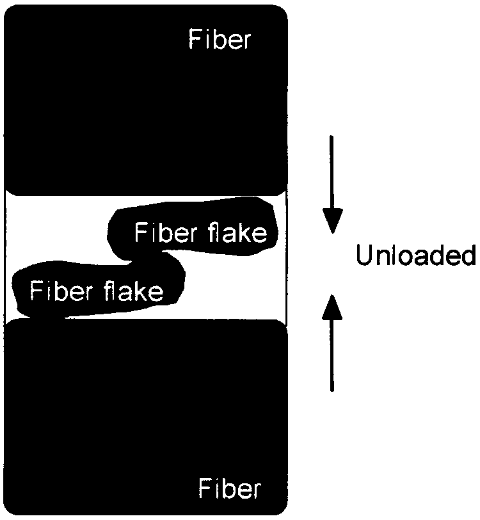

Figure 7: Schematic of electrical conductive path formed by fractured cabon flakes

ANALYTICAL MODEL AND DISCUSSION

As mentioned above, the electrical conductivity of a fragmented single fiber is recovered during the unloading process. Based on the experimental data, the electrical resistance R^{frag} of a fragmented single fiber can be described by

$$R^{frag} / R_0 = \exp(10^3 \times \varepsilon) \qquad (5)$$

where R_0 is the initial fiber resistance Our previous model assumes that the conductivity of a broken fiber does not recover during the unloading process. However, the electrical resistance behavior of broken fibers should be considered. Based on the DC circuit model with series and parallel arrays of resistors, the electrical resistance of a multifiber-reinforced composite is modified as

$$\frac{\Delta R_{total}}{R_{0,total}} = [\frac{1-P_f(\varepsilon^{\max})}{(1+\alpha\varepsilon(t))} + \frac{P_f(\varepsilon^{\max})}{\exp(10^3 \times \varepsilon(t))}]^{-1} - 1 \qquad (6)$$

Prediction with Eq. 6 is shown in Fig. 8 and shows a good agreement with the experimental result. It is true that the internal strain distribution in the composite is more complicated than that of the single fiber composite. However, the electrical resistance behavior can be easily predicted with Eq. 6. Thus, Eq. 6 is the most important result of the present paper.

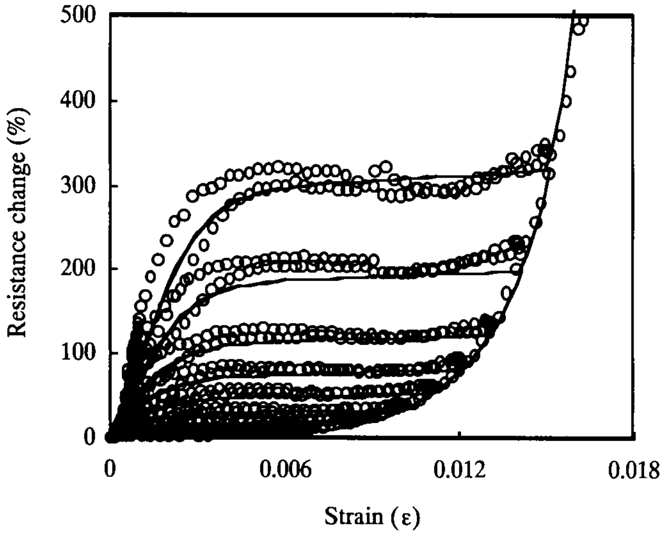

Figure 8: Prediction of electrical resistance curve of mulitfiber composite

CONCLUSION

In the present paper, we have discussed the electrical resistance behavior of conductive fiber reinforced composites. To consider the electrical resistance behavior of broken fibers, we modified our previous model by incorporating the experimental relationship obtained from a fragmented single fiber. The history of the electrical resistance change of the CFRP can be predicted with our modified model. In a view of application, the present technique can contributes to the insitu and nondestructive inspection of the composite structure.

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