Materials Design for Explicit Warning of Fracturing*

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It was found that measurement of electrical resistance in the CFGFRP (carbon fiber-glass fiber reinforced plastic) composites during and after loading is a very promising method for monitoring residual damage. CFGFRP composites containing three types of carbon fibers along with 31.6 V% glass fibers were tested. With loading, the CFGFRP specimens were able to withstand load/strain beyond the point where carbon fibers alone were fractured. At the transition point a tremendous change in electrical resistance was seen, and this point could be controlled through suitable selection of the type of carbon fibers according to their values of ultimate elongation. The signal is very distinct and the method is very simple. The design concept for explicit warning of fracturing is to combine a conductive material with a small value of ultimate elongation and an insulating material with a large value of ultimate elongation.

Key Words: Material Design, Nondestructive Inspection, Composite Material, CFGFRP, Carbon Fiber, Elongation, Resistance Change, Fatal Fracture

1. Introduction

Sudden fracture of materials often leads to tragic accidents. Most of them could be avoided if we could detect some signals of the initiation of fracture while the materials are still practically sound. Sensors to monitor stress/strain can be installed. However, the part where the gauge is placed may not coincide with the point where fracture initiates. To monitor large specimens, many monitoring units are needed. An acoustic emission method may be applied to detect

initiation of cracks, but the apparatus is very expensive. This sort of sophisticated or costly method is not acceptable for conventional structures. The method to warn of fracturing must be simple, and the signal must be distinct. We propose a method for monitoring slight damage which may lead to fatal breakdown, while the materials are still in safe practical use^{(1),(2)}. The signal is very distinct, and the method is very simple. A similar method has been devised by Schulte and Baron⁽³⁾ for CFRP composites. However, CFRP composites are brittle which may limit the application of this new method to only CFRP composites. In the present paper, materials design for explicit warning of fracturing is reported.

2. Experimental Procedure

In the present work, three types of carbon fibers (pitch-HPCF, pitch-based high property carbon fibers; PAN-HSCF, polyacrylonitrile-based high-strength carbon fibers; and PAN-HMCF, PAN-based high modulus carbon fibers) and one type of glass fiber with different elongation have been used as raw materials. The properties of these raw materials are shown in Table 1. A distinct change in the electri-

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cal resistance occurs due to the difference in the values of ultimate elongation between carbon fibers and glass fibers. The ultimate elongations of the fibers are 0.8% for pitch-HPCF, 1.0% for PAN-HMCF, 1.4% for PAN-HSCF and 4.8% for glass fibers. Carbon fibers of 0.38 V% pitch-HPCF along with 31.6 V% glass fibers were incorporated unidirectionally in a vinyl ester plastic. Two other types of carbon fibers were also tested: 0.33 V% PAN-HMCF and 0.72 V% PAN-HSCF. The size of the test piece was 64 mm² in cross section and 450 mm in length. A 6 mm × 2.4 mm strain gauge with a gauge factor of 2.1 was attached onto a specimen to measure strain. U-shaped copper electrodes were attached to both ends of the CFGFRP composites with conductive adhesive. The electrical resistance of the contact between these electrodes and fibers could be neglected. Specimens were loaded and unloaded cyclically in tension with a progressive increase in strain at a rate of 0.1 mm/min. Electrical resistance was measured via a two-terminal d.c. method using an X-Y recorder during and after loading. Current was kept constant at 1 mA.

3. Results and Discussion

The strain-stress characteristic of the materials (CFGFRP), carbon fibers (CF)/glass fibers (GF) composites bonded by plastic, is shown in Fig. 1,

Table 1 The properties of raw materials

Type	Tensile strength	Elastic modulus	Elongation	Diameter	Filament number	Electrical resistivity
Pitch-HPCF	kgf/mm ² 260	tonf/mm ² 24.5	% 0.8	μm 10.0	3000	μΩcm 148
PAN-HMCF	300	35.0	1.0	6.7	6000	263
PAN-HSCF	400	24.0	1.7	7.0	6000	244
Glass fibers	250	7.4	4.8	16.0	4200	
Vinyl ester	8.3	0.35	5.3

Fig. 1 Change in load as a function of strain in CFGFRP composites containing 0.38 V% pitch-HPCF

where 0.38 V% pitch-HPCF was tested. A transition in the strain-stress characteristic is observed around point A in Fig. 1, which corresponds to the point where carbon fibers are broken, while glass fibers still resist the load until point B in Fig. 1. This means the composite material does not break suddenly. Transition point A may be considered to be a signal indicating that further loading may lead to fatal fracture. However, the transition around A is mechanically very vague. The gradient of the curve does not change greatly at transition point A due to the small volume fraction of carbon fibers in the CFGFRP composites. We must make the signal much more distinct.

If we examine the CFGFRP composites from the aspect of electrical properties, CF is conductive while GF is insulating. Fracture of CF gives rise to an increase in electrical resistance. Changes in electrical resistance of a CFGFRP specimen are plotted vs strain (elongation) in Fig. 2. Specimens were loaded and unloaded cyclically with progressive increase in strain, as indicated by arrows in Figs. 2 to 5. The value R_0 of initial electrical resistance in the CFGFRP specimen was 42Ω. At transition point A we observe a tremendous change in electrical resistance. The signal is remarkably distinct. Despite this, the CFGFRP composites still withstood load/strain beyond the point where carbon fibers fractured.

If the strength of specimens is reinforced by carbon fibers, increase of electrical resistance must be small until fatal breakdown, as Schulte and Baron reported⁽³⁾. Figure 3 shows changes in electrical resistance ($R - R_0$), the relative changes in electrical resistance $(R - R_0)/R_0$ and load as a function of strain in the CFRP composites containing 3.9 V% PAN-HMCF ($R_0 = 1.2\Omega$). Figure 3 shows results similar to those reported by Schulte and Baron⁽³⁾. In Fig. 3, the increase of electrical resistance until fatal breakdown

Fig. 2 Changes in electrical resistance as a function of strain in CFGFRP composites containing 0.38 V% pitch-HPCF

is shown to be only a few percent. A distinct increase in electrical resistance of CFRP composites could only

Fig. 3 Changes in electrical resistance, the relative changes in electrical resistance and load as a function of strain in CFRP composites containing 3.9 V% PAN-HMCF

Fig. 4 Changes in electrical resistance, the relative changes in electrical resistance and load as a function of strain in CFGFRP composites containing 0.33 V% PAN-HMCF

Fig. 5 Changes in electrical resistance, the relative changes in electrical resistance and load as a function of strain in CFGFRP composites containing 0.72 V% PAN-HSCF

be seen after materials suffered fatal breakdown. In this case, the CFRP composites could not withstand load/strain beyond the point of fracture of carbon fibers. Thus, the signal appeared too late to warn of fracturing in the CFRP composites.

Schulte and Baron required many carbon fibers to maintain mechanical strength in CFRP composites. They needed to compensate for the effect of temperature since the carbon fibers had a higher temperature coefficient of resistivity than well-carbonized carbon fiber. CFGFRP composites in our test, on the other hand, contained only 0.3 V% carbon fibers. CFGFRP composites may not require carbon fibers with higher resistivity. The resistivity of carbon fibers used in the present experiments is virtually independent of temperature since the fibers are well carbonized. We did not need to compensate for the effect of temperature on resistivity. Accordingly, we observed the transition without any ambiguity by measuring the change of electrical resistance.

Figures 4 and 5 show changes in electrical resistance ($R - R_0$), the relative changes in electrical resistance $(R - R_0)/R_0$ and load as a function of strain in the CFGFRP composites containing 0.33 V% PAN-HMCF ($R_0 = 40\Omega$) and 0.72 V% PAN-HSCF ($R_0 = 103\Omega$), respectively. Figures 2, 4 and 5 show that the position of distinct change in electrical resistance shifted to less strain when ultimate elongation of the carbon fibers became smaller. This means that the transition point could be controlled through suitable selection of the type of carbon fibers according to their values of ultimate elongation.

From Figs. 2, 4 and 5, residual strain reached a constant value, showing no further increase with increasing strain. However, the residual electrical resistance increased nonlinearly with increasing strain. Residual damage after removal of load is easily observed from the change in electrical resistance. Since the CFGFRP composites are already commercially used to reinforce concrete structures^{(4),(5)}, measurement of residual electrical resistance is a very promising method to also monitor residual damage.

The design concept for explicit warning of fracturing is, therefore, to combine a conductive material A with a small value of ultimate elongation and an insulating material B with a large value of ultimate elongation. Hybrid composites have been developed^{(6),(7)} for structural materials, and an example of hybrid composites for functional materials has been given in the present paper. Here, material A was carbon fiber and B, glass fiber. If light transmission is applied to detect damage, A can be a glass optical guide while B, an iron bar.

4. Conclusions

Materials design for explicit warning of fracturing was studied, and the following results were obtained.

1. The transition point which corresponds to the point where carbon fibers are broken showed a tremendous change in electrical resistance.
2. The transition point could be controlled through suitable selection of the type of carbon fibers according to their different values of ultimate elongation.
3. Measurement of changes in electrical resistance during and after loading is a very promising method to monitor residual damage.
4. The design concept for explicit warning of fracturing is to combine a conductive material with a small value of ultimate elongation and an insulating material with a large value of ultimate elongation.

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