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HEALTH MONITORING TECHNIQUES TO DETECT DAMAGE TO CONCRETE STRUCTURES USING SELF-DIAGNOSIS MATERIALS

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Abstract

In this paper, the health monitoring techniques using the self-diagnosis materials, which is the conductive fiber reinforced composites containing carbon particles, has been proposed and evaluated. The sensor has been developed to possess the ability to memorize the applied maximum strain, and enables the judgment of the maximum damage to the target structures based only on the measurement conducted after the occurrence of the event such as earthquakes. Here, the performance of one type of the sensors, which is utilized embedded in the concrete, is evaluated through a series of experimental studies. Then, the applicability of the self-diagnosis materials for the monitoring of the integrity of RC structures is also demonstrated by the experiment using large sized RC specimens.

INTRODUCTION

Recently, the development of structural health monitoring to detect damage to structures is attracting wide attention, and several types of monitoring systems using advanced technology such as fiber optic sensors, piezoelectric transducers and MEMS sensors have been proposed and investigated by a number of researchers. Although some of those developed systems have been demonstrated to show satisfactory performance as a monitoring sensor, difficulties have also been pointed out in regard to their cost or practical applicability. In contrast, the monitoring technique based on the electrical conductivity of carbon materials has also been investigated from a relatively early stage in the course of research on structural health monitoring[1]. This method makes use of the property of carbon materials to change their electrical resistance values according to the applied strain, and has advantages of being easy to operate and economical to measure. In past studies, continuous long carbon fiber has been generally adopted as detective materials[2, 3]. Whereas, the application of carbon particles or short (discontinuous) fibers, has also been investigated by several researchers[4]. Okuhara et al.[5] developed conductive fiber reinforced composite, which is the glass fiber reinforced plastics containing carbon particles, and proposed as self-diagnosis material.

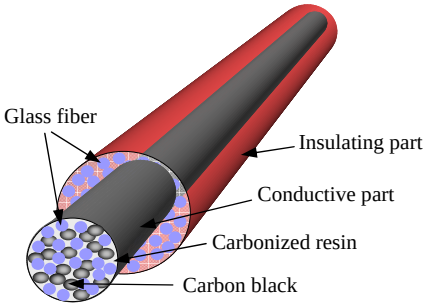


Figure 1. Schematic description of material.

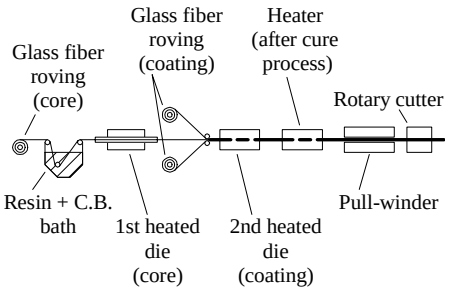


Figure2. Production system.

The authors have continuously conducted research projects on the development of the self-diagnosis materials as a monitoring sensor and its application for monitoring of civil infrastructures and buildings. The application of the nano-sized carbon black enables the sensor to possess the ability to memorize the applied maximum strain[6]. Because the percolation structure formed by carbon black causes irreversible resistance change, the sensor always keeps the electrical resistance value corresponding to the applied maximum strain. The application of the sensor with such memory function makes it possible to eliminate the necessity of continuous monitoring, and enables the assessment of the maximum damage to the target structures based only on the measurement conducted after the occurrence of events such as earthquakes. In this paper, the characteristics and performance of proposed self-diagnosis materials are evaluated through several experimental studies. The sensitivity of the materials to respond to the applied strain is evaluated through tensile tests of the materials. Then, in order to investigate the performance of developed systems for the damage detection of RC structural members in buildings, the bending tests using beam to column joint specimens, were performed.

SELF-DIAGNOSIS MATERIALS

Characteristics of the Materials

Several types of materials have been developed in our research to suit different purposes. In this paper, the characteristics of one type of the materials, which is utilized embedded in the concrete, is mainly discussed. The schematic drawings of the structural design of self-diagnosis materials are shown in Figure 1. This type of material is named rod type after its configuration. In the center core of the material, the carbon black (MITSUBISHI Chemical, 3050B) with a mean diameter of 50nm are dispersed in a thermoset epoxy resin to form a conductive part. Surrounding it, the glass fiber filaments are incorporated in the mixture as an insulating part. The diameter of the core is about 2mm, and the overall diameter is about 4mm. In the conductive part, the carbon particles form a continuous link (percolation structure) with each other to make a conductive path. Applying tensile strain to the material interrupts the conductive path and increases the electrical resistance. Because disconnected contacts between the particles are not restored even after unloading, the material keeps the resistance value corresponding to the experienced maximum strain until the applied strain exceeds the original peak value. Furthermore, carbonizing the material through a pyrolysis process at 500°C in N_2 ambient is found to give the pretension effect to the materials and improve the sensitivity[7].

Investigation on Production System of Materials

In our early development stage, the materials have been fabricated by molding manually by one batch at a time. For practical application, the production system has been modified to enable stable mass production. The production system using pultrusion process as shown in Figure 2 has been developed, and tentatively set up in the FRP plant. By this method, the materials with constant cross section can be produced continuously, making it possible to reduce both cost and performance variation of the sensors.

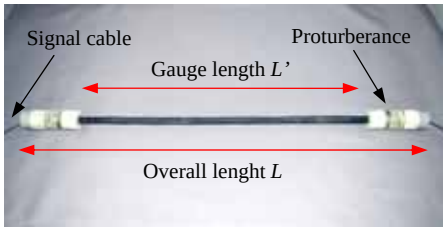


Figure 3. Details of sensor.

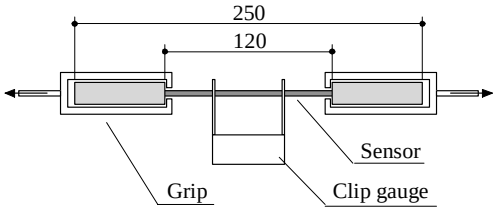


Figure 4. Tensile tests.

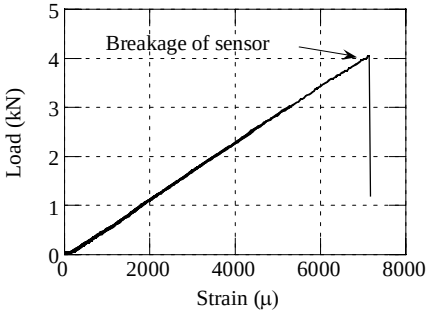


Figure 5. Load – strain curve.

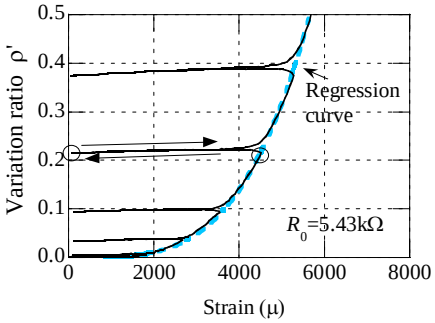


Figure 6. Resistance - strain.

THE SENSOR USING SELF-DIAGNOSIS MATERIALS

Improvement of Sensor

In order to improve the sensitivity and stability of the material as a sensor, it is most important to disperse uniformly the appropriate amount of carbon black in the resin. In our previous studies, the experimental results using our "original type" sensors with dispersion of carbon black with 5% volume fraction. Lately, "modified type" sensors, with increased volume fraction of 11%, have been developed through improving their dispersibility by the addition of coupling agent. The comparison of the results using two types of the sensors is going to be shown in this paper.
The configuration of the sensor is shown in Figure 3, which is processed its shape to bond with the surrounding concrete and connecting the signal cables. The sensor, which is named dumbbell sensor, has protuberances at the both sides of the sensor, and is expected to respond against the average strain in the gauge length of the sensor.

Tensile Tests of the Sensor

The tensile tests of the original and modified type sensors have been conducted as shown in Figure 4, in order to investigate the characteristics of the materials as a sensor[8]. Original and modified types of dumbbell sensors with lengths of 250mm are applied as test specimens, and are loaded by gripping the protuberances. The strain of the sensor is measured by the clip gauge attached at the center of the specimen. As for one original type sensor, the relation between applied load and strain, electrical resistance and strain are shown in Figures 5 and 6, respectively. The relation between the load and strain almost keeps the linear relation until the breakage of the sensor. The variation in electrical resistance R of the sensor is illustrated as variation ratio ρ from the initial value R_0. In addition, the modified variation ratio ρ' is adopted to transform the variation in the gauge length of the sensor, supposing that no variation in electrical resistance is caused in the protuberances at both sides of the sensor. These variation ratios are defined as follows:

$$\rho = \Delta R/R_0 = (R - R_0)/R_0 \quad (1)$$

$$\rho' = \rho L/L' \quad (2)$$

Although no significant change in variation ratio can be observed under the strain of 1500μ, the sensor increases its resistance value against the tensile strain and keeps the peak value during unloading. The sensor is confirmed to possess the ability to memorize the applied maximum strain. The regression curve using the exponential function illustrated as a broken line in the Figure, shows good agreement to the result of the measurement.

Derivation of the Equation to Estimate Applied Strain

Based on the above mentioned results, the relationship between the strain ε and the variation ratio ρ' is supposed to follow the exponential function as shown below:

$$\varepsilon = a\rho'^{b} \quad (3)$$

The coefficients a and b for each specimen are calculated by the regression analysis. Then, the coefficients representing the characteristics of two types of the sensors are obtained as average values as shown in Table 1. Figure 7 shows the derived relation between the applied strain and variation ratio of both types. The modified type initiates the increase of resistance against smaller strain than the original type, and shows larger variation rate. It is confirmed that the higher resolution and sensitivity of strain have been achieved by the modification of the sensor.

Calculating the estimated strain at the peak load of each loading cycle for all specimens using equation (3) and coefficients in Table 1, comparison of the estimated value against the strain measured by the clip gauge is shown in Figure 8. The correlation between the measured and estimated values is relatively high in both results, and the applied strain can be estimated from the measured resistance value. Especially, as for the result of modified type, variation of the data is much reduced, although the number of the specimen is larger than the original type as shown in Table 1. Additionally, while the original type shows the inferior accuracy of estimation in small range of strain, the modified

Table 1. Derived coefficients.

type of sensor	Coefficients		Number of specimen N
	a	b	
Original	8.13×10^{-3}	0.296	18
Modified	6.86×10-3	0.384	46

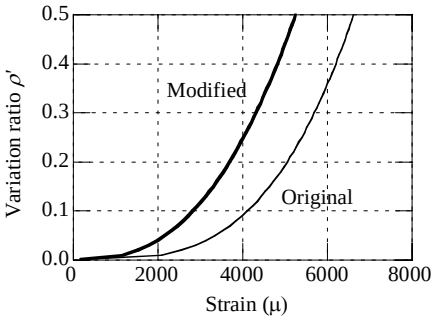


Figure 7. Strain estimation.

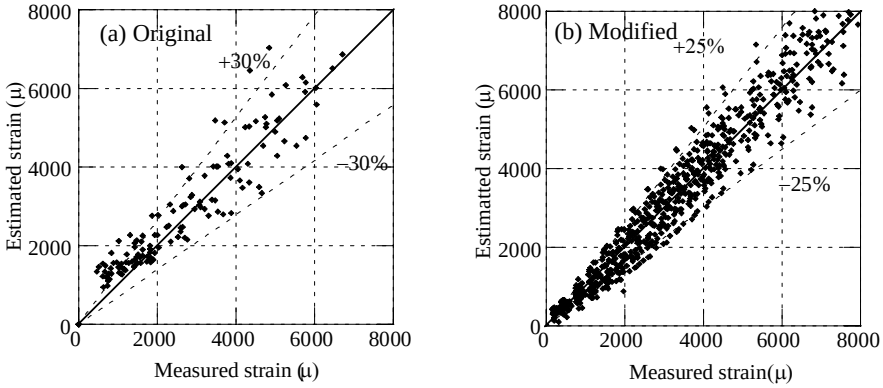


Figure 8. Comparison of measured and estimated strain.

type demonstrates good agreements in wide range of strain. The extent of strain, where the modified type can be applied appropriately, is from 1,000μ to 10,000 μ. However, about 25% variation in estimation still remains, even in the result of modified type. The reason for the variation is regarded as ununiformity of the materials or distortion of the configuration caused in manufacturing process. It is our task in future research to improve the stability and sensitivity of the sensor by refining the composition and the manufacturing method of the sensor.

BENDING TEST OF LARGE-SCALE RC MODEL

Specimen and Loading Condition

In order to investigate the practical applicability of our monitoring system for damage detection of the RC buildings, the experimental study using the beam to column joint specimen has been carried out. The general description of the specimen and arrangement of the sensors are shown in Figure 9. The specimen is designed to model a connection part between the column and the beam in a mid-size conventional apartment building. The specimen has a shape of reverse-T, reduced to 1/2.5 in size and rotated 90 degrees from the original structure. The cross section of the column is 400mm×400mm, and that of the beam is 300mm×300mm. As a result of material tests, the yielding strength of the main reinforcing bar was 390N/mm^2, and the compressive strength of the concrete was 35.3N/mm^2. Three specimens of the same specifications were prepared. In each specimen, four sensors were installed in the connection part of the beam to the column. As shown in Figure, two couples of original and modified type sensors were placed parallel in the opposite sides of the beam in the loading direction. The gauge length of the sensors is 30cm, and the lower ends of each sensor are embedded 5cm deep in the column.

The specimen was fixed on the reaction floor with pin supports at mid height of the column so as not to restrain rotation of the fixed position. Then, the specimens were subjected to quasi-static cyclic lateral loading by the actuator having capacity of 200kN as shown in Figure 10. As shown in the Figure, the direction in which the actuator pushes out is regarded as positive direction, and the compressive side of the beam during the positive loading is called fore side. Loading and unloading were repeated while gradually increasing the maximum load symmetrically to 40kN, 80kN, and 120kN. After the main reinforcing bars yielded, the load was increased until the horizontal displacement at the loading position reached 2, 3, and 4 times the displacement at the loading point δ_y when the reinforcing bar yielded.

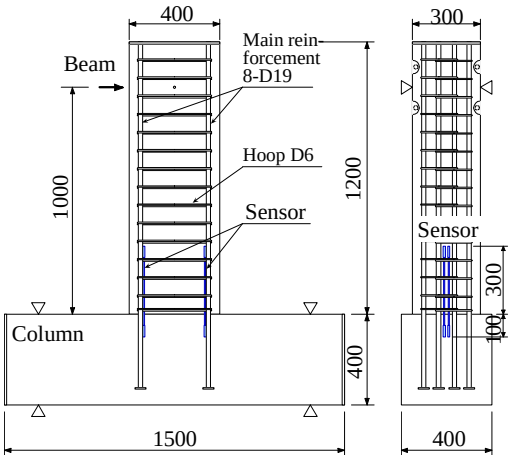


Figure 9. Details of model.

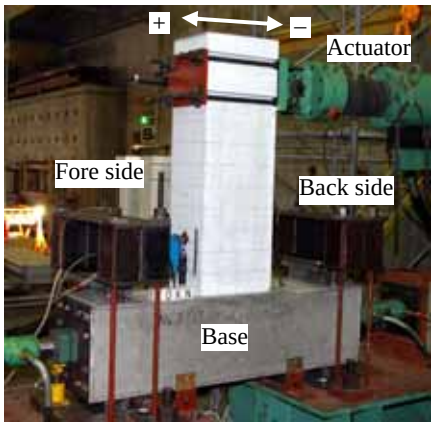


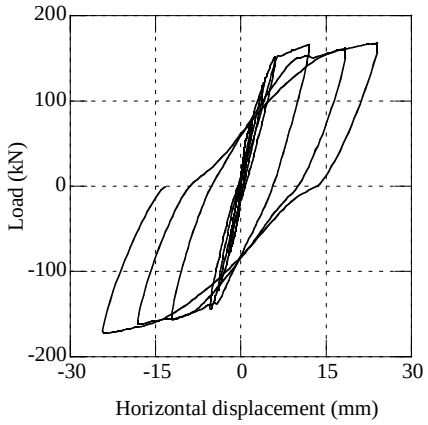
Figure 10. Experimental setup

Behavior of Specimen and Response of the Sensor

The horizontal displacement at the loading position against the load is shown in Figure 11. The deformation of the specimen to the positive and negative direction is almost the same, and the responses of the three specimens agree well. The initial cracks were caused at the load of 45kN, and the main reinforcing bars yielded at the load of 150kN. The total crack widths caused in the gauge length of the sensors are measured as relative vertical displacements using displacement meter. The variation of the crack width against the load is shown in Figure 12. Almost three cracks were caused inside the gauge length of the sensors, and the measured crack width corresponds to the total displacement of those cracks and the gap at the bottom end of the beam.

The corresponding responses of original and modified type sensors against the horizontal displacement at the loading position are shown in Figures 13. In the Figures, the results of a couple of the same type of sensors which are placed at foreside and backside of the same specimen are compared. A couple of sensors respond almost symmetrically on the loading direction, and show relatively good agreement. All sensors initiate the increase of their resistance value even in small displacement, and show rapid growth after the main reinforcing bar yields. Although both sensors generally

hold their peak value during the loading of compressive direction, a certain degree of decrease of the resistance value can be observed, especially in case of the original type. However, as shown in Figure 13, the modified type shows larger resistance change and better capability to keep the peak value than the original type.



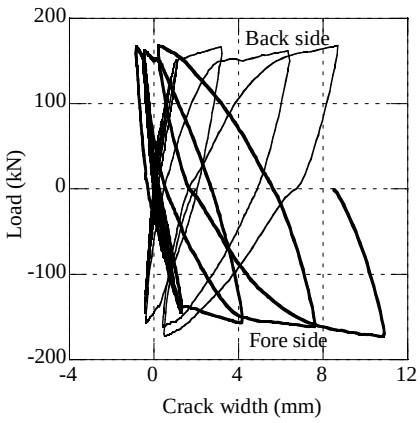


Figure 11. Load-displacement curves Figure 12. Load-crack width curves

Performance Evaluation of the Sensor

Dividing the above-mentioned measured crack width by the gauge length of the sensor, the average strain applied to the sensor can be evaluated. As for the original and modified type sensors in the three specimens, the relation between the average strain and the variation ratio at the peak load in each loading cycle are shown in Figure 14. Similar to the results of the tensile tests, the variation ratios increase exponentially against the average strain, and the variation in the performance of sensors is observed. However, the variation of the data in modified type becomes much smaller than that of the original type. Furthermore, the slope of the curve of modified type is much sharper, representing that the sensor gets higher sensitivity. It is confirmed that the modified type sensor is capable of maintaining its expected performance, even in the application to the actual, large sized structures.

Investigation on Crack Detectability of Sensor

The crack width w caused inside the gauge length L' of the sensor can be estimated using equation (3). Then, the equation of the sensor to estimate the crack width is defined as follows:

$$w = \varepsilon L' = a\rho'^{b} L' \qquad (4)$$

Here, the estimated crack width using equation (4) represents total widths of the cracks caused inside the gauge length of the sensor. Figure 15 shows the comparison of the measured crack widths and estimated values using equation (4) for two types of sensors. In the result of the original type, the crack width can not be correctly estimated in small range of crack width. On the other hand, the estimated crack widths for the modified type show good agreement to the measured values in wide range of crack width. Even in the result of modified type, however, the estimated crack widths tend to be a little smaller than the measured values. The cause of the difference can be due to the fact that the crack width at the location of the sensor inside the concrete is smaller than the measured value at the surface of concrete. Therefore, it is decided that the sensor has the capability to estimate the crack width even for the actual large structures.

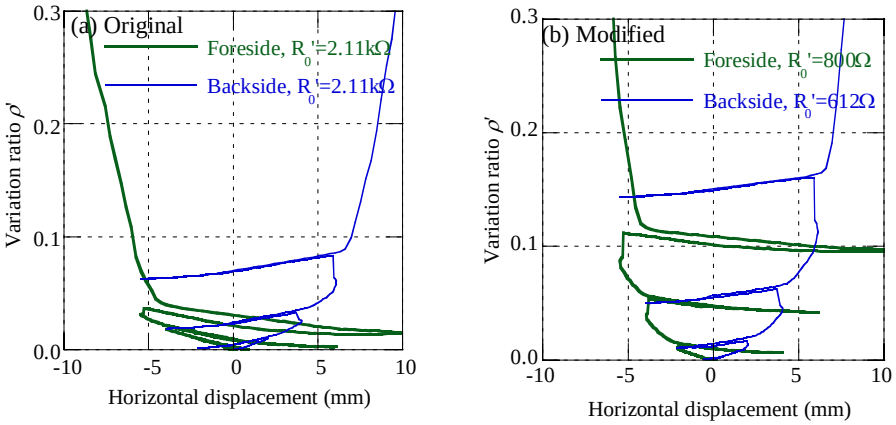


Figure 13. Response of sensors against the horizontal displacement.

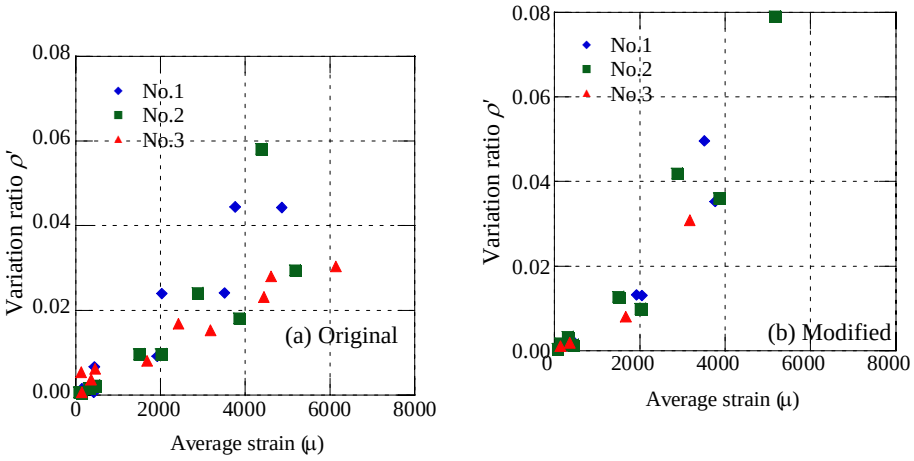


Figure 14. Comparison of performance of sensor

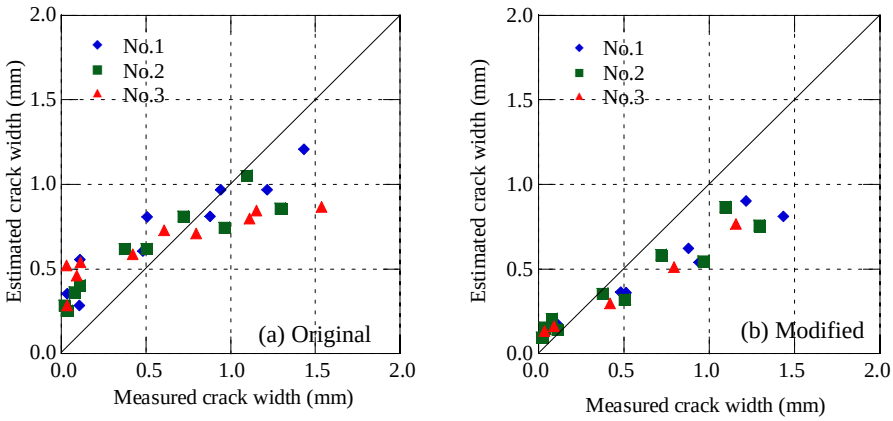


Figure 15. Crack width detectability of the sensor.

CONCLUSIONS

Our study covers newly developed monitoring techniques using self-diagnosis materials, and their applicability to the detection of damage to concrete structures. The self-diagnosis materials with the ability to memorize applied maximum strain have been proposed as a sensor. As a result of several experimental studies, the developed system has been demonstrated to possess reliable performance as follows:

i) The sensor shows apparent irreversible electrical resistance change and possesses superior ability to memorize load and damage.
ii) The developed monitoring system is capable of displaying the expected capability to detect damage to the actual large structures.
iii) The relationship between the variation of resistance and the applied strain or the caused crack width is formulated using exponential function.

ACKNOWLEDGEMENTS

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