Performance Evaluation of Self-Diagnosis Materials to Detect Damage to Concrete Structures

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ABSTRACT:

The authors have continuously conducted research project on the development of the self-diagnosis materials as a monitoring sensor and its application for monitoring of civil infrastructures. The fiber reinforced composite, namely the glass fiber reinforced plastics containing carbon particles as electrical conductor, has been confirmed to possess excellent sensitivity as a self-diagnosis material. The sensor has been developed to possess the ability to memorize the applied maximum strain, and enables the judgment of maximum damage to the target structures based only on the measurement conducted after the occurrence of the event such as earthquakes. In this paper, the performance of the 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 high 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 possess satisfactory performance as a monitoring sensor, difficulties have also been indicated in regard to their cost or practical applicability. Then, the monitoring techniques which can diagnose the integrity of the structures rapidly and accurately after the occurrence of catastrophic disaster are highly

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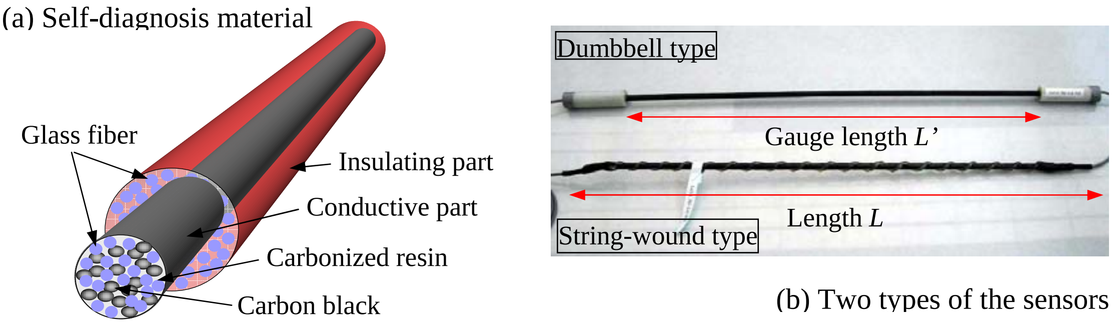
required. The authors have continuously conducted research project on the development of the self-diagnosis materials as a monitoring sensor and its application for monitoring of civil infrastructures and buildings. The function of the sensor to detect damage is based on the property of carbon materials as an electrical conductor, and has advantages of being easy to operate and economical to measure. In previous studies, the conductive fiber reinforced composite, which is the glass fiber reinforced plastics containing carbon particles as an electrical conductor, has been confirmed to possess excellent sensitivity as self-diagnosis materials [1]. The variation in electrical conductivity is observed against even slight strains. Based on the following studies, the application of the nano-sized carbon black enables the sensor to possess the ability to memorize the applied maximum strain [2]. Because the percolation structure formed by spherical 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 memory function makes it possible to eliminate the necessity of continuous monitoring, and enables the assessment of maximum damage to the target structures based only on the measurement conducted after the occurrence of 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.

DEVELOPMENT OF THE SENSOR

Self-diagnosis materials

Several types of self-diagnosis materials have been developed in our research to adapt to different purposes. In this paper, the characteristics of one type of the materials, which is utilized embedded in the concrete, is discussed in detail. The schematic drawings of the structural design of self-diagnosis materials are shown in Figure 1(a). This type of material is named rod type sensor after its configuration. In the sensor, 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



(b) Two types of the sensors

Figure 1: Self-diagnosis materials and manufactured sensors.

incorporated in the mixture as an insulating part. The diameter of the sensor 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 sensor interrupts the conductive path and increases the electrical resistance of the sensor. Because disconnected contacts between the particles are not restored even after unloading, the sensor keeps the resistance value corresponding to the experienced maximum strain until the applied strain exceeds the original peak value. Furthermore, carbonizing the material by heating the composite in nitrogenous atmosphere is found to give the pretension effect to the materials and improve the sensitivity [3].

Characteristics of the sensor

Two types of the sensor, dumbbell type and string-wound type as shown in Figure 1(b), have been manufactured using self-diagnosis materials. The dumbbell type has the protuberances at the both sides of the sensor, and is expected to respond against the average strain in the gauge length of the sensor. The string-wound type is a sensor of glass fiber wound along whole length of the sensor to make the sensor sensitive to the local strain. The volume fraction of carbon black is 5%.

The tensile tests of the materials have been conducted to investigate the characteristics of the materials as a sensor [4]. The dumbbell type sensors are applied as test specimens, and are loaded by gripping the protuberances. The length of the specimen is 250mm, and the gauge length is 120mm as shown in Figure 1(b). The strain of the sensor is measured by the clip gauge attached at the center of the specimen. The example of the results of tensile tests is shown in Figure 3. The variation in electrical resistance R of the sensor is illustrated as variation ratio ρ from the initial value R_0. As for the dumbbell type, 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 the both side of the sensor. These variation ratios are defined as follows.

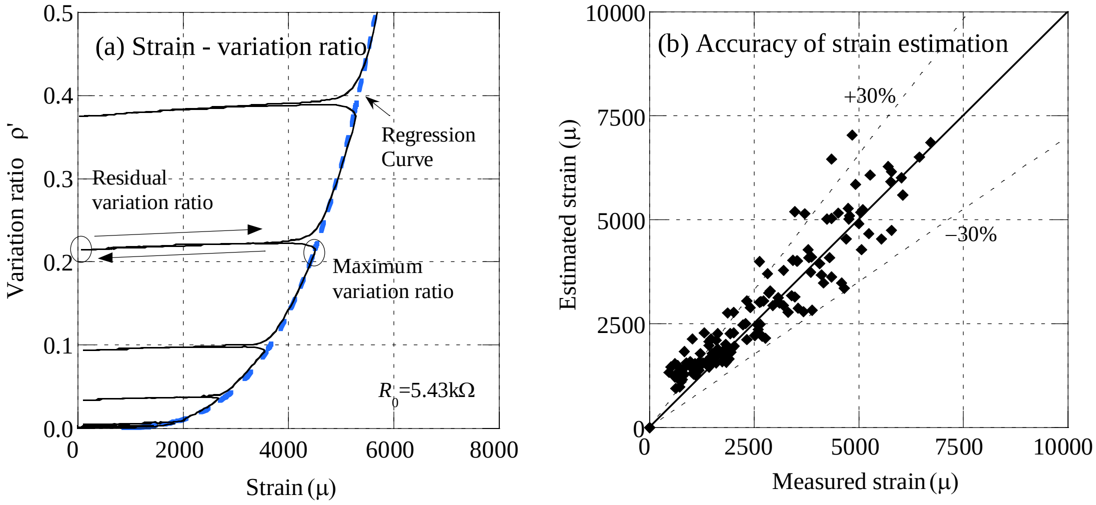


Figure 2: Result of the tensile tests of the sensor.

$$\rho = \Delta R / R_0 = (R - R_0) / R_0 \tag{1}$$

$$\rho' = \rho L / L' \tag{2}$$

Although no significant change in variation ratio can be seen 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. Based on the results of 18 specimens, the relationship between the strain ε and the variation ratio ρ' is derived as follows.

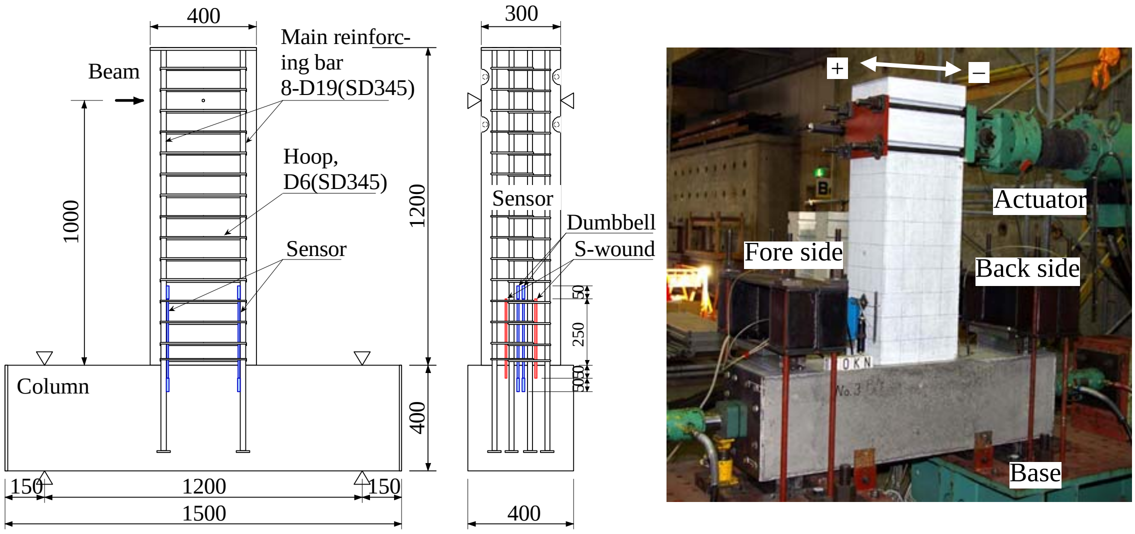
$$\varepsilon = a\rho'^{b}, \quad a = 8.13 \times 10^{-3}, b = 0.296 \tag{3}$$

Using equation (3), the strain of the sensor can be estimated from the measured variation ratio. Figure 4 shows comparison of the strain measured by the clip gauge and the estimated value at the maximum load of each loading cycle for all the specimens. The correlation between the measured and estimated values is relatively high. From this result, it is found that the applied strain of the sensor can be estimated with the error of less than 30%.

BENDING TEST OF LARGE SIZED RC SPECIMEN

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 3(a). The specimen is designed to model a connection part



(a) Specification of specimen

(b) Experimental setup

Figure 3: Outline of specimen and bending test.

between the column and 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 degree 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, eight sensors were installed in the connection part of the beam to the column. As shown in figure 5, two couples of sensors of each dumbbell and string-wound types were placed parallel in the opposite sides of the beam in the loading direction. The gauge length of the sensors is 30cm, and lower end of each sensor is 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 3(b). As shown in Figure 3(b), 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 δy when the reinforcing bar yielded.

Behavior of specimen and response of the sensor

The horizontal displacement at the loading position against the load is shown in Figure 4(a). The deformation of the specimen to the positive and negative direction is almost the same, and the responses of four specimens agree well. The initial cracks are caused at the load of 45kN, and the main reinforcing bars yielded at the load of 150kN. The 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 4(b). Almost three cracks are caused inside the gauge length of the sensors, and the

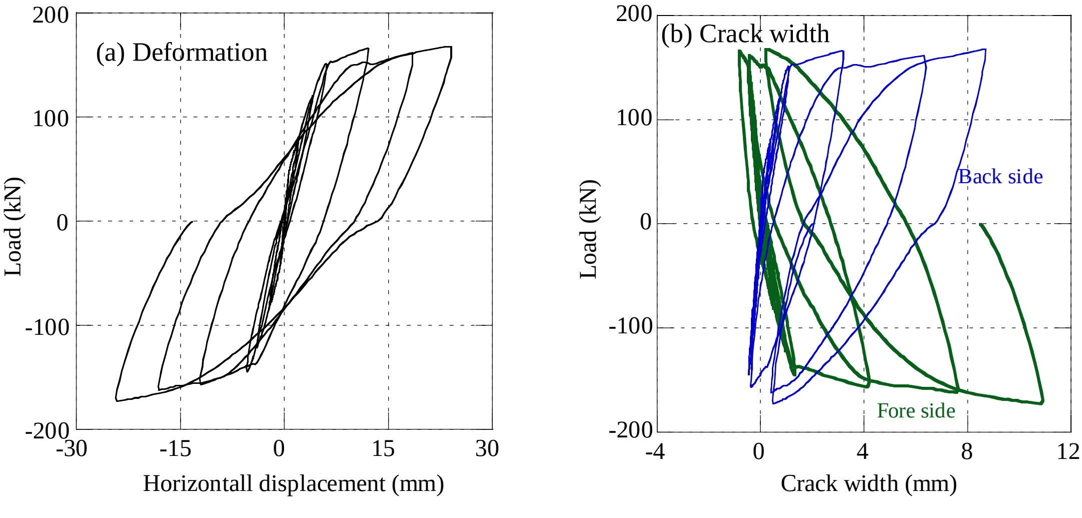


Figure 4: Deformation of the specimens.

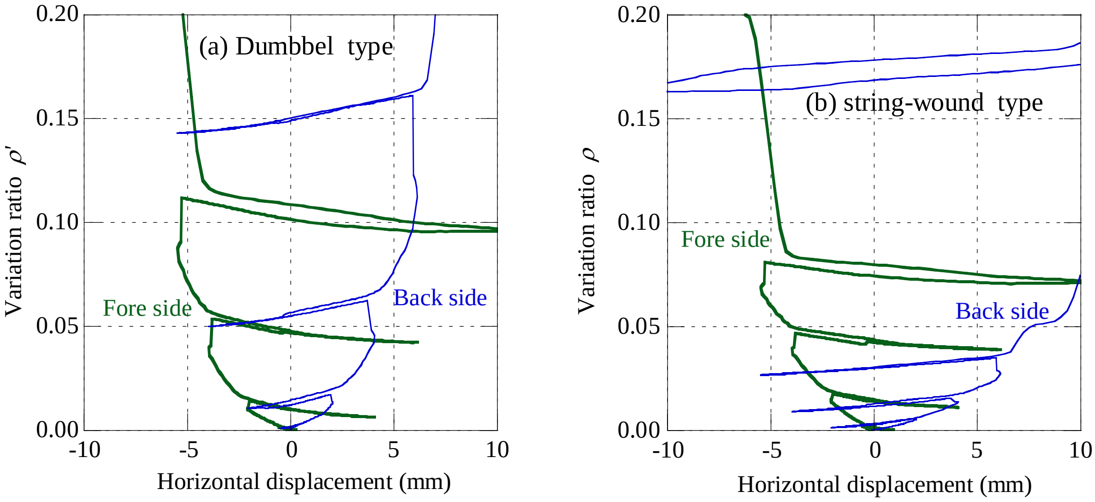


Figure 5: Response of two types of sensors in bending tests.

measured crack width corresponds to the total displacement of those cracks and the gap at the bottom end of the column.

The corresponding responses of dumbbell and string-wound type sensors are shown in Figures 5(a) and 5(b), respectively. In the Figures, the result of a couple of the sensors which were placed at foreside and backside of the same specimen are compared. The sensors respond to the crack width shown in Figure 4(b). The sensor located in the foreside of the column increases its electrical resistance value due to the tensile strain during negative loading. On the other hand, the decrease during the positive loading is much smaller. The sensors generally hold their peak value until the deformation of the specimen exceeds the experienced maximum displacement. The electrical resistance of the sensor shows rapid increase when the main reinforcing bar yields. No significant differences are observed in the result of two types of the sensors.

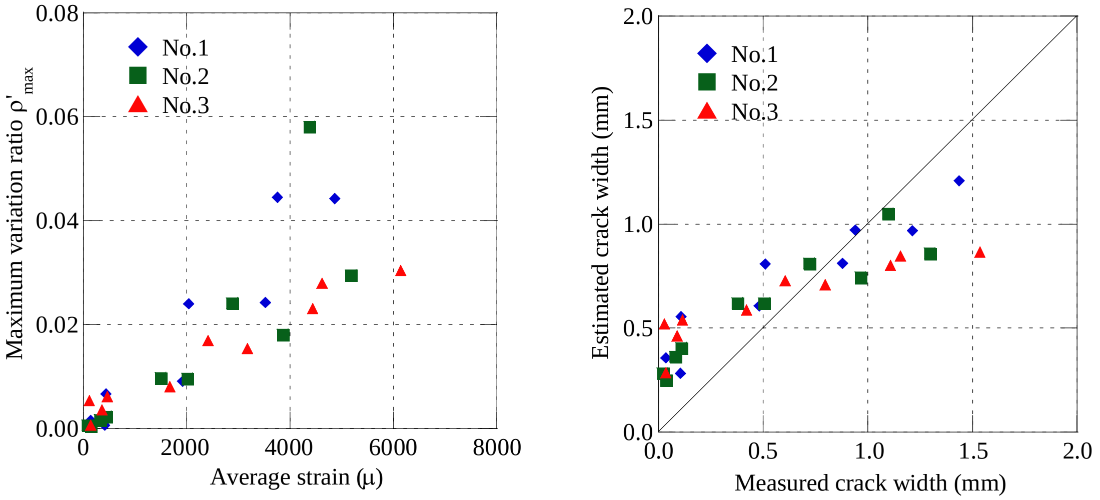
Performance evaluation of the sensor

The total crack width caused inside the gauge length of the sensor is measured using displacement meter as a relative distance between the location of the upper end of the sensor and the position directly below on the upper surface of the column. Calculating the average strain in the gauge length of the sensor, the performance of the sensor to memorize the applied maximum strain is evaluated. As for the dumbbell type sensors in three specimens, the relation between the maximum variation ratio and the mean strain at the maximum load in each loading cycle is shown in Figure 6(a). The result of the sensors shows considerably good agreement, and the maximum variation ratio is found to respond almost linearly to the applied strain in the range of small strain.

The crack width w caused inside the gauge length *L'* of the sensor can be estimated using equation (3) as follows;

$$w = \varepsilon L' = 8.13\times10^{-3}\rho'^{0.296}\times300 \tag{4}$$

Here, the estimated crack width using equation (4) represents total widths of the cracks caused inside the gauge length of the sensor. Figure 6(b) shows the comparison of the measured crack widths and estimated values using equation (4). The estimated crack widths



(a) Response of dumbbel type sensor

(b) Accuracy of estimation of crack widhth

Figure 6: Performance of the developed sensor.

show good agreement to the measured values. Therefore, it is capable of estimating the crack width from the variation of electrical resistance of the sensor even for the actual large structures. However, considerable variation is still observed in the performance of the sensor, and the estimated value tends to reach the ceiling in the range of large crack width. It is still necessary for the sensor to reduce the variation in its performance even more for wide range of crack width.

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:

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

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