Development of monitoring techniques for concrete structures using self-diagnosis materials and wireless measurement systems

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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 to confer electrical conductivity, has been confirmed to possess excellent sensitivity as self-diagnosis material. In this paper, two types of the materials with the ability to memorize the applied maximum strain are proposed. Furthermore, the wireless measurement system which enables the measurement of the electrical conductivity of the sensor has been developed. The maximum strain memory sensor with the wireless measurement system can eliminate the necessity for the continuous monitoring and reduce time consuming measurement work. Then, the applicability of the self-diagnosis materials and the wireless monitoring systems for the monitoring of the integrity of structures has been evaluated through experimental studies using large sized RC specimens.

1 INTRODUCTION

A lot of civil infrastructures suffered devastating damage due to the 1995 Hyogoken-nambu earthquake, and the urgent need for the development of the damage detection method has been pointed out. Since then, 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. In Japan, another large earthquake hit Chuetsu, middle part of Niigata prefecture in the last year, and considerable structures have been found to suffer severe damage. It is also recognized that the difficulty arose in the operation of inquiry and rehabilitation, under the condition of continual occurrence of many large aftershocks. Consequently, the monitoring techniques which can diagnose the integrity of the structures rapidly and readily after the occurrence of catastrophic disaster are highly 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 (Okuhara, et. al. 2003, Kumagai, et. al 2003). The function of the sensor to detect damage is based on the property of carbon materials as a conductor of electricity, and has advantages of being easy to operate and economical in the measurement. In previous studies, the conductive fiber reinforced composite, which is the glass fiber reinforced plastics containing carbon particles to give electrical conductivity, has been confirmed to possess excellent sensitivity as self-diagnosis materials (Inada, et. al. 2003). The variation in electrical conductivity is observed against the 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 (Inada, et. al. 2004). Because the percolation structure formed from 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 judgment of maximum damage to the target structures based only on the measurement conducted after the occurrence of earthquakes.

Recently, wireless monitoring systems are attracting attention as a technology to achieve the efficient installation and measurement for monitoring system. The application of wireless monitoring coupled with the conductive sensor has also been studied by several researchers (Simonen, et. al. 2003, Hou, et. al. 2005). In our study, the wireless measurement system which enables the measurement of the electrical conductivity of the sensor without the distribution of signal cables to the instruments for data acquisition has been developed. Because the maximum strain memory sensor with integrated the wireless measurement system can reduce time consuming measurement works, quick and effective health monitoring of structures after the occurrence of earthquakes can be accomplished.

In this paper, the characteristics and performance of proposed self-diagnosis materials and wireless measurement system are evaluated experimentally. In order to investigate the performance of developed systems for the damage detection of RC structural members in buildings, the experiments using two types of RC beam-column specimens have been carried out. Firstly, the bending tests using beam to column joint specimens were performed to investigate the characteristics of the developed self-diagnosis materials. Secondly, the applicability of total monitoring system is demonstrated in the experiments using large sized RC frame specimen. Here, the results obtained from those experiments are discussed comprehensively.

2 DEVELOPMENT OF MONITORING SYSTEM

2.1 *Self-diagnosis material with the Ability to memorize the maximum strain*

The schematic drawings of the structural design of self-diagnosis materials are shown in Figure 1. Two types of materials with different configurations, which are named rod type and sheet type, respectively, have been applied. While the rod type serves as a monitoring sensor attached into the structures prior to the casting of concrete, the sheet type is expected to function as a sensor bonded on the surface of the structures. In the rod type sensors, 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 rod type sensor is about 4mm. As for the sheet type sensor, the flat conductive part using same carbon black as the rod type is enclosed between the glass clothes. The thickness of the sheet type sensor is about 0.2mm, and the sensor is made flexible to enable easy bonding to the surface of the structures.

In the conductive part of both type sensors, the carbon particles form a continuous link (percolation structure) with each other to make a conductive path. The result of tensile test of the rod type sensor is shown in Figure 2. The variation in the electrical resistances of the sensor is illustrated as variation ratio $\Delta R/R_0$ from the initial value. 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. In previous studies, this memory function of the sensor is achieved by dispersing the carbon black with high density. The processing, however, causes complexity in manufacturing and instability in performance of the sensor. In recent study, carbonizing the material by heating the composite in nitrogenous atmosphere is found to give the pretension effect to the materials and improve the sensitivity. In this way, the sensor is made to possess the distinguished memory function as shown in Figure 1 with volume fraction of 5% of carbon black.

2.2 *Wireless measurement system*

The outline of our developed wireless measurement system is shown in Figure 3. The system consists of transmitter, receiver and PC. The sensor is installed in the concrete or bonded on the surface of the target structures, and signal cables from the sensor are distributed to the transmitter which is placed in a position appropriate for the measurement near the sensor. In case of damage detection after the earthquakes or regular inspections, the electrical resistance value of the sensor is immediately acquired in the PC only by putting the receiver close to the transmitter.

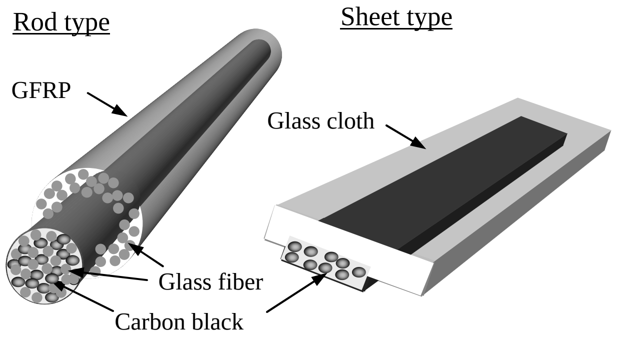


Figure 1. Schematic description of carbon fiber

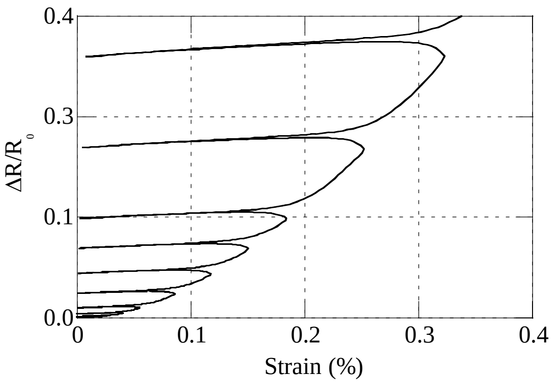


Figure 2. Basic performance of rod type sensor.

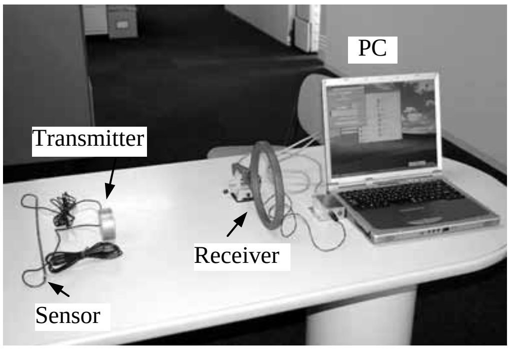


Figure 3. Total wireless measurement system.

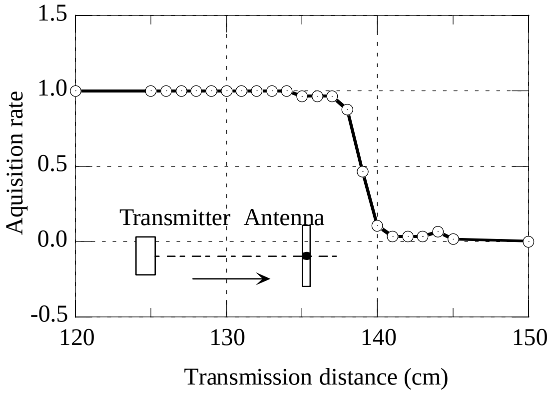


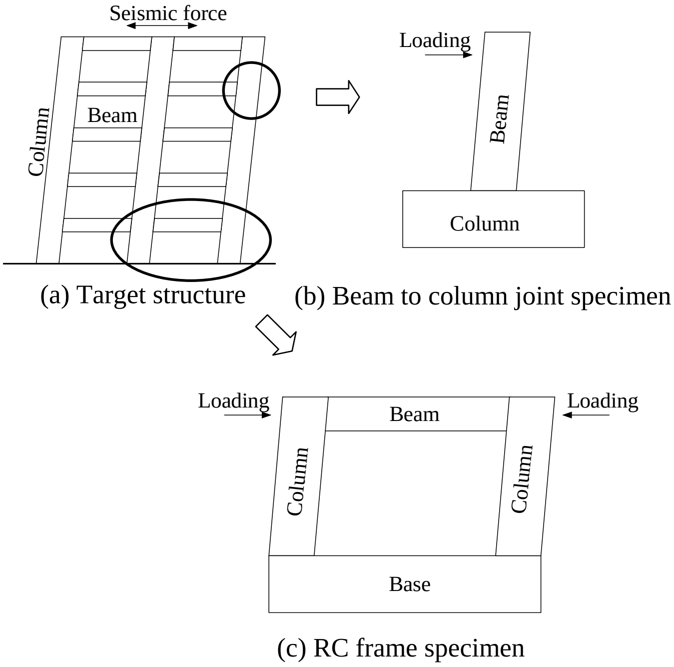
Figure 4. Capability of wireless monitoring system.

The transmitter has the cylindrical shape with diameter of 7cm and thickness of 3cm, complete with the electronic circuit to measure the resistance value of the sensor and transmit the data, antenna and battery of 3V. The electrical conductivity is evaluated based on the measurement of the duration needed for the discharge from the capacitor in the circuit involving the sensor. The carrier frequency in the data transmission is 2MHz, and the data converted to Manchester code is transmitted. The round shaped antenna of the receiver has diameter of 20cm. Control and storage of the data are conducted by PC connected to the receiver via RS-232C.

Here, the capability of the system to transmit the data wirelessly is evaluated in the laboratory tests. Figure 4 shows the variation of the data acquisition rate against the transmission distance. It is confirmed that the system is capable of transmitting the data completely up to the distance of 1.3m under the ideal condition.

3 OUTLINE OF EXPERIMENTAL STUDY

In order to investigate the applicability of our developed monitoring systems for damage detection of the RC buildings, the experimental study using two types of specimens has been conducted. Figure 5 illustrates the conception of the experiments and the outline of the two types of the specimen. In the first stage of this study, the bending tests using the beam to column joint specimen as shown in (b) in the figure 5 were conducted to investigate the performance of the rod type sensors in detail (Shiraishi, et. al., 2005). The obtained results and discussions on the characteristics of the self-diagnosis materials as a sensor are shown in the next chapter. Subsequently, the practical applicability to actual structures is discussed based on the results of the experiment using the large sized RC specimens shown as (c) in the figure. Here, the latter specimen is called RC frame specimen, and the results is going to be shown in chapter 5.



(a) Target structure (b) Beam to column joint specimen

(c) RC frame specimen

Figure 5. Outline of the test specimens.

4 BENDING TESTS OF BEAM TO COLUMN JOINT SPECIMEN

4.1 *Specimen and loading condition*

The general description of the specimen and arrangement of the sensors is shown in Figure 6. The specimen is designed to model a connection part between the column and beam in a mid-size conventional apartment building. The specimen has a shape of reverse-T, reduced 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 45.8N/mm^2.

Four specimens of the same specifications were prepared. 8 types of sensors with different lengths were installed in each specimen. The sheet sensors are not applied in this experiment.

The specimen was fixed on the reaction floor with pin supports at mid height of the column so as not restrain rotation of the fixed position. Then, the

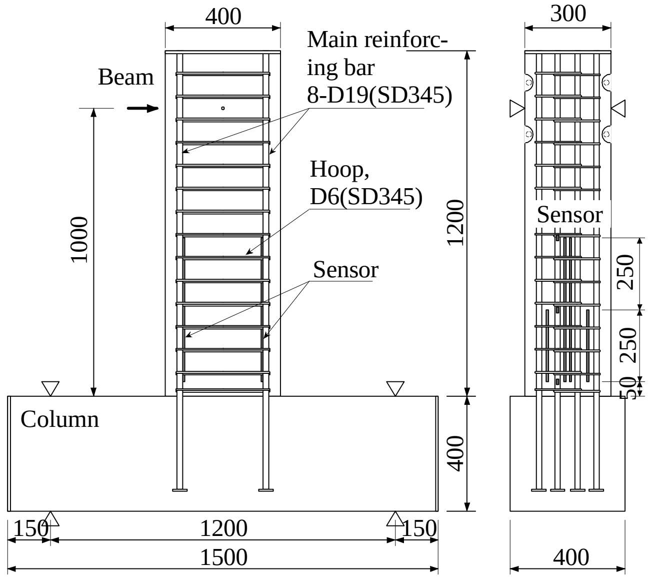


Figure 6. Arrangement of reinforcement and sensors.

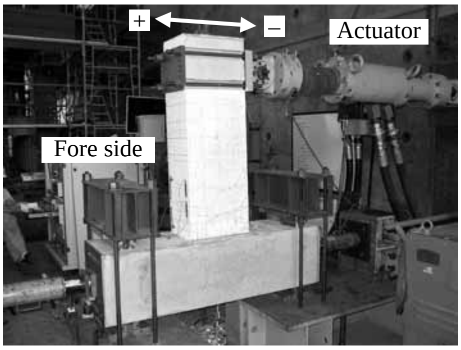


Figure 7. Experimental setup.

specimens were subjected to quasi-static cyclic lateral loading by the actuator having capacity of 200kN as shown in Figure 7. As shown in the Figure 7, 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 displacement 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.

4.2 *Behavior of specimen and response of the sensor*

The horizontal displacement at the loading position against the load is shown in Figure 8. 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.

Figure 9 shows the corresponding response of rod type sensors with length of 25cm, which are placed at foreside and backside of the same specimen as shown in Figure 8. The sensor located in foreside of the column increases its electrical resistance value due to the tensile strain during positive loading. On the other hand, the decrease during the negative 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. The residual variation of electrical resistance is found against small deformation, and remarkable memory function of the sensors is demonstrated.

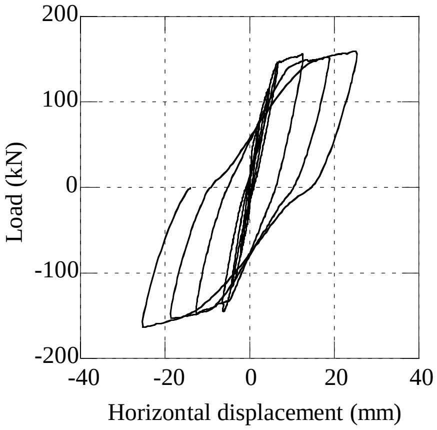
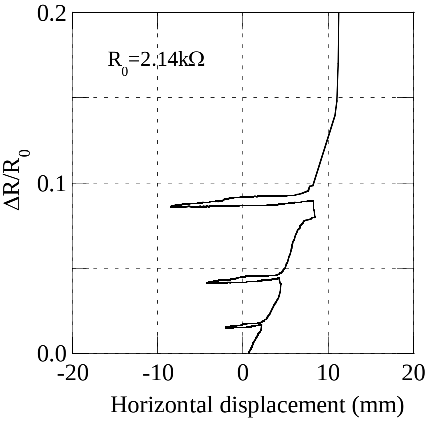
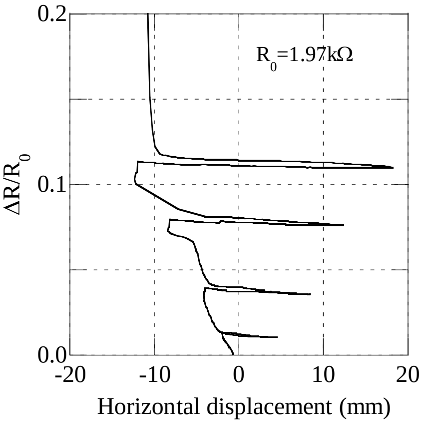


Figure 8. Deformation of the specimen.



(a) Fore side



(b) Back side

Figure 9. Variation of the electrical resistance of the sensor against the horizontal displacement.

4.3 *Evaluation of memory function of the sensor*

From two to three cracks are caused on the concrete surface at the location of the sensor with length of 25cm. Total crack widths of the cracks are measured by the pi-shaped displacement meter with length of 30cm attached on the concrete surface. Calculating the mean strain in the gauge length of the pi-shaped displacement meter, the performance of the sensor to memorize the applied maximum strain is evaluated.

As for the twelve sensors with length of 25cm in four specimens, the relation between the residual variation ratio when the load is off and the mean strain at the maximum load is shown in Figure 10. As shown in the upper figure, when the mean strain exceeds 0.5%, the residual variation ratio increases rapidly. The data distributed inside of the circle in the left figure are enlarged in to the lower figure in Figure 9. The result of the sensors shows considerably good agreement, and the residual variation of the sensor is found to respond almost linearly in the range of small strain. The obtained results demonstrate the sensor is capable of detecting the applied maximum strain by the measurement after the load is off.

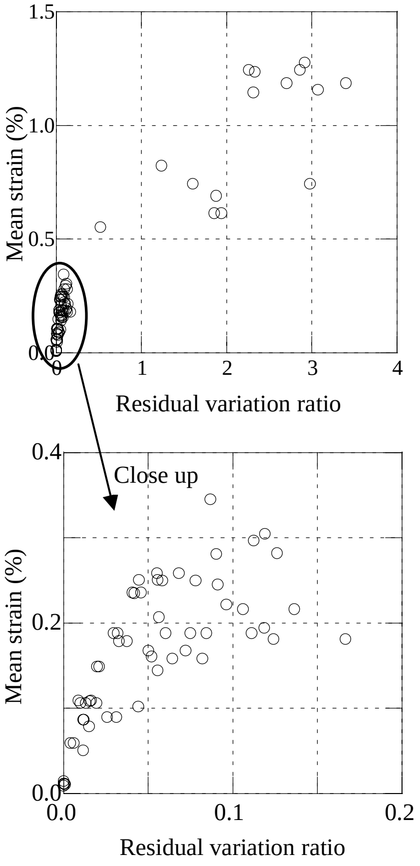


Figure 10. Performance of the sensor to memorize mean strain at the maximum load.

5 BENDING TESTS OF RC BEAM TO RC FRAME SPECIMEN

5.1 *Specimen and loading condition*

The practical applicability to actual structures is discussed based on the experiment using large sized RC specimens. The general description of the specimen and arrangement of the sensors is shown in Figure 11. Two specimens of the same specifications were prepared. While the cross section of the column is 400mm×400mm, the cross section of the beam is reduced to 280mm×360mm. As a result of material tests, the yielding strength of the main reinforcing bar was 393N/mm^2, and the compressive strength of the concrete was 39.1N/mm^2.

5.2 *Installation of the sensor and wireless measurement system*

In each specimen, sensors were installed at the position numbered from 1 to 12 in Figure 11, so as to detect damage at the connecting part of beam to column and column to footing. 14 rod type sensors were attached in the reinforcement. At each position, the sensors with length of 40cm were placed straddling across the connecting part. Having completed the casting and curing of concrete, 8 sheet type sensors with a length of 20cm were bonded onto both

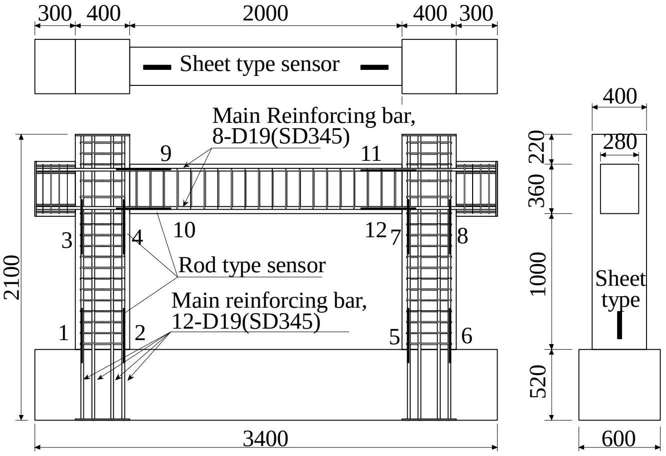


Figure 11. Arrangement of reinforcement and sensors.

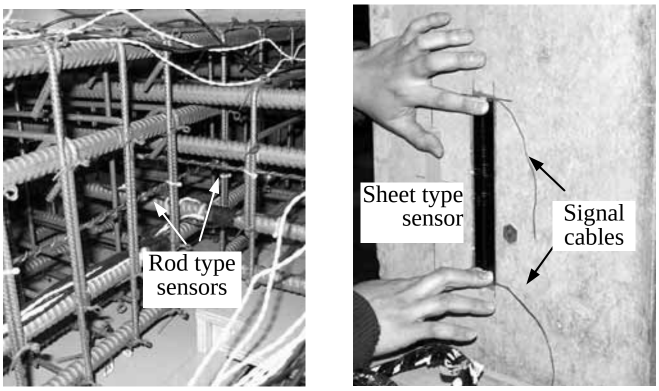


Figure 12. Attachment of sensors.

sides of the columns and beams using epoxy adhesive resin as shown in Figure 12.

At the position of Nos.1 and 6 in Figure 11, a couple of the rod type sensors were placed in parallel. Wireless measurement system was applied for one sensor, and the other sensor was measured by ordinary wired measurement as shown in Figure 13. The setup for the wireless measurement systems is shown in Figure 14.

The specimens were fixed in the loading frame and subjected to quasi-static cyclic lateral loading by the hydraulic jacks connected to both sides of the beam as shown in Figure 15. Loading and unloading were repeated while gradually increasing the maximum displacement symmetrically.

5.3 *Behavior of specimen and response of the sensor*

The horizontal displacement at the loading position against the load is shown in Figure 16. The deformation of the specimen to the positive and negative direction is almost the same, and the responses of two specimens agree well. The main reinforcing bars yield at the load of 650kN, and the deformation of the specimen grows larger after that. In the 6th loading cycle, after the drift angle of the column reaches 1/33 in positive direction, large shear crack is caused in the column during negative loading.

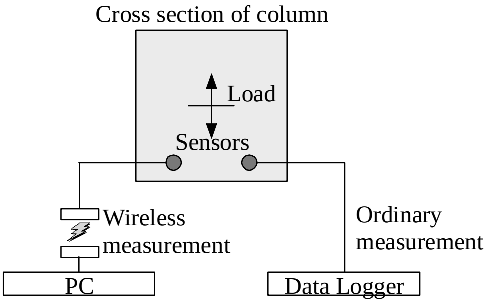


Figure 13. Diagram for measurement.

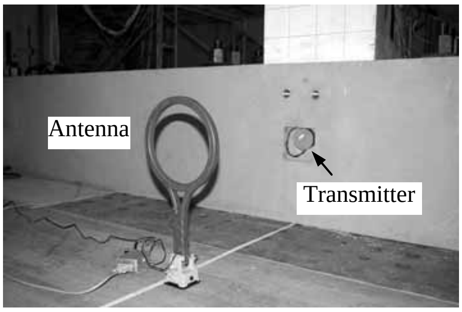


Figure 14. Setup for wireless monitoring system.

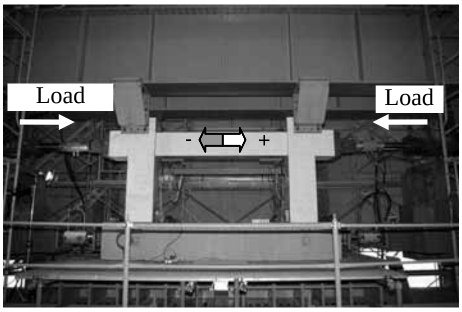


Figure 15. Experimental Setup.

Figure 17(a) shows the corresponding response of rod type sensor which is placed at location of No.11 in the beam in Figure 11. The sensors generally hold their peak value until the deformation of the specimen exceeds the experienced maximum displacement, and demonstrate remarkable memory function in the same manner as the experiment of the beam column joint specimen.

The response of the sheet type sensors shows

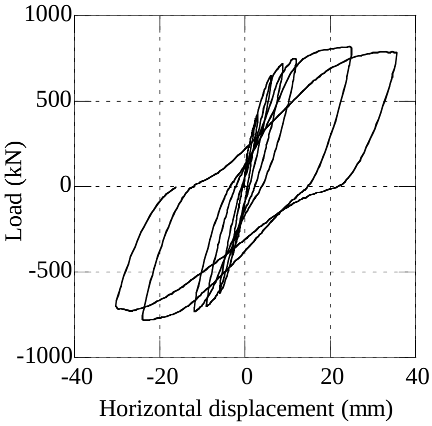
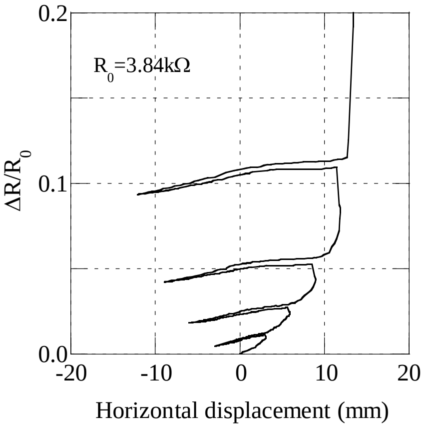
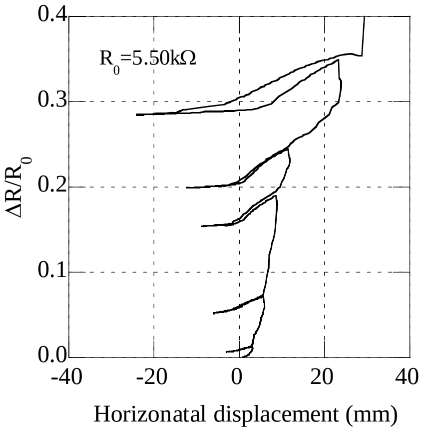


Figure 16. Deformation of the specimen.



(a) Rod type sensor



(b) Sheet type sensor

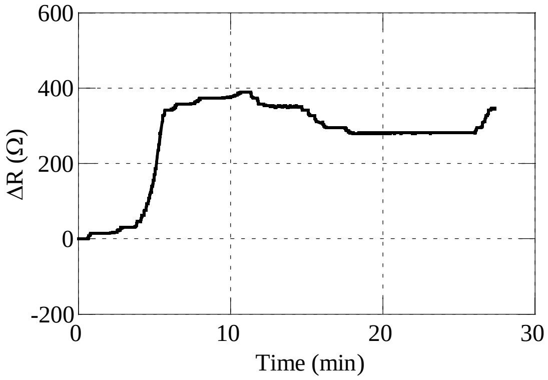
Figure 17. Variation of the electrical resistance of the sensor against the horizontal displacement.

considerable difference corresponding to the location of the sensor and appearance of cracks. The sensors can be bonded to the concrete surface firmly, so they do not peel off until cracks grow significantly large. The relation between the horizontal displacement and the variation ratio of the sheet sensor, located at the same position as rod type sensor, is shown in Figure 17(b). Their characteristics as maximum strain memory sensor to keep the peak value are clearly observed. Because the sheet type sensor is still under development, the sensitivity and stability of the sensor are not so good compared with the rod type sensor. However, the sheet type sensor will be applicable to the existing structures, and is expected to have wide application.

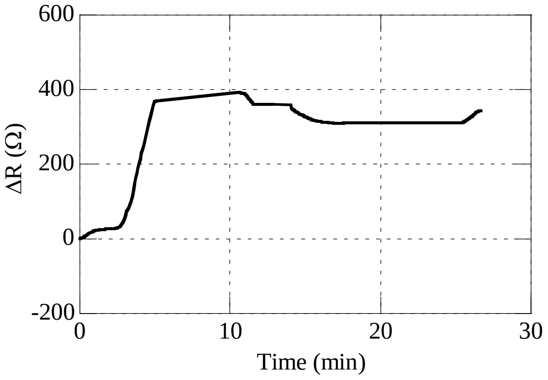
5.4 *Verification of the Wireless Monitoring System*

The variations in the electrical resistance of the sensor measured by the wireless measurement system and ordinary wired system during second loading cycle are compared in Figure 18. The figures show the relation between the time and the variation in the electrical resistance, which is represented as the fluctuation from its initial value at the beginning of loading cycle. At first, both sensors increase their resistance values due to the tensile strain by the positive loading, and generally hold their peak values after that. The results measured by both systems agree well. It is confirmed that the developed wireless monitoring system measures the electrical resistance of the sensor correctly.

In this case, the transmission distance is 60cm. For this experiment, data transmission is achieved up to the distance of about 60cm, and it is impossible to collect the data at the distance over 70cm. The result shows apparent difference against the result of the laboratory tests shown in Figure 2. This limitation of transmission distance is supposed to be caused by the absorption of the radio wave by the concrete or the influence of the ambient temperature on the electronic circuit. The system is undergoing the improvement to make it viable for the practical application.



(a) Wireless measurement



(b) Ordinary wired measurement

Figure 18. Comparison of the data measured by the wireless measurement system and ordinary wired system.

6 CONCLUDING REMARKS

Our study covers newly developed techniques using self-diagnosis materials combined with wireless measurement system, 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. With integrated the wireless measurement system, quick and effective health monitoring of structures after the occurrence of the earthquakes can be accomplished.

As a result of the experimental study, the developed system has been demonstrated to possess reliable performance as follows:

1. The rod type sensor shows apparent irreversible electrical resistance change and possesses superior ability to memorize load and damage.
2. The sheet type sensor is also demonstrated to function as a sensor with memory function, bonded onto the surface of the concrete.
3. The wireless measurement system satisfies the required performance, enabling rapid measurement of the electrical conductivity of the sensor.

7 ACKNOWLEDGEMENTS

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