Force Sensor System for Structural Health Monitoring using Passive RFID Tags for Structural Health Monitoring

Yusuke Ikemoto, Shingo Suzuki, Hiroyuki Okamoto, Hiroki Murakami, Xin Lin, Hideo Itoh, and Hajime Asama

***Abstract*—For this study, we developed a contactless loading sensor system that can measure the internal loading of an object structure through several covering materials for the purpose of structural health monitoring. The developed system can be inserted into objects without a battery because the system consists of passive RFID for data communication and a power supply. The system uses little electric power because the power supply with RFID is generally very low. We propose an architecture by which two RFID tags are used in the system. The functions of the tags are separated for communication and for the power supply as a circuit design contraption to solve the problem. First, we explain how the developed system is useful in an actual environment and introduce details of the developed sensor system. Second, the sensor system performance is evaluated through comparison of calculated results and experimental results. Based on those evaluations, the practical utility for structural health monitoring of the system is described.**

***Index Terms*—Structural health monitoring, loading sensor, passive RFID, low electric power design.**

I. Introduction

It is important to detect the underlying danger of structures and to monitor the physical fatigue of materials. However, materials of living spaces are almost always covered with concrete. For that reason, it is difficult to measure the internal loadings and status of such structures.

To maintain the health and safety of the structural objects and to predict the destruction moment, time-series sensing of the internal loading monitoring, called structural health monitoring, is an important area of development[1][2].

Structural objects in living spaces are damaged by natural hazards over a long term and are affected by accumulation of damage. If the damage reaches the limit of the safety range or the demand standard, repairs or additional strength must be adequately performed. Therefore, rapid and easy scheduled maintenance are expected to be necessary. To enable convenient maintenance work, structural health monitoring systems should preferably have wireless and batteryless performance, which can be satisfied if passive RFID tags are

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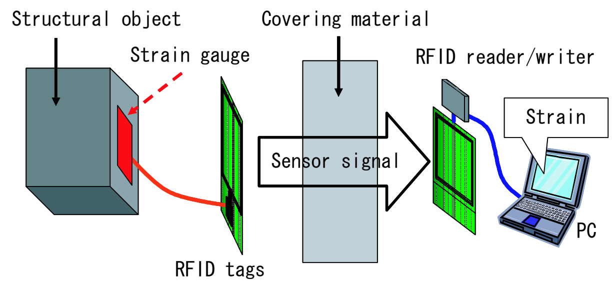

Fig. 1. Develop a structural health monitoring system using passive RFID tags

used because the user tries to sense the internal physical state of structures. However, it has been difficult to apply a passive RFID as a force sensor because RFIDs generally can drive only imperceptible electrical power devices such as temperature sensors[3]. Power supply problems must be considered consistently if an any-band RFID is used. We developed a force sensor system using passive RFID tags by physically separating a power supply module and a communication module to address these problems. For this study, we developed loading monitoring of measurement objects using a passive RFID tag.

Two major contributions are provided by this study. First, we developed a sensor system using passive RFID, which enables measurement of load-deformation information inside a structural object. Moreover, the inexpensive wireless, batteryless devices used in this system require little maintenance, and applications for the user interface are also included in the developed system for uniform management of structural health monitoring. Second is evaluation of the developed system in an actual situation using not only concrete but also other materials as covering materials on a structural object. With those evaluations, the practical utility is indicated. In particular, the measurement of the structural internal loading with $20.0_{[mm]}$ depth through concrete as a covering material. with a resolution performance from 10×10^{-6} to 40×10^{-6}.

II. Approach

A. Related Works and the Proposed System

Passive RFID is used to achieve remote measurement of interior load-deformation information. Some studies have used optical fiber[6][7][8][9], wireless LAN devices[12], crack sensors[10], or ultrasound waves [11] for maintenance of structures by placement in an iron frame, a concrete frame, a wall panel, or other material. In this study, passive RFID tags are examined [14][15][16]. They are expected to be used for structural health monitoring. Recently, studies using RFID tags for structural database management increases with RFID technology that sends and receives data without using physical contact with a wireless that uses electromagnetic fields, electric waves, etc., for communication. For instance, Yabuki described a system by which the construction process can be known immediately to users using the RFID tag for the checking and repairing structures [5]. The YRP Ubiquitous Networking Laboratory developed a system that can support management of a structural database and construction processes by putting an RFID tag on a steel column or wall panel; they developed an RFID tag that can be implanted into concrete[4]. Therefore, research using RFID tags, implant inside structures for structural maintenance has been actively pursued.

In this research, we develop the structural health monitoring system using passive RFID tags that can measure the strain loadings of structures (see Fig. 1) and evaluate the effectiveness using general covering materials. The developed system enables users to measure structural strain through the covering materials with no contact, and electrical wires in the signal for communication and a power supply is unnecessary.

B. Problems and Solution Method

The displacement range of a strain gauge, which is used in the developed system, is so minute that the sensor board consists of an amplifier circuit for detection of sensor output and a lowpass filter for high-frequency denoising, and a partial circuit to input to the lowpass filter and ADCIN terminal.

The strain gauges must be driven with a very small power supply from RFID tags. In addition to the power supply, this system needs a power supply to communicate: for transmission of the material's state data. The energy passed through an RFID decreases with the distance between the RFID reader/writer and the tags. It is, however, difficult to combine their power supply. Therefore, a contactless sensor system using RFID is limited to low power and responsible sensor devices such as a thermistor.

To solve the power supply problem and to realize stable communication using RFID, In the developed system, we propose a method using functional distribution of RFID tags of two kinds of RFID for communication and power supply. One RFID tag is specialized as a power supply for communication of strain loading information through A/D conversion. Another is specialized to supply power for driving the strain gauges bridge circuit. Herewith, using the separation of RFID functions, we develop structural health monitoring systems to realize contactless sensing with very small power and within current legal restrictions.

III. Developed Systems

A. System Architecture

1) Overview of the architecture: Fig. 2 shows architectonics of the developed system, which consists of an RFID sensor module put into a structure inside of covering materials; it

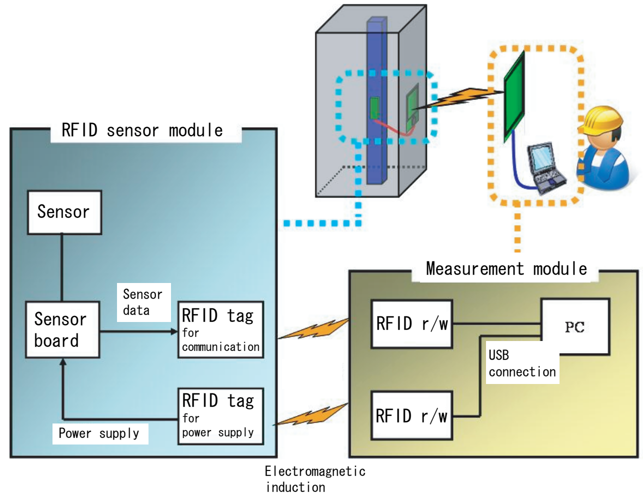

Fig. 2. Developed system architecture

also shows the measurement module for data acquisition. In the RFID sensor module, the strain gauge data are converted to A/D through a sensor on the RFID tag. The data are transported to the measurement module through the covering materials with RFID reader/writer devices. ¿From the data, information about deformation volume and loading are calculated without computers. Details of devices used in this system are described in the Appendix section.

2) RFID Sensor Module: Each RFID sensor module comprises strain gauge sensors, a sensor board, and RFID tags. A bridge circuit is configured with strain gauge sensors in the sensor board. The sensor board consists of an amplifier circuit for detection of sensor output and a lowpass filter for high-frequency denoising, in addition to a partial circuit to input to the lowpass filter and the ADCIN terminal.

The most important problem for designing the modules is how the strain gauges on a sensor board are driven with a small power supply from RFID tags. Both the ADC function of RFID and the communication process using RFID tags require high power consumption. Therefore, sensor systems using an RFID tag with ADC functions are limited to applications such as a thermistor, which has low power consumption, without an amplifier. To solve these problems, we developed an RFID sensor module consisting of two kinds of RFID tags, one is for the power supply, another is for communications. To separate the functions is a utilitarian architecture because the electricity consumption is expected to be an important consideration when an RFID is used for sensing. This architecture realizes stable communication.

Fig. 3 portrays the circuitry of the developed RFID sensor module. The voltages of a bridge circuit, an amplifier circuit, and a lowpass filter are supplied from the left side RFID tags of Fig. 3. This circuit is driven by constant voltage, $2.25_{[V]}$, between the VDD and GND terminal. The fixed resistance is inserted to input wiring to the bridge circuit to avoid carrying high level electric current. The drive current of the bridge circuit is set to $0.1_{[mA]}$ and the power consumption of the modules is set to $2.5_{[mW]}$. The offset calibration is carried

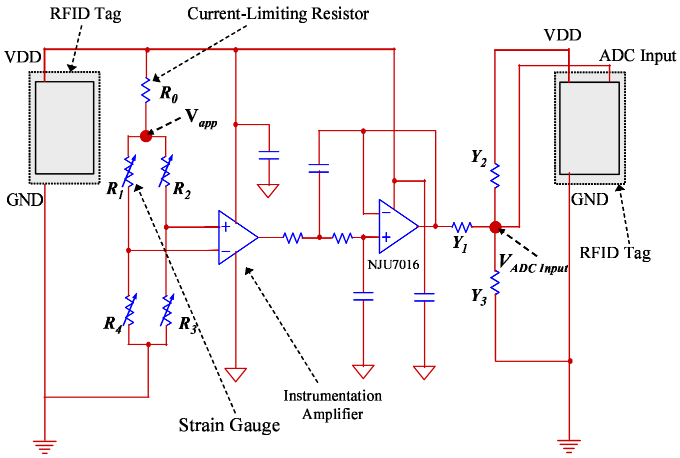

Fig. 3. Developed RFID sensor module circuit

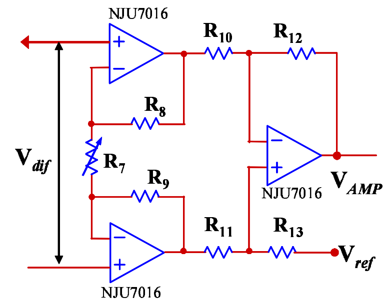

Fig. 4. Instrumentation amplifier circuit

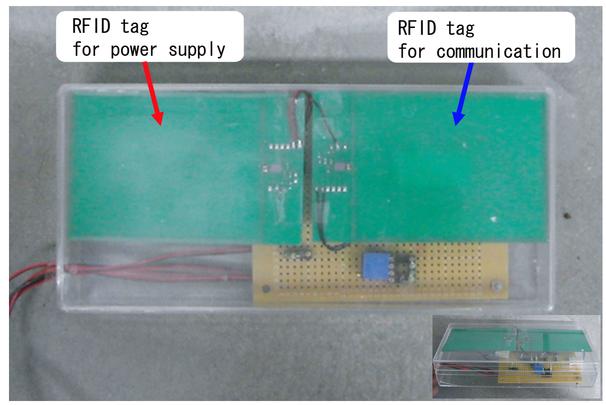

Fig. 5. Developed RFID sensor module

out by adjusting R_V in the figure. The operational amplifier (NJU7016D) is used for the amplifier circuit and is driven with low voltage. To filter out the noise from RFID electrical wave, three operational amplifiers are used for common mode noise rejection between both ends of a bridge circuit, as shown in Fig. 4). The cutoff frequency of the lowpass filter is set to $fc = 1.6_{[kHz]}$.

The right side RFID tags of Fig. 3 are for data acquisition from a measurement module. The partial voltage with three resistances Y_1, Y_2, and Y_3 from the amplifier circuit is input to the ADCIN terminal.

In Fig. 3, the input voltage to ADCIN terminal is described as below. In this regard, however, the effect of R_V is approximately negligible because $R_V << R_1, R_2, R_3, R_4$.

Let ε be the strain of R_1 in Fig. 3. The small resistance changes ΔR_1 occur and the relationship between the gauge coefficient of the strain gauge is described as

$$\frac{\Delta R_1}{R_1} = K\varepsilon. \tag{1}$$

Let V_{dif} be the difference of voltages generated by the bridge circuit. Before generating the difference of voltages, the bridge circuit is in an equilibrium state because of $R_1R_3 = R_2R_4$. Let V_{app} be the applied voltage to the bridge circuit; we have

$$V_{dif} = \frac{R_1R_2}{(R_1+R_2)^2} K\varepsilon V_{app}. \tag{2}$$

The output voltage from the amplifier circuit V_{AMP} is described as follows using amplifier gain A.

$$V_{AMP} = A \times V_{dif} \tag{3}$$

When setting $R_8 = R_9$, $R_{10} = R_{11}$, $R_{12} = R_{13}$, the amplifier gain A is described as follows.

$$A = \left(1 + \frac{2R_7}{R_8}\right)\frac{R_{12}}{R_{10}} \tag{4}$$

Let V_{ADCIN} be the input voltage from the ADCIN terminal and let $Y1$, $Y2$, and $Y3$ be the conductances between V_{AMP} - ADCIN terminals, VDD - ADCIN terminals, and ADCIN - GND terminals. Thereby, we have

$$\begin{aligned} V_{ADCIN} &= \frac{1}{Y_1+Y_2+Y_3}(V_{AMP}Y_1 + 2.25Y_2) \\ &= \frac{1}{Y_1+Y_2+Y_3} \\ &\quad \times \left(\frac{R_1R_2}{(R_1+R_2)^2}K\varepsilon AV_{app}Y_1 + 2.25Y_2\right). \end{aligned} \tag{5}$$

The output of V_{AMP} can be input to ADCIN terminal if we set $Y_1 >> Y_2$. The developed system has $0.05_{[V]} \leqq V_{AMP} \leqq 2.20_{[V]}$ because the output amplifier range is set as $0.05_{[V]}$ to $2.20_{[V]}$. Fig. 5 shows the developed RFID sensor module, which is encapsulated in an acrylic package. The figure shows that they are located parallel with $30_{[mm]}$ distance to avoid interference between RFID tags. The component parts of the RFID sensor module are presented in Table I.

3) Measurement Module: The developed measurement module consists of two RFID reader/writers and a computer for data processing and a user interface as Fig. 2. One RFID reader/writer is for communication; another is for the power supply with an RFID sensor module. The measurement module obtains the value of V_{ADCIN} from the RFID module and the strain is calculated using the computer according to Eq. (**??**). In the computer, the structure model, such as the parameters in Eq. (**??**), is known for uniform management of structural health monitoring. The application for the user interface, which is one component of the developed system, is portrayed

TABLE I
COMPONENT PARTS OF THE RFID SENSOR MODULE

Component	Quantity
RFID tag	2
Strain gauge	4
Operational amplifier (NJU7016D)	2
Fixed resistance ($\pm 0.1\%$)	12
Variable resistance	2
Multilayer ceramic capacitor	7

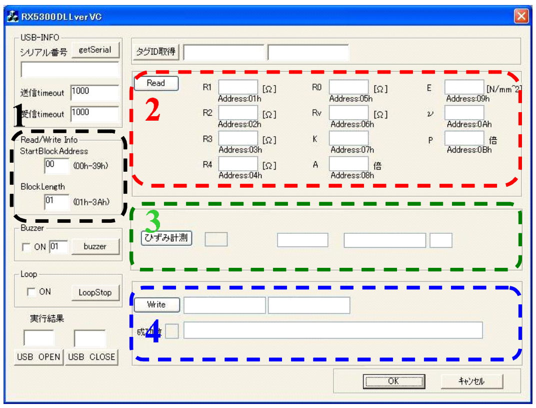

Fig. 6. User interface for uniform management of structural health monitoring

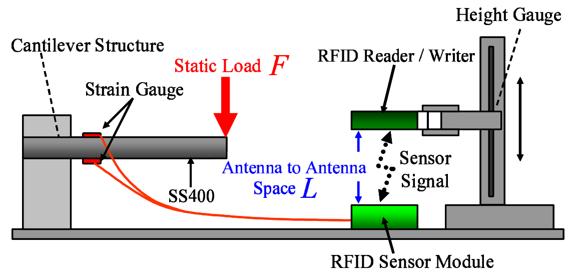

Fig. 7. Experimental equipment

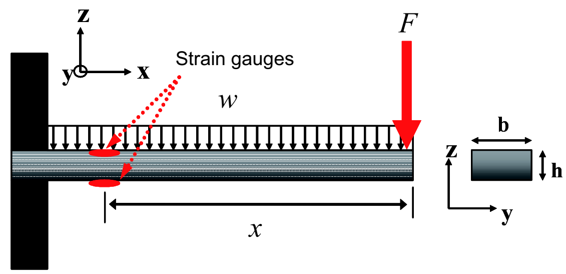

Fig. 8. Cantilever beam examination.

in Fig. 6. Users can acquire the strain information of the target structure through covering materials. The application has materials parameters and transit from V_{ADCIN} to strain with (**??**).

IV. EXPERIMENTS

A. Experiments for Evaluation of Basic Properties

1) Experimental overview: In this developed system, concern exists that the power supply to a sensor module decreases when the distance separating the RFID sensor module and a reader module increases. Therefore, unstable operation of each circuit and communication might occur from a low power supply. First, in this section, the effective distances for measurement without covering materials are evaluated as basic properties of the proposed system.

2) Experimental equipment: Fig. 7 shows the experimental equipment In this experiment, cantilever examination is carried out using a general structural rolled steel (SS400). The vertical load is added gradually to the free end. The strain in the surface of the target member of framework is measured using the proposed system. Through this experiment, the effective distances without covering materials are demonstrated. In the fixed end, the member of the framework is fixed to the base with a precision vise. A digital force gauge (DS2-500N) is fixed to the same base to avoid momentum; it is used to measure the additional forces imparted to the free end.

In this experimental device, the strain ε is described as Eq. (6) when F is added to the free end, as shown in Fig. 8.

$$\varepsilon = \frac{6x}{bh^2E}\left(F + \frac{wx}{2}\right) \tag{6}$$

In that equation, w represents the distributed load under its own weight, and E, b, and h respectively signify the Young's modulus, width, and thickness of the member of the framework.

3) RFID module settings: In this experiment, the four strain gauges are set into an x configuration in corners of the surface of the member of the framework so that all distance x between the strain gauges' position and the free end are equal, as shown in Fig. 9. Then, the output value of V_{dif} in Eq. 2 quadruples; we have

$$V_{dif} = K\varepsilon V_{app}. \tag{7}$$

Actually, considering the effect of the offset adjusting resistance R_V of Fig. 3, we have

$$V_{dif} = \frac{R_1}{R_1 + \frac{R_V}{4}} K\varepsilon V_{app}, \tag{8}$$

where it is approximated that $V_{dif} = 0$ because the differences between the resistances of strain gauges are very small. Table II shows the parameter value set in this experimental condition and equipment. Then, equation (5) is described as

$$V_{ADCIN} = 2.35 \times 10^3 \varepsilon + 0.35 \times 10^{-3}. \tag{9}$$

The second terms of the right side of Eq. (9) are negligible because the resolution of ADC in a RFID tag is about $8.8_{[mV]}$.

In addition, the strain gauge and gain A is determined based on design strength $F_{max} = 235_{[N/mm^2]} \times 80\%$ of SS400 of thickness $40_{[mm]}$. In this measurement range, SS400 is within the elastic area.

4) Experimental Methods: The sequence of experiments is explained as follows:

1) The antenna of the reader module is moved close to the RFID tag antenna.
2) The distance between each antenna is $5.0_{[mm]}$ from $2.5_{[mm]}$ as the origin.

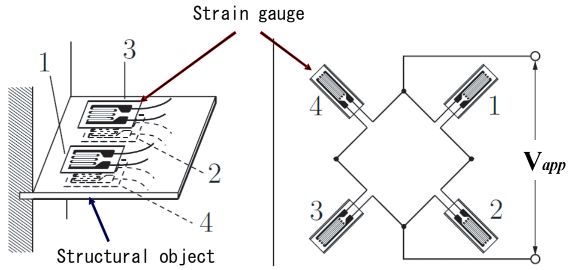

Fig. 9. Strain measurement using the four active gauge method

TABLE II
EXPERIMENTAL PARAMETER SET

x	Distance of load-point	$300_{[mm]}$
h	Thickness of testing material	$10_{[mm]}$
b	Width of testing material	$20_{[mm]}$
w	Own weight	$1.55 \times 10^{-2}_{[N/mm]}$
E	Young's modulus of	$205 \times 10^{3}_{[N/mm^2]}$
V_{app}	Bridge applied voltage	$1.13_{[V]}$ current-limiting resistor $R_0 = 1000_{[\Omega]}$
R_1	Unloaded resistance of strain gauges	$1000_{[\Omega]}$
K	Gauge factor	2.1
R_v	offset adjusting resistance	$50_{[\Omega]}$
A	Gain	1000
Y_1	Conductance of partial voltage resistance	$\frac{1}{100}\,[S]$
Y_2, Y_3	Conductance of partial voltage resistance	$\frac{1}{630}\,[S]$

3) A load is added to the free end by $10_{[N]}$ steps from $0_{[N]}$ to $200_{[N]}$ at each antenna distance.
4) The strain is measured using the developed system 10 times for each distance and load.

5) Results: The experimental results of evaluations of basic properties are shown in Fig. 10. The black line shows a realistic value predicted using Eq. (9). The m in the figure represents the mean squared error. When approaching $L = 32.5_{[mm]}$, m increases because of the power supply reduction. The developed system enables measurement of the forces from $L = 2.5_{[mm]}$ to $L = 32.5_{[mm]}$.

B. Experiments for Evaluation in actual environmental conditions

1) Experimental overview: It is necessary to evaluate the possibility that the developed system can work stably in an actual environment, which includes measurement through the covered materials. The assuming situation is to hold the reader module over a typical wall; the RFID sensor modules are present inside the wall. In this section, we configure situations of several covering materials inserted between reader modules and RFID sensor modules, and perform experiments to evaluate the developed system's function.

2) Experimental equipment: The equipment for experiments is shown in Fig. 11. The reader module is located in parallel opposite from the RFID sensor module. The experiments are carried out in identical conditions (see Figs. 7, 8,

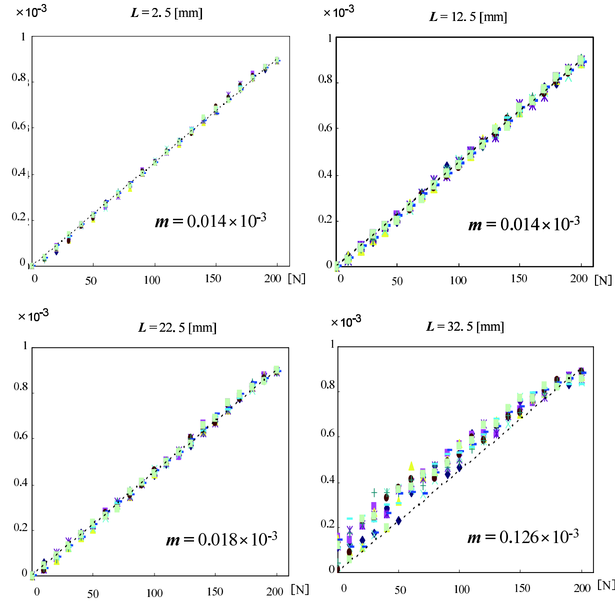

Fig. 10. Experimental result of evaluations of basic properties

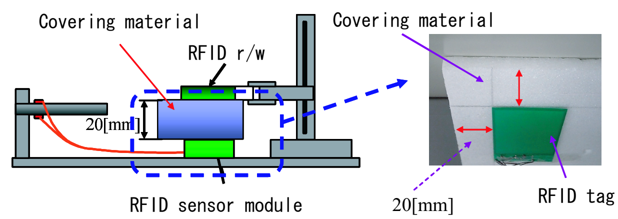

Fig. 11. Experimental equipment with covering materials

and 9). The loadings are added to free end and the equipment by $10_{[N]}$ steps from $0_{[N]}$ to $200_{[N]}$.

3) Experimental Methods: Concrete as covering materials are used. These materials are often present in typical walls. The materials' thicknesses are all set to $20_{[mm]}$. Therefore, the distance between reader modules and sensor modules is fixed at $20_{[mm]}$.

4) Results: The experimental results of using each covering material are portrayed in Fig. 12. The theoretical values obtained by Eq. (9) are shown as a continuous line on each figure. The m represents the mean squared error, as in previous experiments.

C. Summary of Results

The system can measure the internal loadings of the structure by $L = 32.5_{[mm]}$ without covering materials. When covering materials are inserted and $L = 20_{[mm]}$, the measurement can be carried out. For details, when L increase from $L = 2.5_{[mm]}$ to $L = 32.5_{[mm]}$. The measuring error also increased from 1% to 13% for the set measurement range. Within the range of $L = 30_{[mm]}$, it is possible to measure with strain resolution from 10×10^{-6} to 40×10^{-6}. Although the ADC in the RFID sensor tag module has 8 bit memory and $\frac{1}{256}$ resolution performance of measurement range, the result of the range actually remains

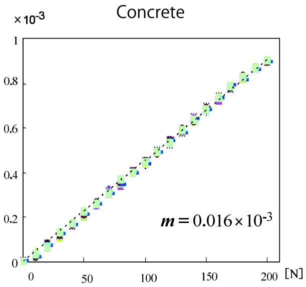

Fig. 12. Experiments in actual environmental conditions

at a low level. It is considered that around $L = 32.5_{[mm]}$ is the limited for the power supply depending on the device-specific characteristics. In addition, regarding the experiment with concrete, the performance is evaluated toward use in an actual environment.

V. Conclusion

We developed a force sensor system for structural health monitoring. Using an RFID, the system can measure the internal load of structural objects without contact for this study. Additionally, we carried out an experiment through several covering materials that are assumed to be used in actual situations. To solve dissipation power problems, we proposed a simple idea: the separation of the RFID module to power supply and communications. The developed system can also be configured using commercially available and inexpensive devices.

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