Improvement on Health Monitoring System Using Self-diagnosis Materials for Practical Application

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ABSTRACT: Electrically conductive glass-fiber-reinforced polymer composites containing carbon black have been prepared for strain sensing materials, and proposed as self-diagnosis materials. In this paper, improvement on the health monitoring systems using self-diagnosis materials for practical application is demonstrated. Firstly, production system of materials using pultrusion process has been established. Secondly, measuring devices to enable versatile and efficient evaluation have also been developed. Finally, the effort to enlarge the scope of applied target of our methods has been made. Applicability of our system to damage detection of wooden houses is discussed based on the experiments using timber frame structures.

1 INTRODUCTION

Recently, risks engendered by deterioration of civil infrastructures such as bridges and tunnels have risen up to the surface as a social issue. In order to establish appropriate maintenance strategy for infrastructures throughout their service life, it is urgently required to develop effective methods to monitor structural performance and diagnose damage to the structures continually. In practical health monitoring of large sized civil infrastructures, however, acquisition and processing of a great amount of data obtained by long term monitoring have become challenging tasks. Several innovative research using advanced technology such as distributed processing or data mining has been started to cope with these tasks. Meanwhile, the application of the sensor to memorize peak values can also be a simple and promising candidate. In order to evaluate residual performance of the structures after the catastrophic disaster such as earthquakes, detection of the maximum deformation or strain caused to the structures is essentially required. Then, the application of the sensor that is able to retain experienced information makes it possible to eliminate the necessity of continuous monitoring, and enables the assessment of maximum damage to the structures based only on the measurement conducted after the occurrence of the event.

The authors have continuously conducted research on the development of electrical conductive sensors using carbon materials, and proposed them as self-diagnosis materials. In previous studies, the conductive fiber reinforced composite, the glass fiber reinforced plastics containing carbon black particles, has been confirmed to respond sensitively against applied strain and memorize the peak value. Because the percolation structure formed by carbon black causes irreversible change in resistance, the sensor maintains the electrical resistance value corresponding to the applied peak strain. Applicability of our damage detection method using self-diagnosis materials to RC or steel structures has also been demonstrated by several experimental studies (Inada et al. 2005).

In this paper, our recent achievements of research aiming to put developed method in practical use are shown in detail. Firstly, investigation of production method of materials has been conducted, and pultrusion process has been employed. In previous studies, the materials are mainly applied to concrete structures, by installing them in the concrete. The installation to inside of the structures is naturally limited to the application to newly built structures. Then, displacement measuring devices, which can be attached externally even to the existing structures, have been developed using self-diagnosis materials. Furthermore, the effort to enlarge the scope of applied target of our methods has been made. A lot of Japanese traditional wooden houses have suffered severe damage due to recent major earthquakes in Japan. One of the authors has continuously conducted investigation on structural capability and redundancy of timber structures against the large deformation caused by the earthquakes (Hayashi et al. 2007). A series of experimental studies using timber frame specimens have been carried out. Here, our developed damage detection systems are applied to those experiments to investigate the applicability to damage detection of wooden houses, because they are expected to contribute as versatile damage detection method applicable to a number of conventional houses due to their low cost and serviceability.

2 SELF-DIAGNOSIS MATERIALS AND THEIR PRODUCTION

2.1 Characteristics of materials

The schematic drawing of self-diagnosis materials is shown in Figure 1. The rod-shaped FRP is composed of glass fibers (ER1150, Asahi Fiber Glass) and matrix phase consisting of thermoset epoxy resin (Epikote 807, Japan Epoxy Resin). High-structure carbon black (#3050B, Mitsubishi Chemical) is dispersed into resin as conductive particles. The particle volume fraction is typically set at 5.8 vol.%. After being cured at 160°C for 90min, the materials are carbonized through a pyrolysis process at 500°C in N_2 ambient. The carbonized composites were found to acquire high sensitivity and distinguished ability to memorize peak strain (Okuhara, et al. 2007). The composite is utilized as a sensor by attaching grips and electrodes at both ends. In this study, two sizes of sensors as shown in Figure 2 are applied. Small sized sensor with length of 45mm is newly developed for the application to the displacement measuring device shown in Chapter 2. The electrical resistance of small sensor is so small that the resistivity of sensor is measured by four-probe method. As shown in the figure, two pairs of cables, connecting to outer current electrodes and inner voltage electrodes, are attached.

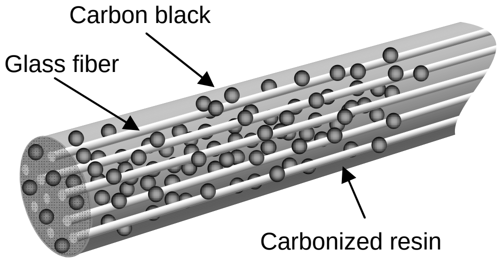

Figure 1. Schematic drawing of materials.

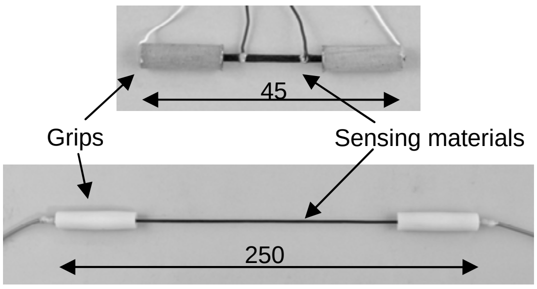

Figure 2. Two types of sensors.

Tensile tests of the sensors have been conducted in order to evaluate characteristics of the materials as a strain sensor (Inada, et al. 2007). As a result, the relation between the applied strain ε and electrical resistance of sensor R has been derived as follows:

$$\varepsilon = a\rho^b; \quad a = 6.86\times10^{-3}, \quad b = 0.384 \tag{1}$$

In equation (1), resistance variation is represented by variation ratio ρ (= (R–R_0) / R_0, R_0; initial resistance value). Hereafter, the variation ratio is used to evaluate resistance change of the sensor. And coefficients a and b in the equation are obtained by regression of test data. At the present stage, however, this equation has been derived based on the tests using products currently being developed. For actual application, reevaluation based on the definitive products is also required.

The example of results obtained by tensile test and estimated relation by equation (1) is shown in figure 3. As shown in the figure, sensor shows a distinguished memory function, but has lower detectivity against small strain under 1000μ.

2.2 *Development of production method of materials*

As a result of tensile tests, developed materials are also found to possess performance variability, which makes the sensor unstable. The variability is supposed to be caused mainly by nonuniformity in the cross sectional shape and dispersion of carbon black in the resin. In our early developmental stage, the materials have been fabricated by molding manually by one batch at a time. For the practical application, the production method is established to ensure stable performance of the sensor and reduce manufacturing costs.

The production system using pultrusion process has been employed, and the mass production line shown in Figure 4 was actually set up in the FRP factory. As shown in the upper photograph in Figure 5, carbon black is dispersed into resin and warmed well in temperature-controlled bath of 80°C in order to accelerate uniform impregnation into glass fiber. The composites are gradually shaped into rod and cured at the same time, by passing them through a heated die with inner Teflon-coating. As a result, two rod shaped materials with different diameters for two types of sensors are formed simultaneously as shown in lower photograph in figure 5. The diameters of each composite are 1.5mm and 0.9mm, respectively.

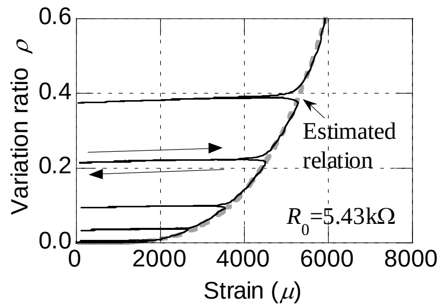

Figure 3. Result of tensile test and regression.

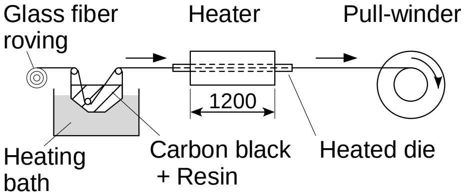

Figure 4. Production system of materials.

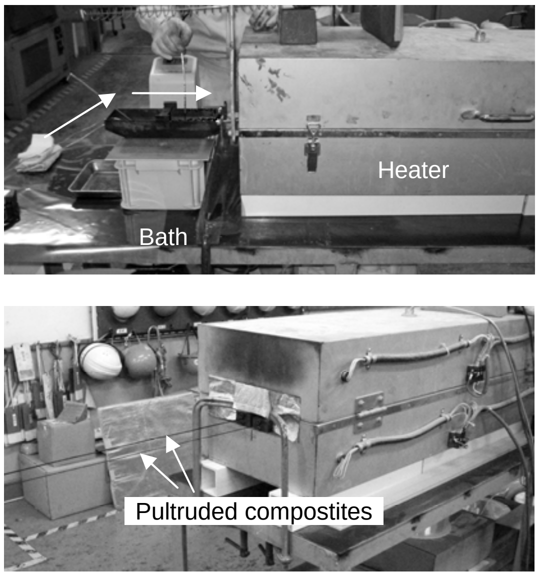

Figure 5. Manufacturing process.

3 DISPLACEMENT MEASURING DEVICE USING SELF-DIAGNOS MATERIALS

3.1 Development of device

The general description of developed measuring device is show in Figure 5. The device is composed of small sized sensor in figure 2, with helical compression spring, aluminum cylinder and tensile rod, which are all set coaxially. The rod and the cylinder are connected to two fix points, and slides from side to side smoothly with each other. The sensor is installed in the cylinder for protection and made watertight. Both ends of the sensor are clamped to cylinder and rod via spring, and relative displacement caused between two fix positions are distributed to sensor (SE) and spring (SP) allocated according to their stiffness. Setting the gauge length and stiffness of the sensor L_{SE} and EA_{SE}, the constant of spring k_{SP}, relation between displacement X and strain of sensor $\varepsilon_{\mathrm{SE}}$ is represented as follows:

$$X = (EA_{\mathrm{SE}} + L_{\mathrm{SE}} k_{\mathrm{SP}}) \cdot \varepsilon_{\mathrm{SE}} / k_{\mathrm{SP}} \tag{2}$$

Therefore, sensitivity and allowable displacement of the device can be controlled by specification of spring. Experimental results shown below have been obtained by specifying allowable displacement as 10cm using spring with constant of 28.3N/mm.

While FRP materials generally work well against the tensile force, compressive strength is comparatively low. As shown in figure 5, fix part on the left side of device only pulls tensile rod when it moves leftward, and tensile strain alone is transferred to the sensor. Furthermore, adjusting nut is inserted to the left end of rod. Then, the low detectivity of the sensor against small strain can be improved by introducing initial tensile force.

3.2 Vibration tests of displacement measuring device

Vibration tests using one-directional shaking table as vibration exciter are conducted to investigate the applicability and performance of displacement measuring device. Because the peak memory sensor is applied to static post-event measurement, its performance is generally evaluated through static tests. In actual situation, however, the sensor is required to follow the response of target structures against dynamic loading such as earthquakes and winds. Therefore, this vibration tests are planned not only to check the static performance of device but also to confirm vibration following capability of the sensor.

Figure 6 shows the outline of experiments. One fix part of device is mounted on the fixed table, and the other end on shaking table, vibrating in horizontal direction. Setting frequency of vibration to 1, 2, 5Hz, amplitude of vibration is gradually increased to target amplitude of 10, 10 and 5cm, respectively. After oscillating in constant amplitude during certain period, amplitude is decreased gradually. Number of specimens for each frequency is three. Relative displacement of shaking table is measured by laser displacement meter for comparison.

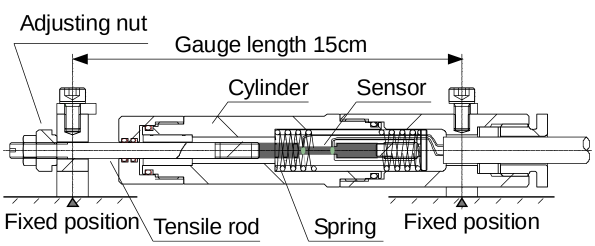

Figure 5. Displacement measuring device.

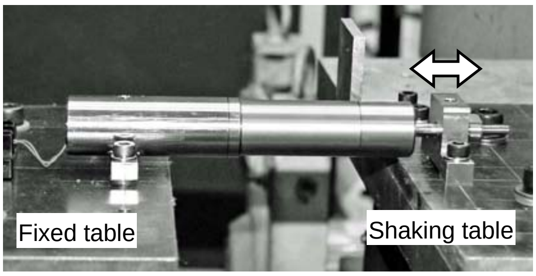

Figure 6. Outline of vibration test.

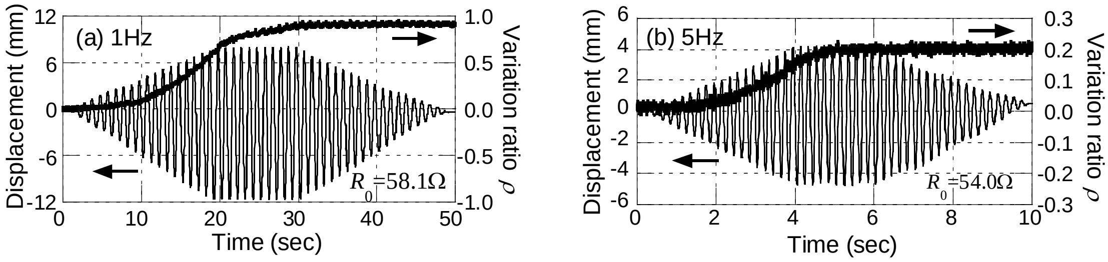

Figure 7. Examples of test results.

The examples of obtained time waveforms of displacement and electrical resistance of the sensors are shown in Figure 7. Variation of resistance is represented as above-mentioned variation ratio ρ. In all test condition, the sensor increases its resistance value only against the displacement in tensile direction, and keeps peak value corresponding to the maximum displacement. Therefore, the sensor is confirmed to show the expected performance as peak memory measuring device even against dynamic loading. The sensor also shows apparent resistance variation up to the maximum frequency of 5Hz in the tests, which demonstrates enough capability to follow the response of general structures against external excitations such as earthquakes. In the result of higher frequency, slight phase delay in response of the sensor against displacement has been observed. The mechanism and the effect on the sensing accuracy are being investigated in foregoing studies.

4 APPLICATION TO DAMAGE DETECTION OF WOODEN HOUSES

4.1 Outline of experiment

Applying to damage detection of wooden houses, we focused our attention to observe connection parts of column to beam and column to base. Deformation caused in these parts is likely to return seemingly to their original state after unloading, but the estimation of experienced deformation is required to judge the residual capability of structures. Then, the uplift of upper beam and the rotation of column against its base are selected as objective measuring values. Several types of timber frame specimens with different sizes, number of columns, existence of wall or lintel, etc, have been investigated in the experiments.

Figure 8 shows the general description of typical specimen and location of detecting devices. To monitor the uplift of upper beam due to the unfastening of tenon, displacement measuring device shown in chapter 3 is applied. Meanwhile, deformation caused by the rotation of the column is larger than the uplift and not unidirectional, new device is fabricated for the purpose. Hereafter, these two devices are called uplift measuring device and rotation measuring device, respectively. Both devices are attached to the specimen by wood screws as shown in Figure 9. The displacement measuring device is modified for uplift measurement by attaching the rod-end bearing to upper fix position to allow rotation of the column. The rotation measuring device employs the same mechanism as displacement measuring device, and relative displacement is transferred to the sensor via compressive spring with constant of 62.4N/mm. The sensor with length of 250mm as shown in figure 2, is fixed on the cylinder and rod to enable simple and flexible installation. The rod-end bearings are inserted at both ends, in order to follow various directions of movements caused between the column and base.

The constant current of 1mA is applied to the sensor, and induced voltage is measured and stored by data-logger. The electrical resistances of the sensors are calculated from the voltage value. The displacement meters are attached on the opposite side of the specimen at the same position of the devices for comparative measurement.

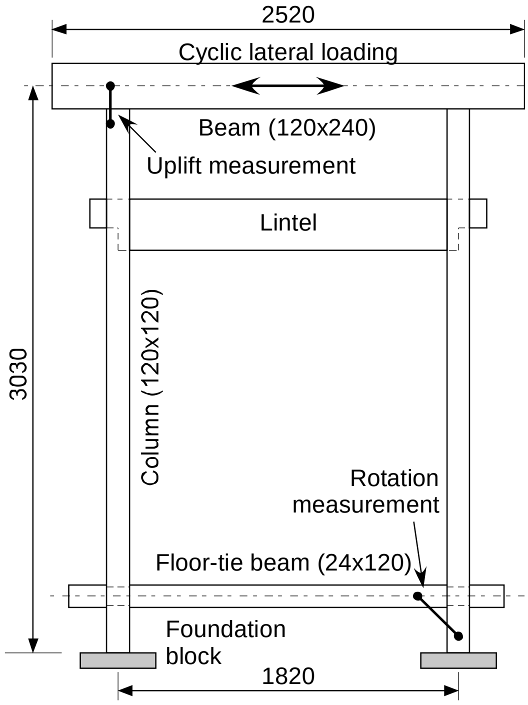

Figure 8. General description of experiments.

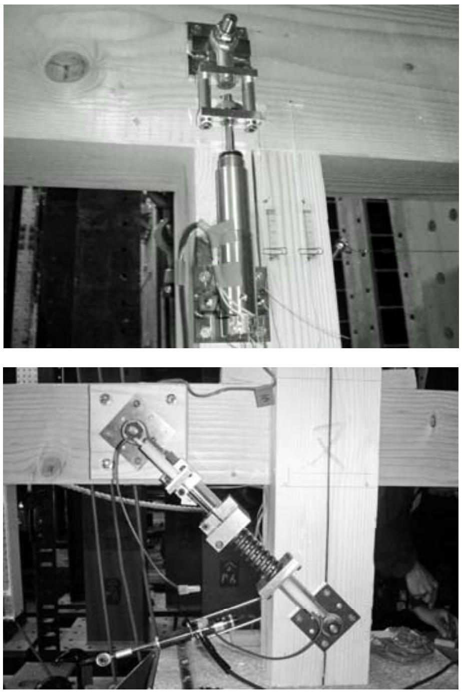

Figure 9. Two measuring devices.

4.2 *Behavior of specimen and response of detecting devices*

After being vertically loaded corresponding to the weight of superstructures, the specimens are subjected to quasi-static cyclic lateral loading, gradually increasing the maximum deformation angle symmetrically from 1/60, 1/30, and so on, until the structures reach to the final collapse. Final collapses are caused by bending fractures in the column or failure at the connection parts depending on the specification of the specimen.

The uplift measurement device has been applied to eight specimens with different specification, and reasonable data was obtained in almost all cases. On the other hand, rotation measurement devices have been adopted in four specimens, but the measurement has been successfully conducted only for two specimens. Because the mechanical system of the device to transfer the displacement to sensor has not been optimized enough, the sensor could not follow large deformation. The mechanism of the rotation measurement device is still being investigated.

As examples of obtained results of uplift measurement, relation between the lateral load and uplift and between electrical resistance variation of the sensor and uplift are shown in Figure 10. In the small range of loading, uplift is only caused during a positive loading, unfastening of tenon is gradually induced along with the increase of load. Although the response of the sensor is not observed against small displacement, the remarkable increase of electrical resistance arises over displacement of 2mm. After that, the sensor increases its resistance against displacement, and keeps the peak value during previously-experienced load. The appropriate measurement can be conducted in a wide range of displacement until the breakage of the sensor.

Figure 11 shows the corresponding results of rotation measurement for the different specimen. The displacement caused by the rotation of the column shows symmetrical appearance against the load. The displacement grows rapidly against the load comparing the uplift. The sensor initiates the response against small displacement, but the variation ratio keeps smaller value than the uplift measurement. The reason is presumably that the sensor suffers not only the tensile strain but bending or other directional forces.

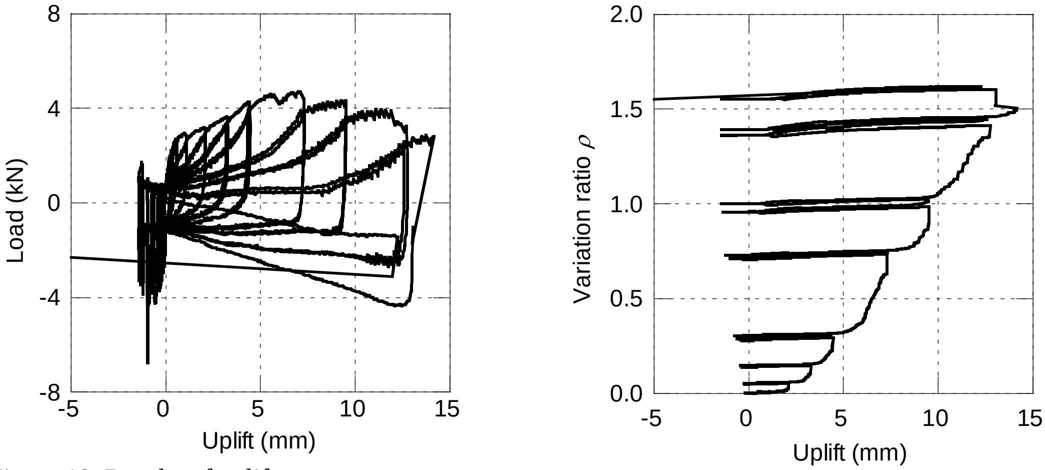

Figure 10. Results of uplift measurement

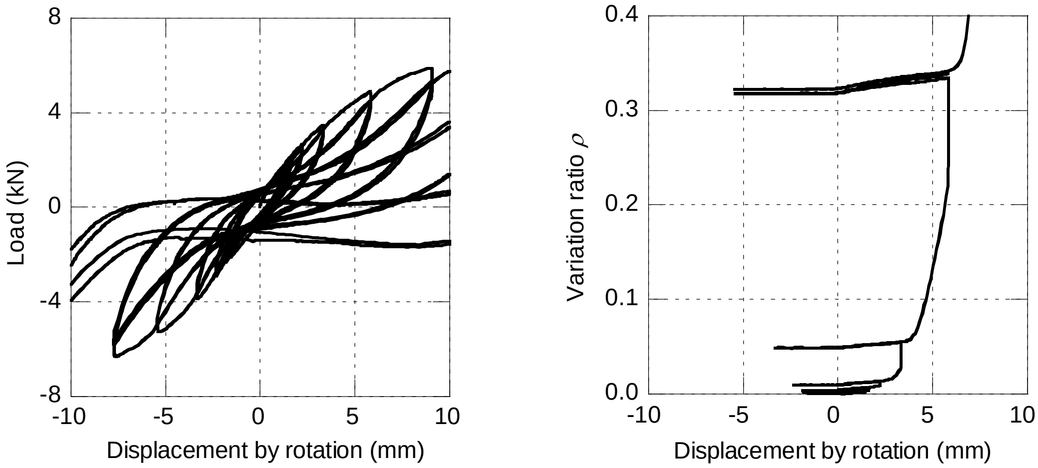

Figure 11. Results of rotation measurement.

4.3 *Detectability and accuracy of devices*

Substituting the measured resistance value into equation (1), the strain of the sensor $\varepsilon_{\mathrm{SE}}$ can be estimated. Then, using equation (2), estimating equation of displacement is derived as follows:

$$X = (EA_{\mathrm{SE}} + L_{\mathrm{SE}} k_{\mathrm{SP}}) \cdot (a\rho^{b}) / k_{\mathrm{SP}} \tag{3}$$

The relations between the estimated displacement obtained by equation (3) and measured displacement in case of the result of figures 10 and 11 are shown in figure 12. The estimated displacement in uplift measurement shows good agreement to the measurement. In this case, the maximum displacement can be obtained throughout the loading. Although the displacement can be estimated up to the allowable value of 10cm, the estimated value tends to become smaller than the measurement near the allowable limit. While the uplift grows larger, the angle between rod-end connected to the upper fix point and tension rod becomes larger. As a result, displacement becomes hard to transfer to the sensor as tensile strain. As for the rotation measurement device, estimated value agrees relatively well in a small range of loading. After that, however, considerable difference in the response of the sensor is observed. As shown here, the applicability of developed devices to damage detection of timber structures has been confirmed. But there still remains the necessity to refine the mechanism of measurement. Detailed investigation of performance and improvement of devices are in progress.

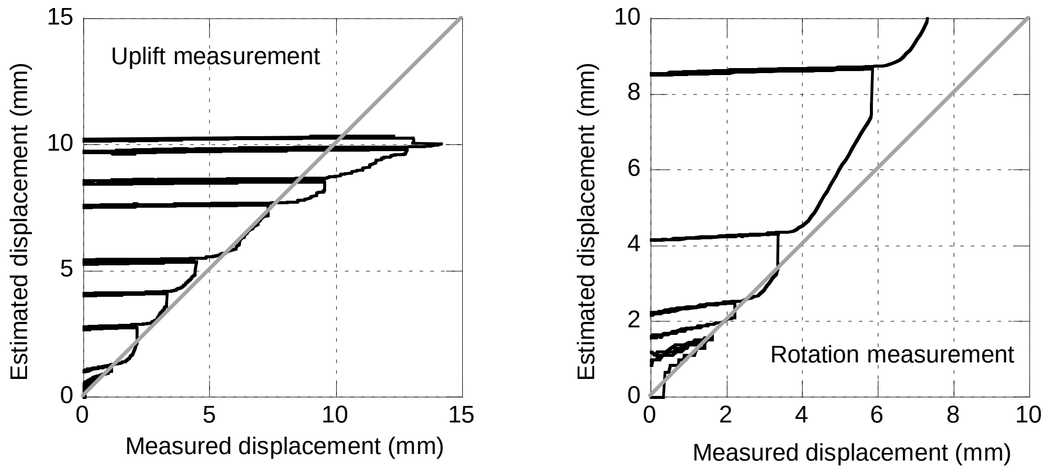

Figure 12. Accuracy of estimation.

5 CONCLUSION

Our study covers newly developed damage detection devices using self-diagnosis materials, and their applicability to damage detection of wooden houses is investigated. As a result of several experimental studies, the developed system has been demonstrated to possess reliable performance as follows:

i) Production system using pultrusion process has been established in order to reduce both performance variability and manufacturing cost of sensor.

ii) The displacement measuring devices with peak memory function have been developed, and their performances are investigated by vibration tests.

iii) The applicability and required improvements for the damage detection of wooden houses have been demonstrated by experiments using timber frame structures.

ACKNOWLEDGEMENTS

A part of this research was conducted as “Advancement of Basic Technological Research” supported by NEDO (New Energy and Industrial Technology Development Organization), Japan. The authors are grateful to AGC Matex Co., LTD and, Kyowa Electronic Instruments, Co., LTD for their cooperation to develop the materials and devices. We also would like to show our appreciation to Dr. Morii, Kyoto-Univ. for his great contribution to the experiments.

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