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Communication

Piezoelectric Joint Sensors Shape to Sensor Response Characteristics by FEM Analysis and Measuring Result

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Abstract: After the huge earthquake many steel structures were constructed using frame welded joints of welded construction and welded base. Steel structures are considered earthquake resistance structures however, many steel structures are constructed using frame-welded joints of fillet welded construction and welded column bases. These weld joints could result to have low capacity to absorb energy during earthquakes. Therefore, the application of structural health monitoring to the maintenance of infrastructures is extensively expected for new technology. However, in order to achieve practical utilization of new sensors, both accumulation of data and evaluation method to derive information about structural conditions from the measured data is highly required. To solve such a problem, we would like to measure the structure by health monitoring using a piezoelectric sensor. In this paper, measurements output voltage because using piezoelectric joint sensors, we recorded the sensor characteristics during measuring robot measurement because of changes in the thickness and shape of the base plate of the piezo joint sensor. Structural FEM for sensor analysis is also introduced to evaluate the mechanism and influence of various environmental factors on the response of the structures. In other hand, the introduction of the sensor measurement robot has reduced the working hours required for measurement experiments of sensor characteristics to about 1/19, which is expected to boost the cycle of sensor improvements in the future significantly. We will use robotics to promote research on the performance characteristics of piezoelectric joint sensors for a safe society.

Keywords: Control Engineering, Health Monitoring, Piezoelectric Joint Sensor, FEM Analysis

1. Introduction

Japan has much infrastructure such as bridges and tunnels that were constructed more than 50 years ago. Increasingly repairs will be necessary to avoid risks of their collapse [1]. Column base joining methods used in many steel-framed buildings include fastening with bolts and welding. For bolt fastening, if a dynamic external force such as an impact, vibration, or heat load (expansion) acts, then the bolt might not perform its fastening function because of frequent loosening of the nut. An accident might occur. In the case of welded joints, few accidents occur because of vibration and loosening of nuts, but brittleness occurs simultaneously as hardening around the joints because of heat effects during welding [2]. Because the heat treatment relation between quenching and annealing of steel materials is created, controlling the soundness of structures is regarded as a very difficult task. Solving difficulties at the construction site necessitates quantitative judgment of the relation between the ductility and toughness of the welded part and the residual stress. General issues must also be overcome [3]. In the case of welded joints, there are few accidents due to vibration or loosening of nuts, but brittleness occurs at the same time as hardening around the joint due to the heat effect during welding [4]. It is also necessary to overcome the general problem that ductility and toughness decrease as the strength of steel materials increases, leading to a decrease in fatigue strength.

However, to guarantee the strength and other characteristics if the steel material strength increases, it is said that the ductility and toughness would decrease, leading to decreased fatigue strength. Therefore, achieving structural soundness might be difficult. Even if one strives to analyze the results of measurements at the initial stage of joining along with the results of aging for over 10 years using finite element method (FEM), one cannot assess crack growth or perform defect location realistically [5].

The purpose of the research was as follows. (1) Evaluate the output characteristics of the sensor with the improved shape of the base plate by FEM analysis. (2) A piezo composite sensor that uses a measurement robot that can measure the output of a piezo composite sensor at low cost and in a short period of time to study measurement technology through sensor breakage damage tests and to determine the degree of danger when a force is applied to a structure. Evaluate the availability of the product [6]. (3) Select the optimum sensor base plate thickness of this sensor from the sensor output in the range of 5 to 10 mm for the displacement of the joint obtained from the numerical calculation by the measurement test. In addition, the performance is evaluated by comparing the mounting test using the sensor under the obtained conditions and the measurement result of the robot [7-10].

2. Examination of Joint Soundness Measurement Technology Using Piezo Composite Sensor

2.1. Examination of Sensors for Long-term Measurement Technology

The piezo composite sensor was manufactured for the purpose of measuring the voltage according to the fracture at the welded joint of the steel structure. This sensor is inexpensive and is a consumable sensor that breaks after failure measurement. Since the piezo film used is a piezoelectric element and emits electric power by itself, a power supply for measurement is not required when it is used for field measurement. In this study, we prototyped two types of piezo composite sensors using metal plates of five different thicknesses, and compared and examined the output intensities when a force was applied to each sensor Figure 1(a) shows the configuration of the A-type piezo composite sensor, and Figure 1(b). The configuration of the B-type piezo composite sensor is shown in. The piezo composite sensor is a base metal plate made of approximately 16×73 mm piezo film (Tokyo Electronics: DT2-028K / L) and 25×75 ×1 mm hard plate glass with an ultraviolet curable adhesive (Henkel Japan: Loctite 3851) [11]. It is a structure that is adhesively fixed to. The glass plate is also intended to prevent peeling and deterioration of the piezo film. A general rolled steel plate of 40 × 190 mm was used as the base metal plate of the sensor, and five types with plate thicknesses of 1.0, 1.2, 1.6, 2.0, and 2.3 mm were compared. The base plate is made by drilling two holes for bolt fastening with a diameter of 12.1 mm and holes for a cable duct with a diameter of 8.0 mm, and then bending 40 mm at both ends at 135 degrees. This shape makes it possible to mount the piezo composite sensor at an angle of 45 degrees to the right-angled welded surface of the square steel pipe column used in the mounting test.

According to the test results conducted using the A-type piezo composite sensor so far, the sensors with a plate thickness of 1.6 mm and a plate thickness of 2.0 mm generally satisfied the measurement conditions [6]. However, the magnitude of the sensor output value was uneven between the tensile load and the compressive load. Therefore, we devised the shape of the B-type piezo composite sensor with the expectation that the deformation stress applied to the sensor will be concentrated in the center of the sensor and a more uniform sensor output will be obtained than the A-type sensor in both the tensile test and the compression test. In this study, the tensile test is defined as the test in which the sensor installed at the welded joint applies a force in the direction of bending outward, and the compression test is defined as the test in which the sensor is applied in the direction of bending inward. The direction to turn inward.

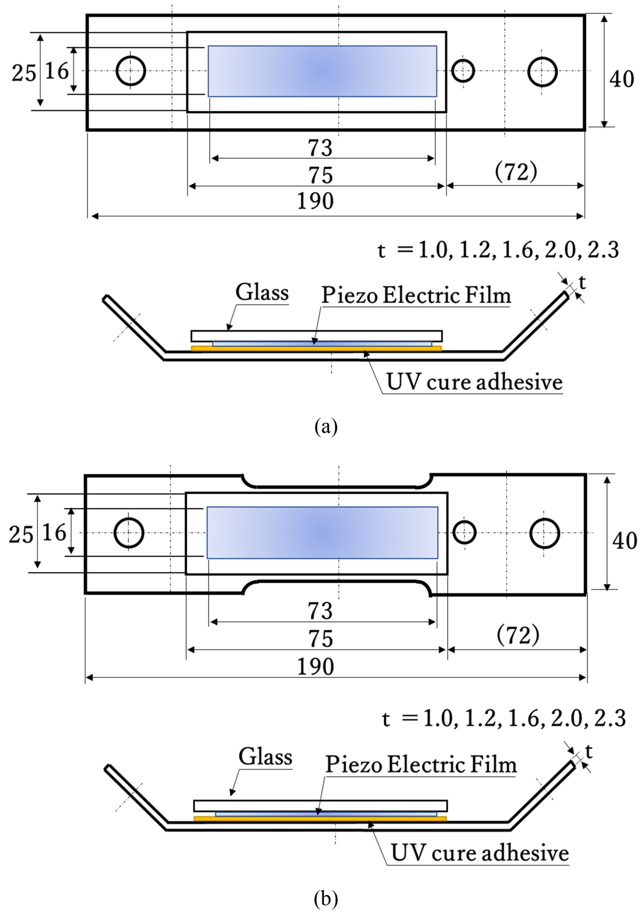


Figure 1. *Characteristics of piezoelectric composite sensor for A type and B type.*

2.2. FEM Analysis

FEM analysis of the A-type piezo composite sensor and the B-type piezo composite sensor was performed to examine how the shape of the sensor base plate is affected by the stress due to the load. Figure 2 shows the FEM analysis results of the A-type sensor and B-type sensor with a sensor plate thickness of 2.0 mm. In the case of the A-type sensor, the tensile test shown in Figure 3(a) found that the applied force was dispersed and the plastic deformation at the center of the sensor base plate could not be increased. Also, in the compression test (b), it is expected that it will be difficult to concentrate the force on the center of the sensor. On the other hand, in the case of the B-type sensor, in the tensile test of (c), the plastic deformation was concentrated in the center of the sensor compared to the FEM analysis result of the A-type sensor, and the effect of the improved design was confirmed. In the compression test of (d), unlike the result of the A type sensor, the applied force was concentrated in the center of the sensor, so the sensor output of the B type sensor was made uniform in both the tensile test and the compression test. As a result of the test, I had high expectations.

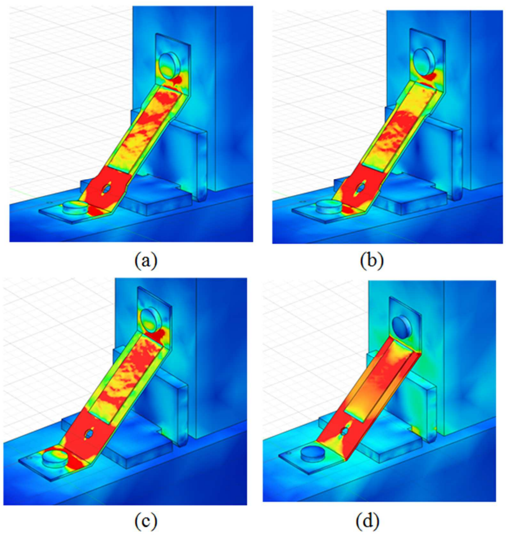


Figure 2. *Simulation of piezoelectric composite sensors A type and B type for difference of displacement pitch by FEM.*

2.3. Sensor Characteristics Measurement of Power Mounting Test and Robot (SALLY).

Figure 3(a) shows load test devices by mounting test details. This test model structure has 1100 mm height and 975 mm width. To it, 100 mm of steel pipe is welded and joined in a T tip shape. A hydraulic jack is applied to this test model structure to measure the displacement, sensor type, and force. At the development stage of the new monitoring sensor, as shown in a steel-framed T-shaped test model structure for mounting that imitates the welded joint of the structure has been manufactured [12, 13]. Displacement of the complete fracture during the mounting test is calculated as about 5–10 mm, assuming a gradient of 1/200 to 1/100 according to the safety standards of the Building Law. The presents mounting test details. (1) Experiment of load and displacement load test devices. (2) The piezoelectric composite sensor. Figure 3(b) shows the device configuration of SALLY. A robot that measures the output of the piezo composite sensor corresponding to the deformation angle of the column joint. The forward rotation of the motor, in which the right-angled column tilts leftward with the sensor mounting side facing the front, was used as the compression test; the reverse rotation was used as the tensile test. The measurement time requires about 20 min to obtain the sensor characteristics of one item. In addition, the measurement data are sampled at 100 Hz. The sensor output, force and displacement are measured simultaneously. Robot control is controlled automatically by mode selection of the motor control program of the notebook PC. At the time of test implementation, after installing the piezo junction sensor in SALLY with a maximum load of 500 N, the logger and PC control program are started simultaneously. The maximum tensile and maximum compression test displacements are set to 35 mm. The base plate sensor records the sensor output when the tensile and compression tests at 2.0 were performed three times. (1) Drive stepping motor, (2) Horizontal pillar, (3) Load cell sensor, (4) Displacement meter, (5) Sensor mount [7].

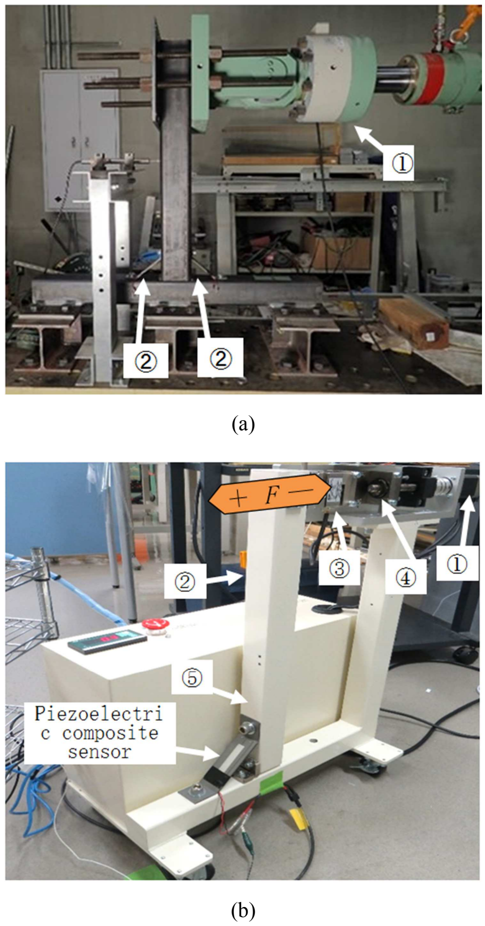


Figure 3. *Setting of piezoelectric composite sensor on the steel specimen and measurement robot.*

For sensor development, the conventional method is to attach a prototype sensor to the test piece directly and to obtain the sensor characteristics by destructive testing. The labor and cost are about 15 hundred yen for the test piece to obtain the sensor characteristics of one item. The efforts of about three people are necessary for sensing of the desorption time: they must install the test piece on the gantry and operate and measure the hydraulic system. The process takes about one day. It required much money and time. To obtain the sensor characteristics of 30 items using the conventional method, the cost of the specimen to be damaged is about 2.25 million yen, even if the running cost of the hydraulic system is ignored. It takes 15 days of measurement by three people. We strongly recognized the necessity of designing a measurement robot that dramatically improves the measurement time and cost to implement many characteristics of the piezo junction sensor, and thereby enable efficient measurement. The authors have long experience in robot research and development. The humanitarian anti-personnel landmine detection robot (COMET I) is a robot of representative authors introduced by the Society and the Science Council of Japan [14].

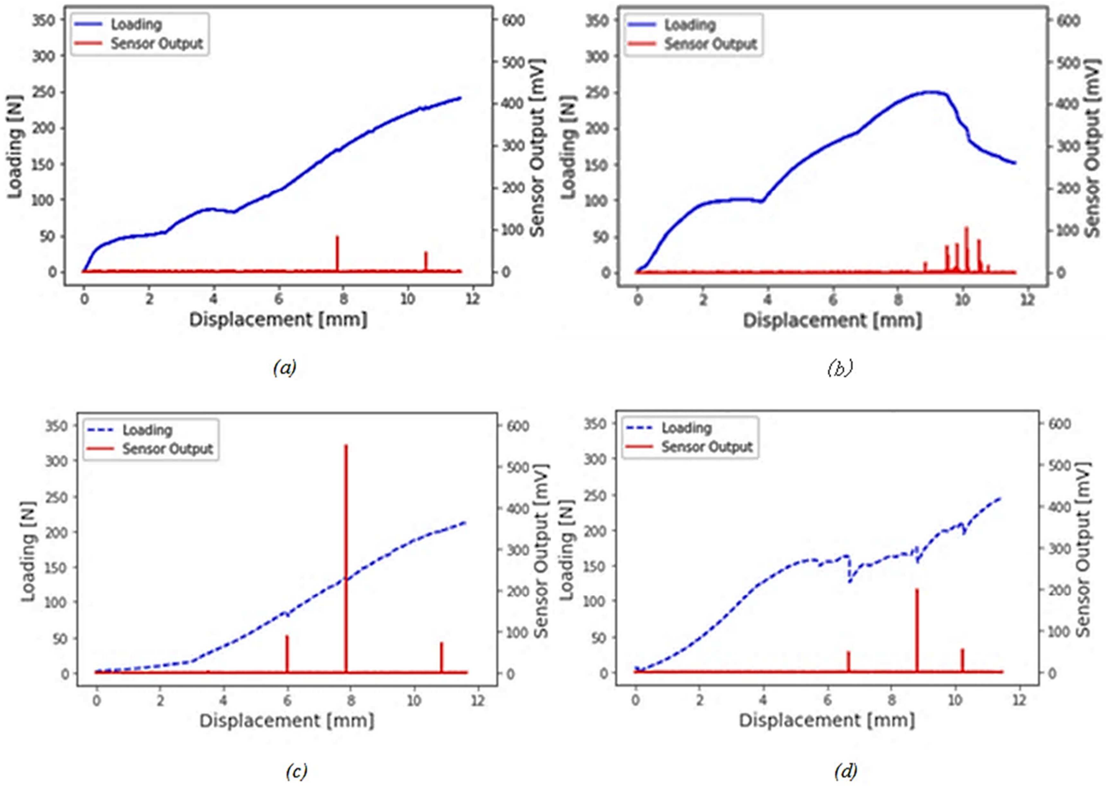


Figure 4. *Piezoelectric composite sensors measurement result by power mounting test and robot measurement.*

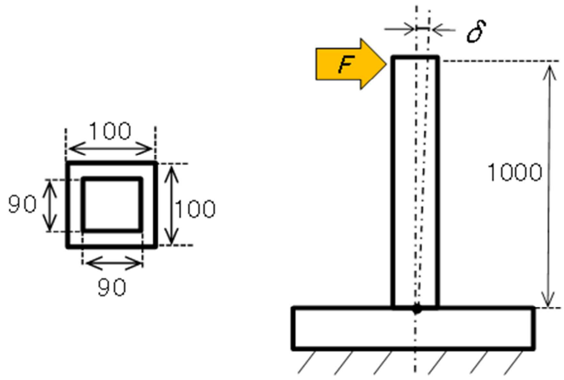
3. Examination of Measurement Results

3.1. Measurement Result Obtained by Power Mounting Test

Figure 4(a) shows piezoelectric composite sensors measurement result by power mounting test. This test is an experiment of tension by A type, Figure 4(b) shows an experiment of compression by A type. The displacement by the negative direction force and the output result of a side strain and compression when piezoelectric composite sensor. (Sensor base bode: 2.0 mm). The sensor output before fracture during the tensile test was measured at about 580 mV when the displacement was 8 mm, resulting in fracture. The assumed sensor output was measured at about 300 mV when the displacement was 10 mm. For the compression test, the displacement of the sensor output before fracture was 9.8 mm at about 120 mV. The sensor output of the assumed fracture was measured at about 150 mV when the displacement was 10.8 mm. Table 1 shows the values obtained by calculating the force and displacement by calculation using equations (1) to (4) with reference to the reference values for building structures [10] In the structural model shown in Figure 4, the applied force F when the displacement δ corresponding to the fracture deformation angle of the structure corresponds to 4 mm, 5 mm, 8 mm, and 10 mm is shown [7, 9]. Deformation angle 1/200 (displacement amount 5 mm) assumes structural safety in building structures, and deformation angle 1/100 (displacement amount 10 mm) assumes the limit value of destruction of building structures during a large earthquake. In addition, Japanese architectural design standards require that the entire building be plasticized to absorb seismic energy and prevent collapse as a measure to avoid structural collapse in the event of a large earthquake [15]. When the cross-sectional area of the square pipe of the test piece is obtained by Eq. (1), the moment of inertia of area I and the section coefficient Z are obtained by Eqs. (2) and (3), and the displacement amount δ is calculated by Eq. (4). A force F with a displacement δ of about 4 mm is about 7 kN, a force F with a displacement δ of about 5 mm (deformation angle 1/200) is about 9 kN, and a force F with a displacement δ is about 7.94 mm. The force F was determined to be 14 kN (deformation angle 1/125), and the applied force F at which the displacement amount δ, which is the design failure region, is about 9.68 mm, was calculated to be 17 kN (deformation angle 1/150). However, in the mounting test shown in Figure 4(a), the bearing capacity of the structure was lost when the applied force was about 13 to 14 kN and the displacement was 10 mm or more. It is considered that the fracture state of the structure was shown, and the result of the numerical calculation was slightly different from the numerical calculation regarding the force of the fracture limit. The results using the model of Figure 5 are shown numerically in Table 1 as the relationship between the deformation angle and the force leading to the fracture of the test piece.

Table 1. *Load pattern characteristics by simulation.*

Load (kN)	Displacement by simulation (mm)	Maximum displacement (mm)	[angle]	Load direction
7	3.97	4	1/250	+ -
9	5.11	5	1/200	
14	7.94	8	1/125	+ -
17	9.68	10	1/100	



$A = 100\times100 - 90\times90$ (mm²) (1)

$I = bh^3/12$ (mm⁴) (2)

$Z = bh^2/6$ (mm³) (3)

$\delta = WL^3/3EI$ (mm) (4)

A : 1900 mm², E : 2866×10³MPa, δ : Displacement
I : 2866×10³mm⁴ , z : 57×10³ mm³, W : 7 kN, 9kN, 14kN, 17kN, L : 1000 mm

Figure 5. *Shape of square pipe and outer shape of experiment structures. The relationship between displacement and load force was obtained from each condition and from (1) to (4) formula used in the numerical calculation.*

Table 2. *Sensor output in tensile test and compression test for changes in base plate thickness by A type. (Average of 3 times each).*

Base plate (mm)	Tension test (mm)	Compression test (mm)	Sensor output (mV)	Sensor output (mV)
1.0	3.3 ~7.5	6.5~ 7.0	50~200	30~550
1.2	3.3~7.8	10.8 ~ 11.3	50 ~ 100	20~550
1.6	8.3 ~9.3	9.3~ 10.5	80 ~ 35	40~200
2.0	7.8 ~10.5	8.8 ~ 11.0	50 ~100	80~110
2.3	8.8 ~9.5	9.0 ~ 10.3	30 ~890	30~80

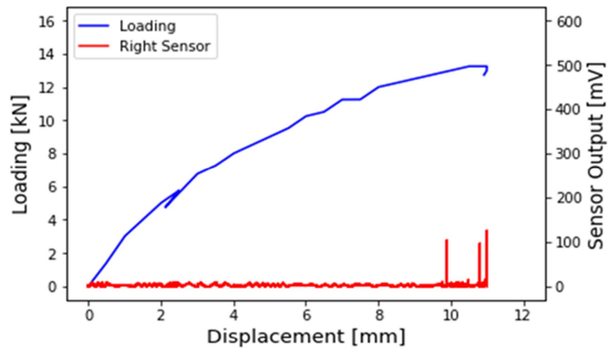
Table 3. *Sensor output in tensile test and compression test for changes in base plate thickness by B type. (Average of 3 times each).*

Base plate (mm)	Tension test (mm)	Compression test (mm)	Sensor output (mV)	Sensor output (mV)
1.0	1.2 ~2.5	5.8~ 7.80	10~ 120	10～180
1.2	2.0 ~5.5	10.2 ~ 10.7	40 ~ 350	100~ 190
1.6	4.8 ~9.5	9.5~ 11.0	80 ~ 35	50~100
2.0	6.0 ~7.8	6.8 ~10.2	167 ~ 60	80~35
2.3	5.5 ~11.0	8.8 ~ 9.0	150 ~ 90	167~6

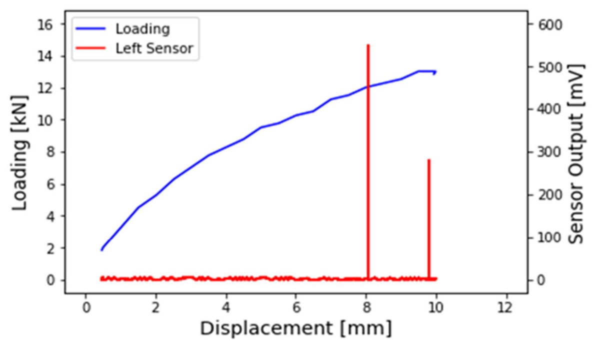
3.2. Measurement Result Obtained by Robot SALLY

Figure 6(a) shows the sensor output results regarding the force and displacement of the A-type and B-type piezo composite sensors with a sensor base plate thickness of 2.0 mm. In the A-type piezo composite sensor with a plate thickness of 2.0 mm, the sensor output was observed when the displacement was 7.8 to 10.5 mm in the tensile test of (a). From the applied curve, it is said that the "pre-breakage output" of the welded joint had a sensor output of about 100 mV when the displacement was about 7.8 mm, and the "breaking output" had a sensor output of about 50 mV when the displacement was about 10.5 mm. It is judged. In the compression test of (b), the sensor output was observed with a displacement of about 8.8 to 11.0 mm. According to the pressurization curve, it is judged that the sensor output is measured when the displacement is 8.8 mm as the "pre-destruction output" and the sensor output is 100 mV when the displacement is about 10.0 mm as the "destruction output"., There were multiple sensor outputs whose judgment was unknown. Figure 6(c), On the other hand, in the tensile test (c) of the B-type piezo composite sensor with a plate thickness of

2.0 mm, a remarkable sensor output of 100 mV was observed when the displacement was 6 mm, and a larger output of 550 mV was observed when the displacement was 7.8 mm. According to the applied curve, the displacement of the welded joint assuming the “output at break” is considered to be about 80 mV at around 11 mm. The output value of the B-type sensor was more than five times that of the A-type sensor, and the effect of improving the sensor shape was recognized. In the compression test of (d), a sensor output of about 70 mV was observed when the displacement was about 6.8 mm, and a maximum output of 200 mV was measured when the displacement was 8.8 mm. It is assumed that the sensor output was 70 mV when the displacement was 10.2 mm. Similar to the tensile test, the output value of the B-type sensor was more than double that of the A-type sensor in the compression test, and the effect of improving the shape of the sensor was confirmed. The sensor output corresponding to the displacement was also good. Table 2 shows the relationship between the output and displacement of the piezo junction sensor, which was subjected to three tensile tests and three compression tests (total 30 times) for each plate thickness, as an average value [16]. Table 2 Sensor output in tensile test and compression test for changes in base plate thickness by A type. (Average of 3 times each). Table 3 shows Sensor output in tensile test and compression test for changes in base plate thickness by B type. (Average of 3 times each).



(a)



(b)

Figure 6. *Relationship between the output and displacement of the piezoelectric composite sensor.*

4. Conclusion

In the results of this mounting test, the fracture of the test piece was confirmed at a deformation angle of 1/125 to 1/100. When the characteristics of the sensor output by the measuring robot and the sensor output by the mounting test using the T-shaped test piece were compared [16], similar results were obtained in the relationship between the displacement and the sensor output in both tests. Looking at the relationship between the thickness of the base plate of the piezo composite sensor and the sensor output, in the tensile test, the sensor with a thinner base plate recorded a larger sensor output, and even with a small displacement, there was an output. On the other hand, in the compression test, a certain reproducibility was confirmed when a plate thickness of 1.6 mm or more was used, but no remarkable features were observed at 1.0 m and 1.2 mm. It was the sensor with a base plate thickness of 2 mm that was able to obtain measurement results near the target in both the tensile and compressive directions, and obtained good results for the sensor output measurement targets at displacements of 8 mm and displacement of 10 mm. I was able to. From the results of this experiment, it can be recognized that it is necessary to obtain the optimum size and shape design of the base plate of the sensor in order to obtain a large sensor output at the desired displacement in proportion to the development of the soundness measurement sensor for the structure. rice field. It was also found that it is important to derive the optimum conditions such as the position where the piezo film is attached on the sensor base plate. The development of sensors and the construction of simple monitoring technology that enable long-term measurement of the soundness of structures are extremely important issues [17]. In order to verify the characteristics of new sensors, it is necessary to develop a robot that can quantitatively measure the characteristics of a large number of sensors, and this is a field where practical application is strongly desired in the future. We will continue to make efforts to improve the automatic measurement technology and build the FEM technology for the sensor alone.

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