



Comparison of Sensor Output Because Base Plate Thickness and Shape Change of Piezoelectric Composite Sensor for Long-Term Measurement

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To cite this article:

Nobuhiro Shimoi, Kazuhisa Nakasho, Carlos Cuadra. Comparison of Sensor Output Because Base Plate Thickness and Shape Change of Piezoelectric Composite Sensor for Long-Term Measurement. *American Journal of Science, Engineering and Technology*. Special Issue: *Constructing the Next Generation of Artificial Intelligence*. Vol. 7, No. 3, 2022, pp. 114-120. doi: 10.11648/j.ajset.20220703.17

Received: July 23, 2022; Accepted: August 24, 2022; Published: August 31, 2022

Abstract: After strong earthquakes, many steel structures were built with frame welded joints of welded construction and a welded base. Although steel structures are regarded as highly resistant to earthquakes, many were constructed using frame-welded joints of fillet welded construction and welded column bases. These weld joints can have a low capacity to absorb energy during earthquakes. Infrastructure built during the era of high economic growth in Japan is deteriorating. Furthermore, costs pose difficulties because mandatory checking is necessary once every five years. Structural health monitoring for infrastructure maintenance is widely anticipated as new technology. To put such a new sensor to practical use, it is necessary to accumulate measurement data and establish evaluation methods to derive information about the states of structures. As described herein, A development method for sensor measuring displacement is proposed using composite piezoelectric film and glass. Moreover, that is investigated the relationship between the structure displacement and the output voltage from the piezoelectric joint sensor to record the sensor characteristics. Structural analysis was also done to evaluate sensor characteristics and to assess the mechanisms and effects of environmental factors on the structure's response. On the other hand, conducted a similar experiment using a measurement robot and compared the sensor characteristics. Herein, results obtained using the measurement robot (SALLY) for the relation between the output and displacement of piezo compound sensors is explained. The mounting test of the piezo junction sensor used under the optimum conditions for the robot measurement confirmed that the target displacement measurement can be measured from the sensor output by changing the piezo-composite sensor plate thickness.

Keywords: Anchor Bolt, Deformed Bar, Health Monitoring, Piezoelectric Joint Sensor

1. Introduction

In Japan, many infrastructurally important structures such as bridges and tunnels have been produced for more than 50 years [1]. However, in real life, bridges that have already reached the end of their useful life must continue to be used. It therefore becomes necessary to detect dangerous conditions such as the collapse of these structures as soon as possible. It is important to monitor deterioration and structural changes constantly over the long term, because those changes play a major role in building a safe and secure

society. Realizing such monitoring can be supported by the study of measurement and evaluation methods after fully understanding the usage environment, such as the characteristics of the structure to be measured and its years of use. The authors are developing a monitoring system they can support long-term, inexpensive, and easy measurement of structural integrity at welded joints of steel frames [2]. This system uses output of the original passive piezo composite sensor to predict the structural displacement. During the development stage to date, there have recognized a need to evaluate the base plate thickness and sensor shape further to obtain stable measurement results [3].

Evaluating the sensor output characteristics necessitates measurement of numerous sensors. Nevertheless, measurement using a test piece is unrealistic in terms of measurement time and cost. In this study, to resolve these difficulties, there evaluate the use of automatic measurement technology with robots and breaking tests of many sensors. Then describe the results obtained from examining differences in output and stability attributable to changed shapes of welded members [4]. Furthermore, that is assessed the design and measurement technologies of a piezoelectric joint sensor that enables displacement prediction [5].

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

2.1. Comparison with Conventional Technology

Various measurement techniques are used for the quantitative evaluation of soundness for disaster prevention and mitigation of structures. Static load measurements include displacement measurement using a laser displacement meter or contact displacement meter, constant tremor vibration measurement, and identification of fracture status and stress concentration points from the natural frequency by analysis [6]. Also, as a non-destructive and quantitative method for evaluating residual stress in structures, X-ray analysis by FEM is used, but it is difficult to use for crack growth analysis [7-9].

2.2. Examination of Sensor Technology That Can Support Long-Term Measurement

The piezo composite sensor was manufactured for measuring a voltage according to a fracture at the welded joint of a steel structure. This sensor is an inexpensive and consumable sensor that breaks after failure measurement. Because the piezo film used is a piezoelectric element and because it emits electric power by itself, a power supply is unnecessary for field measurements [10, 11]. For this study, it is used a sensor in which a piezo film was bonded and fixed to five types (1.0, 1.2, 1.6, 2.0, 2.3 mm) of metal plates

(general rolled steel) with different thicknesses; then a glass plate was further bonded. Piezo composite sensors of two shapes were prototyped. Differences in output according to the quantitative changes in the loads of sensors were measured in both robot measurements and mounting measurements. The output values were compared and examined. In addition, the manufactured sensors are installed simultaneously outdoors for about two years. Their output changes and performance were evaluated.

3. Sensor Design

3.1. Shape Comparison

Figure 1(a) presents the shape of the A-type sensor base plate. Figure 1(b) portrays the shape of the B-type sensor base plate. Figure 2(a) depicts the configuration of the A-type piezo composite sensor. Figure 2(b) shows the configuration of the B-type piezo composite sensor. The piezo composite sensor is a base metal plate made of approximately 16×73 mm piezo film (DT2-028K/L; Tyco Electronics Corp.) and $25 \times 75 \times 1$ mm hard plate glass with an ultraviolet curable adhesive (Loctite 3851; Henkel Japan Ltd.) [12]. The structure is fixed with adhesive. The glass plate also serves the purpose of preventing piezo film peeling and deterioration. To stabilize the measurement result, the sensor response is considered so that a crack is formed in a certain place in the center and so that an output because of voltage is likely to occur. Assuming that the difference in sensor output from comparison of the shapes of A type and B type with 2 mm plate thickness is an approximate value by simple calculation using Poisson's ratio, an A type sensor can detect the deformation of the plate material itself. However, the B-type sensor with a constriction in the center is expected to deform about 86% of the A-type sensor. Using this value, the average displacement of the A-type sensor at the time of complete failure in the tensile test is 9.15 mm. If the value of 86% is calculated, then the displacement is about 7.9 mm. Similarly, the average displacement at the time of complete fracture during the compression test is 9.9 mm by the A-type sensor. The displacement amount is therefore expected to be about 8.5 mm in calculation when the B-type sensor is used.

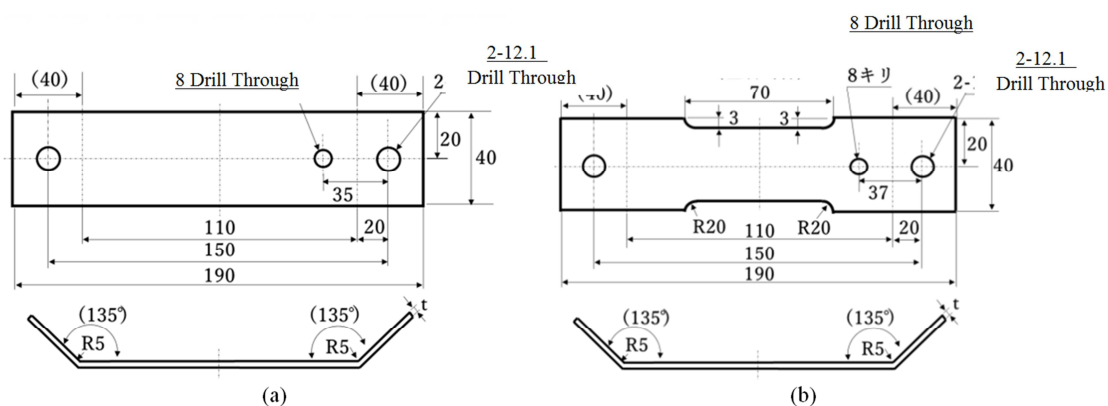


Figure 1. Details of shapes and dimensions of the piezoelectric composite sensor for A type (a) and B type (b).

Figure 1(a) presents type A piezoelectric composite sensor characteristics. The piezoelectric composite sensor base plate is a $40 \times 190 \times t$ mm general rolled steel plate, after drilling two 12.3 mm drill holes and an 8 mm hole for cable ducts, and after bending of both ends of about 40 mm at 135 deg. Figure 1(b) shows the shape and dimensions of the piezoelectric composite sensor for type B. The piezoelectric composite sensor base plate is a $40 \times 190 \times t$

mm general rolled steel plate, after drilling two 12.1 mm drill holes and an 8 mm hole for cable ducts, after bending of both ends of about 40 mm at 135 deg, and 3 mm notching on both sides [13].

Figure 2(a) Piezoelectric composite sensor of the A type configuration and each part in the setting position. Figure 2(b) the piezoelectric composite sensor of the B type configuration and each part in the setting position.

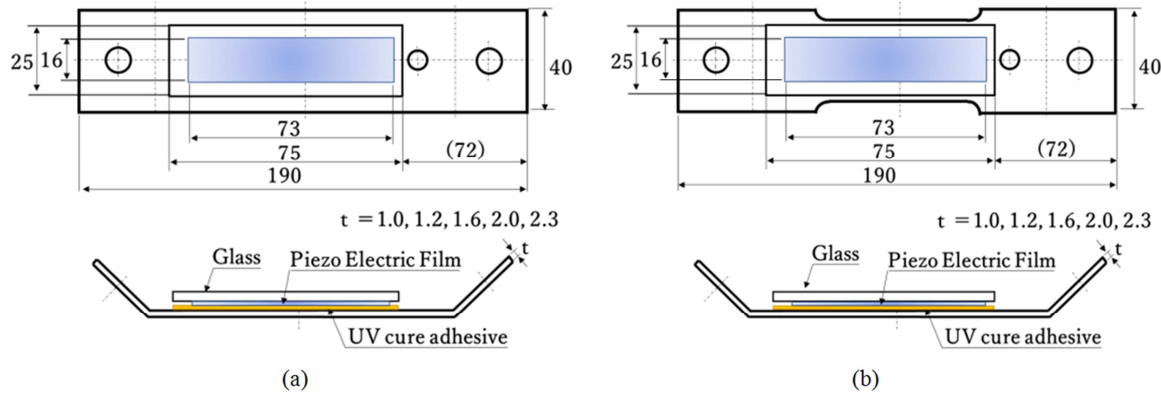


Figure 2. Characteristics of piezoelectric composite sensor for A type (a) and B type (b).

3.2. Construction of Automated Measurement Technology

At the development stage of the new monitoring sensor, it manufactured a steel-framed T-shaped test piece ($1000 \text{ mm} \times 1200 \text{ mm} \times 450 \text{ mm}$) for mounting that imitates the welded joint of the structure, as shown in Figure 3(a), with the test specimen. Figure 3(b) portrays the load test devices, displacement measurement devices, and the setup of the piezoelectric joint sensor. A prototype sensor was attached to the joint of the T-shaped test piece. Characteristic data such as the sensor output strength were measured using a destructive test in which the column was tilted with a hydraulic device to damage the joint. However, using this method to obtain two types of sensor output characteristics takes about 150,000 yen to manufacture a T-shaped test piece, and about one day for three people to install and remove the

test piece and operate and measure the hydraulic system. Therefore, the author created a SALLY measurement robot to improve the efficiency of the sensor output characteristic test. Figure 3(c) depicts this measurement robot, as designed by the author and outsourced to a venture company for parts processing, assembly, and electrical equipment [4]. In terms of calculation, it takes 15 days for 3 people in the mounting test to conduct sensor output characteristic tests of 30 types. However, with robot measurements, it is possible to do measurements in 1.6 days with the work of 2 people. Figure 3(b) shows the SALLY device configuration. SALLY is a robot that measures the output of the piezo composite sensor corresponding to the column joint deformation angle. It has a compact size of $700 \times 450 \times 300 \text{ mm}$ and consists of (1) a drive stepping motor, (2) a horizontal pillar, (3) a load cell sensor, (4) a displacement meter, and (5) a sensor mount.

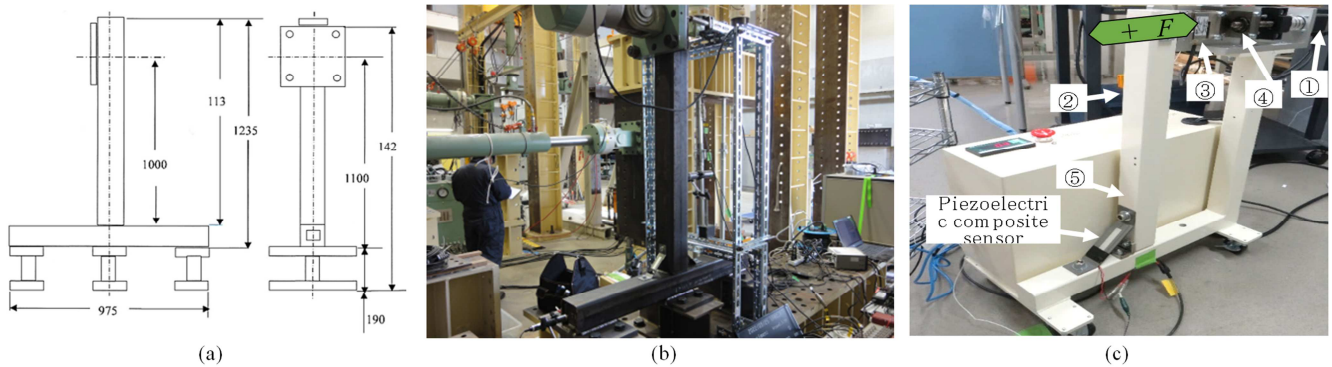


Figure 3. (a) Experiment of load and displacement load test devices and composition of the measurement robot (SALLY).

4. Measurement Results and Consideration

4.1. Measurement Results by Robot

Identical measurement tests were done three times with different plate thicknesses to measure the output characteristics of the automatic measurement robot SALLY

[4] using piezo composite sensors of five types with different shapes of A type and B type. Table 1 presents the results, with sensor A type output from the strain test and compression test for changes in the base plate thickness by SALLY (average of three times each). Table 2 shows the Sensor B type output in strain tests and compression tests for different base plate thicknesses by SALLY (average of three times each).

Table 1. Sensor A type output in strain test and compression test for changes in base plate thickness by Sally (Average of 3 times each).

Base plate thickness (mm)	Strain test			Compression test		
	Displacement (mm)		Sensor output (mV)	Displacement (mm)		Sensor output (mV)
	Min	Max		Min	Max	
1.0	3.0	4.5	50–200	10.3	10.8	30–550
1.2	3.2	7.8	80–200	6.5	7.0	30–550
1.6	8.3	9.3	50–100	9.2	10.3	30–200
2.0	7.8	10.8	50–100	9.0	10.5	80–110
2.3	8.8	9.8	30–90	8.0	8.8	30–80

Table 2. Sensor B type output in strain test and compression test for changes in base plate thickness by Sally (Average of 3 times each).

Base plate thickness (mm)	Strain test			Compression test		
	Displacement (mm)		Sensor output (mV)	Displacement (mm)		Sensor output (mV)
	Min	Max		Min	Max	
1.0	1.8	2.3	20–100	6.0	7.9	80–150
1.2	2.0	5.5	50–470	6.8	11.0	30–200
1.6	5.0	9.5	100–300	9.0	11.5	50–350
2.0	6.0	8.0	100–550	6.5	10.2	80–200
2.3	5.5	11.0	50–550	9.0	9.2	100–500

The average value was calculated. Table 1 presents the output characteristic measurement results of the tensile test and compression test using SALLY with the A-type piezo composite sensor with base plate thicknesses of 1.0, 1.2, 1.6, 2.0, and 2.3 mm. The maximum and minimum values of displacement and sensor output are shown. Table 2 also shows measurement results obtained using the B-type piezo composite sensor. As the name of the danger signal in this experiment, the sensor output at the time of displacement before the destruction of the joint obtained by calculation is defined as the "pre-destruction output." The sensor output at the time of displacement at the time of complete destruction of the joint is "at destruction output." Numerical calculations based on structural mechanics predict that displacement of 5 mm (damage because of fracture is recognized) at an inclination angle of 1/200, and predict that the displacement will be 10 mm (complete fracture is recognized) at 1/100 [3]. In tensile tests, the output value of the B-type sensor was greater than five times that of the A-type sensor. Thereby, the effects of sensor shape improvement were confirmed. In addition, the B-type sensor output value was more than double that of the A-type sensor in the compression test, which demonstrates improvements from the sensor shape. Furthermore, the B-type sensor had good output results corresponding to the displacement amount detected from the deflection calculation of the strength of materials. Results demonstrated that the average displacement amount is within the range of mechanical calculation in both robot

measurement and mounting tests.

From results presented in Tables 1 and 2 for the sensor plate thickness used for the mounting test, the sensor response for measurement purposes in Table 1 was found to satisfy the 5–10 mm displacement amount in the tensile direction of the A-type sensor. The plate thicknesses are 1.6 mm and 2.3 mm, and 2.3 mm in the same compression direction. However, the B-type sensor satisfies the conditions of 1.6 mm and 2 mm plate thicknesses in the tensile direction and 2 mm in the compression direction. The mounting test was conducted under the condition of 2 mm plate thickness.

4.2. Measurement Results from Mounting Tests

To verify the degree of error in sensor displacement measurements caused by differences between robot measurement and mounting measurement, there used a mounting test with three test bodies. A mounting test was performed using the steel-framed T-shaped test piece shown in Figure 3(a), which simulated the welded joint part of the structure. An A-type piezo composite sensor [6] with 2.0 mm base plate thickness was installed on each side of the column joint of the test piece. Then the sensor output, force, and displacement were measured when a horizontal force was applied to the column top using a hydraulic jack.

Figure 4(1) shows the displacement by the negative direction force and the output result of (a) side strain and (b) compression using a piezoelectric composite sensor (sensor type A and base plate body: 2.0 mm). Figure 4(2) shows the

displacement in the negative direction force and the output result of (c) side strain and (d) compression for a piezoelectric composite sensor (sensor type B and base plate body: 2.0 mm).

Force was applied in the direction. The A-type sensor installed on the left side of the column joint was on the strain side. The A-type sensor installed on the right side was on the compression side. The load during application was measured using a load cell installed in the hydraulic jack. The application and displacement were recorded at 1 Hz. To prevent danger from this experiment, the test apparatus was stopped about 2 min after maximum force was applied. Figure 4 shows the force applied, the amount of displacement at the top of the column, and the sensor output results. The piezo composite sensor on the strain side in Figure 4(a) has sensor output of about 320 mV when the force is about 4 kN,

with displacement of 6 mm. Sensor output of 100 mV was recorded when the force was 6 kN and the displacement was 9.8 mm. For the piezo composite sensor on the compression side in Figure 4(b), the sensor output was about 50 mV for applied force of about 4 kN and displacement of 6 mm. The sensor output was 130 mV for the applied force of 5 kN and displacement of 9.2 mm. The piezo composite sensor on the strain side in Figure 4(c) has sensor output of about 250 mV. When the force was about 4 kN, with displacement of 7.3 mm, 320 mV was recorded when the force was 5 kN and the displacement was 11.8 mm. Figure 4(d) shows that the sensor output was about 50 mV when the applied force was about 4 kN and the displacement was 7.1 mm. The sensor output was 50 mV when the applied force was 5.5 kN. The displacement was 11.6 mm.

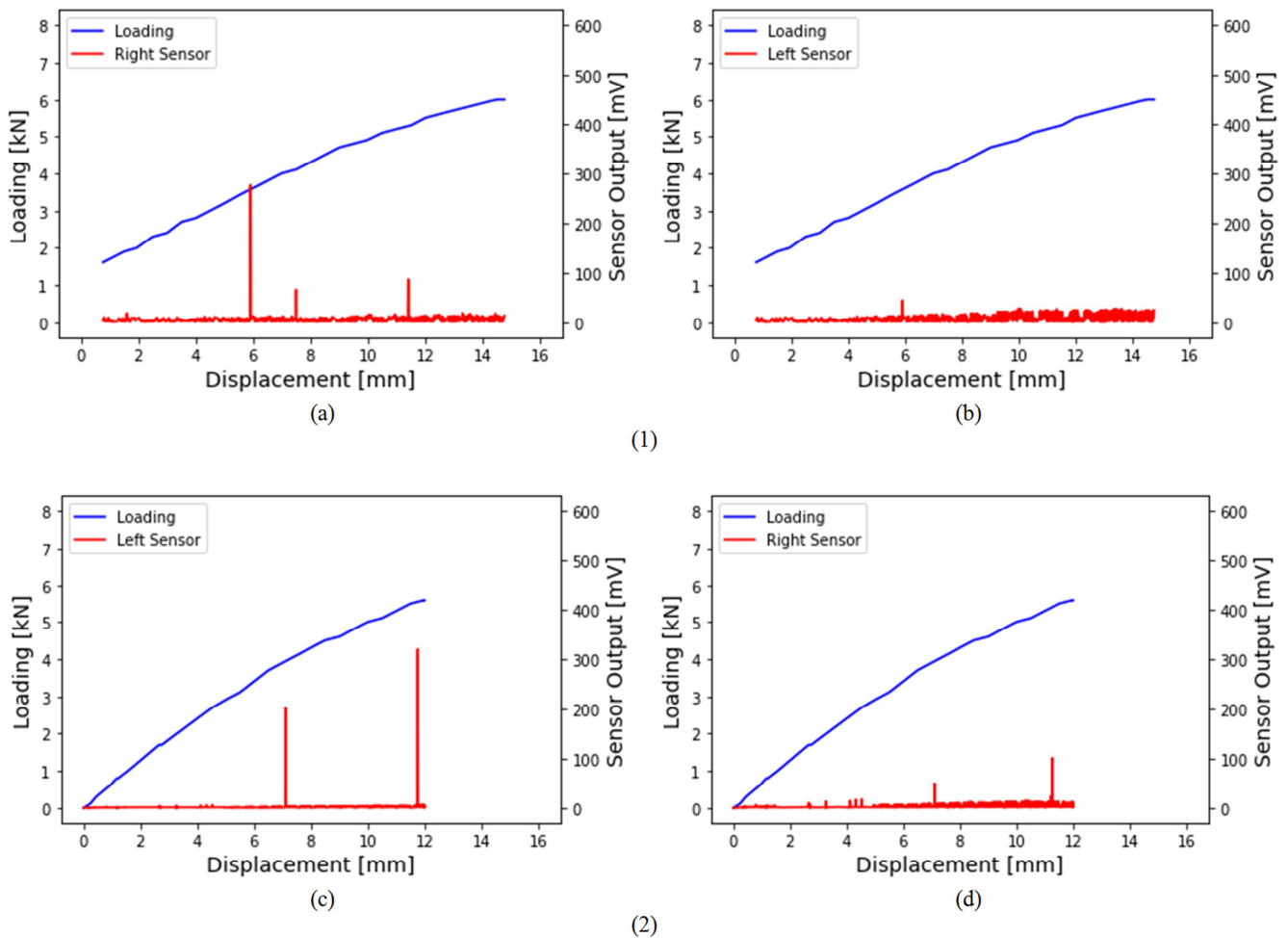


Figure 4. Relation between displacement and piezoelectric joint sensor output by mounting test.

In both cases, the sensor output of the welded part of the T-shaped test piece was clear "before complete destruction" and "at destruction," but the A-type piezo composite sensor output on the compression side was small. Also, the sensor output on the tension side was large.

Figure 5 presents the piezo junction sensor output state after the mounting test: panel (a) depicts the strain test; panel (b) portrays the compression test. Experiment results

showed rough agreement with the stress dispersion predictions and the concentration of the sensor alone, which occurred in the force test by FEM analysis. Concentration of the output near the center to stabilize the sensor response was also confirmed from the reaction situation presented in the sensor diagram.

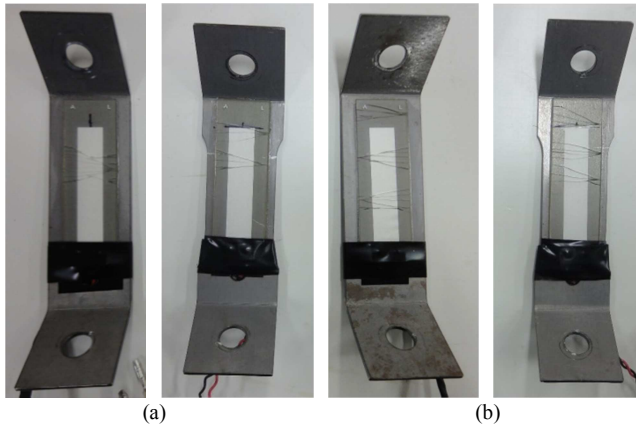


Figure 5. Result of the output state of the piezo composite sensor mounting test.

5. Conclusion

Although development of a reliable sensor necessitates mounting tests, difficulties related to human labor and development costs point to wider use of measurement methods using robots. Using this sensor with different shapes and plate thicknesses under identical conditions demonstrated the necessity of verifying output characteristics during displacement measurements. Mounting test results of the A-type sensor with 2.0 mm plate thickness portrayed in Figure 4 show that the sensor output was generated near the displacement of 8–11 mm. Sensor output was obtained from deflection calculations of the strength of materials at target displacements of 5 mm or more and less than 10 mm [14], [15]. Sensor outputs were confirmed in both the robot and mounting tests, thereby demonstrating the sensor reliability. However, when using the piezo composite sensor with 1.0 mm, 1.2 mm, and 2.3 mm plate thicknesses, it was difficult to judge the sensor output of the sensor alone according to joint damage. Results of this research clarified that the sensor output able to measure the force and displacement proportionally is obtainable by setting the optimum base plate thickness of the piezo composite sensor and by designing the sensor shape. The use of this sensor has demonstrated the possibility of long-term structural safety measurement technology. Verifying the sensor reliability and characteristics requires development of a robot that can measure numerous sensor output characteristics quantitatively. This field is expected to produce invaluable devices for practical application. Developing sensors that enable measurement and the construction of simple monitoring technologies is extremely important. In the future efforts will make steady improvements in constructing measurement systems and improving measurement technologies.

Acknowledgements

This research was partially supported by JSPS KAKENHI Grant No. 20H00290, for which we express our appreciation.

References

- [1] Ministry of Land, Infrastructure and Transport, Infrastructure maintenance information, available from https://www.mlit.go.jp/sogoseisaku/maintenance/02research/02_01_01.html (accessed on 1 October, 2020). (in Japanese).
- [2] Imai, K., Narihara, H., Kawabata, I., Takayama, M., Kimura, Y., Aono, H. and Kameda, R., Development of new type of steel column base: structural experiment of exposed-type column base, TAISEI Construction Technology Center, Technical Report, No. 39 (2006), pp. 1–6. (in Japanese).
- [3] Japan Society of Civil Engineers, Concrete Committee, Final Report Investigation Special Committee on Damage to the Tarui Viaduct, (2008) (in Japanese).
- [4] Shimoi, N. and Nakasho, K., Sally, a Robot for Measuring Piezoelectric Joint Sensor Characteristics, Research & Development, Vol. 1, No. 1, pp. 25–30 (2020).
- [5] Mochizuki, M., Toyoda, M., Morikage, Y. and Kubo, T., Residual stress and fatigue strength in welded joints using low-temperature transformation weld material, Japan Welding Society, No. 72, pp. 242–243 (2003). (in Japanese).
- [6] Shimoi, N., Cuadra, C and Nakasho, K., Comparison in displacement measurements for weld joint of steel column base using piezoelectric joint sensors, International Journal of Science and Engineering Investigations, Vol. 57, No. 5, pp. 253–259 (2021). (in Japanese).
- [7] Kumagai, K., Nakamura, H. and Kobayashi, H., Computer aided nondestructive evaluation method of welding residual stresses by removing reinforcement of weld, Transactions of the Japan Society of Mechanical Engineers, Series A, Vol. 65, No. 629 (1999), pp. 133–140. (in Japanese).
- [8] Ono, K., Study of technology for extending the life of existing structures, New urban society technology fusion research, The Second New Urban Social Technology Seminar, pp. 11–23 (2003). (in Japanese).
- [9] Shimoi, N., Nakasho, K., Cuadra, Saijo, M and Madokoro, H., Avalanche and Falling Rock Measurement Using Piezoelectric Dynamics and Static Sensors, Piezoelectric Dynamics and Static Sensors, American Journal of Remote Sensing, vol. 5, No. 2, pp. 10-15 (2017).
- [10] Nakamura, M., Health monitoring of building structures, Society of Instrument and Control Engineers, Vol. 41, No. 11, pp. 819–824 (2002). (in Japanese).
- [11] Shimoi, N., Cuadra, C., Madokoro, H. and Nakasho, K., Comparison in displacement measurements for fillet weld of steel column base utilizing piezoelectric joint sensors, International Journal of Science and Engineering Investigations, Vol. 9, No. 102 (2020), pp 99-103. (in Japanese).
- [12] placement measurements in exposed type column base using piezoelectric dynamic sensors and static sensors, American Journal of Remote Sensing, Vol. 4, No. 5, pp. 23–32 (2016).
- [13] Khanna, P. K., Hornbostel, B., Grimme, R., Schäfer, W. and Dörner, J., Miniature pressure sensor and micromachined actuator structure based on low-temperature-cofired ceramics and piezoelectric material, Materials Chemistry and Physics, No. 87, No. 1, pp. 173–178 (2004).

- [14] Tamai, H., Elasto Plastic Analysis Method for frame with exposed-type column base considering influence of variable axial force, Journal of Structural and Construction Engineering, Vol. 68, No. 571 (2003), pp. 127–135. (in Japanese).
- [15] Steel committee of Kinki Branch the Architectural Institute of Japan, Reconnaissance report on damage to steel building structures observed from the 1995 Hyogoken-Nanbu earthquake, (2005), pp. 22–108. (in Japanese).