International Journal of Mechanical Engineering and Applications
2022; 10(5): 105-112
http://www.sciencepublishinggroup.com/j/ijmea
doi: 10.11648/j.ijmea.20221005.12
ISSN: 2330-023X (Print); ISSN: 2330-0248 (Online)

Sensor Characteristics Attributable to Base Plate Thickness of Piezo-Composite Sensors

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To cite this article:
Nobuhiro Shimoi, Kazuhisa Nakasho, Carlos Cuadra. Sensor Characteristics Attributable to Base Plate Thickness of Piezo-Composite Sensors. *International Journal of Mechanical Engineering and Applications*. Vol. 10, No. 5, 2022, pp. 105-112. doi: 10.11648/j.ijmea.20221005.12

Received: August 16, 2022; **Accepted**: August 30, 2022; **Published**: September 16, 2022

Abstract: After the huge East Japan Earthquake, many steel structures have been constructed using welded frame welded joints and welded foundation construction. Although steel-frame structures are regarded as earthquake-resistant structures, many steel-frame structures are built using fillet-welded frame-welded joints and welded column bases. These welded joints might have less ability to absorb energy during an earthquake. Therefore, when designing steel structures that use welded joints, it is necessary to consider the seismic resistance of column bases in particular. To confirm the safety of these unstable structures, we propose measurements using piezo-composite sensors. The measurement results suggest long-term evaluation of these structures. As described in this paper, the relation between the sensor output and the thickness of the piezo-composite sensor base plate was found quantitatively using data obtained using a measurement robot (SALLY). Next, after fabricating a piezo-composite sensor that can measure displacement when the deformation angle of the strut is 1/100 or 1/200, we verified it using a mounting test. We 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, Steel Weld Joint

1. Introduction

Japan has superannuated infrastructure that includes numerous structures such as bridges and tunnels that are more than 50 years old. After 2023, more than 39% of all bridges will have exceeded 50 years of service life [1]. To avoid hazards from their collapse, inspections and repairs will be increasingly necessary in the future. Soundness measurements of current structures can evaluate performance for a 50-year period of guaranteed durability. However, in the future, it will be necessary to verify the soundness of bridges that have passed their service life, rather than merely conducting monitoring of their integrity during their service life. For long-term measurements using MEMS acceleration sensors, optical fibers, and other methods for monitoring, it is considered difficult to find data sufficient to consider system costs, environmental conditions, and changes in the sensor measurement environment over time [2–4]. To overcome these difficulties, constructing a durable, simple, and low-cost sensor and monitoring technology is considered necessary [5]. This study specifically examined a joint method of column bases used in many steel-framed buildings. We aim at developing low-cost sensors and at constructing an autonomous simple measurement system. The purposes of the research are the following: (1) development of a disposable simple sensor using a piezoelectric element; (2) development of a geometry and measurement logic that enables displacement measurement of joints by sensor output; and (3) construction of an inexpensive measurement system capable of long-term measurement.

Target bridge components are joined by fastening with bolts or by welding. Figure 1(a) portrays the welded structure. Panel (b) depicts the bolted structure.

In the case of bolt fastening, frequent external dynamic forces such as impact, vibration, and thermal loading (expansion) might loosen the nut and cause a collapse by failure of its fastening function. For welded joints, although few accidents occur because of vibration and loosening of nuts, the possibility of deterioration caused by hardening and brittleness around the joint exists because of heat effects during welding [6].

Strain measurement relies on soundness monitoring technology [7, 8] for aging deterioration because of fatigue, corrosion, etc., but it requires the attachment of numerous strain gauges. Moreover, measurement results can only be obtained for specific locations. Therefore, strain measurement is unsuitable for wide-area measurements.

(a) (b)

Figure 1. *Assembly bridge structure.*

2. Health Monitoring Using Piezo-Composite Sensors for Weld Joints

2.1. Comparison with Conventional Technology

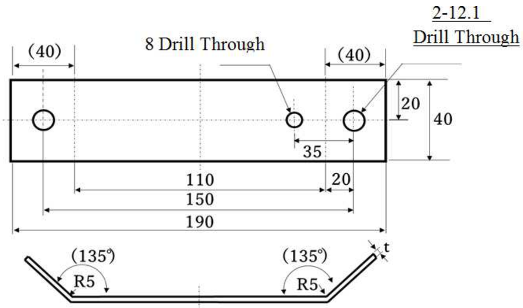
In addition to X-ray analysis using FEM, several methods can be used for non-destructive and quantitative strain evaluation in structures. Micro-tremor vibration measurements [9] can yield a Fourier spectrum ratio of a vertical component and a horizontal motion component. Therefore, such measurements normalize the horizontal vibration to the vertical vibration, and obtain amplification characteristics and the natural period of the structure. This measurement system consists of a microtremor meter, a data logger, and a PC. It costs about 1,500,000 – 2,500,000 yen (approx. 11,500 – 19,000 US dollars). Because of the Doppler effect between irradiated light and reflected light, Laser Doppler velocimetry (LDV) [7] can also be used to detect the velocity from phase differences when the laser light is irradiated to the measurement target. The measurement system consists of two LDV devices, a data logger, a PC, and a digital displacement gauge. Equipment for non-destructive X-ray examination can be installed for monitoring limited areas, but the apparatus is not practical for long-term measurements because it requires a power supply and entails equipment costs of 8–10 million yen (0.3–0.4 million US dollars). Moreover, long-term monitoring for more than 20 years is necessary to evaluate the safety and soundness of structural joints. At present, no measuring device for danger prediction can guarantee smart sensing, inexpensive sensor systems, or a sufficiently long monitoring period [10–12].

2.2. Issues Related to Monitoring Technology

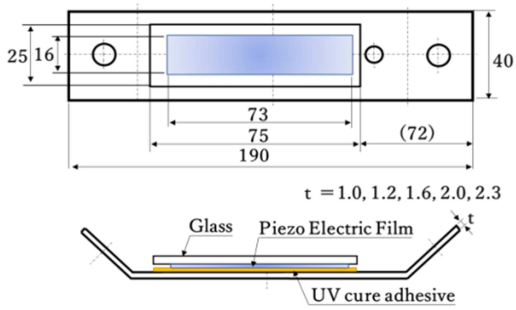
For structural monitoring today, strain and deflection measurements are used widely as soundness evaluation methods. Nevertheless, it is extremely difficult to aggregate and evaluate long-term measurement results over a period of 10–20 years. Evaluation methods such as improvements in measurement methods and data analysis software are expected to change considerably over many years. Even if a destructive test of a 1/1 scale model of a structure is conducted indoors, it is no more than a model that shortens structural deterioration occurring over several decades to one or two days. Resolving such shortcomings necessitates research on risk prediction measurement technology and development of long-term measurement technology [13].

2.3. Sensor Study for Long-Term Measurement Technology

Piezo-composite sensors have been manufactured to measure voltage according to the fracture at the welded joint of the steel structure. This inexpensive sensor is disposable: it breaks during a failure measurement. Because the piezo film used is a piezoelectric element that emits electric power by itself, no power supply is necessary for measurement when a sensor is used for field measurements. For this study, after prototyping piezo-composite sensors of two types using metal plates of five thicknesses, we compared and examined the output intensities that were obtained when a force was applied to each sensor. Figure 2(a) portrays the A-type piezo-composite sensor configuration. Figure 2(b) shows the piezo-composite sensor base metal plate, made of approximately 16 × 73 mm piezo film (DT2-028K / L; Tokyo Electronics) and 25 × 75 × 1 mm hard plate glass with an ultraviolet curable adhesive (Loctite 3851; Henkel Japan) [11]. Figure 3 shows the piezo-composite sensor attached to a welded joint of the steel T-shaped specimen.



(a)



(b)

Figure 2. *Presents details of the shape and dimensions of the piezoelectric composite sensor.*

Figure 3. *Setting of piezoelectric composite sensor.*

This structure is adhesively fixed. The glass plate is intended to prevent piezo-film peeling and deterioration. A general 40 × 190 mm rolled steel plate was used as the base metal sensor plate. Five 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 12.1 mm diameter holes for bolt fastening and 8.0 mm diameter holes for a cable duct, with 135-degree bending of 40 mm at both ends. This shape facilitates piezo-composite sensor mounting at a 45-degree angle to the right-angled welded surface of the square steel pipe column used for the mounting test. Earlier test results for the A-type piezo-composite sensor showed that sensor plate thicknesses of 1.6 mm and 2.0 mm satisfied the measurement conditions [6].

3. Confirmation Testing of Sensor Characteristics

3.1. Construction of Automatic Measurement Technology

During development of the new monitoring sensors, we outsourced the production of steel-framed T-shaped specimens for mounting to represent the welded joints of structures. Characteristic data such as the output strength of the prototype sensor were obtained using destructive testing that damages the T-shaped specimen joints. However, the production cost of the T-shaped test body, the installation time of the test body, and the measurement time presented numerous difficulties: the author keenly felt the need to measure the performance of various sensors quickly and at low cost.

3.2. Robot SALLY result

The authors produced a robot, SALLY, to improve the efficiency of the sensor output characteristics testing of piezo junction sensors [15]. After SALLY was designed by the author, the related electrical equipment, parts processing, and assembly were outsourced to a venture company. The SALLY robot simulates the steel frame welded joints of structures. The angle of the support mounting part can be changed by application of force *F* to the top of the support. An arbitrary deformation angle can be set for the time of fracture of the structure's welded joint. The piezo junction sensor output corresponding to the deformation angle was measured. Figure 4 shows the appearance of SALLY. Table 1 shows its specifications. SALLY has a compact size of 700 × 450 × 300 mm that includes (1) a drive pulse motor, (2) a post, (3) a horizontal post, (4) a load cell, (5) a displacement gauge, (6) a sensor mounting base, (7) a control PC, and (8) a logger instrument. After fixing the piezo-bonded sensor to a SALLY strut mounting part, force F (+ direction or - direction) was applied to the top of the strut by a pulse motor. The strut tilts according to the load, thereby measuring the sensor output. Force measurement by a load cell and displacement measurement by a displacement meter are also possible. The logger records measured sensor output, force, and displacement in real time on along with the test date and time and file number. Data sampling is done at 100 Hz. Compression tests (applying force in the + direction) or tensile tests (applying force in the - direction) can be program-controlled by the control PC. The motor rotates forward and reverse at speeds of approximately 1.6 mm/s. For this study, forward rotation of the motor, for which the strut tilts to the left with the sensor mounting base facing the front, is applied in the positive direction (compression test). Its reverse rotation is applied in the negative direction (tension test). The piezo junction sensor bends inward under applied force during compression testing and warps outward during tensile testing. Because it is possible to tilt the column repeatedly, SALLY has excellent cost performance. The output characteristics of one sensor can be measured in about 20 min. With SALLY, 1–2 days of measurements using a conventional T-shaped specimen by two people can be completed in about 1/18 of the duration necessary when using the conventional method. Furthermore, if one ignores the robot manufacturing cost, then no costs are incurred aside from the loss of the test piece destroyed during the mounting test. Therefore, costs of measurement are extremely low.

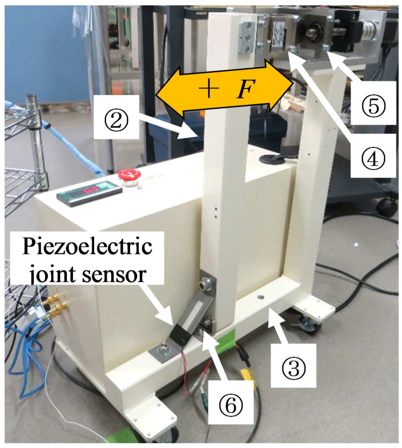


Figure 4. *Composition of measurement robot (SALLY).*

Table 1. *SALLYs specifications.*

Measurement time (min/peace)	Load force (N)	Strokes (mm)	External dimensions (mm)	Motor speed (mm/sec)
20	1000 [Max]	±12 [Each side]	300×450×700	1.6

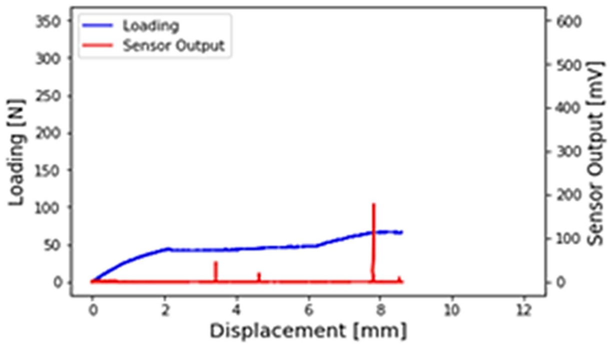
4. Tests for Sensor Characteristic Confirmation: Results and Discussion

4.1. Results of Sensor Characteristic Measurements by SALLY

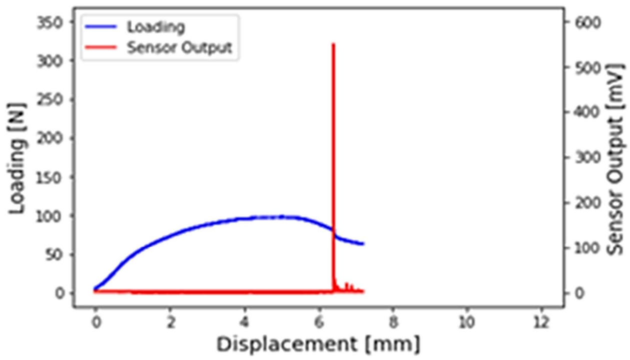
Three piezo junction sensors with base plate thicknesses of 1.0, 1.2, 1.6, 2.0, and 2.3 mm were used to perform tensile tests (applying force in the negative direction) and compression tests (applying force in the positive direction) using SALLY. We calculated the average values of three measurements [15]. For this experiment, based on the calculated displacement value, the sensor output at the time of displacement before fracture of the joint is called the "output before failure." The sensor output is defined as the "output at failure."

Figure 5(1) shows the sensor output related to the applied force and the amount of displacement of the piezo junction sensor with 1.0 mm base plate thickness. In the tensile test shown in panel (a), the sensor output was observed when the displacement amount was 3–7.5 mm. According to the force curve, when the displacement was about 3 mm, the sensor output was about 80 mV as the "output before failure" of the welded joint. When the displacement was about 7.5 mm, the sensor output was about 200 mV as the "output at failure." In the compression test shown in panel (b), a sensor output was observed at 6.5–7.0 mm displacement. Sensor output of 550 mV was obtained as the "output at failure" when the displacement was 6.5 mm. Subsequently, the sensor output was only about 20 mV until the displacement amount was about 7 mm. large variation was found in the measurement results obtained from the three sensor outputs. Sensor output stability was not found.

Figure 5(2) presents the sensor output results related to force and displacement of the piezo junction sensor with 1.2 mm base plate thickness. For the tensile test shown in panel (a), the sensor output was observed at 3.3–7.5 mm displacement. From the load curve, when the displacement was about 3.3 mm, sensor output of about 70 mV was the "output before fracture" of the welded joint. It can be inferred that the "output at failure" was about 200 mV when the displacement was about 4.5 mm. In the compression test shown in panel (b), the sensor output was observed at displacement of approximately 10.8–11.0 mm. For a 10.8 mm displacement amount, sensor output of about 550 mV was inferred as the "output before failure." Subsequently a small output was seen repeatedly until the displacement was about 11.3 mm. No regularity was found in the sensor outputs of the three sensors in both the tensile test and the compression test results.

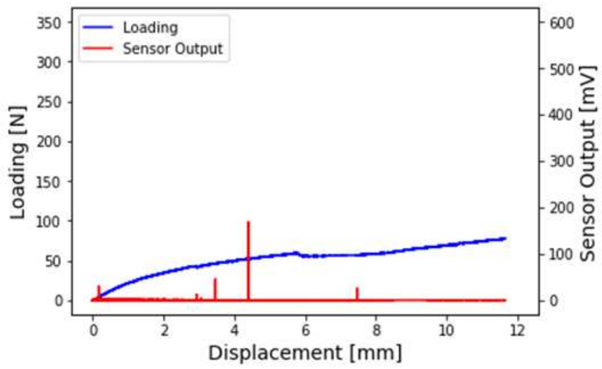


(a)



(b)

(1). Sensor base 1.0 mm



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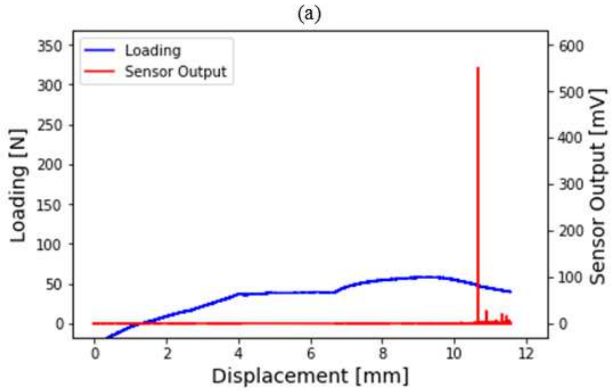
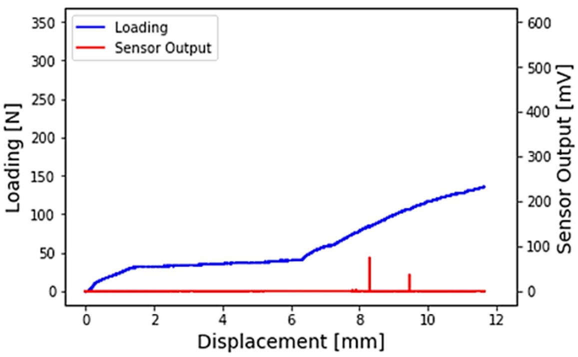


(b)

(2) Sensor base 12 mm.



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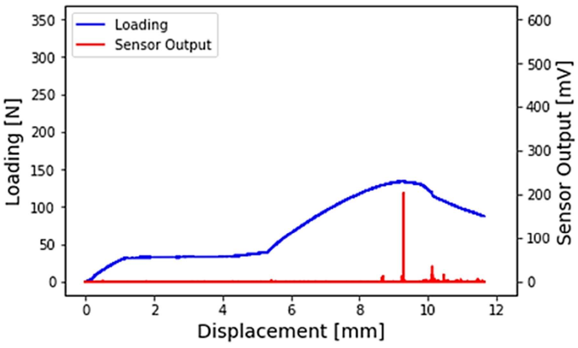
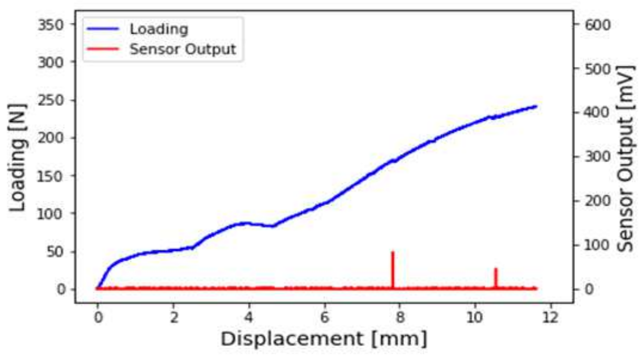


(b)

(3) Sensor base 1.6 mm



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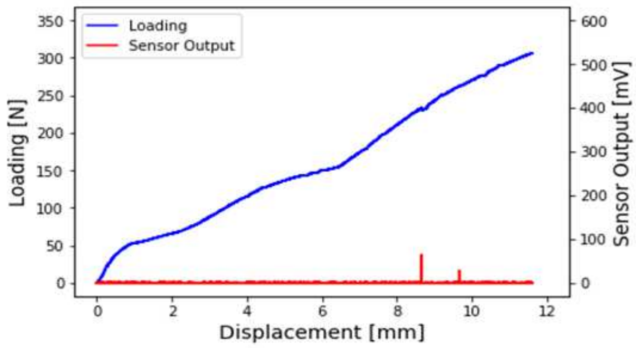
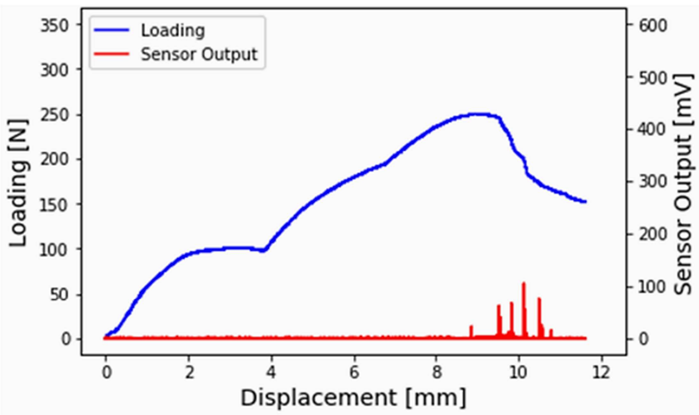


(b)

(4) Sensor base 2.0 mm



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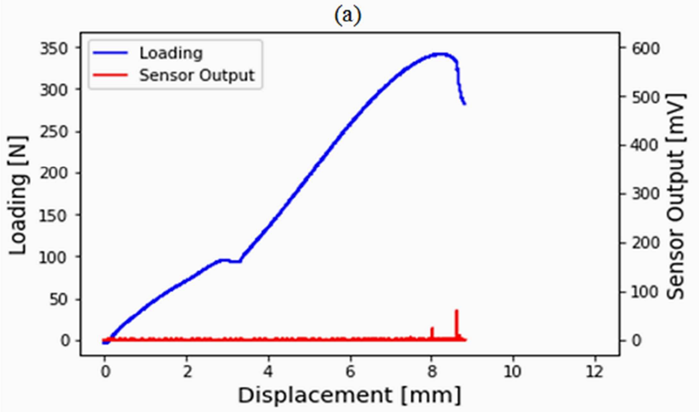


(b)

(5) Sensor base 2.3 mm

Figure 5. *Relation between displacement and piezoelectric composite sensor output by measuring SALLY.*

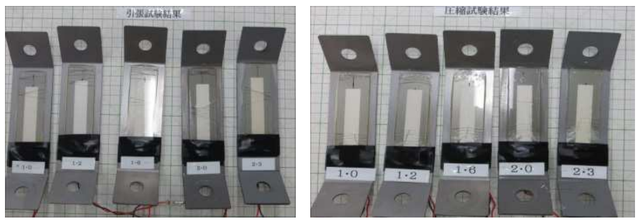
Figure 5(3) presents output results obtained for the applied force and the amount of displacement with the piezo junction sensor with 1.6 mm base plate thickness. The sensor output for the tensile test shown in panel (a) was observed at approximately 8.3–9.5 mm displacement. It can be inferred that the sensor output was about 50 mV as the "output at failure" when the amount was about 9.5 mm. However, because the sensor output value is low compared to the magnitude of the applied force, it is difficult to judge the fracture of the joint. From the compression test shown in panel (b), the sensor output was observed at 8.5–10.5 mm displacement, but the pressurization curve shows the “output before failure” as about 200 mV at 9.0 mm displacement, and “output at failure” as about 200 mV. The sensor output was 40 mV when the displacement was about 10 mm.

Figure 5(4) portrays output results of the sensor with respect to the applied force and the amount of displacement of the piezo junction sensor with 2.0 mm base plate thickness. In the tensile test shown in panel (a), a sensor output was observed at 7.8–10.8 mm displacement. For displacement of about 10.8 mm, sensor output of about 50 mV was inferred as the “output at failure.” In the compression test shown in panel (b), sensor output was observed at about 9.0–11.0 mm displacement. The pressurization curve suggests that the sensor output was about 30 mV and the displacement was about 10.0 mm when the displacement was 9.0 mm. It is judged that the sensor output of 100 mV is measured as the “output at break” when the distance is mm.

Figure 5(5) shows sensor output results for the applied force and the amount of displacement of the piezo junction sensor with 2.3 mm base plate thickness. The sensor output in the tensile test shown in panel (a) was observed at 8.8–9.5 mm displacement. Sensor output of about 30 mV can be inferred as the "output at break" when it was about 9.5 mm. In the compression test shown in panel (b), the sensor output was observed at displacement of approximately 8.0–8.8 mm. From the pressurization curve, for 8.8 mm displacement, the sensor output was approximately 30 mV. The displacement was approximately 8.8 mm as the "output before failure." The sensor output of 80 mV was judged as "output at break" when mm.

Comparing these measurement results with those of SALLY clarified that the sensor output state at the time of fracture of the welded joint differs depending on the base metal plate thickness. Piezo-bonded sensors with 2.0 mm and 2.3 mm base plate thicknesses produced stable measurement results for both the tensile test and the compression test. It became difficult to judge the sensor output corresponding to destruction. Particularly, piezo-bonded sensors with plate thicknesses of 1.0 mm and 1.2 mm showed large variations in sensor output at 5–10 mm displacement, which was the purpose of this experiment, for both tensile and compression tests, rendering it difficult to evaluate the sensor performance.

Figure 6 presents measured sensors of the respective base plate thicknesses after tension testing and compression testing of the piezo junction sensor. For the tensile test of Figure 6(a) sensors with 1.0 mm and 1.2 mm base plate thicknesses showed variations in the position of the crack in the glass plate which generated the sensor output. The measured displacement value was also indeterminate. Sensors with base plate thicknesses of 1.6 mm, 2.0 mm, and 2.3 mm were able to measure the sensor output within the 8–11 mm target displacement range. No variation was found in the measured values, indicating that the target was achieved. In compression tests shown in Figure 6(b), sensors with 1.0 mm and 1.2 mm base plate thicknesses showed large variation in the sensor output values. The displacement measurement values were also inconsistent. However, sensors with 1.6 mm, 2.0 mm, and 2.3 mm base plate thicknesses slightly exceeded the sensor output value at 5–10 mm displacement, which is the target value of the measurement range. The results can be regarded as generally good. Based on the results of these experiments, and particularly considering the stability of the measurement results, we infer that the sensor with the optimum risk prediction in the target displacement of 5–10 mm is the piezo junction sensor with 2.0 mm base plate thickness.



(a) (b)

Figure 6. *Relation between tension and compression by plate thickness difference of piezoelectric joint sensor.*

4.2. Measurement Comparison by Mounting Tests Using T-Shaped Specimens

A mounting test was conducted using a steel framed T-shaped test body that simulated the welded joints of structures. Piezo-bonded sensors [7] with 2.0 mm base plate thickness were installed on both sides of the support column joint of the specimen. The sensor output, applied force, and displacement were measured when force was applied to the top of the support column with a hydraulic jack. The force is applied in the direction that the column tilts to the right. The load during application was measured using a load cell installed on the hydraulic jack. The application and displacement were recorded at 1 Hz. The horizontal load was based on the column top displacement. The standard values of the three items in Table 2 were used for the load and the deformation angle.

Table 2. *Sensor output in strain test and compression test for changes in base plate thickness (Average of three times each).*

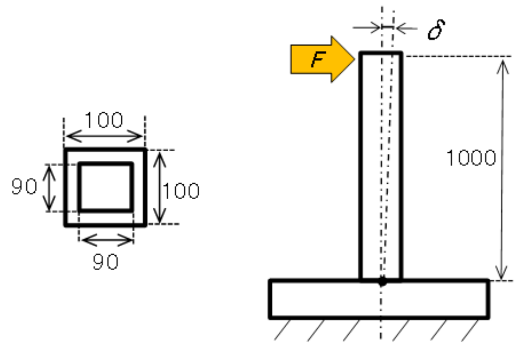
Base plate thickness (mm)	Displacement (mm)		Sensor output (mV)
	Tension test	Compression test	
1.0	3.0–7.5	6.5–7.0	50–550
1.2	3.2–7.8	10.8–11.3	30–550
1.6	8.3–9.3	9.2–10.3	30–200
2.0	7.8–10.8	9.0–10.5	80–110
2.3	8.8–9.8	8.0–8.8	30–80

Table 3. *Load pattern characteristics by simulation.*

Load (kN)	Displacement (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]	+ −

The numerical values presented in Table 2 were verified by simulation using the model shown in Figure 7 along with the material conditions and applied formulas. When the cross-sectional area of the square pipe used in the test piece is obtained from formula (1), the geometric moment of inertia, I, and section modulus Z are obtained from formulas (2) and (3), and from formula (4). Displacement δ can be calculated. Table 3 presents values of the applied force F that give 4 mm, 5 mm, 8 mm, and 10 mm of displacement δ corresponding to the deformation angle corresponding to the fracture of the structure. They are summarized in earlier reports of the literature [11, 16]. The 1/200 deformation angle is the value which causes structural damage. The value of 1/100 is the value assuming damage after the earthquake. Displacement δ becomes 3.97 mm when the applied force is approximately 7 kN. Displacement δ becomes 5.11 mm when the applied force is approximately 9 kN. Displacement δ becomes 7.94 mm when the applied force is approximately 7 kN. For 14 kN, the value of displacement δ, which is the design fracture region, is 9.68 mm when the applied force is 17 kN. However, the mounting test showed the displacement as 10 mm or more when 13–14 kN was applied. It was recognized as a complete failure state. From these findings, the damage state of the structure at the time of the earthquake was inferred as that shown at 13–14 kN of applied force. The results of the applied force of the fracture limit were slightly different from the numerically calculated values.

Figure 7 presents sensor output results for force and displacement when a piezo-bonded sensor with 2.0 mm base plate thickness was installed at the bottom of the steel frame T-shaped specimen. The sensor on the tension side in panel (a) recorded output of about 580 mV from the piezo junction sensor with applied force of about 12 kN and 8 mm displacement, and sensor output of 300 mV with applied force of 13 kN and 9.8 mm displacement. The sensor on the compression side in panel (b) recorded sensor output of approximately 150 mV with applied force of approximately 12.5 kN and 9.8 mm displacement. Also, sensor output of 140 mV was recorded with applied force of 13 kN and 11 mm displacement. In both cases, the sensor output was confirmed before "complete destruction" of the specimen and "at the time of destruction of the specimen." To prevent danger, the test equipment was stopped after about 2 min after the maximum force was applied. As a feature of this measurement result, similar to our finding of the relation between the displacement amount by SALLY and the output result of the piezo junction sensor, the output of the piezo junction sensor on the compression side was found to be similar to the relation between the displacement amount and the output result of the piezo junction sensor in the T-shaped test body mounting test [13, 14].



(a)

$A = 100\times100 - 90\times90$ (mm^2) (1)

$I = bh^3/12$ (mm^4) (2)

$Z = bh^2/6$ (mm^3) (3)

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

A : 1900 mm^2, E : 2866×10^{3}MPa, δ : Displacement
I : 2866×10^{3}mm^4 , z : 57×10^3 mm^3, W : 7 kN, 9kN, 14kN, 17kN, L : 1000 mm

(b)

Figure 7. *Square pipe shape and outer shape of experiment structures.*

5. Conclusion

Measurement results of this mounting test confirmed that the specimen fractured at deformation angles of 1/125–1/100.

The damage was reported as attributable to structural damage incurred by steel materials when the deformation was about 1/100 [17]. Comparison of the sensor output obtained from the sensor characteristic measurement robot and the sensor output obtained from the mounting test using the T-shaped specimen [15] showed similar results for terms of the relation between the displacement and the sensor output in both tests. The relation between the piezo junction sensor base plate thickness and the sensor output shows that sensors with a thin base plate recorded greater sensor output from tensile tests. There was output even with slight displacement. From compression tests, a certain degree of reproducibility was confirmed when 1.6 mm base plate thickness or more was used, but no remarkable characteristics were observed with 1.0 mm and 1.2 mm. In both tensile tests and compression tests, the sensor with 2.0 mm base plate thickness was able to obtain measurement results near the target, which is good for the sensor output measurement target at displacements of 8 mm and 10 mm. We obtained good results. Results of these experiments show the necessity of designing an optimum size and shape for the sensor base plate to obtain large sensor output at the target displacement when developing a sensor for measuring structural integrity. Moreover, results underscore the importance of deriving optimum conditions such as the piezo film position on the sensor base plate. The development of sensors that enable long-term measurement of structural integrity and the establishment of simple monitoring technologies are very important issues [17]. We expect to continue our efforts at improving automatic measurement technologies and at building FEM technologies for single sensors.

Acknowledgements

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

I would like to express my sincere gratitude for your research support.

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