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Sally, a Robot for Measuring Piezoelectric Joint Sensor Characteristics

Nobuhiro Shimoi[1, *], Kazuhisa Nakasho[2]

[1]Faculty of Systems Science and Technology, Akita Prefectural University, Yurihonjo, Japan

[2]Graduate School of Sciences & Technology for Innovation, Yamaguchi University, Ube, Japan

Email address:
Shimoi@Akita-Pu.Ac.Jp (N. Shimoi), nakasho@yamaguchi-u.ac.jp (K. Nakasho)

[*]Corresponding author

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Abstract: Japan's social capital was accumulated and concentrated during the period of rapid economic growth. However, there are concerns about future deterioration, and it is expected that the number of facilities that are more than 50 years old will increase over the next 20 years. Therefore, there is an urgent need to maintain and update such aging infrastructure. Many steel structures are constructed using fillet-welded frame weld joints and welded substructures. Moreover, these weld joints have little capacity to absorb energy during earthquakes. Therefore, for designing steel structures incorporating welded joints, strong earthquake-resistance characteristics must be specially provided for those joints of steel welded bases. Furthermore, structural monitoring will be necessary. This report describes, using simple model structure of measurements our piezoelectric joint sensors for evaluating resistance and displacement characteristics of fillet welded Construction. On the other hand, as described in this paper, we present results for evaluating the load of resistance and displacement characteristics of piezoelectric joint sensors using a sensor measurement robot (SALLY). 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 SALLY to promote research on the performance characteristics of piezoelectric joint sensors.

Keywords: Anchor Bolt, Control Engineering, Health Monitoring, Piezoelectric Joint Sensor

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]. 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. The problem is regarded as extremely difficult.

In Japan, which has experienced the extremely powerful Great East Japan Earthquake, architectural design standards are necessary to prevent buildings from collapsing when a huge earthquake with seismic intensity of 6 or greater occurs. Buildings must be able to absorb seismic energy capable of plasticizing an entire building. However, no report of the relevant literature describes monitoring of structural integrity using long-term precise measurements concentrated only on the joint part [4]. Other economically developed countries that have experienced strong earthquakes also lack monitoring methods for joint parts. For this study, we constructed a monitoring system able to measure structural soundness "easily," "inexpensively," and "over a long-term" using sensor output through autonomous damage inspection of welded joints of steel structures. We investigated the design and measurement technology of a piezoelectric joint sensor that enables displacement prediction [5].

2. Destructive Testing of Fillet Welds

Various methods are used as measurement technologies for quantitative evaluation of soundness for disaster prevention and reduction of structures. Assuming a sensor system used for displacement and vibration measurements with static loading, displacement is measured using a laser displacement meter or a contact displacement meter. Natural vibrations are always measured using a fine vibration meter. A method exists of identifying fracture and stress concentration locations using FEM analysis [6, 7]. Moreover, X-ray analysis using FEM is useful for nondestructive and quantitative evaluation of the residual stress of structures. Nevertheless, analyzing crack growth using this method it is difficult. Among these methods, for microwave tremor measurement, the natural period of the structure is obtained using the Fourier spectrum ratio of the vertical component and the horizontal component. The amplification characteristics and natural period are obtained by finding the H/V spectrum ratio and by normalizing the horizontal vibration to vertical vibration. The measurement system unit costs about 1.5–2.5 million yen; it comprises a microwave tremor generator, a data logger, and a PC [8-10].

3. Sensor Measurement Robot (SALLY) Development

3.1. Piezo Junction Sensor

Figure 1 portrays the piezo joint sensor structure. Figure 2(a) depicts the piezo joint sensor attached to the welded joint of the test piece.

Figure 2(b) shows the sensor attached to the SALLY measurement unit. A 40 × 190 × 2 mm general rolled steel sheet was used as the base metal for the piezo junction sensor. After making two holes for fastening Φ12.3 mm bolts and a hole for a cable duct of φ8 mm in the metal plate, about 40 mm at both ends was bent at 135 degrees [11, 12].

This shape is designed so that the piezo joint sensor can be attached to the welded surface of a square steel pipe column welded in a T shape at a 45 degree angle. The piezo bonding sensor is aimed at preventing film peeling and deterioration after adhesive fixation to a piezo film (DT2-028K / L; Tokyo Sensor) [13] of approximately 10 × 65 mm to the base metal plate surface with ultraviolet curable resin (UV). Hard plate glass is adhered and fixed with about 25 × 75 × 1 mm thickness with ultraviolet curable resin. This sensor is designed to enable measurement according to fracture at the welded joint. It also has the feature of requiring no power supply for measurement, which is a characteristic of piezoelectric elements. As a measurement principle, when the base metal to which the piezo film is adhered undergoes plastic deformation, the glass plate covering the piezo film is damaged. Simultaneously, the piezo film, which is the detection unit, is affected. Sensor output becomes possible. Because of the difference in the yield point between metal and glass, adhesion of the glass plate using the ultraviolet curable resin is lost. The piezo film outputs a voltage. By contrast, if the welded joint is in a healthy state and if there is no displacement or abnormal vibration, then the sensor output attributable to the voltage is not measured because the piezo film does not undergo plastic deformation [14].

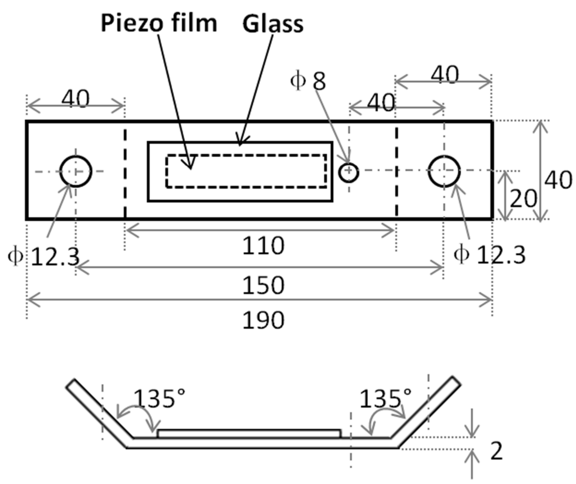
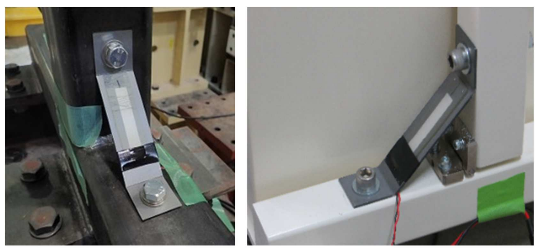


Figure 1. *Characteristics of piezoelectric joint sensor.*

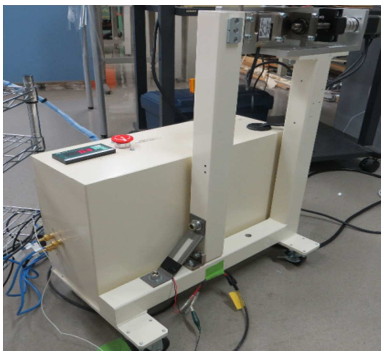


(a) (b)

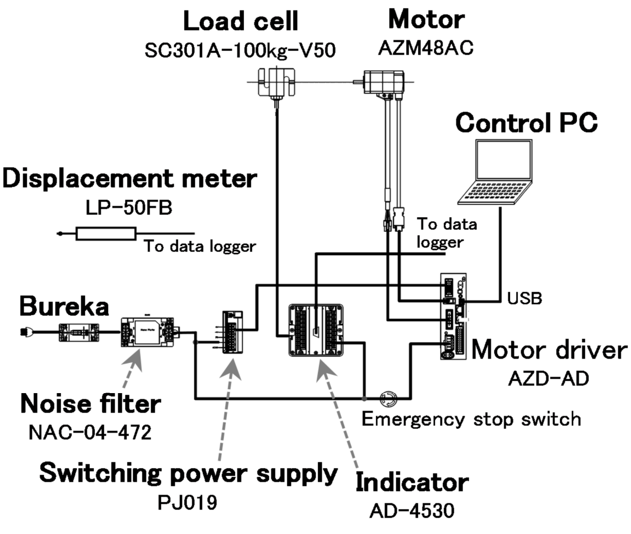
Figure 2. *Setting of piezoelectric joint sensor on the steel specimen and SALLY.*

3.2. Measurement Robot (SALLY)

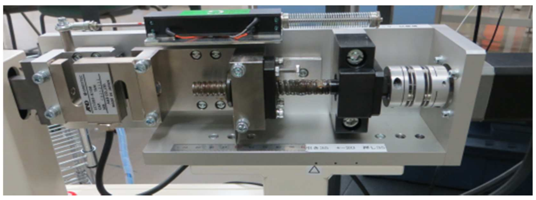
For sensor development, the conventional method is to attach a prototype sensor to the test piece directly and to obtain the sensor characteristics by destructive testing. The labor and cost are about 15 hundred yen for the test piece to obtain the sensor characteristics of one item. The efforts of about 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 [15].



(a)



(b)



(c)

Figure 3. *Robot mechanism and automatic control system for sensor measurement.*

For this robot development experience, we designed the measurement robot (SALLY) used for the present study.

The configuration diagram is shown in Figure 3(a). The drive control diagram is shown in Figure 3(b). SALLY is compact: 300 × 450 × 700 mm. The configuration consists of a drive pulse motor, columns, horizontal columns, load cells, displacement meters, sensor mounts, control PC, and logger measuring instruments. After designing the measurement robot, parts processing, assembly, and electrical equipment are manufactured by request of a startup company. It also has an origin return function to reduce alignment errors when measuring sensor characteristics. The configuration control mechanize diagram is in Figure 3(c). The strut can move 35 mm leftward (compression) and 35 mm rightward (tension). It is designed so that it is controllable such that the same method as the conventional measurement situation using a test piece can be performed. Program control of arbitrary measurement (compression test / tensile test) is possible using the control PC, The motor rotates forward and backward at a speed of about 1.6 mm per second. It is also possible to return to the origin, adjust the speed, measurement the force with the load cell, and measure force and displacement using the displacement sensor. Furthermore, the measured force, displacement, and sensor output are designed to be stored in the logger in real time according to the test date and time, and file number. When calculating the running cost compared to the conventional measurement method, if the robot depreciation cost is ignored, then the same test can be performed by two people in 1.2 days, reducing the time to about 1/19. An important benefit is that test pieces are not lost during testing.

4. Measurement Results and Discussion

4.1. Measurement Result Obtained by SALLY

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.

Displacement of the complete fracture during the mounting test is calculated as about 5–10 mm, assuming a gradient of 1/100 to 1/50 according to the safety standards of the Building Law. Figure 4 presents mounting test details.

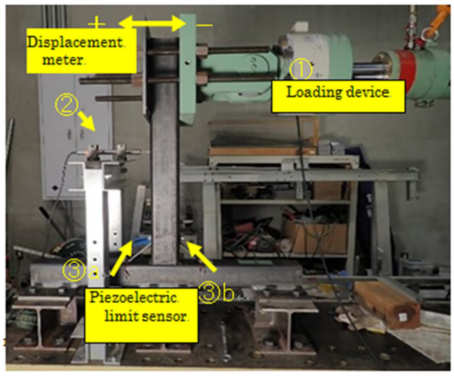


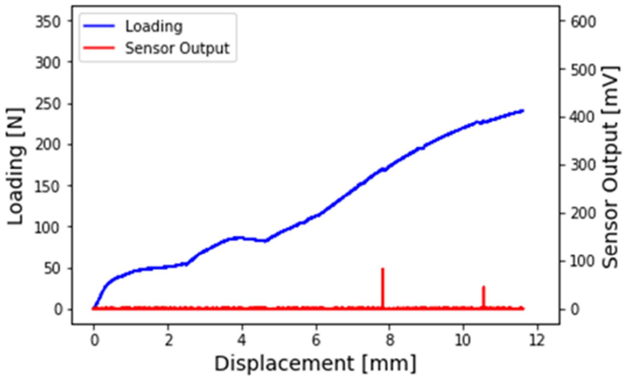
Figure 4. *Load test devices.*

The test piece has 900 mm height and 975 mm width. To it, 100 mm of steel is welded and joined in a T shape. A hydraulic jack is applied to this test piece to measure the displacement, sensor type, and force.

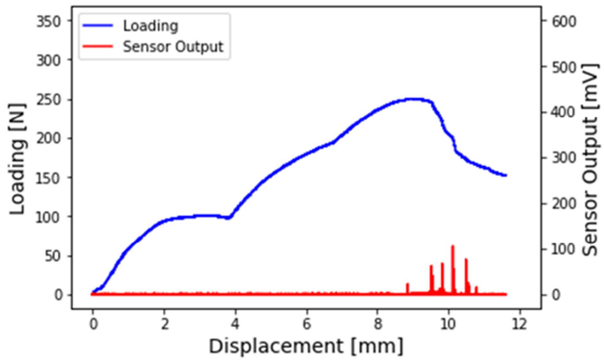
For this test, the process from the healthy state to the destruction of the test piece is recorded as a mounting test. Figures 5(a) and (b) present results of the SALLY test. Figures 4(c) and (d) present results of the mounting test using the test piece. The test results allow comparison of the results obtained using a piezo junction sensor with a sensor-based plate of 2 mm thickness. The measurement result obtained by SALLY indicated that the sensor output before fracture during the tensile test was 100 mV when the displacement was 7.8 mm. The output at the time of fracture was about 50 mV when the displacement was 10 mm. Regarding the compression test, the sensor output assuming fracture was 50 mV when the displacement was 8.3 mm. The sensor output assuming fracture was about 120 mV when the displacement was 9.8 mm. However, for the mounting test in which the piezo junction sensor was installed directly on the test piece shown in Figures 5(c) and (d), the sensor output before fracture during the tensile test was measured at about 600 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 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 1. *Sensor output in tensile test and compression test for changes in base plate thickness (Average of 3 times each).*

Base plate (mm)	Tension test (mm)	Compression test (mm)	Sensor output (mV)	Sensor output (mV)
1.0	2.7 ~3.2	10.7~ 11.0	80 ~480	80~480
1.2	5.1 ~6.5	10.2 ~ 10.7	50 ~ 100	
1.6	6.4 ~7.3	10.2 ~ 10.5	80 ~ 35	50~100
2.0	7.8 ~9.3	9.4 ~ 9.9	167 ~ 60	80~35
2.3	7.0 ~9. 6	9.0 ~ 10.3	150 ~ 90	167~60



(a)



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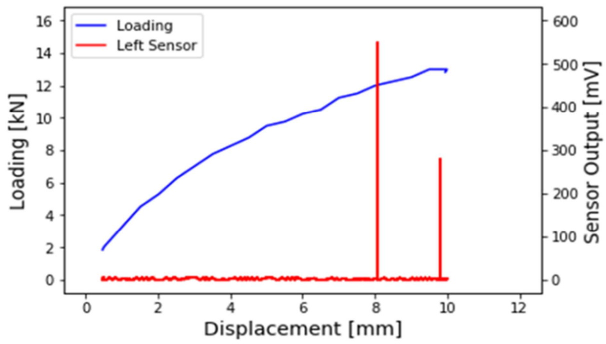
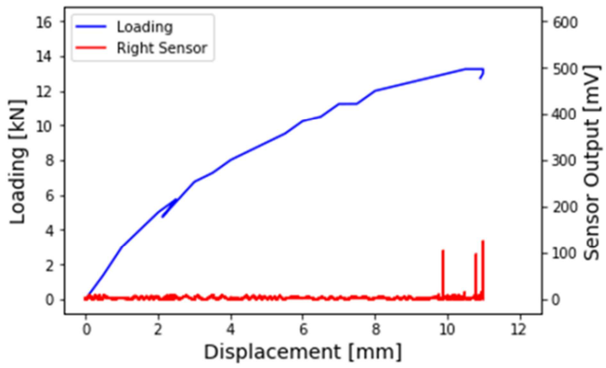


(c)



(d)

Figure 5. *Robot (SALLY) Experiment and Compression Test.*

4.2. Comparing SALLY Measurements and Mounting Tests

The SALLY measurement results were 7.8–10 mm for the tensile test and 8.3–9.8 mm for the compression test. For the mounting test, we were able to obtain results of 8–10 mm for the tensile test and 9.8–10.8 mm for the compression test. Based on these findings, although the measured values are slightly different, the SALLY measuring robot performance is good. It is considered to be an effective measuring method for assessing characteristics of numerous sensors.

Regarding work efficiency in the characteristic test, for the mounting test, if 30 items are to be tested, then the mounting time is limited to measurement of one test piece per day by three workers including the mounting and detachment and measurement time. Therefore, 15 days × 3 people (45 days in total) are necessary. Furthermore, because the price of the test body is 150,000 yen per body, a cost of 2.25 million yen is incurred. However, for SALLY, the measurement time for one item is about 20 min. Therefore, two measuring workers can test 24 items a day. For 30 items, the total number of days would be 1.2 days × 2 people, consequently requiring 2.4 days. Therefore, results demonstrated that the human cost was reduced to about 1/19 by robot measurement. The Speed is the key to product development. In order to solve such problems, it is necessary to develop measurement robot SALLY.

Although depreciation costs for robots must also be considered, equipment costs for cranes and the purchase price for hydraulic jacks are included in mounting tests. They are ignored herein for comparison. A similar instrument is the force tester, but it is very expensive and cannot be used to measure this sensor [17].

5. Summary

Developing sensors that enable long-term measurement and the construction of simple monitoring technologies are fundamental issues for structural evaluation. In this research, verification of the sensor characteristics is essential. Our sensor measurement robot SALLY successfully reduced the cost of test bodies and lowered the working hours to 1/19. Therefore, the efficiency of the sensor improvement process will be significantly improved. Developing robots for numerous sensors used in future quantitative measurements is a field supporting many desirable practical applications.

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