

Verification of Strain Visualization Sheet with Aim of Field Application

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Abstract

In recent years, aging and deterioration of bridges, tunnels, and other social infrastructure has become a serious problem in Japan. Maintenance control of these structures is essential for securing safety. Although the current main stream in operation and maintenance (O&M) of structures is periodical inspection based on visual inspection, introduction of stress monitoring of structural members, etc. is extremely effective for O&M of structures. However, due to financial constraints, the structures where costly stress monitoring has been performed are limited. To solve this problem, the authors previously developed an inexpensive strain visualization sheet based on the principle of Moiré fringes. As features of that device, absolutely no electrical elements such as amplifiers, strain gauges, signal cables, etc. are necessary, large strain values can be read with the unaided eye, and it is possible to obtain strain values with accuracy equal to that of conventional strain gauges by processing images photographed with a digital camera.

With the aim of application in the field, in the present research, some problems of the previously-developed strain visualization sheet were solved, the materials and structure of the device were improved in order to achieve higher accuracy and simplify the installation method, and the performance of the improved device was verified. As a result, it is possible to obtain strain values with resolution of $<100 \mu\epsilon$ by visual observation and accuracy of approximately $10 \mu\epsilon$ by image processing. The temperature characteristics of the strain visualization sheet were also clarified, and simplification of the installation method was possible. Thus, this study confirmed the applicability of the strain visualization sheet for use in the field.

1. Introduction

In Japan, many huge structures were constructed from the post-war economic recovery through the period of high economic growth up to the present. Due to aging and deterioration of these large structures, numerous cases in which safety, utility, and functionality have declined can also be seen. Therefore, with appropriate operation and management (O&M) of structures now becoming a social requirement, rational and efficient O&M of structures has become an important issue. At present, periodical inspection based on visual inspection is the main stream in O&M of structures, but if information on the stress of members, etc. can be obtained by monitoring utilizing sensors, more rational O&M is possible. However, due to recent problems such as severe constraints on public finances and a declining number of engineers, sensor-based stress monitoring has

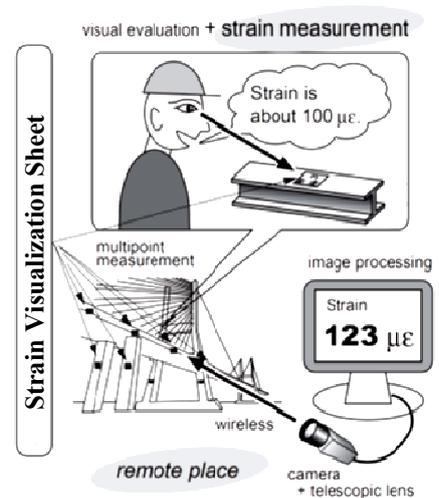


Figure1. Concept of a proposed Strain Visualization Sheet

been implemented for only a limited number of structures, and even visual inspections are not always fully implemented. When stress monitoring is introduced in O&M of structures, it is necessary to install strain gauges, strain meters, etc., wire the signal cables, and connect these electrical elements to a measuring device before monitoring can be performed. Various problems are obstacles to implementation of these systems, including the fact that this installation work is complicated and the cost increases with the number of installation points, and in many cases, this work is not realized. Therefore, the authors are engaged in the development of a “strain visualization sheet” based the concept shown in Figure 1. in order to enable simple, inexpensive strain measurement by non-specialist personnel and establish an efficient strain measurement method by a remote, non-contact technique. (Umemoto, S. et al. 2012) (Omachi, M. et al. 2013) The strain visualization sheet is a novel type of sensor for strain measurement using the principle of Moiré fringes, and has the following distinctive features.

- i) Possible to read strain values directly with the unaided eye.
- ii) Absolutely no electrical elements, such as strain gauges, amplifiers, and signal cables are used.
- iii) Strain with high accuracy can be measured by a remote, non-contact technique by using an ordinary digital camera, etc.

With the aim of application in the field, in the present work, several problems of the strain visualization sheet developed to date were solved, and the materials and structure of the strain visualization sheet were improved in order to further enhance the accuracy of the sensor and simplify the installation method. This paper presents an outline of the newly improved strain visualization sheet and reports the results of tests to verify its performance.

2. Outline of Measurement Principle of Strain Visualization Sheet

As shown in Figure 2.(1), when a line grating 1 with a pitch p and a line grating 2 having a pitch $p + \Delta p$, which is Δp ($\ll p$) larger than the pitch of line grating 1, are superimposed, a striped pattern called Moiré fringes with a pitch W larger than that of these line gratings 1 and 2 appears. As illustrated in Figure 2.(2), if line grating 1 is moved in the direction of (A) by a pitch p , the Moiré fringes also move in the direction of (A) by pitch W . This means a displacement Δx can be displayed in a form visually enlarged by M times. Utilizing this principle, an enlarged display of a microscopic displacement is possible. In the same, by using a grating in the character form (character grating) instead of line grating 1, as in Figure 3., the amount of movement when the character grating is moved in the direction of (A) can be displayed as a change in the characters displayed, as shown in (i') – (iii').

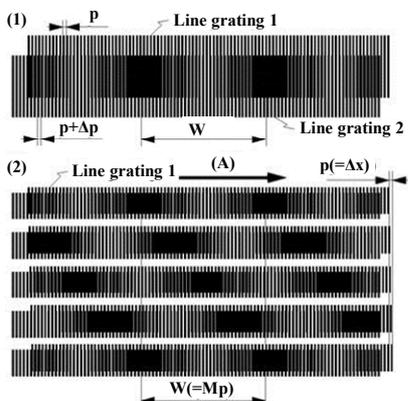


Figure2. Example of a moiré fringe

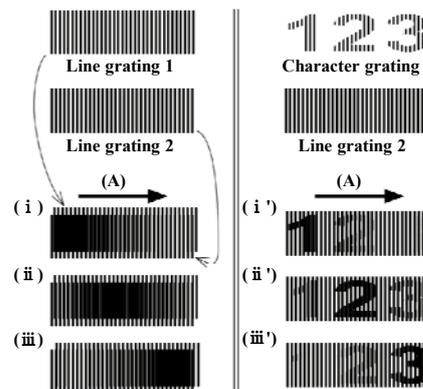


Figure3. A moiré fringe with characters

3. Structure of Newly Improved Strain Visualization Sheet

Figure 4. shows the structure of the newly improved strain visualization sheet. Although the character grating, enlargement ratio of the Moiré fringes, and other features are the same as in the previous version, the material of the newly improved strain visualization sheet has been changed from the film used in the past to glass (thickness: 2.3 mm), which has a small coefficient of thermal expansion and is not affected by humidity. In addition, jigs (width: 5 mm) which enable easy installation on the object of measurement are attached to the both ends of the glass plates, and as a result, the two glass plates form a single unit.

Figure 5. shows the appearance of the newly improved strain visualization sheet. The length, width, and thickness of the strain visualization sheet are 120 mm, 14 mm, and 4.6 mm, respectively, and the reference length is 100 mm. The upper row of this sheet shows a character display with a scale of $100 \mu\text{e}$ pitch, and makes it possible to read strain values directly from the device with the unaided eye. The middle row is a simple Moiré fringe display for stain measurement by image processing, and the lower row is a reference Moiré fringe display for improved image clipping during image processing.

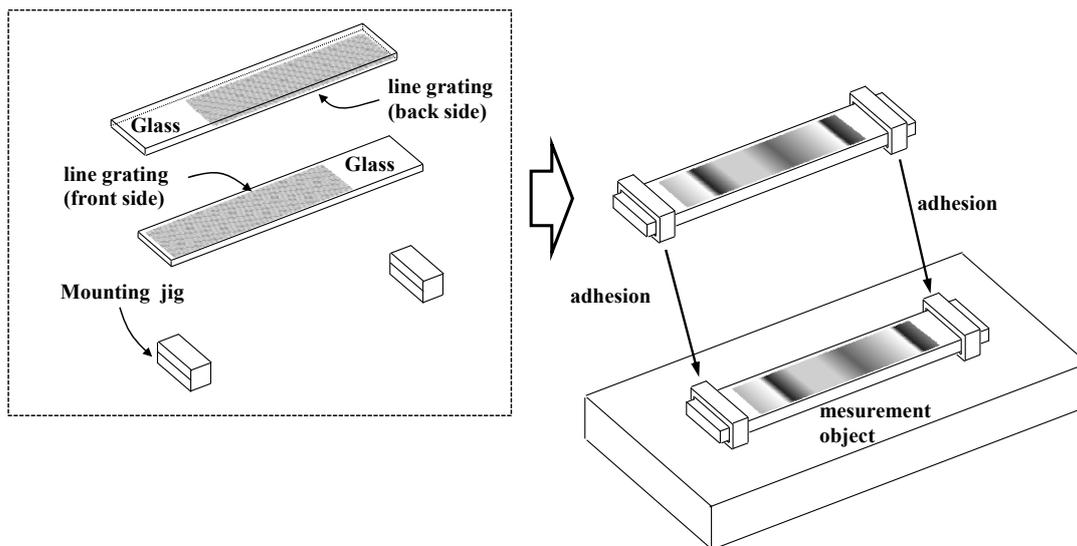


Figure4. Structure of Strain Visualization Sheet

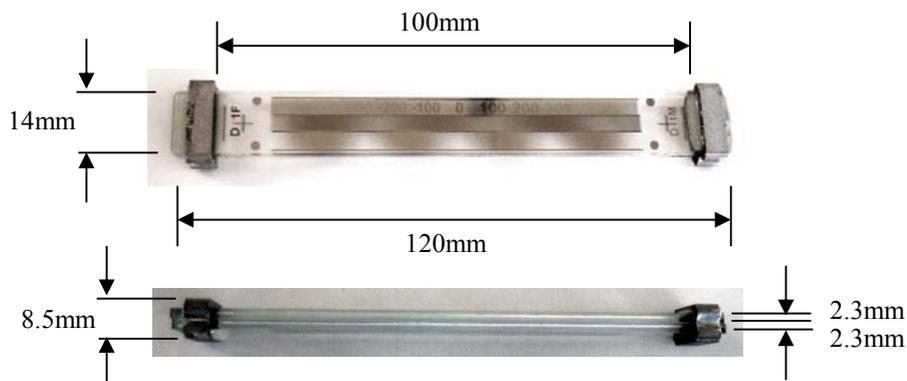


Figure5. Prototype of Strain Visualization Sheet

4. Verification of Accuracy by Tensile Test

4.1 Test piece

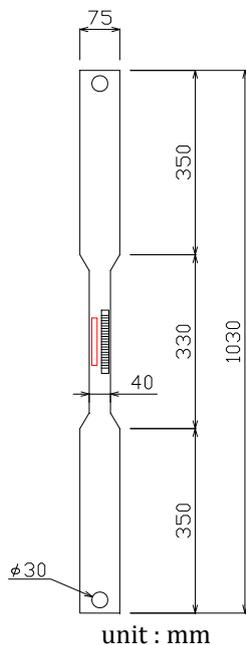
The test piece (JIS Z2201, No. 14) for the tensile test is shown in Figure 6. The strain visualization sheet was fixed at the center of the test piece with glue. For comparison, a strain gauge was also attached adjacent to the strain visualization sheet.

4.2 Outline of apparatus for tensile test

As shown in Figure 7., the test piece was set in a testing machine (rated capacity: 1000 kN), and a digital video camera for photographing digital images of the strain visualization sheet was set up facing the test piece at a distance of approximately 80 cm from the test piece. The digital video camera was a commercially-available USB type with resolution of 2×10^6 pixels. The camera was connected to a real-time image processing device, and the strain gauge was connected to a strain measurement device.

4.3 Test method

As the test method, loading was applied in steps of 20 kN at a uniform speed so as not to cause impact on the test piece. Loading was continued up to a maximum load of 140 kN. After reaching this load, the test piece was unloaded by the same procedure. During the test, the strain visualization sheet was photographed continuously with the digital video camera, and the amount of strain was calculated in real time by image processing. The stain of the strain gauge was measured continuously using the strain measurement device.



- : Strain gauge
- : Strain Visualization Sheet

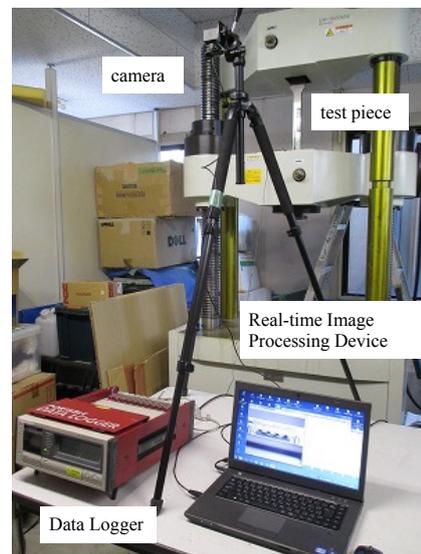


Figure7. Apparatus for Tensile Test

Figure6. Test Piece for Tensile Test

4.4 Verification results

Figure 8. shows the time-strain relationship. Figure 9. shows the stress-strain relationship. From the start of loading, the measured values of the strain visualization sheet show substantially the same values as the strain gauge, the difference being generally within $5 \mu\epsilon$ except for a partial difference of approximately $10 \mu\epsilon$. A similar tendency was also observed during unloading. Likewise, in the stress-strain relationship, a linear relationship was obtained during both loading and unloading, and the results of the strain visualization sheet and the strain gauge showed extremely good agreement. These results verified the fact that strain can be measured with the newly improved strain visualization sheet with the same accuracy as with a conventional strain gauge.

Next, Figure 10. shows images of the strain visualization sheet at intervals of $100 \mu\epsilon$. As can be clearly seen in the figure, when no load was applied, the scale around 0μ appears dark, and the dark part of the scale shifts to the right with each $100 \mu\epsilon$ increment of strain. Moreover, the darkest part of the scale also coincides with the value of generated strain. Based on these results, the possibility of reading generated strain with the naked eye with resolution of at least $100 \mu\epsilon$ was verified.

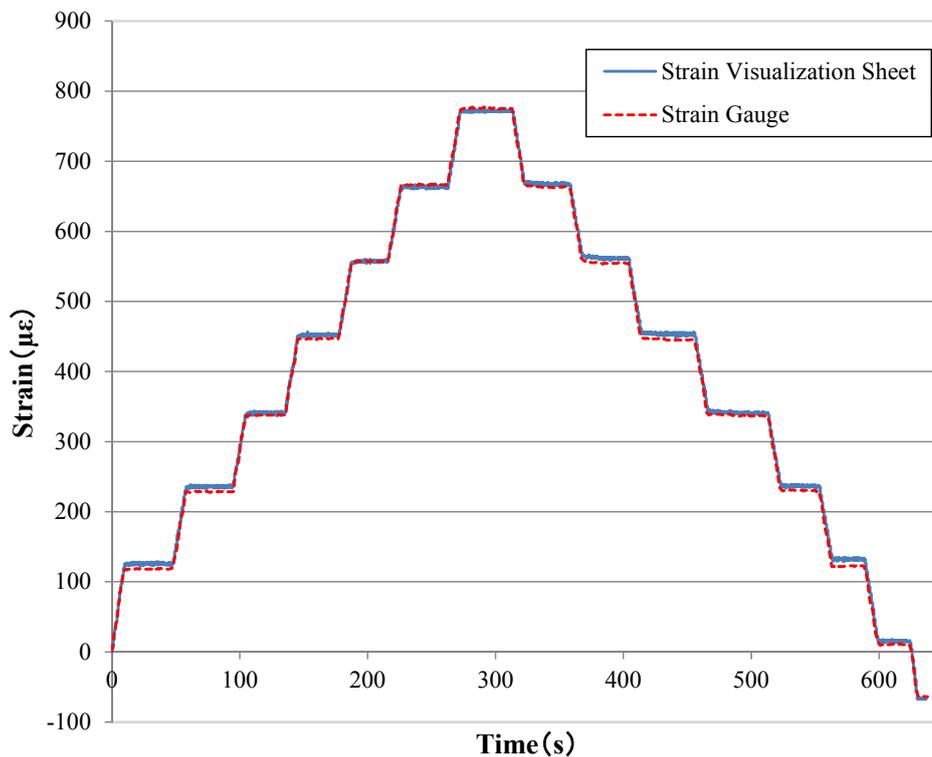


Figure8. Time-strain relationship

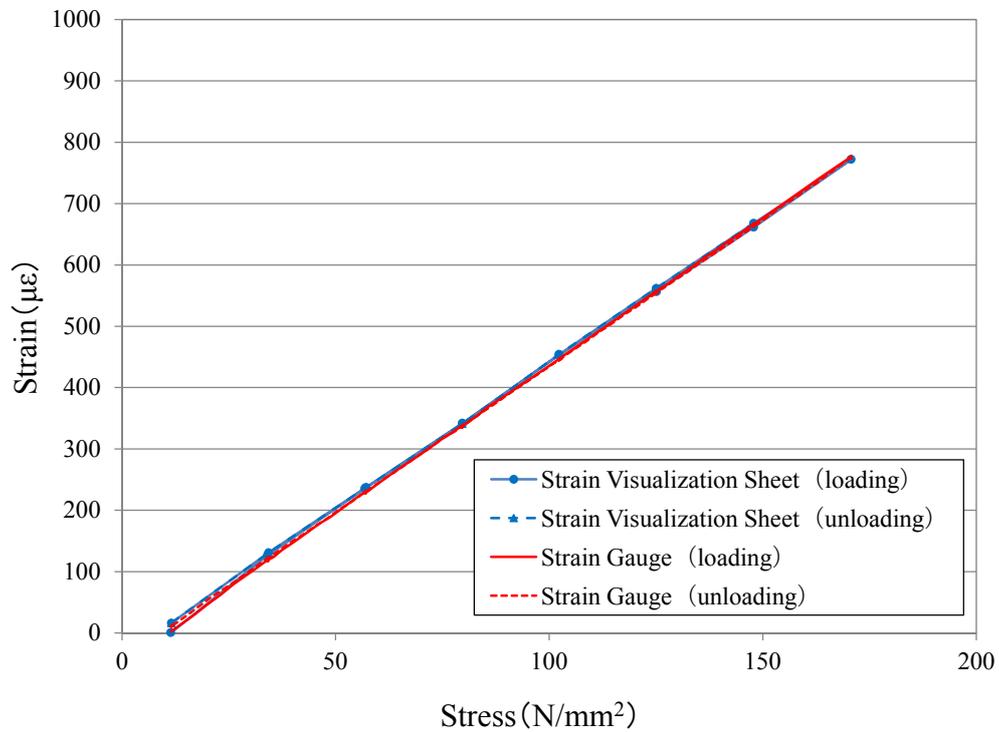


Figure9. Stress-strain relationship

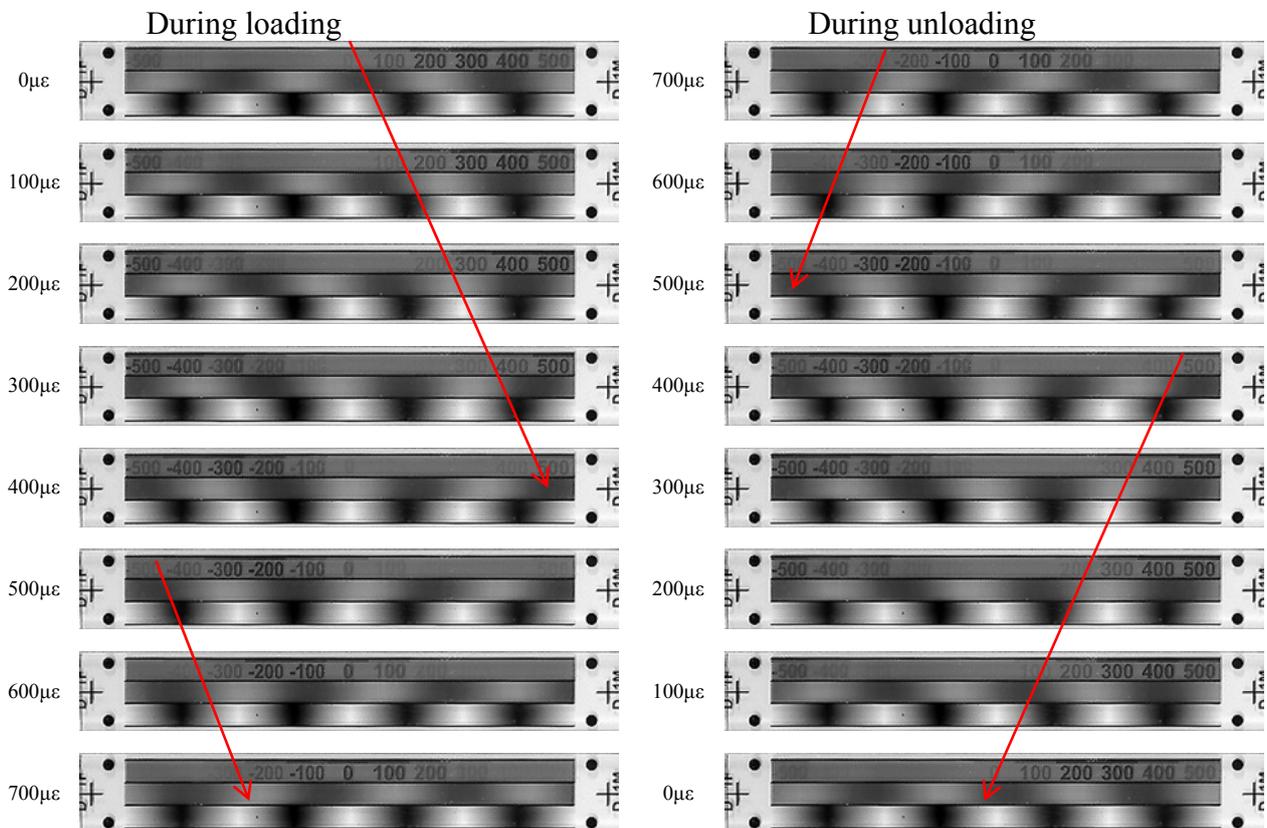


Figure10. Change in character display with increasing strain

5. Temperature Characteristics Test

5.1 Test method

In order to verify the temperature characteristics of the strain visualization sheet, a temperature characteristics test was performed using a thermostatic chamber. The strain visualization sheet and a strain gauge were fixed with glue on a steel plate (SS400, coefficient of thermal expansion: $11.8 \times 10^{-6}/^{\circ}\text{C}$), as shown in Figure 11., and a thermometer was also installed to measure the temperature of the steel plate. The steel plate was placed at rest in the thermostatic chamber so as to avoid the action of constraining force, and a digital video camera was set up about 80 cm from the plate. During the test, the temperature was changed in the range of -10°C to 50°C in steps of 10°C , and the strain value was acquired when the plate reached the specified temperature. A humidity of 40% was maintained during the test.

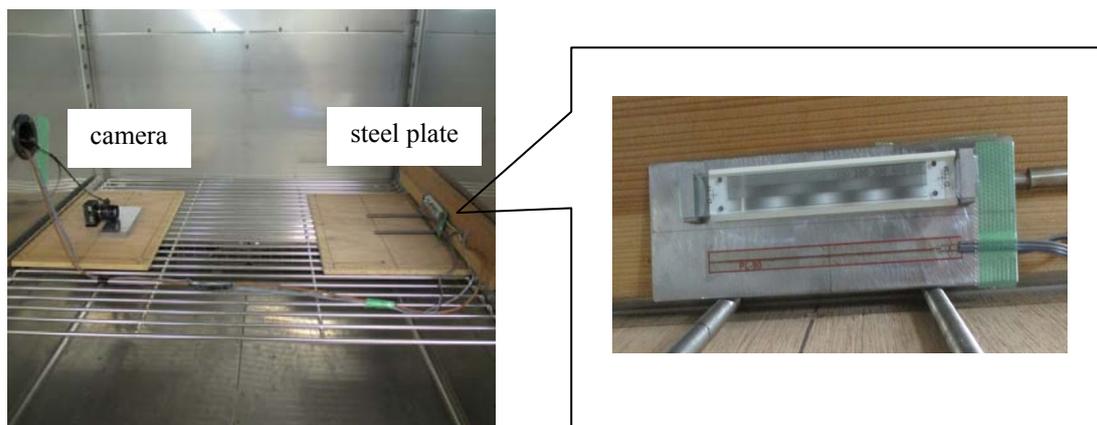


Figure11. Condition of temperature characteristics test

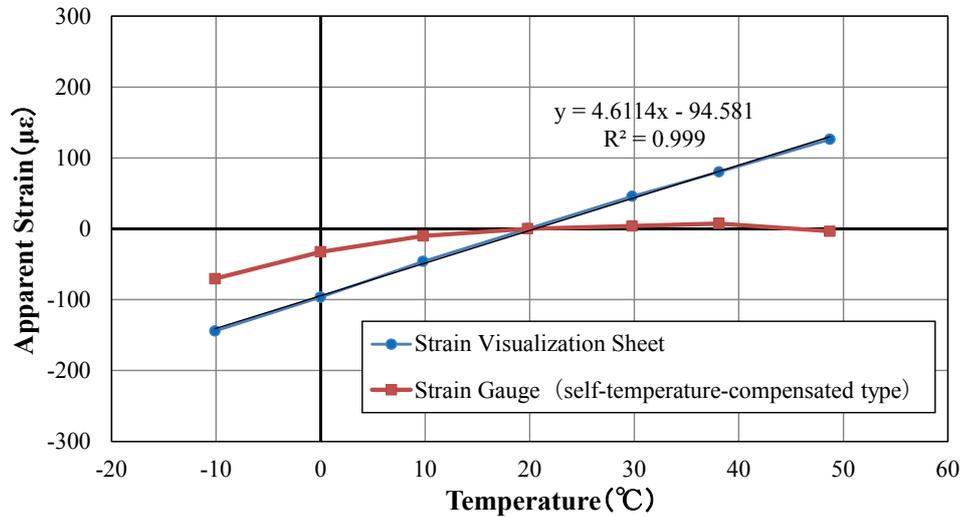


Figure12. Relationship between temperature and apparent strain

5.2 Test result

Figure 12. shows the relationship between the temperatures of the strain gauge and the strain visualization sheet and apparent strain. With the strain gauge, it can be understood that virtually no apparent strain is generated in the range of 10°C to 50°C because the strain gauge is a self-temperature-compensated type. In contrast, with the strain visualization sheet, apparent strain increases in a linear manner as the temperature increases. The temperature characteristic of the strain visualization sheet was 4.6 µε/°C. Thus, for application in the field, restudy of the strain visualization sheet will be necessary in order to realize a self-temperature-compensated type, like the strain gauge, in which apparent strain is not generated.

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