The 8th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
Brisbane, Australia | 5-8 December 2017

Development of Self-Temperature Compensated Strain Visualization Sheet

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Abstract

Health monitoring of rapidly-aging structures has become an urgent issue. A strain visualization device and new strain measurement technology were developed to address this problem. The device, called the “Strain Visualization Sheet,” enables quantitative visualization of strain based on the principle of Moiré fringes. It is also possible to obtain extremely accurate strain values from photographed digital images. A power supply is not required, as no electrical elements are used, and durability is also excellent. Thus, this is a suitable sensor for long-term monitoring. The effect of temperature was one problem for field application of the Strain Visualization Sheet. When a strain measurement sensor is attached to the material being measured, temperature changes, which are unrelated to strain due to external force, cause apparent strain as a result of the difference between the linear thermal expansion coefficients of the object material and the strain measurement sensor. Therefore, a self-temperature compensated Strain Visualization Sheet which minimizes this apparent strain was developed and verified for steel and concrete materials. As a result, apparent strain of less than ±1$\mu\varepsilon$ was obtained in the temperature range of –20°C to +70°C, demonstrating successful self-temperature compensation of the Strain Visualization Sheet. As this temperature compensation range is wider than that of conventional strain gauges, application to structural health monitoring under various environmental temperatures is expected.

1. Introduction

The authors developed a strain visualization device called the “Strain Visualization Sheet” for health monitoring of aging structures. The most important feature of the Strain Visualization Sheet is that quantitative visualization of strain is possible by utilizing the principle of Moiré fringes, without using any electrical elements such as a conventional strain gauge or strain meter. It is also possible to calculate strain values with high accuracy from photographed digital images of the Strain Visualization Sheet. Because no electrical elements are used, a power supply is not required and device life is not limited by electrical failure. Laboratory tests have confirmed measurement accuracy of 50 μm/m by visually reading the strain values and 20 μm/m by digital image analysis.

For application of the Strain Visualization Sheet to steel and concrete structures in the field, the following problems must be solved: (1) Self-temperature compensation suitable for the object of measurement, (2) Improvement of durability and (3) Improvement of ease of installation. This paper discusses the development of a self-temperature compensated type of Strain Visualization Sheet which does not cause apparent strain due to temperature. The principle of self-temperature compensation is discussed, and the developed Self-Temperature Compensated Strain Visualization Sheet is introduced. The results of verification tests are also reported.

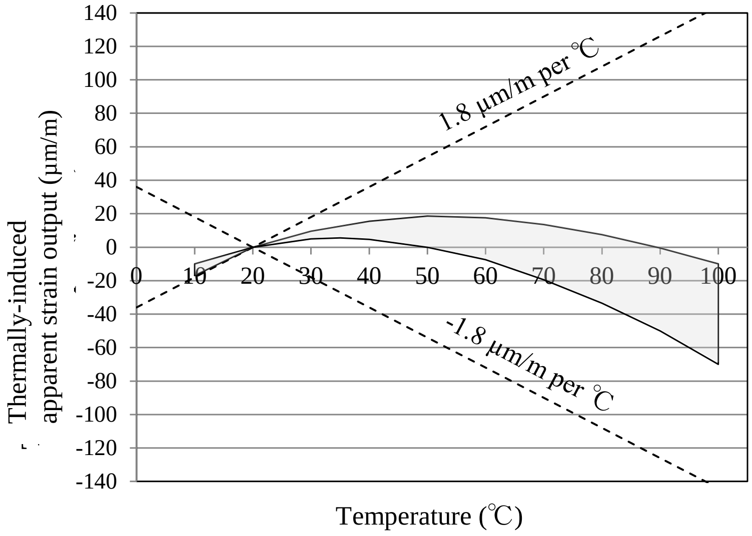

Fig.1 Typical characteristic curve of thermally-induced apparent strain with strain gauges

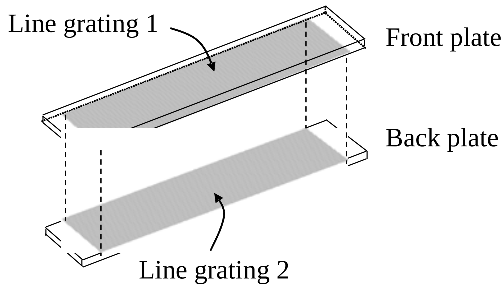

Fig.2 Basic Structure of Strain Visualization Sheet

2. Outline of Self-Temperature Compensated Strain Visualization Sheet

When a strain measurement sensor is installed on a material being measured, temperature changes cause apparent strain in addition to the strain caused by external forces, as a result of the difference in the linear thermal expansion coefficients of the object material and the strain measurement sensor. A self-temperature compensated strain measurement sensor is a type of sensor which minimizes the apparent strain caused by temperature changes. Considering the example of a strain gauge, as shown in Fig. 1, a device which achieves accuracy within ±1.8 μm/m/°C in the prescribed temperature range when installed on a suitable material is called a self-temperature compensated gauge. There are also gauges that achieve ±1.0 μm/m/°C in the 20-40°C range, where they are frequently used. With strain measurement sensors that are self-temperature compensated, the device itself can cancel the apparent strain caused by temperature and output only the strain caused by external force.

3. Principle of Self-Temperature Compensation

3.1 Basic Structure and Measurement Principle of Strain Visualization Sheet

The basic structure of the Strain Visualization Sheet is shown in Fig. 2. Line grating 1 and line grating 2 are drawn on the front plate and back plate, respectively, the two plates are overlaid, and the relative displacement of the two plates in the longitudinal direction is detected by the principle of Moiré fringes. As shown in Fig. 3(1), a striped pattern with a pitch W larger than line gratings 1 and 2 appears due to the superimposition of line grating 1 with pitch p and line grating 2 with pitch $p+\Delta p$, which is Δp ($<<p$) larger than the pitch of line grating 1. This pattern is called a Moiré fringe. The relationship between the Moiré fringe with the pitch W and line grating 1 with the pitch p is shown in Eq. (1). The display of pitch p can be enlarged visually by ($p+\Delta p$) / Δp times by the Moiré fringe.

$$W = \frac{p + \Delta p}{\Delta p} \cdot p \tag{1}$$

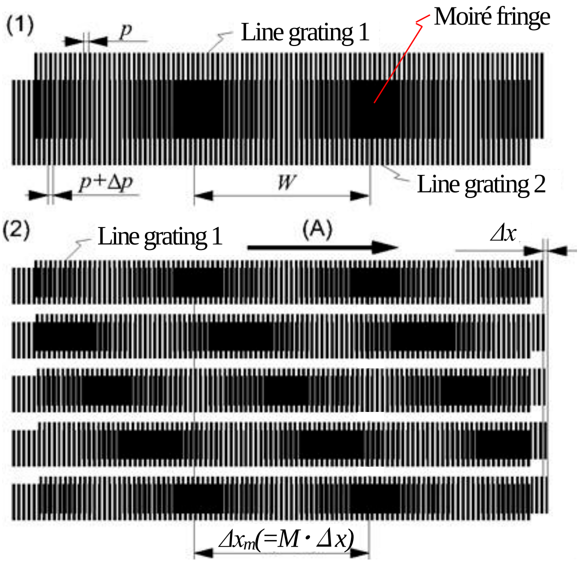

Fig.3 Example of a moiré fringe

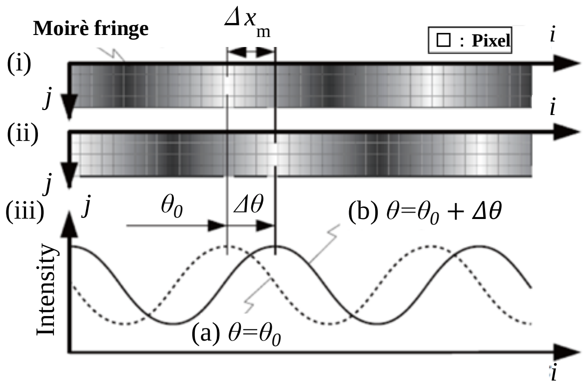

Fig.4 Phase of a moiré fringe

As shown in Fig. 3(2), assuming this magnification factor $(p+\Delta p) / \Delta p$ is M, the amount of shift Δx_m of the Moiré fringe in direction (A) when line grating 1 is moved Δx in direction (A) can be expressed by Eq. (2). In other words, the Strain Visualization Sheet makes it possible to enlarged display of the very small amount of relative displacement of the two plate Δx as the amount of shift Δx_m of the Moiré fringe.

$$\Delta x_m = M \cdot \Delta x \tag{2}$$

Here, we consider the case of that the strain value is calculated by acquiring digital images and performing image processing (Takaki, T. et al. 2012). As shown in Fig. 4, the phase difference $\Delta\theta$ is calculated by a sine curve approximation of the luminance distribution of the Moiré fringe. Further, the amount of shift Δx_m of the Moiré fringe is calculated from the phase difference $\Delta\theta$. and the relationship between Δx_m and $\Delta\theta$ is shown by Eq. (3).

$$\Delta x_m = \frac{W}{2\pi} \Delta\theta \tag{3}$$

Therefore, from Eqs. (1), (2) and (3), the relative displacement of the two plates Δx can be expressed by Eq. (4).

$$\Delta x = \frac{p}{2\pi} \Delta\theta \tag{4}$$

For example, when the amount of relative displacement of the two plate Δx occurs with respect to the reference length L, strain ε can be obtained by Eq. (5).

$$\varepsilon = \frac{p}{2\pi L} \Delta\theta \tag{5}$$

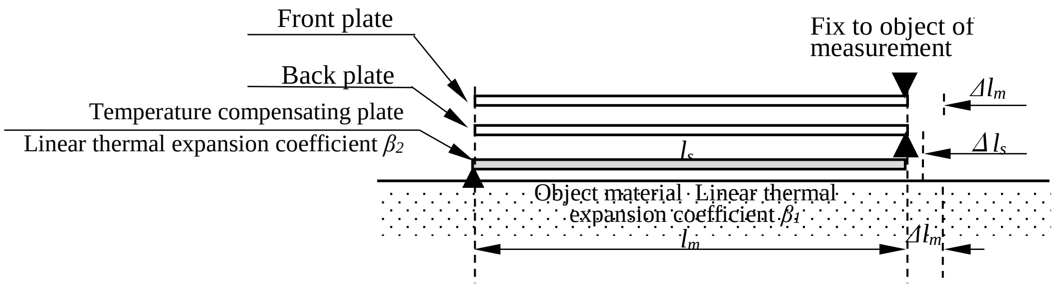

Fig. 5 Proposed self-temperature compensated structure

In addition, in visualization of strain, the Moiré fringe is shown as a numerical value by providing a grating with numerical characters in place of line grating 2, and a numerical value corresponding to the amount of actually occurring strain is displayed by adjusting the magnification factor (Takaki, T. et al. 2012).

3.2 Self-Temperature Compensating Structure

As shown in Fig. 5, the authors conceived a structure in which a temperature compensating plate is incorporated in the basic structure of the Strain Visualization Sheet. When a stress σ acts on an object material which is subjected to a temperature change Δt, the amount of change Δl_m of the length l_m of the object material is equal to the sum of the change of length due to stress σ and the change of length due temperature change Δt. If the elastic modulus of the object material is E and the linear thermal expansion coefficient is β_1, this is expressed by Eq. (6).

$$\Delta l_m = l_m \frac{\sigma}{E} + \beta_1 \cdot \Delta t \cdot l_m \tag{6}$$

If the linear thermal expansion coefficient of the temperature compensation plate is β_2, the amount of change Δl_s in the length l_s of the temperature compensation plate at this time is expressed by Eq. (7).

$$\Delta l_s = \beta_2 \cdot \Delta t \cdot l_s \tag{7}$$

Because the displacement of the front plate is the same as the change Δl_m of the length of the object material, and the displacement of the back plate is the same as the change Δl_s of the length of the temperature compensation plate, the relative displacement Δx of the front plate and back plate can be expressed by the following equation.

$$\Delta x = \Delta l_m - \Delta l_s \tag{8}$$

From Eqs. (6), (7) and (8),

$$\Delta x = l_m \cdot \frac{\sigma}{E} + \beta_1 \cdot \Delta t \cdot l_m - \beta_2 \cdot \Delta t \cdot l_s \tag{9}$$

Assuming $l_m = l_s$ and $\beta_1 = \beta_2$,

$$\Delta x = l_m \cdot \frac{\sigma}{E} \tag{10}$$

Accordingly, equalizing the lengths and linear thermal expansion coefficients of the object material and the temperature compensation plate makes it possible to obtain only the relative displacement Δx of the front plate and back plate caused by acting stress σ, and relative displacement due to temperature change Δt does not occur.

4. Structure of Self-Temperature Compensated Strain Visualization Sheet

The appearance and structure of the developed Self-Temperature Compensated Strain Visualization Sheet are shown in Fig. 6 and Fig. 7, respectively. The device consists of the two glass plates which form the Moiré fringe pattern and a temperature compensating steel plate, and is assembled in a unit form by using a pair of fixing rings. Its external dimensions are 17 mm x 120 mm x 8 mm (thickness), and its gauge length is 105 mm. The Strain Visualization Sheet consists of three types of Moiré fringes. The numbers shown in the upper line are used for strain visualization, the middle line is used for calculation of strain by image processing, and the lower line is a reference moiré for improving the accuracy of image processing. Because the numbers in the upper line are arranged in the form of a scale with an interval of 100 μm/m, strain values can be read directly from this line.

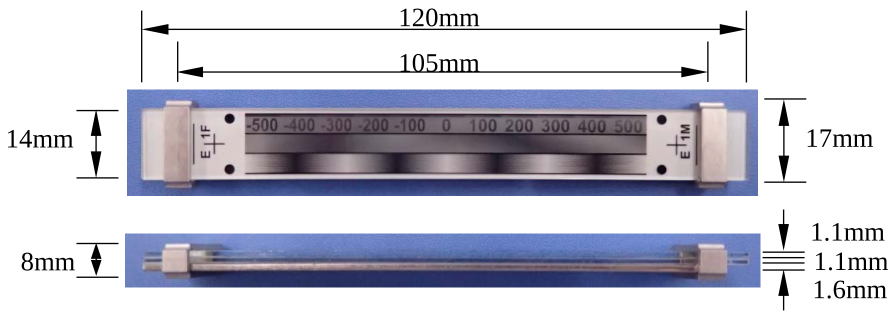

Fig. 6 Appearance of Strain Visualization Sheet

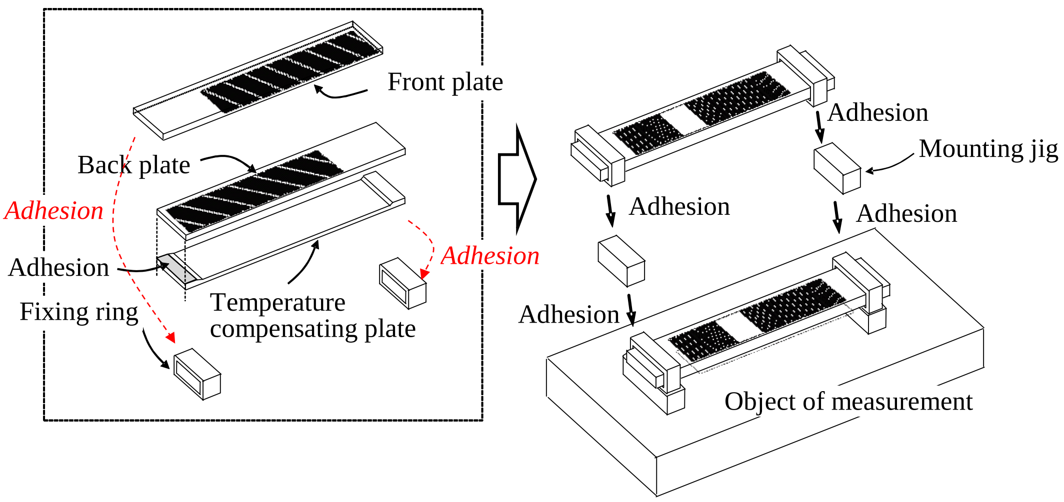

Fig.7 Structure of Strain Visualization Sheet

5. Verification of Self-Temperature Compensated Strain Visualization Sheet

5.1 Test Piece

A steel plate (SPCC, linear thermal expansion coefficient: 11.7 μm/m/°C) with dimensions of 50 mm x 150 mm (t = 1.6 mm) was used as the test piece. The arrangement of sensors on the test piece is shown in Fig. 8, and a photograph of the test piece with the installed sensors is shown in Fig. 9. A conventional strain gauge (gauge length L = 90 mm) was installed on the surface of the steel plate for comparison with the Strain Visualization Sheet. The same type of strain gauge was also installed on the back side of the plate to check for bending of the plate due to temperature. A thermocouple thermometer was installed on the back side of the steel plate to measure the temperature of the plate.

5.2 Verification Method

The test piece was placed in a thermostatic chamber so as to allow free expansion and contraction accompanying temperature changes, and a USB camera was also placed in the chamber for photography (Fig. 10). The USB camera was connected to an external real-time image processing device, and the signal cables of the strain gauges and thermocouple were connected to an external data logger. After measuring the initial strain values, the temperature was changed in the range from –20°C to 70°C in steps of 10°C, and the values of the Strain Visualization Sheet and the strain gauges were recorded when the temperature of the test piece reached the set temperature.

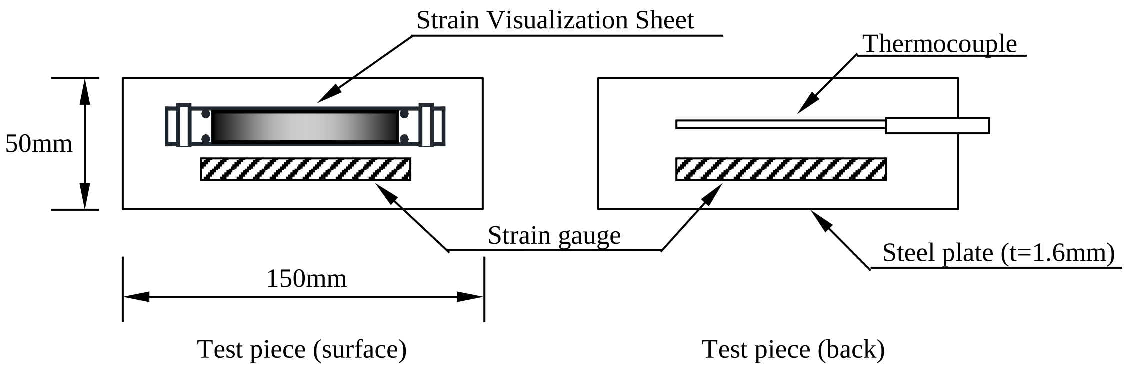

Fig.8 Sensor arrangement

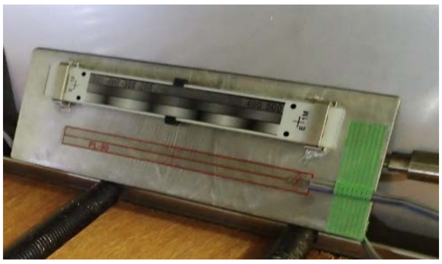

Fig.9 Sensor installation condition

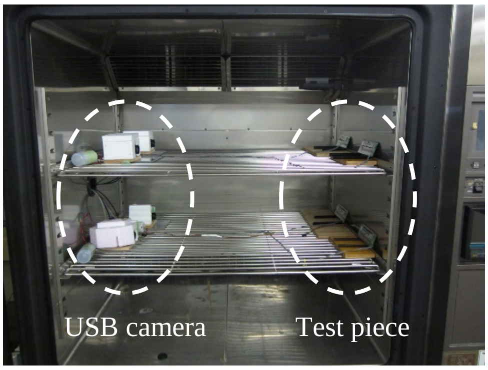

Fig.10 Installation of test piece and USB camera in the thermostatic chamber

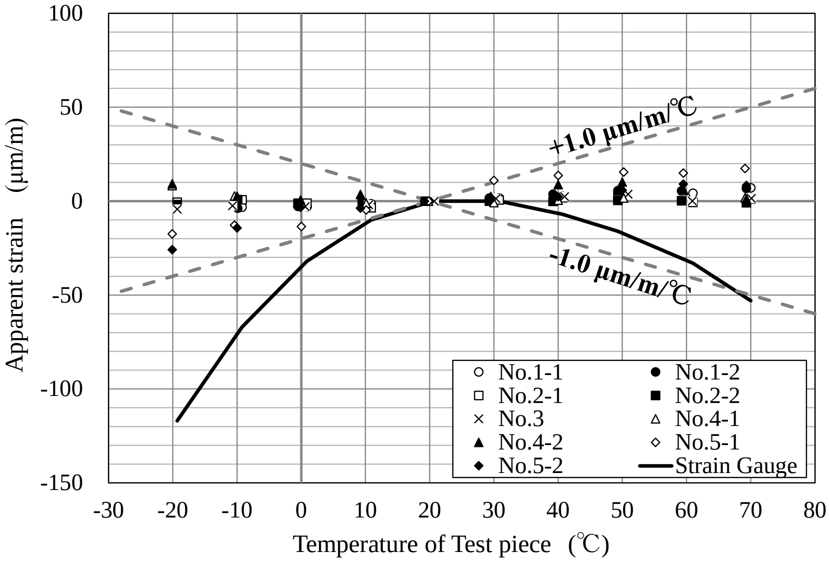

Fig. 11 Relationship between temperature and apparent strain of test piece

5.3 Results of Verification

The relationship between the temperature of a test piece and apparent strain occurred by temperature change is shown in Fig. 11. The apparent strain of the Strain Visualization Sheet was < ±1.0 μm/m/°C, confirming the self-temperature compensation. It is also noteworthy that the Strain Visualization Sheet has a wider self-temperature compensation range than the conventional strain gauge, showing extremely small apparent strain values of approximately 20 μm/m at the high temperature of 70°C and approximately –20 μm/m at –20°C below freezing. The results of this verification test verified the fact that the developed Self-Temperature Compensated Strain Visualization Sheet is a strain measurement sensor with temperature characteristics superior to those of conventional strain gauges.

6. Conclusion

With conventional strain gauges, the self-temperature compensation function is realized by adjusting the temperature coefficient of resistance (TCR) of the strain gauge resistance element material so as to conform to the material being measured. In contrast to this, with the Strain Visualization Sheet discussed in this paper, self-temperature compensation conforming to mild steel and concrete was realized by the constituent materials and structure of the device itself. The development of this new Self-Temperature Compensated Strain Visualization Sheet made it possible to improve applicability in the field. As future work, verification of durability in the field, simplification of the installation method and efforts to realize a low-cost device are planned.

References

Takaki, T. et al., 2012, ‘Strain Visualization Sticker using Moiré fringe for remote sensing’, *Proceeding of the 6th International Conference on Bridge Maintenance, Safety and Management (IABMAS2012)*, Stresa, Lake Maggiore, Italy, 8-12 July, p. 442.