The 6th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
Hong Kong | 9-11 December 2013

STRAIN VISUALIZATION STICKER FOR STRUCTURAL HEALTH MONITORING

Masakazu Omachi [1], Shuji Umemoto [1], Takeshi Takaki [2], Noriyuki Miyamoto [1],
Idaku Ishii [2] and Tadayoshi Aoyama [2]
[1] Department of Plan and Development, Keisoku Research Consultant CO., Hiroshima, Japan.
Email: oomachi@krcnet.co.jp
[2] Division of Electrical, Systems and Mathematical Engineering, Hiroshima University,
Higashi-Hiroshima, Japan.

ABSTRACT

"Stress of members" is a critical item in structural health monitoring. Stress is generally measured by installing strain gauges or meters on the structure being measured, and those measuring devices must be connected to an amplifier in order to obtain strain values. When numerous devices are installed, the scale of the system becomes unwieldy, and the cost may become prohibitive. To solve these problems, the authors developed a new type of sensor called a "Strain Visualization Sticker," which makes it possible to display characters or patterns corresponding to strain without using electrical elements such as strain gauges or meters, signal cables, or an amplifier. This new sensor, which utilizes the principle of Moiré fringes, consists of a part that allows the user to read the approximate strain value with the unassisted eye, and a part that enables remote, noncontact measurement of strain values with high accuracy by processing digital images acquired with a digital camera. In previous research, basic performance tests were carried out with steel and concrete, and the applicability of the new device to structural health monitoring was verified. In the present research, the Strain Visualization Sticker was redesigned for field application with the aim of further improving its measurement accuracy and developing a practical installation method, and a prototype of the improved device was produced. Based on verification of its performance and installation method, the improved device can be installed easily on measurement objects, in the same manner as conventional strain gauges, and is suitable for field application. Resolution of 100με is possible when reading strain values by simple visual inspection, and strain measurement accuracy of about 10με can be realized with image processing.

KEYWORDS

Strain visualization sticker, structural health monitoring, Moiré Fringes, noncontact measurement, image processing.

INTRODUCTION

In response to the increasing social need for safe, economical operation and maintenance (O&M) of structures, including bridges and other aging infrastructure, realizing rational and efficient O&M has become an important issue. Assessment of the "stress of members" is a critical item in structural health monitoring for O&M. Stress is generally measured by installing stress gauges or meters on structures, but conventional sensors must be connected to the strain measurement unit via cables. Stress measurement using these sensors involves various problems, as the installation work is complex and costs increase with the number of measurement locations. To solve these problems, the authors developed a "Strain Visualization Sticker" (Figure 1) based on the principle of Moiré fringes, which ① makes it possible to read strain values directly with the unassisted eye and ② enables remote, noncontact strain measurement by an ordinary digital camera without using electrical elements such as strain gauges, signal cables, or an amplifier. In previous research, Strain Visualization Stickers for steel and concrete were developed and verified. To achieve higher measurement accuracy in field application, the Strain Visualization Sticker and real-time image processing system were improved, and a prototype of the improved device was produced. This paper presents an outline of the prototype Strain Visualization Sticker and the results of verification of its performance.

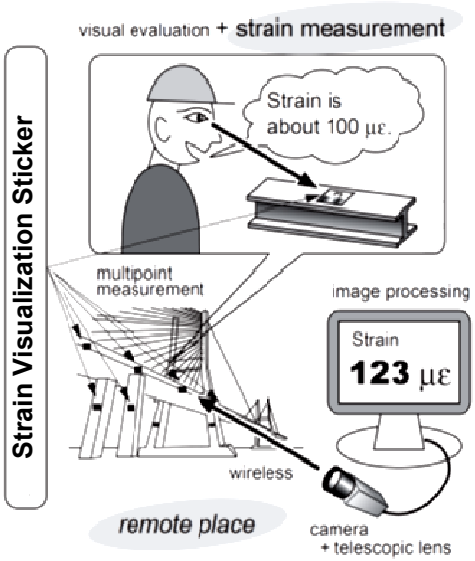

Figure 1. Concept of proposed Strain Visualization Sticker

OUTLINE OF STRAIN VISUALIZATION STICKER

Principle of Moiré Fringes

As shown in Figure 2. (1), when a line grating 1 of pitch p and a line grating 2 of pitch $p + \Delta p$, which is Δp ($<<p$) larger than that of line grating 1, are overlaid, a pattern called a Moiré fringe appears. This Moiré fringe has a pitch W which is larger than that of line gratings 1 and 2. The relationship of the pitches of the line gratings and Moiré fringe produced by overlapping the two line gratings is expressed by Eq. (1).

$$W=(p+\Delta p)/\Delta p \cdot p \tag{1}$$

Furthermore, as shown in Figure 2. (2), when line grating 1 is moved in direction (A) by pitch p, the Moiré fringe also moves in direction (A) by pitch W. In other words, it is possible to display displacement Δx visually enlarged by $(p + \Delta p) / \Delta p$ times. This enlargement factor, or magnification, is expressed by M. When the amount of movement of the Moiré fringe is Δx_m, this relationship can be expressed by Eq. (2).

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

Structure of Strain Visualization Sticker

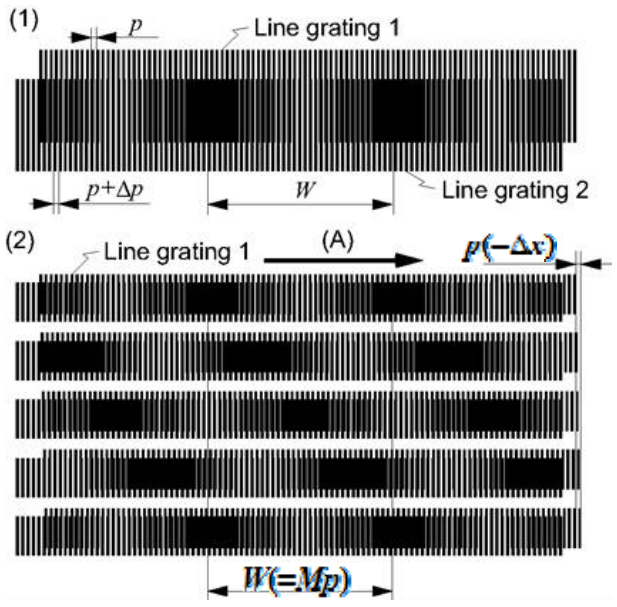

Figure 2. Example of a moiré fringe

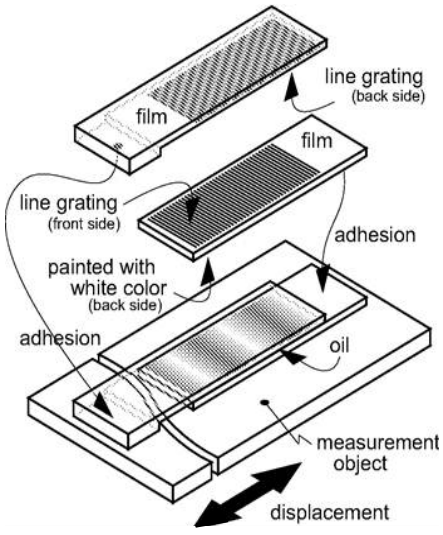

Figure 3. Structure of Strain Visualization Sticker

Figure 3 shows the basic structure of the Strain Visualization Sticker. The Sticker consists of two films with line gratings printed on the back side of the top film and the front side of the bottom film. The back side of the bottom film is painted white to obtain a clear Moiré fringe, and the space between the two films is filled with oil to prevent separation of the films.

STRAIN VISUALIZATION STICKER FOR STRUCTURAL HEALTH MONITORING

Figure 4 shows the structure of the newly-developed Strain Visualization Sticker for field application. Although the character patterns and magnification of the Moiré fringe are the same as in the previous devices, a unitary design was adopted for the newly-developed Strain Visualization Sticker in which the two films printed with the line gratings are fixed on a base. With the earlier versions, it had been necessary to attach the top and bottom films to the measurement object separately. The unitary design enables extremely easy installation, similar to that with gauges, simply by attaching the two ends of the unitary Strain Visualization Sticker to the measurement object with an adhesive. The unitary design also solves the problems of nonuniformity in the initial scale (visualization part), reduced measurement accuracy, etc. due to variations in the accuracy of installation of the top and bottom films.

Figure 5 shows a prototype of the developed Strain Visualization Sticker. The length, width, and thickness of the prototype are 105 mm, 14 mm, and 0.70 mm, respectively, and the reference length is 95 mm. The top line of the sticker is printed with characters in a scale form with intervals of 100 με, which makes it possible to read strain values directly with the unassisted eye. The middle line is a simple Moiré fringe for calculation of strain by image processing, and the bottom line is a reference Moiré fringe for improvement of image cutout accuracy in image processing.

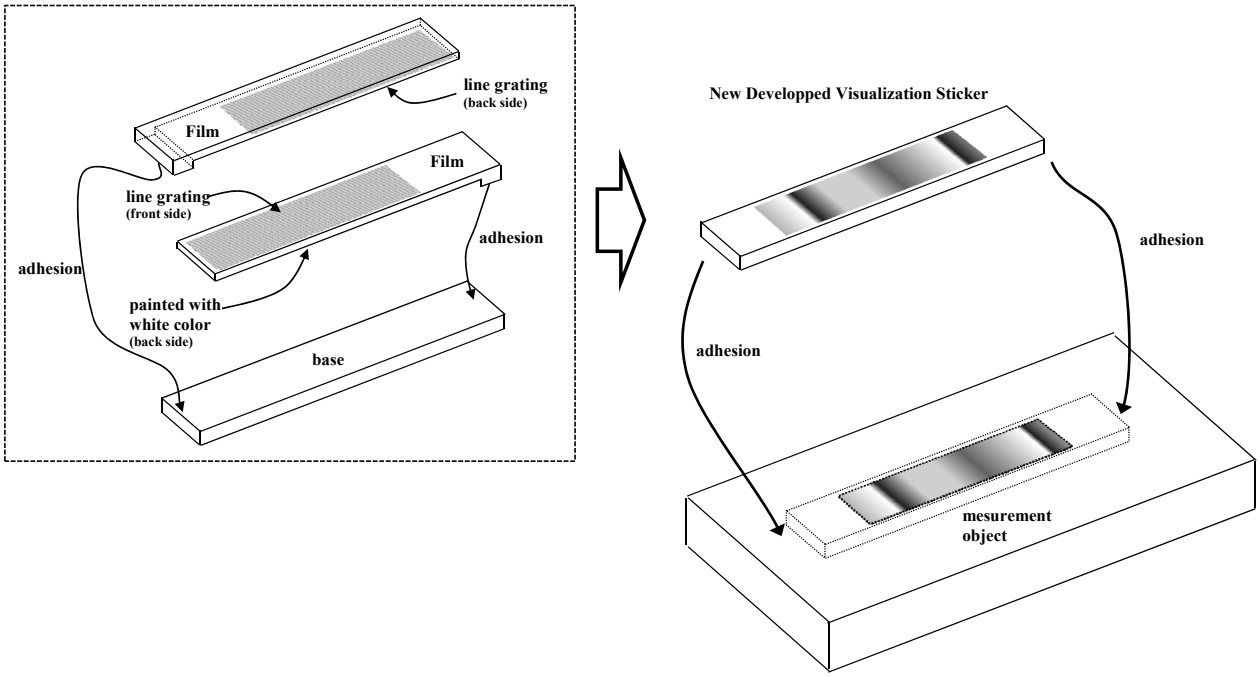

Figure 4. Structure of newly-developed Strain Visualization Sticker

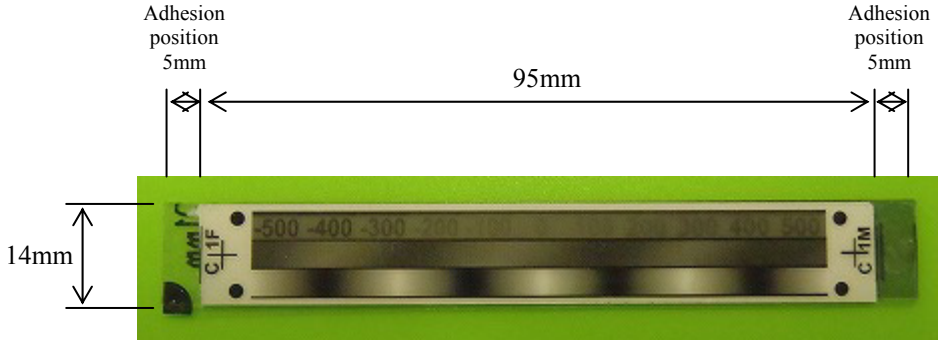

Figure 5. Prototype of Strain Visualization Sticker

PERFORMANCE TEST OF PROTOTYPE

Specimen

Figure 6 shows positions of the installation of the Strain Visualization Sticker and strain gauges on the performance test specimen. The specimen is a mortar cylinder with a diameter of 100 mm and height of 200 mm. The properties of the mortar are shown in Table 1. After preparation, the specimen was cured in water and a compression test was performed after 28 days. The Strain Visualization Sticker was attached to the center of the specimen, and for comparison, strain gauges for use with concrete were attached on both sides of the Sticker. Sections 5 mm in length at the two ends of the Sticker were glued to the cylinder with an adhesive. (The adhesion positions were shown in Figure 5 above.) After the Sticker was glued to the specimen, the base film was cut and removed to prevent buckling of the Strain Visualization Sticker.

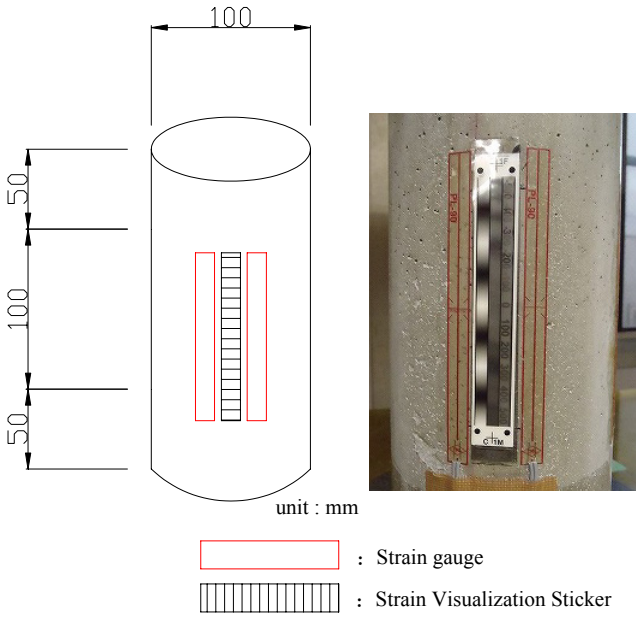

Figure 6. Specimen for Compression Test

Table 1. Properties of sample material

Material	Water/binder ratio (%)	Compressive strength (N/mm^2)	
		3 days	28 days
Shrinkage-compensating mortar	18	25 or more	45 or more

Outline of Apparatus for Performance Test

As shown in Figure 7, the specimen was set in a compression testing machine (rated capacity: 1000 kN), and a digital video camera for measurement of the Strain Visualization Sticker was set up directly facing the specimen at a position approximately 80 cm from testing machine. The camera was a commercially-available USB type digital video camera with 2 megapixel resolution. The camera was connected to a real-time image processing device, and the strain gauges were connected to a strain measurement device.

Test Method

As the test method, loading was applied up to 200 kN at a uniform speed so as not to cause shock to the specimen, after which unloading was performed by the same method. During this process, the Strain Visualization Sticker was photographed continuously with the digital video camera, and strain was calculated in real time by image processing. The strain gauges were also measured continuously by the strain measurement device.

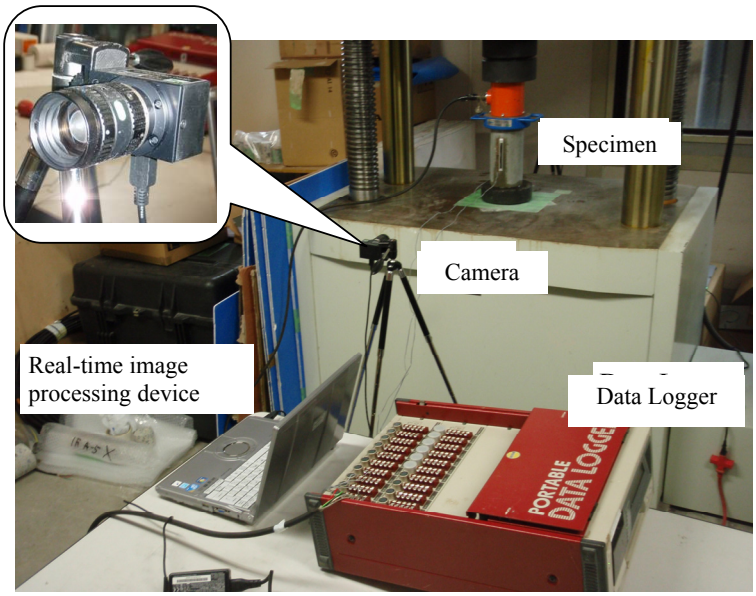

Figure 7. Apparatus for compression test

RESULTS AND DISCUSSION

Figure 8 shows the relationship between test time and strain for the strain gauges and the Strain Visualization Sticker. Figures 9-11 show the stress-strain relationship by test cycle. In these figures, the strain gauge value means the average value of the two strain gauges. The Strain Visualization Sticker shows values similar to the strain gauge value from the start of loading, the difference being on the order of 10-15 με even at maximum load (200 kN). During unloading, however, the Strain Visualization Sticker displayed a value 20-30 με larger than the strain gauge value. These results were the same even when loading-unloading was repeated three cycles.

From these test results, a problem of followability during unloading remains to be solved with the newly-developed Strain Visualization Sticker prototype. Nevertheless, this test demonstrated that strain can be measured with good accuracy by a noncontact method using this device, and the reproducibility of data is also good.

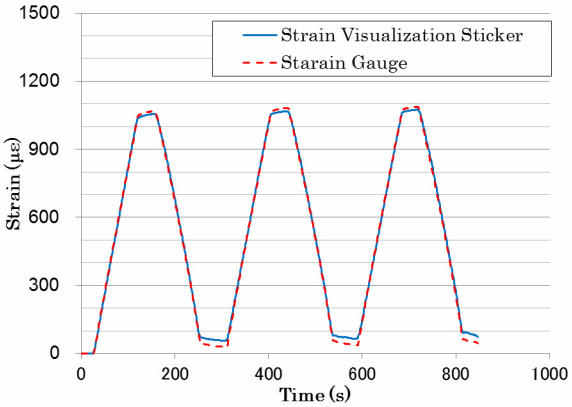

Figure 8. Relationship of test time and strain

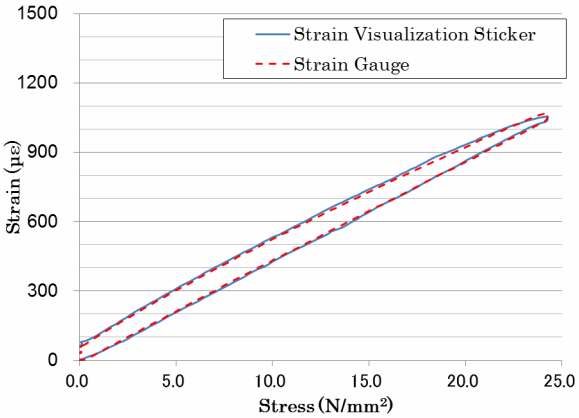

Figure 9. Stress-strain relationship (1st cycle)

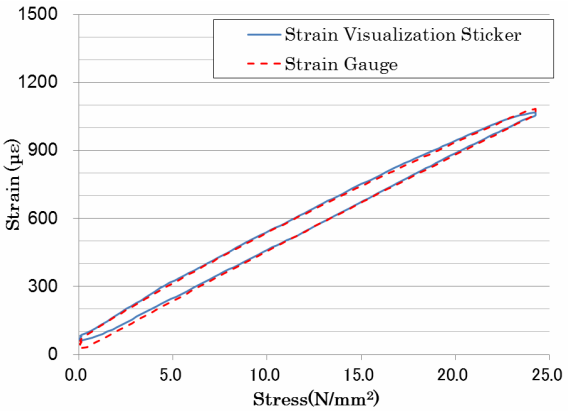

Figure 10. Stress-strain relationship (2nd cycle)

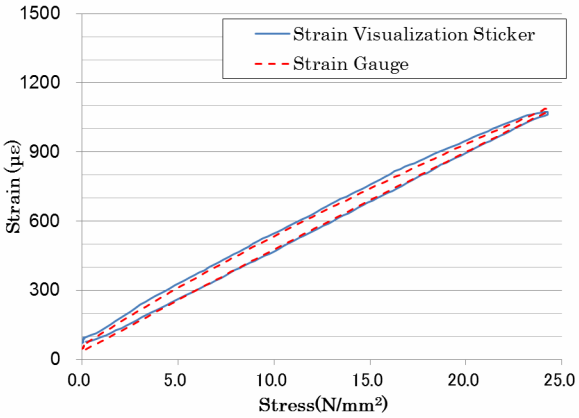

Figure 11. Stress-strain relationship (3rd cycle)

Next, Figure 12 shows images of the Strain Visualization Sticker at strain increments of 100 με. The scale appears dark around 0 when in the no-load condition. The dark area on the scale shifts to the left with each strain increment of 100 με, and the darkest area of the scale is also in good agreement with the generated strain. Thus, this test verified the possibility of reading generated strain with resolution of 100 με with the unassisted eye.

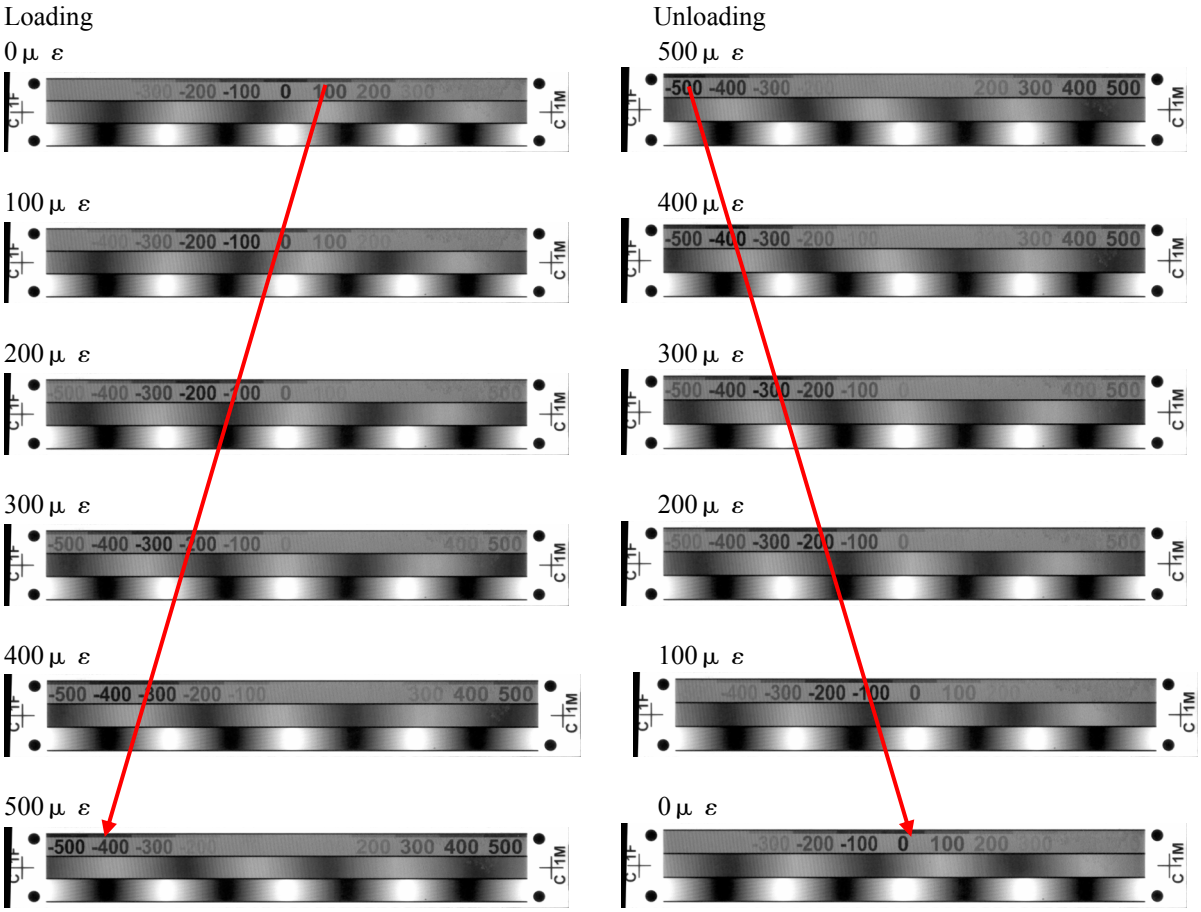

Figure 12. Change in character display with increasing strain

CONCLUSIONS

A new Strain Visualization Sticker was developed for field application. In a performance verification test, changes in strain could be clearly observed with 100 με resolution with the unassisted eye. Although some issues remain, strain could be measured with high accuracy by performing image processing of images of the Strain Visualization Sticker acquired by a remote, noncontact technique (digital video photography). Tests also verified that the data reproducibility of the newly-developed system is excellent. These results demonstrated the possibility of field application. As continuing work, the authors hope to solve the problems identified in this research and conduct verification tests in the field, with the aim of developing this technology to practical structural health monitoring.

REFERENCES

Umemoto, S., Ohata, H., Miyamoto, N., Okamoto, T., Takaki, T., Fujii, K. and Ishii, I. (2012). "Strain measurement of bridge members using Strain Visualization Sticker", *Proceeding of the Sixth International Conference on Bridge Maintenance, Safety and Management*, Stresa, Lake Maggiore, Italy, 8-12 July.