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Concrete Surface Strain Measurement using Moiré Fringes

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ABSTRACT

Assessment of the stress state of concrete in prestressed concrete (PC) structures is extremely important for construction management and operation and maintenance (O&M). The authors developed a strain visualization sticker using the principle of moiré fringes, which makes it possible to read the rough strain value of the concrete surface directly by visual inspection and enables remote, noncontact measurement of strain using a digital camera or similar device. This paper presents an outline of the strain visualization sticker and reports the results of verification of its performance.

Keywords. Moiré Fringes, Strain Visualization Sticker, Remote Measurement, Noncontact Measurement, Image processing

1. INTRODUCTION

Assessment of the stress state of concrete in prestressed concrete (PC) structures is extremely important for construction management and operation and maintenance. As a strain measurement method, the authors have been engaged in development of strain visualization stickers using the principle of moiré fringes, which enables remote, noncontact measurement of strain using a general digital camera or similar device (Figure 1) (Takaki, T. et al. 2012) (Umemoto, S. et al. 2012). As advantages of this technique, i) It is possible to read strain values directly by visual inspection, and ii) the strain visualization sticker does not use electrical elements such as a strain gauge, amplifier, or signal cable. In previous work, we developed and verified the performance of strain visualization stickers for use with steel. Recently, we developed a new strain visualization sticker for strain measurement of concrete surfaces in order to apply this technique to strain measurement of concrete, which requires higher measurement accuracy. This paper presents an outline of the newly-developed strain visualization sticker and reports the results of verification of its performance.

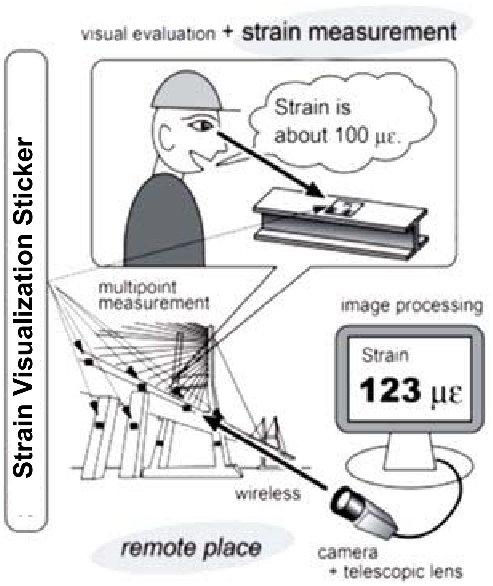

Figure 1. Concept of a proposed Strain Visualization Sticker

2. OUTLINE OF STRAIN VISUALIZATION STICKER

2.1 Principle of Moiré Fringes

As shown in Figure 2(1), when a line grating 1 having a pitch p is overlaid on a second line grating 2 having a pitch p+Δp which is Δp (<<p) larger than the pitch of grating 1, a pattern called a "moiré fringe" appears, which has a pitch W that is larger than the pitches of gratings 1 and 2. Moiré fringes are produced by overlapping two line gratings. Their relationship is expressed by Eq. (1) (Takaki, T. et al. 2012).

$$W=(p+\Delta p)/\Delta p \cdot p \quad (1)$$

As shown in Figure 2(2), when line grating 1 is moved in direction (A) by pitch p, the moiré fringes move in direction (A) by pitch W. In other words, displacement Δx can be displayed visually as enlargement by a ratio of (p+Δp)/Δp. This enlargement ratio is defined as M. If the amount of movement of the moiré fringes is Δx_m, this relationship is given by Eq. (2).

$$\Delta x_m=M \cdot \Delta x \quad (2)$$

2.2 Structure of Strain Visualization Sticker

Figure 3 shows the structure of the strain visualization sticker. The sticker consists of two films, in which line gratings are printed on the bottom side of the upper film and the top side of the lower film. To obtain clear moiré fringes, the bottom side of the lower film is painted white. The space between the two films is filled with oil so that the two films will not separate.

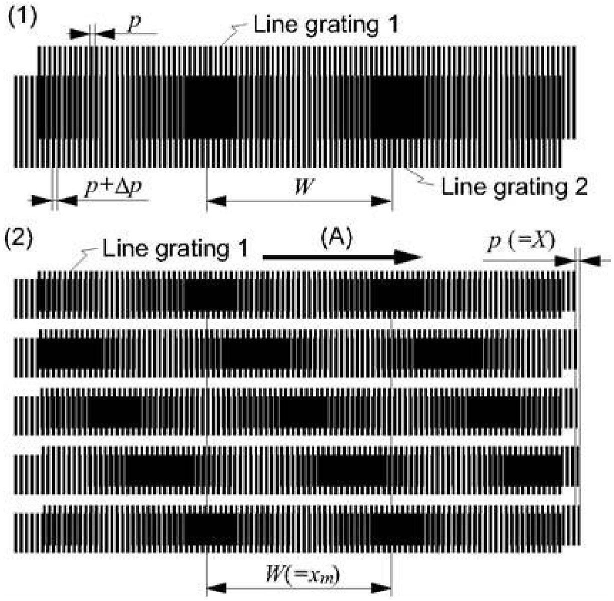

Figure 2. Example of a Moiré Fringe

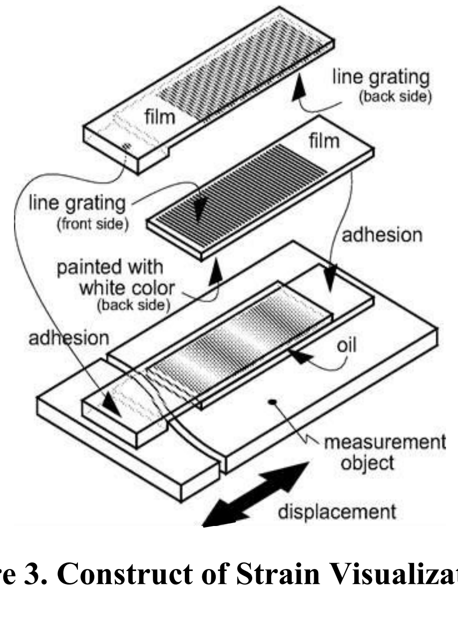

Figure 3. Construct of Strain Visualization Sticker

2.3 Performance of Strain Visualization Sticker

The displacement measurement resolution of the strain visualization sticker is 1 μm. The strain measurement resolution is determined depending on the reference length. Previously-developed strain visualization stickers (Umemoto, S. et al. 2012) are shown in Figure 4, and their performance with steel was verified as shown in Table 1. The visualization resolution of both Sticker I and Sticker II is 200 με (Figure 5). The strain measurement accuracy of the acquired strain visualization stickers obtained by image processing is <10 με for reference length L=200 mm and 32 με for reference length L=50 mm. Thus, measurement accuracy approximately on the order of measurement resolution can be obtained.

Table 1. Performance of Strain Visualization Sticker

Test	Sticker Name	Reference Length	Visualization resolution	Strain measurement accuracy
Tensile Test	Sticker I	L=200 mm (using jig)	-----	< 10 με
Bending Test	Sticker I	L=50 mm	200 με	32 με
	Sticker II	L=50 mm	200 με	-----

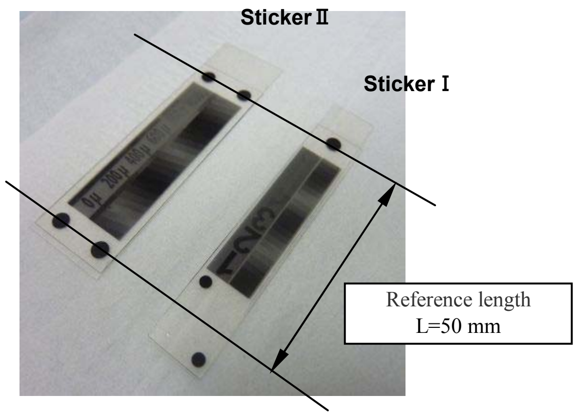

Figure 4. Strain Visualization Sticker

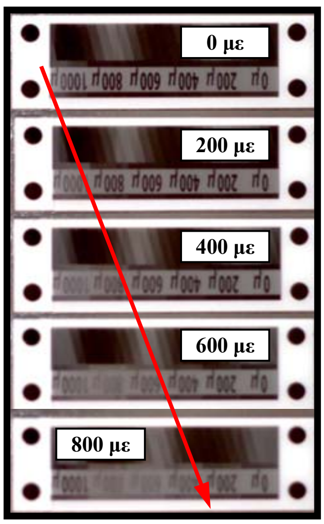

Figure 5. Images of Strain Visualization Sticker

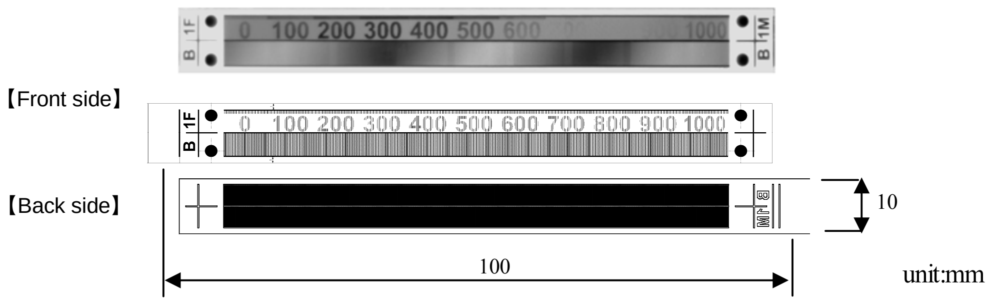

Figure 6. The Developed Strain Visualization Sticker

3. NEWLY-DEVELOPED STRAIN VISUALIZATION STICKER FOR CONCRETE SURFACE STRAIN MEASUREMENT

Figure 6 shows the newly-developed strain visualization sticker. The length, width, and thickness of the strain visualization sticker are 100 mm, 10 mm, and 0.44 mm, respectively, and the reference length is 100 mm. The top side of this sticker shows fringe characters with a scale of 100 με, making it possible to read the strain values directly with the naked eye. The bottom side shows simple moiré fringes for use in image processing. The enlargement ratio M of the characters is 731x, The enlargement ratio M of the moiré fringes is 321x.

4. COMPRESSION TEST

4.1 Specimen

The specimen for the compression test was a cylindrical specimen of shrinkage-compensating mortar with a diameter of 100 mm and height of 200 mm. The properties of the specimen material are shown in Table 2. After the specimen was prepared, it was cured in water for 7 days, after which the test was performed. As shown in Figure 7, a strain gauge for use with concrete was attached to the center of the specimen for comparison purposes, and the strain visualization sticker was attached adjacent to the strain gauge using an instant adhesive.

4.2 Outline of apparatus for compression test

As shown in Figure 8, the specimen was set in a compression test machine (rated capacity: 1000 kN), and a digital video camera for measurement of the strain visualization sticker was set up directly facing the sticker at a distance of 0.7 m from the compression test machine. The digital video camera was a commercially-available USB type product with resolution of 2 million pixels. The digital video camera was connected to a real-time image processing device, and the strain gauges were connected to a strain measuring device.

Table 2. Properties of specimen material

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

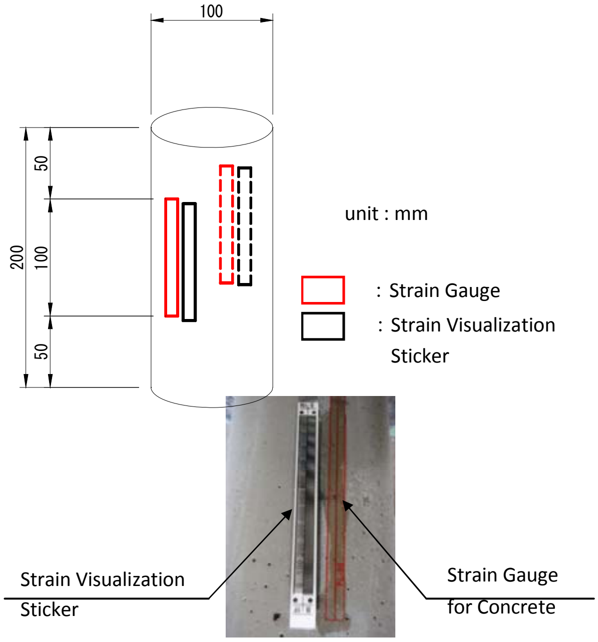

Figure 7. Specimen for compression test

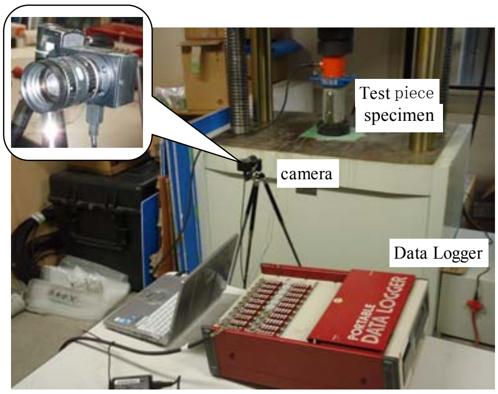

Figure 8. Apparatus for compression test

4.3 Test method

As the test method, loading up to 200 kN was applied at a constant speed so as not to give impact to the specimen, and on reaching 200 kN, unloading was performed by the same method. During the test, the strain visualization sticker was photographed continuously with the digital video camera, and the amount of strain was calculated in real time by image processing. Strain at the strain gauge was also measured continuously using the strain measuring device.

4.4 Result of compression test

Figure 9 shows the relationship of time and strain; Figure 10 shows the relationship of stain and load. Figure 11 shows the difference (error) between the strain values of the strain visualization sticker calculated by image processing and those of the strain gauge. At the start of loading, an error of approximately 30 με occurred with the strain visualization sticker, which is thought to have been caused by buckling of the sticker, as illustrated in Figure 12. However, with the exception of this error, the measurement accuracy of the strain visualization sticker was roughly ±20 με during both loading and unloading. This test result confirmed that the strain visualization sticker can measure strain with comparatively good accuracy by a noncontact method, even in the case of strain generated at a concrete surface. Next, Figure 13 shows images of the strain visualization sticker at 100 με intervals. Focusing on the part where display of the scale begins, display of the scale (characters) inscribed at 100 μ intervals began at each 100 με increment of strain, demonstrating that generated 100με strain can be read with the naked eye.

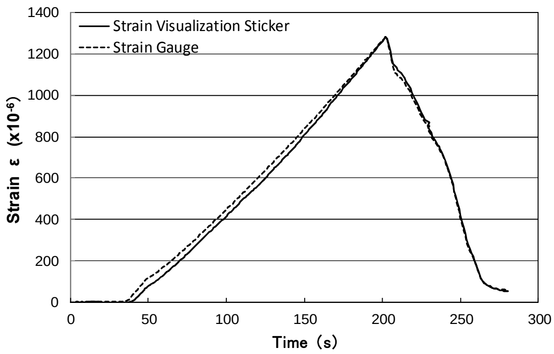

Figure 9. Relationship of time and strain

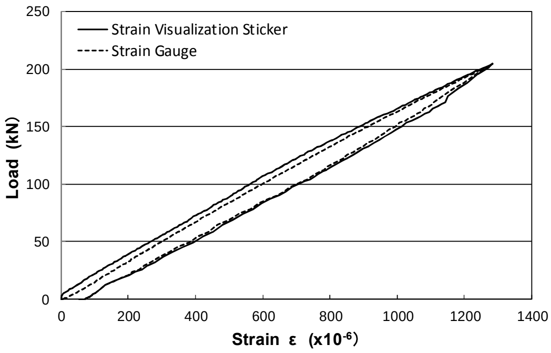

Figure 10. Relationship of strain and load

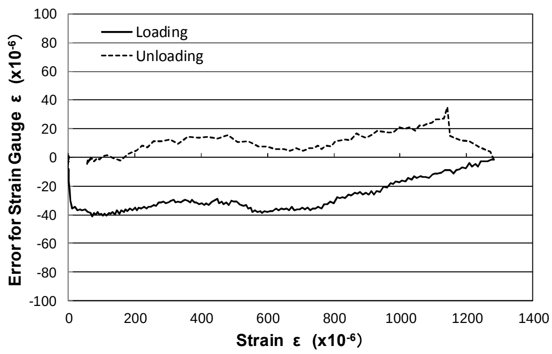

Figure 11. The error for strain gauge

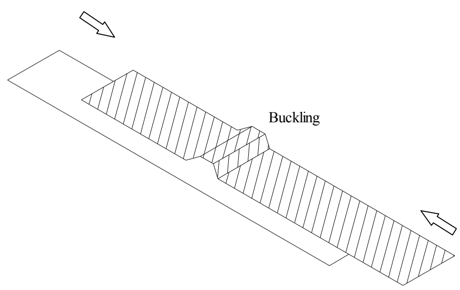

Figure 12. Schematic diagram of film buckling phenomenon

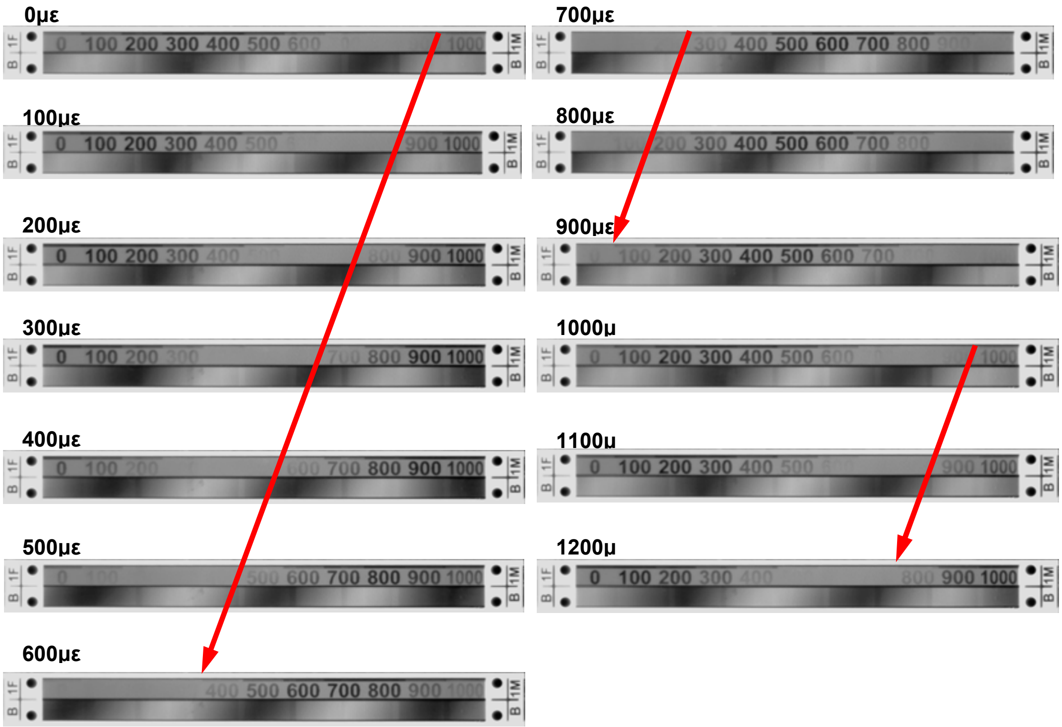

Figure 13. Change in character display with increasing strain

5. CONCLUSION

The authors developed a new strain visualization sticker for use with concrete which makes it possible to read strain values directly with the naked eye and enables measurement of strain by a remote, noncontact method using a general digital camera or similar device, without using electrical elements such as a stain gauge, amplifier, or signal cable. The results of verification of its performance showed that visualization resolution was improved to 100 με. Although some problems remain, it was possible to obtain the amount of strain with comparatively good accuracy by performing image processing of sticker images obtained by a noncontact method. Based on the knowledge obtained in this research, the authors will work to improve strain measurement accuracy, and plan to expand this technique to monitoring of concrete stress when tensile force is introduced during construction of prestressed concrete (PC) structures, understanding of the change of prestress after introduction in the maintenance, and similar issues.

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