報　告

[2141] MEASUREMENT OF SURFACE DISPLACEMENT FIELD OF CONCRETE BY LASER SPECKLE METHOD

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1. INTRODUCTION

Accurate measurement of surface displacement field of a concrete specimen is of much significance in clarifying the governing mechanism of mechanical phenomena in concrete. Fracture phenomenon is a typical case which requires such measurement. Recently a remarkable progress was accomplished in the application of fracture mechanics to concrete. However the governing mechanism has not been clarified completely. Observations with Moire interferometry, laser holography and acoustic emission have been tried; see [1,2].

There are several methods of measurement of a displacement field. The laser speckle method is one such method which provides high accuracy with simple equipment and procedures. With this method it is not necessary to touch the specimen. The information of surface displacement field is kept on a film and the displacement of each point is obtained point wise after developing the film. Accuracy of the technique is subjected to the measurement of fringe spacing projected on a screen. Moire interferometry method and laser holography method provide real time measurement (as the test is being conducted) of displacement field as two dimensional image information. To achieve a high degree of precision, a very fine grating must be carefully pasted on the specimen in Moire interferometry method. Laser holography method provide high accuracy but requires a number of equipment and very delicate settings. The purpose of this article is to report on the application of laser speckle method to concrete. An image analysis technique is employed to improve the precision of measurement. It is shown that relative displacements can be measured with an accuracy of $\pm 1\mu m$ by the present method. The method is employed for several types of fracture tests with a special interest on the measurement of crack length and distribution of crack opening displacement.

2. LASER SPECKLE METHOD [3]

Laser speckle method is based on the utilization of a random speckle pattern generated by laser light over a surface. Surface of a specimen is uniformly illuminated by an expanded laser beam which forms a speckle pattern over the surface. The speckle pattern is a light and dark pattern which is random in shape, but almost constant in size.

An image of this pattern is recorded on photographic film. When any deformation is applied to the surface of the specimen, the speckles will displace in accordance with the displacement at each point. An image of this speckle pattern is also recorded on the same film. This superimposed image is called a specklegram. Application of a laser beam on any point of the superimposed image will yield a far field diffraction spectrum as a fringe pattern corresponding to the displacement vector at that particular point. The direction of the fringe is normal to that of displacement and its spacing is inversely proportional to the magnitude of displacement, that is;

$$u = (k\lambda L)/s$$

where

u - Displacement
λ - Wave length of laser radiation
L - Distance between specklegram and image screen
k - Ratio of real length to the length on the film
s - Spacing of the fringes

See Figure 1 for an illustration of the steps.

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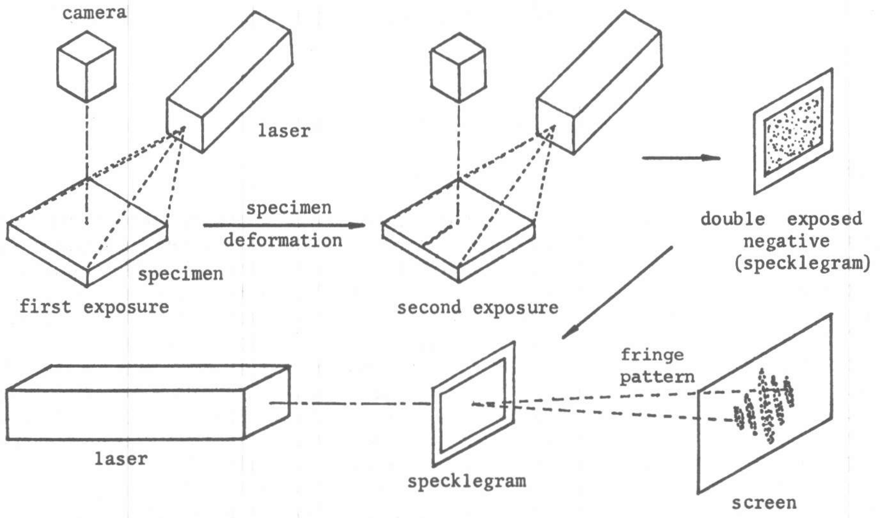

FIG. 1 Illustration of main steps in Laser Speckle Method

3. EQUIPMENT AND PROCEDURE

Main equipment used were;

1. 30 mW He-Ne laser with a wave length of 632.8 nm.
2. Single lens reflex 6 x 7 cm format camera for producing double exposed negative.
3. Video camera to record fringe patterns generated on an image screen.
4. Personal computer with video image A/D converter to digitize and store fringe patterns.

The procedure in the measurement of surface displacements of concrete using laser speckle method is divided into two steps.

1. Preparation of a specklegram by producing a laser speckle pattern on concrete surface and taking exposures on the same film before and after displacement.
2. Measurement of fringe patterns produced by application of a laser beam at a desired spot on a specklegram.

3.1 LABORATORY SETUP AND PROCEDURE

In order to illuminate the specimen surface, the laser beam with diameter of about 1.5 mm is expanded by a small focal length lens which converges it onto a pinhole of 20 μm diameter. The diffraction at the pinhole causes the beam to expand uniformly. For fine adjustments of the pinhole it is mounted on a X-Y-Z-stage. To control the exposure time of the laser beam on to the specimen surface, a shutter is mounted in the path of the laser. The setup of laser is shown in Figure 2. The shutter has a separate mount to avoid vibrations.

Specimen surface to be studied is smoothened with fine sand paper and a grid stamped on it as a reference. The expanded laser light is arranged so that it illuminates the surface area evenly.

The camera is mounted on an X-Y-stage to apply a rigid body motion parallel to the specimen surface. This rigid body motion is for controlling relative displacement during double exposures within 150-300 μm . The appropriate amount of displacement for measurement by laser speckle method is in this range for the present conditions.

The film should have very high resolution power and sensitivity to red radiation. For this purpose a panchromatic film of extreme fine grain (Kodak 6415) is used.

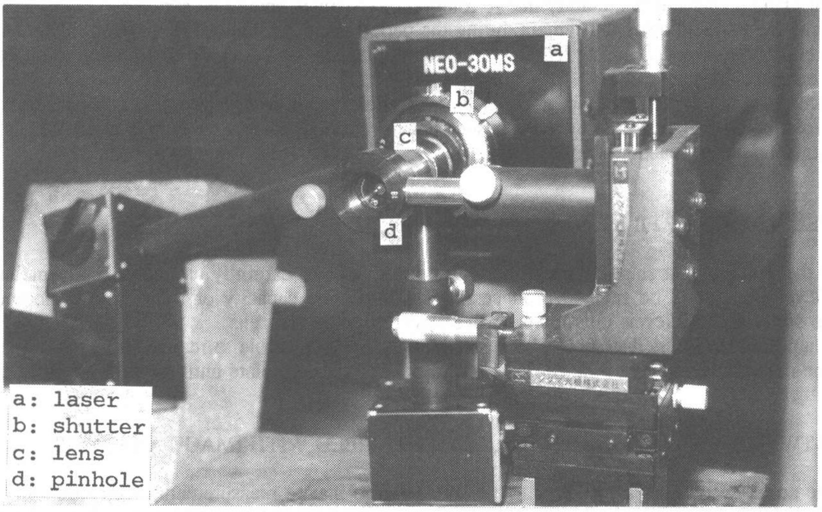

FIG. 2 Setup for expansion of the laser beam

The measurement procedure with the above mentioned apparatus is as follows. Firstly the specimen is stabilized on the loading setup by slightly loading and unloading several times. It is desirable to mount some displacement transducers so that any rigid body movement of the specimen are detected. The room is darkened, then camera shutter is opened and with the aid of the shutter mounted in the laser path required amount of exposure is given for the first image. Still keeping the camera shutter open, the specimen is applied with deformation and the camera is also given a measured displacement to keep the relative displacements in the above mentioned range. After this step the second exposure is done in the same way as the first, on the same film and then the camera shutter is closed. If the deformation of the specimen is to continue further, first exposure of the second specklegram should be taken at this point and the same procedure is repeated. Figure 3 shows the experimental setup.

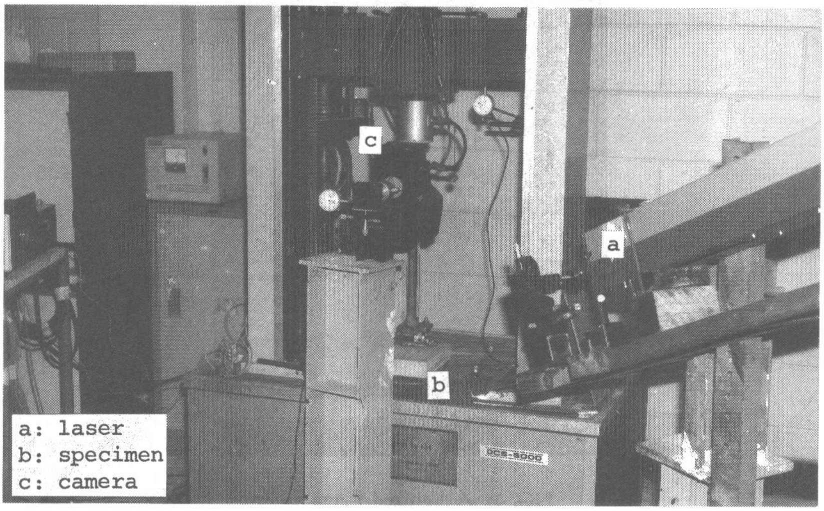

FIG. 3 Experimental setup

In the process of the experiment following points should be observed;

1. Camera, laser and the specimen should not be subjected to any vibrations or jarring.
2. Out of plane displacements, mainly due to rotation of specimen should be avoided.
3. No stray light should enter the camera during the period when its shutter is kept open. If lights are required for observations during loading, an external masking device could be installed to prevent light from entering the camera.
4. The area taken in the film should be under uniform illumination and reflection conditions. Dark and light patches should be avoided since these produce uneven shrinkage when the film is dried, which will result in erroneous fringe spacing near the boundaries.

3.2 DEVELOPMENT OF FILMS

In the development stage of the film, conditions should be carefully and consistently maintained. The selected developer should be such to produce the full resolution capacity of the film. Development time in correlation with exposure levels must be pre-determined by doing test runs.

When the film is dried it should be maintained as flat as possible to reduce shrinkage effects. For this purpose the non-emulsion side of the film is laid flat on a clean glass plate until the film becomes dry.

3.3 POINTWISE EVALUATION OF DISPLACEMENT FIELD WITH IMAGE ANALYSIS

The accuracy of laser speckle method is subjected to that of measurement of direction and spacing of fringes. If they are manually measured directly on screen using a scaler or a Vernier caliper, the accuracy is limited due to the difficulty in identifying the center of a fringe, variation of fringe spacing from the center of the screen to outside and errors in human judgement.

The image analysis technique employed here is according to [4]. Fringe pattern on the screen is taken by a video camera and transformed into a digitized image through an A/D converter to be stored in a computer. Figure 4 shows a digitized fringe pattern. The digitized intensity values are summed up along lines in the image plane with given orientations resulting in "wave data" which is the summed intensity vs distance measured in normal direction to the line. Maximum amplitude "wave" will be obtained when the orientation of the line coincides with that of the fringes. After fixing the orientation of the fringe by this method, Maximum Entropy Method is used to analyze the "frequency spectrum" of the "wave data" from which the spacing of the fringe is obtained.

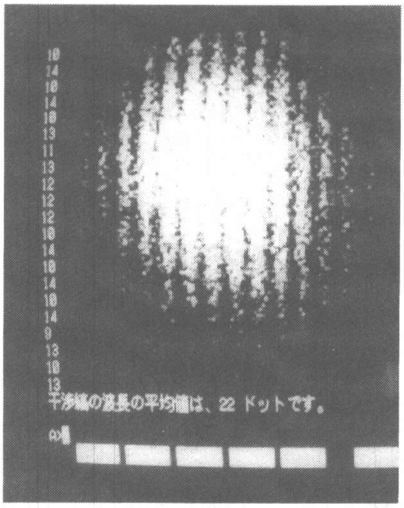

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FIG. 4 A digitized fringe pattern

4. ACCURACY CHECK OF THE METHOD

The accuracy of the method is checked by measuring rigid body displacement of a concrete specimen. Instead of applying rigid body displacement to the specimen the camera is displaced by 50, 100, 150, 200, 250, 300, 350 μ*m*, controlled by a transducer with an accuracy of 1 μ*m*. Rigid body displacements measured by the transducer and by the laser speckle method using both techniques of fringe spacing measurement, on corresponding specklegrams are compared in Table 1. It is evident from this comparison that there is a noticeable discrepancy between transducer readings and laser method. Source of this discrepancy could not be identified. It should be noted that it was reported in [4] that with the same image analysis procedures a displacement of 150 μ*m* was measured with an error of ±2%.

When different points on a single specklegram is analyzed as on nine nodes of a 2mm-square grid in FIG. 5, fringe patterns on the screen appear different but the results of image analysis indicates that there is little scatter in the readings from a single specklegram as shown in Table 2. It is concluded that although measured absolute displacements may have errors as shown in Table 1, relative displacements can be measured with an accuracy of ±1μ*m*.

In the analysis of fracture phenomena, the main interest is the amount of crack opening displacement which is measured as the difference between displacements at two close points on either sides of the crack path. Crack tip is the point at which crack opening displacement vanishes.

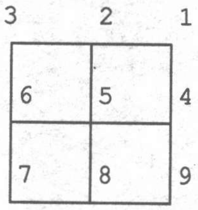

FIG. 5 Square grid points

Table 1 Rigid body displacement in μ*m* measured using different methods

Transducer	Laser speckle method	
	Manual	Image Analysis
52	56.02	65.38
104	95.50	100.60
154	138.79	143.15
203	182.04	177.55
260	225.37	234.25
308	271.48	279.18
350	313.11	317.50

Table 2 Rigid body displacement on the same film by image analysis

Grid point	Displacement by laser method μm
1	189.45
2	189.07
3	189.10
4	189.59
5	190.13
6	189.56
7	189.53
8	189.26
9	189.34

5. APPLICATIONS TO FRACTURE PROBLEMS

Application of the above method to various problems in concrete engineering seems to provide valuable information. The following are some of the applications already tried out.

1. Determination of crack length and distribution of crack opening displacements with increasing load. The result is compared with theoretical prediction to discuss governing mechanism in fracture of concrete.
2. Fatigue crack growth in concrete under cyclic loading.
3. Crack propagation from an anchor embedded in concrete; see FIG. 6. The crack length and mode of deformation are examined. The result is compared with theoretical prediction to evaluate the applicability of fracture mechanics to concrete.
4. Direct measurement of curvature of a RC beam due to flexural cracks. It is for the theoretical prediction of the role of flexural cracks in the deflection of an RC beam.

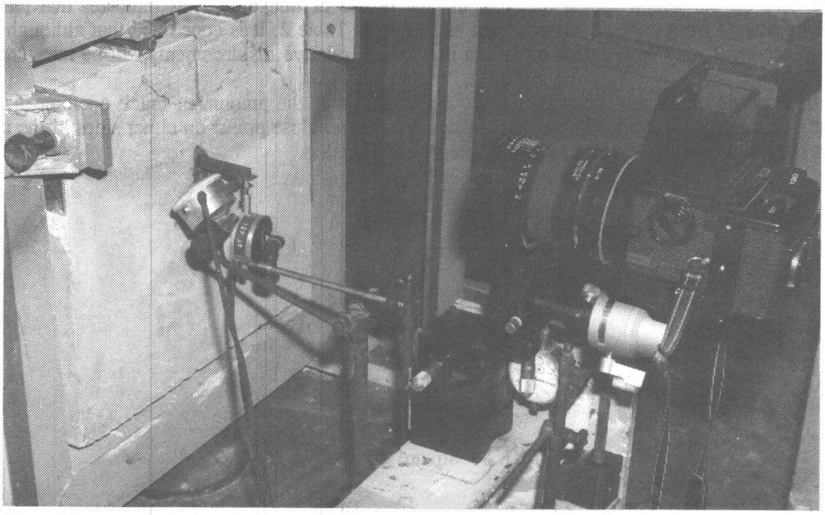

FIG. 6 Concrete specimen with embedded anchor

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