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# Three-dimensional stress and strain detection by photoelasticity using laser-light-sheet

J.D.Ortiz
*ESDISA, Nicaragua*

C.Tamura
*College of Industrial Technology, Nihon University, Japan*

K.Konagai
*Institute of Industrial Science, University of Tokyo, Japan*

**ABSTRACT:** A new photoelastic method to detect three-dimensional strain distribution in massive structure model has been presented by the authors. According to the proposed method, a transparent model of massive soil and structures with high sensitivity of photoelasticity is "sliced" not by a knife but by a laser-light-sheet (LLS). Since the diffused light in the model is plane-polarized, we can use the LLS as the light source for photoelasticity. Through this technique, it becomes possible to obtain the whole-field information of three-dimensional strain distribution. The obtained image of photoelasticity yields the same result as that through the conventional freezing-stress method without destroying the model, and consequently, the method has a high potentiality to be used in the dynamic experiment.

## 1. INTRODUCTION

Model experimentation is one of the important and powerful tools for the study of earthquake resistance of such civil-engineering structures as fill dams, tunnels in a soft ground and so on. Though it provide us important findings, it is not easy to get a clear whole-field image of deformation only by putting sensors if the model is massive like the above-mentioned structures. Visualization technique helps us to overcome this problem and there are some methods available at present. Among them, photoelastic method is a well-known and useful technique. Okamoto[1], Tamura[2] and Morichi[3] have developed various skillful techniques in relation to the photoelastic experiments with soil and structure models made of soft rubber-like materials such as gelatine and poly-acrylamide. These materials are very soft, and consequently it is easy to observe fairly slow wave propagation in those materials. Photoelastic method is, however, essentially a technique for analysis of two-dimensional stress and strain, and thus, special techniques for three-dimensional stress-detection have been developed by many researchers. One of the frequently used techniques is the "stress-freezing method", in which, the model made of resin is loaded at an elevated temperature, and the model is harden again by cooling it to room temperature, and after removing the load, the model is sliced so that we can observe photoelasticity "frozen" in each slice. Since the model is destroyed in this process, it is difficult to apply this method to dynamic stress and strain analyses. Morichi and Tamura overcame the problem by using a Sandwich-like model of transparent poly-acrylamide gel with a thin gelatine plate within. Since the gelatine has a very high sensitivity, when compared with poly-acrylamide gel, only photoelastic fringes on this gelatine plate are observed through the polariscope arrangement. Another skillful method is the so-called "scattered-light-method". This method can be applied to dynamic analyses because a model is sliced optically. However, these method mentioned here yield only information which is not enough to determine completely stress and strain distribution in a model.

This paper describes a new photoelastic method developed by the authors[4] using the laser-light-sheet (LLS) which yields further information about stress and strain condition.

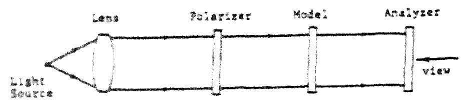


Figure 1. Arrangement of polariscope elements (without quarter wave plate).

## 2. PROPOSED METHOD

The simplest polariscope arrangement for photoelastic experiment is shown in Fig.1. It consists of two polariscope and a model mounted between them. The polarizing element next to the light source is called "polarizer". The plane-polarized light transmitted through the "polarizer" enters the model and is resolved into two components along the axes associated with the principal stresses in a plane normal to the light path. These two components travel with different velocities along the light path, and acquire a certain relative retardation in travelling a certain distance. This retardation is proportional to the cumulation of principal stress difference along the light path in the model. The second polarizing element, which is called "analyzer", acts so as to recompose these two components, and consequently, we can observe, through the analyzer, interference of these two light's components as fringe pattern. It is, however, impossible through this method to obtain three-dimensional stress condition at any arbitrary point in the model, because the observed fringes are showing the cumulation of principal stress difference along the light path. Thus, the "stress-freezing method" is a skillful technique to overcome the problem. However, as has been mentioned above, the model must be sliced so that each slice can be put between polarizing elements.

According to the method proposed by the authors, a model is sliced not by a "knife" but optically by a "laser-light-sheet" (LLS). This LLS travels through any arbitrary chosen cross-section without destroying the model, and the cross-section is illuminated by the diffused laser-light. Since the diffused light is plane-polarized, the illuminated plane within the model can be used as a light source for the photoelastic experiments. The process of this method are schematically illustrated in Fig. 2. When a LLS is transmitted through the model at the cross-section a, photoelastic fringe order $N_a$ observed through the analyzer is obtained by the following equation as;

$$N_a=\alpha\int_{x_a}^{x_o}(\sigma_2-\sigma_3)\,dx \qquad ....(1)$$

where, $\alpha$ = photoelastic sensitivity and

$\sigma_2$, $\sigma_3$ = principal stresses in a plane normal to x axis.

After moving the LLS to the cross-section b, the fringe order changes into;

$$N_b=\alpha\int_{x_b}^{x_o}(\sigma_2-\sigma_3)\,dx \qquad ....(2)$$

Subtracting eq. (2) from eq. (1), the following equation is obtained;

$$N_a-N_b=\Delta N=\alpha\int_{x_a}^{x_b}(\sigma_2-\sigma_3)\,dx \quad ....(3)$$

When the distance $\Delta x$ between cross-sections a is small, right hand side of eq. (3) is rewritten as;

$$\Delta N=\alpha\Delta x(\sigma_2-\sigma_3) \qquad ....(4)$$

This $\Delta N$ is nothing but the same fringe order obtained by the conventional "stress-freezing method". Thus, we can use the same analytical process as that for two-dimensional photoelastic

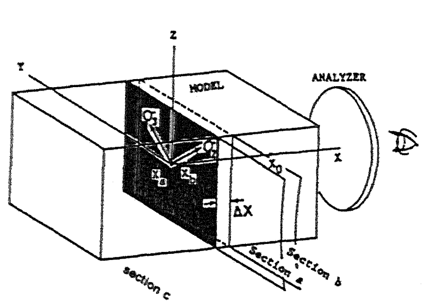


Figure 2. Proposed method using laser-light-sheet.

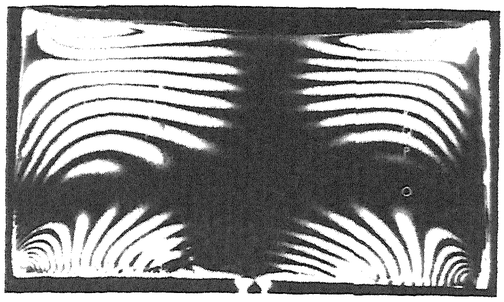

Figure 3,a. Conventional photoelasticity.

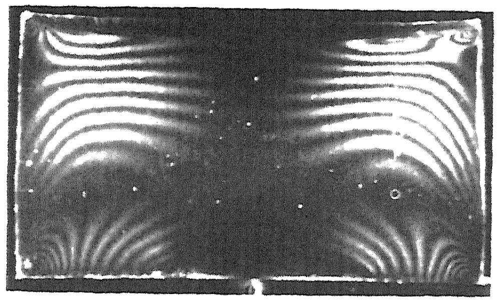

Figure 3,b. Proposed method.

Figure 3. Verification of the proposed method.

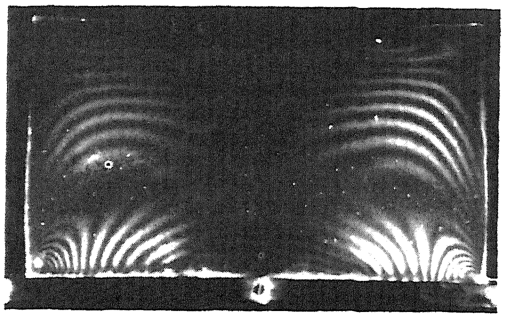

Figure 4,a. $x_0 - x_a = L$

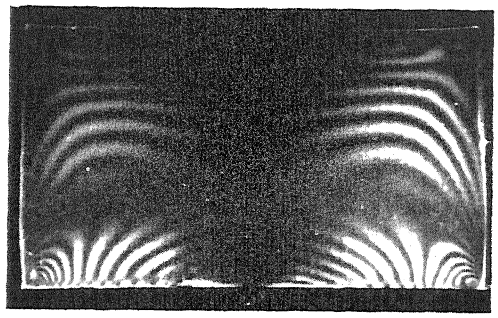

Figure 4,b. $x_0 - x_a = (3/4)L$

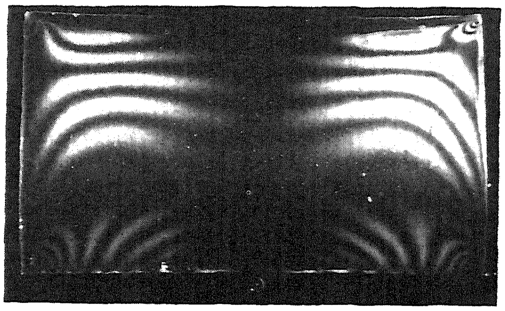

Figure 4,c. $x_0 - x_a = (1/2)L$

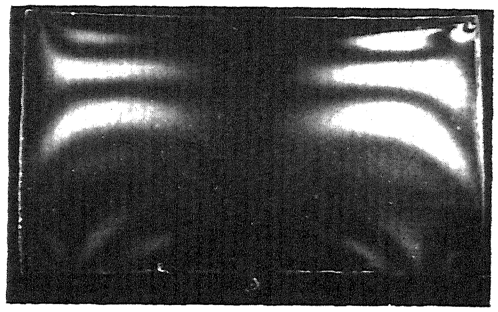

Figure 4,d. $x_0 - x_a = (1/4)L$

Figure 4. Fringe patterns due to dead load at different sections in a gelatin block.

method to determine the stress state in the model.

In order to verify the proposed method, the position of LLS was set at c, very close to the surface of the model in Fig. 2, and the photoelastic fringe pattern was photographed. Since the diffused light of LLS on a cross-section is a good substitute of the plane-polarized light source, The observed fringe pattern should be the same as that by the conventional method, in which the model is put between the polarized-light source and analyzer. The model for the verification was made of gelatine. The

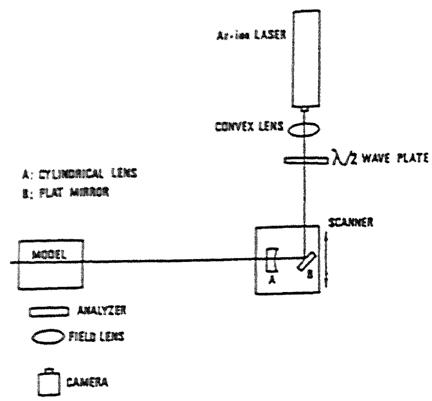


Figure 5. Arrangement of optical elements.

hot solution of gelatine (concentration=10%) was cured in a rectangular mold (W200 × D200 × H125). After removing the mold, the model was deformed by its dead load. The observed fringe pattern through the proposed method is compared in Fig. 3 with the picture by the conventional technique. Good agreement between them validates the present technique.

Cross-shaped dark shade are seen in both pictures in Fig. 3. This shade is the isoclinic lines showing that the principal stress directions on either the cross-section or the surface facing the analyzer are aligned with the axes of polarization. It is often necessary to analyze the isoclinic lines to determine the stress trajectories. In this case, not only the analyzer but also the path of the LLS should be rotated simultaneously, and at every small increment of rotation angle, the change of isoclinic lines must be photographed. Consequently, it is the essential technique to let the LLS be transmitted directly through the model with an irregular shape. This problem can be overcome by immersing the model in a liquid with the same refractive index. Usually mixture of two different oils are used as the liquid for immersion in photoelastic experiments. The gelatine, the model material, however has an advantage that water can be used for this purpose, because the refractive index of the gelatine lies between 1.33 and 1.34, which is almost the same value as the water's one.

Figs. 4(a) through (d) show the change of fringe pattern with change of LLS position. In these figures, $x_o$-$x_a$ denotes the distance between the LLS and the surface facing the analyzer, and L = thickness of the model. Fringe number is gradually decreasing with the decrease of $x_o - x_a$. And the decrement of the fringe order with respect to the $-\Delta x$ is proportional to the principal stress difference induced in the optically-sliced plate.

## 3. STRESS AND STRAIN FIELD UNDER FOOTING

A rigid rectangular footing model (W30 × D120) was put on a homogeneous ground model made of gelatine. The hot solution of gelatine was placed in a rectangular mold (W300 × D300 × H200) and cured in it. This process induces the thermal strain in the cured ground model, and this deteriorates the photoelasticity. In order to overcome of the problem, the mold with the hot solution was bathed in a hot water to avoid a drastic decrease of temperature of the solution.

Fig. 5 shows the arrangement of optical elements. This includes an Ar-ion laser of 4W-power, a half-wave plate, alignments of optical elements to expand the laser beam into the LLS, an analyzer, through which fringe patterns are observed, and a camera. The laser light itself is not needed to be plane-polarized, because plane-polarization is due to the light diffusion in a model. When the incident LLS is plane-polarized, another pattern of photoelastic fringe appears overlapped. This is the conventional scattered photoelasticity showing the stress information in planes normal to the incident light path. Since the Ar-ion laser emits the plane-polarized beam, a half wave plate in front of the laser in Fig. 5 is needed to observe only the fringe patterns through the proposed method.

Fig. 6 is the observed fringe patterns in different cross-sections. Since the LLS was moved in parallel by 1cm, the difference of fringe order between them shows the principal stress (or strain) difference in the optical slice of 1cm in thickness. Dense isochromatic fringe pattern near the edge of the footing shows that stress is not uniformly distributed over the contact surface and is concentrated at its edges. Dark isoclinic lines are superimposed on the isochromatic fringes. Fig. 7 shows the variation of fringe order under the footing with depth $z^*$. The fringe order decreases with the increasing of depth at any cross-section in this

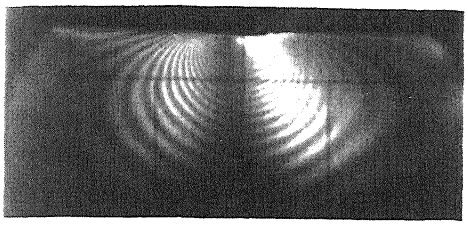

Figure 6,a. Δ = 17 cm

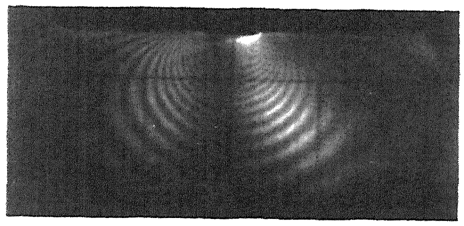

Figure 6,b. Δ = 16 cm

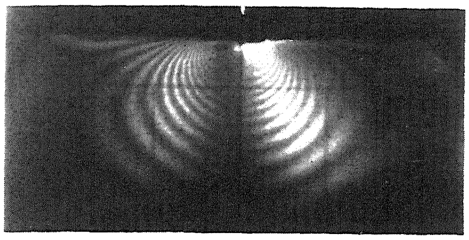

Figure 6,c. Δ = 15 cm

Figure 6. Fringe pattern in ground model.

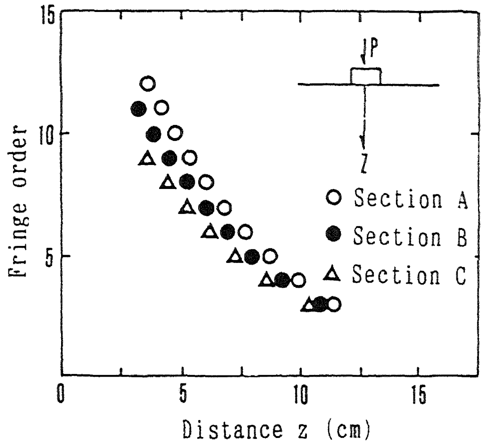



Figure 7. Variation of fringe pattern with z.

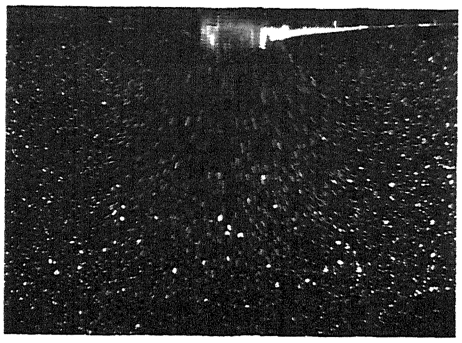

Figure 8. Visualization of deformation (tracer: fine aluminum grains).

figure. The difference between these curves running side by side shows that the farther the distance from the footing is, the smaller the principal strain (or stress) difference is in the optical slice.

Visualization of the whole-field deformation will contribute to a better understanding of the photoelastic information. This is possible by sprinkling aluminum powder in the gel-like ground model. Fig. 8 shows the streaks of aluminum powder observed in the process of step-by-step loading. Very fine grains of aluminum are illuminated by the LLS traveling through the middle depth of the thickness.

## 4. CONCLUSIONS

In order study stress and strain condition in a massive structure models, the authors have developed a new photoelastic technique. Conclusions of this study are summarized as follows:

(1) In the proposed method, a model is sliced optically by a laser-light-sheet (LLS) without destroying the model. Diffused light on the cross-section is a good substitute of a plane-polarized light source for photoelastic experiments, and consequently it is possible to obtain the whole-field information of stress condition, which is the same as that obtained through the conventional "stress-freezing method", in which the model is destroyed by slicing.

(2) Isoclinic lines showing the principal stress directions are superimposed on the iso-chromatic lines, and it is sometimes necessary, for analysis of the stress trajectories, to let the LLS pass through an irregularly-shaped model

without reflection and refraction which will deteriorate the photoelastic fringe patterns. This can be overcome by immersing the model in a liquid with the same refractive index. If the gelatine is used as the model material, water can be used as the liquid for immersion because the refractive index of gelatine lies between 1.33 and 1.34.

(3) Visualization of whole-field deformation is possible by sprinkling fine aluminum powder in a transparent model. A LLS traveling through the model illuminates the fine aluminum grains on the cross-section. This technique contributes to better understanding of the photoelastic information obtained through the proposed method.

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