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Photoelastic Method for Analysis of Stress and Strain in Massive Structure Models using Laser-Light-Sheet

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1. INTRODUCTION

Model experimentation is an important and powerful tool when we study earthquake resistance of such civil engineering structures as fill-type dams, tunnels in soft soil deposits and dynamic behavior of a surface layer with an irregular shape. Okamoto[1], Tamura and Morichi[2],[3],[4] have developed various skillful techniques in relation to dynamic experiment with soil and structure models made of gel-like materials such as gelatine and polyacrylamide. These materials are soft enough to make a clear observation of slow motion of the model. Moreover, when gelatine is chosen as model material, it is possible to detect dynamic stress distribution in the model taking the advantage of high photoelastic sensitivity of gelatine. Photoelastic method is, however, essentially a technique for analysis of two-dimensional stress and strain. Thus it is required for us to devise how to obtain information of three-dimensional stress distribution in the model. There are some conventional photoelastic techniques available for the purpose of three-dimensional stress analysis. One is the "stress-freezing method"[5]. In this method, the model 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 it is difficult to apply this method to dynamic stress analysis without destroying the model, Morichi and Tamura observed dynamic photoelasticity of a Sandwich-like model of transparent polyacrylamide by placing a thin gelatine plate with high photoelastic sensitivity within[4]. The other skillful method is the so-called scattered light method[5]. This method can be

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applied to dynamic analyses because a model is sliced optically in this method. However, these methods mentioned above yield only information which is not enough to determine completely stress distribution in a model.

This paper describes a new photoelastic method developed by the authors using the Laser-light-sheet which yields further information about stress condition.

2. PROCEDURE OF EXPERIMENT

The simplest polariscope arrangement for photoelastic experiment is shown in Fig.1. It consists of two polariscopes, the model being 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 traveling 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 we can observe, through the analyzer, interference of these two light components as a fringe pattern. It is, however, impossible by this method to obtain information about stress condition at an arbitrary point in the model, because the observed fringe pattern is related to the cumulation of stress difference along the light path. The slice method is a skillful technique to overcome this difficulty. But, as has been mentioned above, the model is required to be sliced so that an individual slice can be put between polarizing elements. Thus it is hopelessly difficult to apply this method to dynamic experiments.

In the method proposed by the authors, a model is "sliced" not by a knife but by a laser-light-sheet optically. This laser-light-sheet can be passed through the model at any arbitrary section without destroying the model. The laser-light-sheet is, then, scattered by fine particles on the cross section. This scattered light is plane-polarized and vibrating normal to the incident light path[6]. Thus, we can put a source of plane-polarized light at any cross section in the model by this technique without a polarizing element. The photoelastic equipment for this method is schematically illustrated in Fig.2.

When a laser-light-sheet is transmitted through the model at cross section **a,** fringe order N_a observed through an analyzer is obtained by the following equation as:

$$N_a = \alpha \int_{x_a}^{x_0} (\sigma_2 - \sigma_3)\, dx \qquad (1)$$

where, α : photoelastic sensitivity,

σ_2 , σ_3 : principal stresses in a plane normal to x axis,

After moving the laser-light-sheet to the cross section **b,** the fringe order changes into;

$$N_b = \alpha \int_{x_b}^{x_0} (\sigma_2 - \sigma_3)\, dx \qquad (2)$$

Subtracting of eq.(2) from eq.(1) yields the following;

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

When the distance Δx between cross sections **a** and **b** is sufficiently small, right-hand side of eq.(3) can be rewritten as;

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

This ΔN is nothing but the same fringe order obtained by the conventional "stress freezing method". And we can use the same analytical procedures as those for two-dimensional stress analysis to determine the stress state in the model.

Isoclinic lines superimposed on the fringe pattern show that the principal stress direction on the cross section illuminated by scattered laser light or stress direction on the surface facing to the analyzer is aligned with the axis of polarization. It is often neccessary to analyze the isoclinic lines to determine stress trajectories or to eliminate the isoclinic lines for analysis of isocromatic lines. This is achieved by rotating both the direction of laser-light path and the axis of polarization of the analyzer keeping those angle parallel or crossed each other. In this case, the problem is to let the laser-light-sheet be transmitted directly through an irregularly-shaped model without reflection and refraction. This can be solved by immersing the model in a liquid with the same refractive index. This technique is also powerful when we use the conventional "scattered photoelastic technique". Suitable liquid for the immersion technique is, in many cases, a mixture of oils or aromatic hydrocarbons. However, when gelatine is used as the model material, great advantage is that we can use water as the liquid for immersion because the refractive index of cured gelatine lies between 1.33 and 1.34.

The monochromatic light source used in this technique must be quite intense because of the inefficiency of the scattering process. Thus a laser is a most suitable device for this purpose. An external mirror type laser can emit a plane-polarized beam. But, this is not necessarily required because the polarization by scattering is used in this technique. However, if the laser light is plane-polarized, it is possible to use the scattered photoelastic technique together with the proposed method. Analysis of the scattered photoelasticity yields informations of stress condition in a plane normal to the light path of the laser-light-sheet, while the proposed method gives us those in the plane parallel to the light sheet. Thus, the use of both these methods will be powerful in studying three-dimensional stress condition in a massive model.

3. VERIFICATION OF THE PROPOSED METHOD

In the proposed method, diffused laser light in a model is substituted for a plane-polarized light source. Thus the observed fringe pattern must coincide with that by the conventional method when the laser-light-sheet skims the back of a two-dimensional model.

Fig. 3 shows the system for the experiment schematically. It consists of an Ar-ion laser of 4W type, an alignment of optical elements to expand the laser beam to a thin sheet, a scanner of this light sheet, an analyzer to observe fringe patterns and a camera. Green light (514.5nm) emitted from the laser reaches the power of 1.7W.

The model for the verification is made of gelatine. The hot solution of gelatine with the concentration of 10% was cured in a rectangular mold (20cmx20cmx12.5cm). This model was deformed by its dead load.

The observed fringe pattern by the conventional technique is shown in Fig.4, together with that by the proposed method. Crossed isoclinic lines are superimposed on the isocromatic fringes on both pictures. These isocromatic lines are not even because the base of the model is adhesive enough to prevent the base from slipping. Good agreement between these fringe patterns (Figs.4(a) and 4(b)) validates the present technique.

Figs. 5(a) through 5(d), shows the change of fringe pattern with change of the location of laser-light-sheet. In these figures, x_o-x_a and L denote the distance from the laser-light-sheet to the surface facing to the analyzer and thickness of the model, respectively. Fringe order is gradually decreasing with decreasing x_o-x_a. And the change of fringe order through a small distance of dx is proportional to the principal stress difference in the optically-sliced plate.

Fig. 6(a) shows the fringe pattern induced when a rigid disk (radius=3cm, weight=425gf) was put on the surface of the model, while Fig. 6(b) is the picture of scattered photoelasticity taken by removing analyzer and making the incident laser light plane-polarized. In both cases, the laser-light-sheet was transmitted through the center of the model (x_o-x_a=L/2). As has been mentioned, The former yields information of stress condition in a plane parallel to this laser-light-sheet, while the latter is related to that in a plane normal to the incident light path.

4. CONCLUDING REMARKS

In order to study stress condition in a massive structure models, the authors have developed a new photoelastic technique. Characteristics of the present technique are summarized as follows:

(1) In the proposed method, a model is sliced optically by a laser-light-sheet, and diffused laser light in a model is substituted for a plane-polarized light source. Thus it is possible to obtain the same information of stress condition as that by the conventional "stress freezing method" without destroying the model.

(2) This technique yields information of stress condition in a plane parallel to the laser-light-sheet, while the scattered photoelasticy is related to that in a plane normal to the incident light path. Thus, the use of both these methods will be powerful in studying three-dimensional stress condition in a massive model.

(3) It is sometimes necessary, for construction of stress trajectories from the isoclinic lines, to let the laser-light-sheet pass through an irregularly-shaped model with various angle of incidence. This can be solved by immersing the model in a liquid with the same refractive index. When gelatine is used as the model material, we can use water as the liquid for immersion because the refractive index of cured gelatine lies between 1.33 and

1.34.

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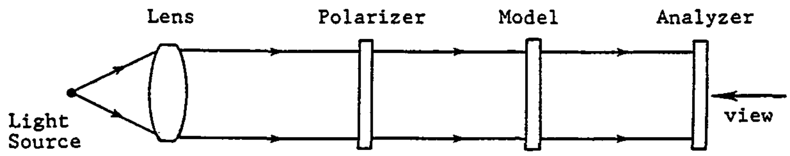


Fig. 1 Arrangement of Polariscope Elements

(without quarter wave plate)

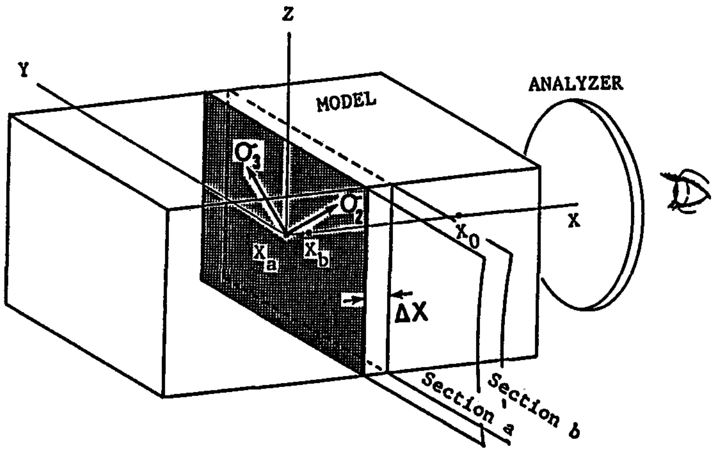


Fig. 2 Proposed Method using Laser-Light-Sheet

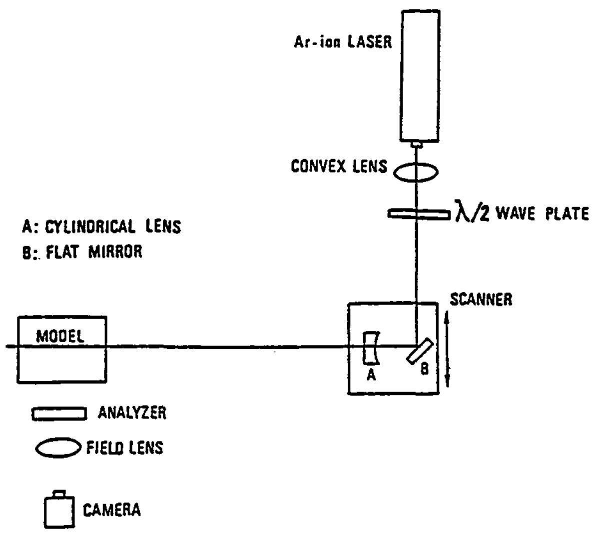
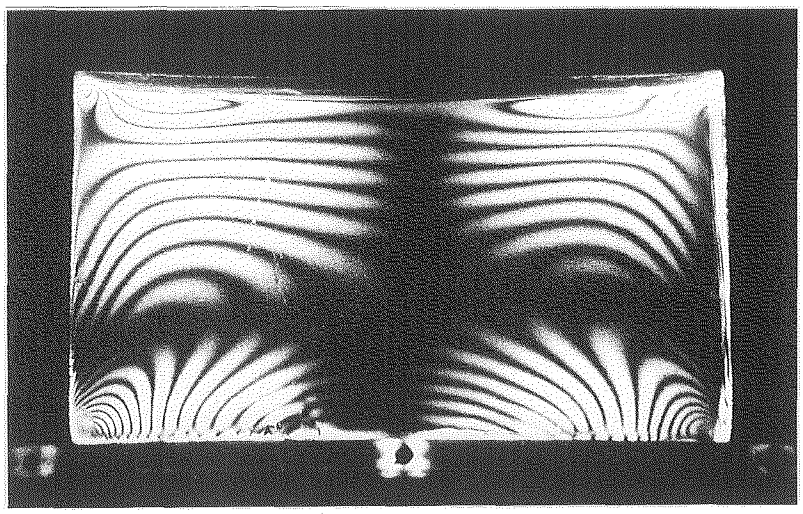
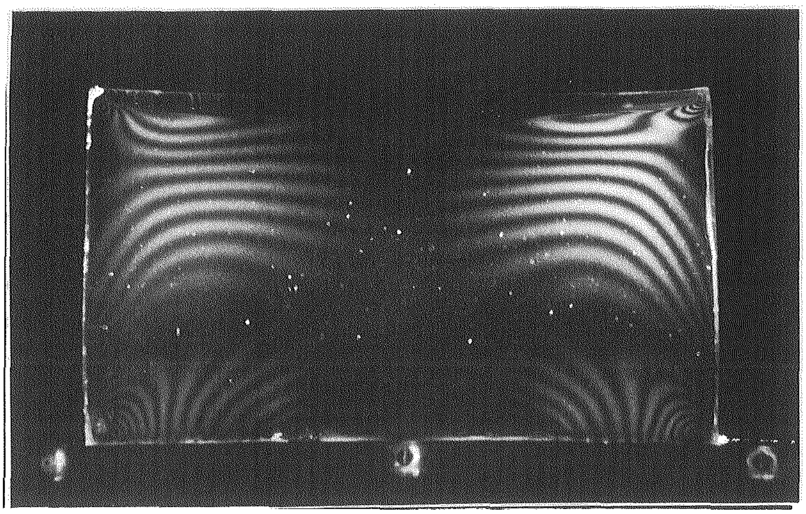


Fig. 3 Arrangement of Optical Elements for the Proposed Method



(a) Conventional Photoelasticity



(b) Proposed Method

Fig. 4 Verification of the Proposed Method

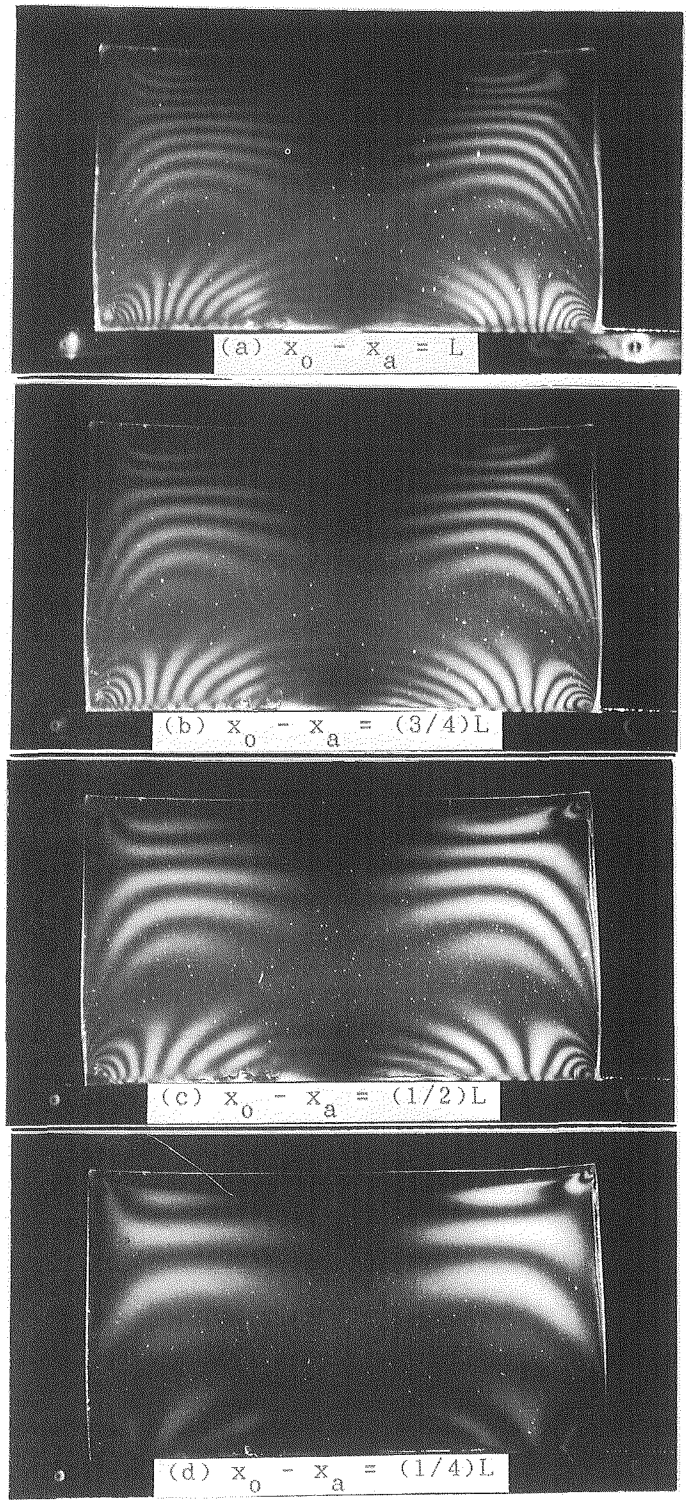
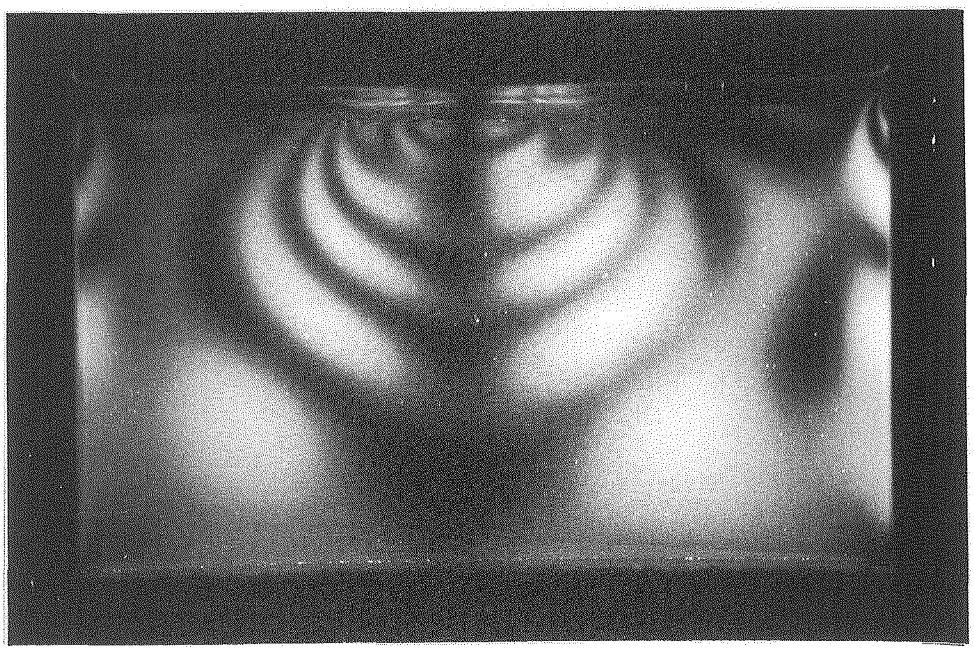
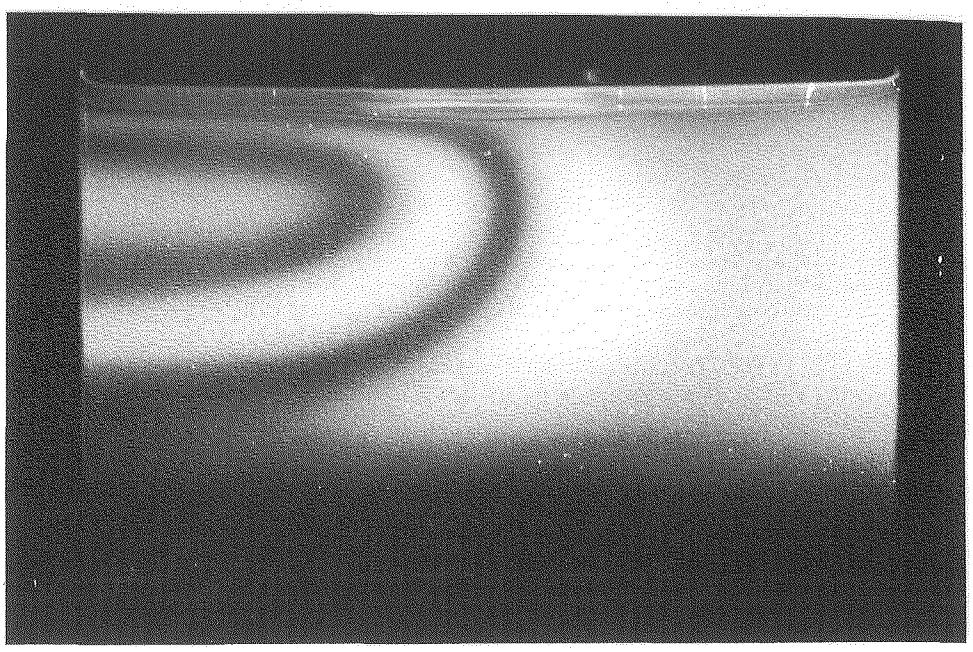


Fig. 5 Fringe Patterns due to Dead Load at Different Sections in a Gelatin Block



(a) Proposed Method



(b) Conventional Scattering Method

Fig. 6 Fringe Pattern Appearance