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Photoelastic Stress Analysis: A Review

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Abstract - *Photo elasticity is whole field technique which works on the property "birefringence" of transparent material. Birefringence means transparent material shows two refractive indices before and after loading. Combined with other optical elements and with white or monochromatic light source, a loaded photo elastic specimen (or photo elastic coating applied to an ordinary specimen) exhibits different fringe patterns which are related to the principal stress difference perpendicular to plane of propagation of light. This technique is widely used in various areas including dentistry, automotive, civil and electrical field also. This review paper provides information regarding the photoelasticity technique used by the various researchers in various fields. The objective of this paper is to provide guidelines regarding use of photoelasticity for several applications in automotive, bio-engineering, electrical fields. A literature search was conducted by using keywords such as photoelasticity, stress analysis, and fringes. Among several articles and research papers, most of the articles related to photoelasticity and stress distribution were shortlisted for complete reading and data extraction. Thus, various applications of photoelasticity are viewed.*

Keywords - *Photoelasticity, Fringes, Dentistry, Principle Stress*

I. INTRODUCTION

Photoelasticity is a whole field experimental technique used for stress analysis of complicated members and loading conditions. For such kind of problems analytical methods are very difficult to use. It is totally based on the property of some transparent materials that it shows fringes when load is applied on that and observed through the polarized light. This effect is the result of refraction of the polarized light by internal deformations due to stresses occurred in the model. Interpretation of these fringes gives all stress distribution and allows the measurement of their direction and magnitude in any model points. Materials having photoelastic properties, change in the refractive index occurs according to the application of load. [1]

Experiment in photoelasticity utilizes a polariscope that is an optical system [1, 2]. Birefringent phenomena of a photoelastic specimen in the polariscope make fringe patterns that depend on external load applied to the specimen. The fringe patterns are captured by CCD camera and saved in a computer. They are analyzed to obtain information about stress of the specimen. The polariscope takes advantages of the optical system that are two-dimensional signal process and non-contact measurement. This means that full-field measurement is available at once on the whole area of specimen through non-contact method in the photoelasticity experiment, compared with conventional point-by-point methods [2].

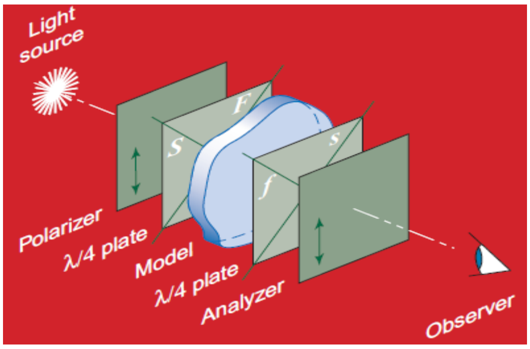

Fig. 1: Arrangment of circular polariscope [1]

Fringe patterns obtained in the polariscope consist of broad fringe bands with different width and they have limited fringe orders. In this paper, image processing techniques are reviewed for better analysis of fringes in photoelasticity [3, 4]. Image sharpening technique is to locate easily maximum or minimum in the fringes.

In photoelastic method, a prototype model similar to the studied structure is made in transparent material that has photoelastic properties. This prototype model is submitted to a representative loading of the work conditions, which take to a deformation. Polariscope is the instrument used in photoelasticity which allows the establishment of the light propagation plane and, therefore, the main stress directions, as well as the difference between the two components of main stress. This instrument is made up of polarizer, analyzer, and wave plates. These three optical elements along with light source form the assembly of polariscope. The polarized light crosses the wave plates and arrives at the observer as an image of the optic parameters. [3]

Analytical Approach

In the photoelastic stress analysis first of all fringe constant of the material is calculated. To calculate the fringe order it is required to find out the fringe orders. N1 and N2 are given by the following relation.

$$N1= n+\frac{\beta}{180} \tag{1}$$

$$N2= n-\frac{\beta}{180} \tag{2}$$

Where n is lower and higher fringe orders respectively.

The average is given by,

$$N=\frac{N1+N2}{2} \tag{3}$$

The next step is to find out material fringe constant. It is calculated by,

$$F\sigma = [8P/\pi DN] \text{ Kg/cm} \tag{4}$$

The stress intensity is given by,

$$I=\frac{NF\sigma}{h} \tag{5}$$

Where,
N- Fringe order
$F\sigma$- Material fringe constant
h- Thickness of model

Now,

$$\text{Maximum shear stress, } \tau = \frac{\sigma1-\sigma2}{2} \tag{6}$$

II. APPLICATIONS OF PHOTOELASTICITY

The photoelastic technique has been very used in the various fields. In this section different kinds of applications of photoelasticity are discussed.

A. Dentistry

The study of photoelasticity in the specific area of dental implant system is of great interest since it can be useful to analyze the stress distribution in both abutments (different designs and types) and implants screws (different types and angulations). Jao Cesar Zielak et al. studied colorimetric photoelastic analysis of tension distribution around dental implants under axial loads. In this study eight different designs of implant from two manufacturers were connected to their abutments, placed into epoxy resin blocks and observed under a polariscope coupled to a universal testing machine while subjected to axial loads of 5 N. The images obtained were quantitatively analyzed by image analysis software. Author found a strong correlation between the surface area and the implant fringe transition area (magenta color) of most samples (r = 0.908), and a moderate correlation was found between the fringe transition area and the mean thread height of the implants (r = 0.706, or r = 0.768 using a quadratic function) [5]. Cristiane Ueda et al. studied the photoelastic analysis of stress distribution on parallel and angled implants after installation of fixed prostheses. The purpose of this study was to compare, stress distribution in the fixed prosthesis with 3 parallel implants, to the stress distribution in the same prosthesis in the existence of an angled central implant. Two transparent photoelastic resin models were made and polariscope was used to visualize isochromatic fringes formed in the models when axial loads of 2 kg, 5 kg and 10 kg applied at the center of the prosthesis. The presence of applied tensions was observed in the models after applying the torque to retention screws. Applied tensions were intensified with the incidence of occlusal forces. In the parallel implants, the force dissipation followed the long axis. The angled implant has smaller quantity of number of fringes and the stresses were located mostly around the apical region of the lateral implants [4]. Marcelo Coelho Goiato1et al. has done the photoelastic Stress Analysis in Prosthetic Implants of Different Diameters: Mini, Narrow, Standard or Wide. Six photoelastic models were fabricated in PL-2 resin as single crowns or splinted 3-unit piece. Models were fixed in a circular polariscope and 100-N axial and oblique (at 45 degrees) loads were applied on the occlusal surface of the crowns by using a universal testing machine (EMIC). The stresses were observed, photographically recorded and qualitatively analyzed by using software (Adobe Photoshop). The result of whole experiment is under axial loading gives that; the number of fringes are inversely proportional to the diameter of the implants in the single crown models. In the splinted 3-unit piece model, the 3.75-mm implant gives lower number of fringes regardless of loading area application. Under oblique loading, a little bit increase in number of fringes was observed for all kind of groups. Author concluded that the standard implant diameter always gives better stress distribution than the narrow and mini diameter implants. Additionally, the splinted crowns shows more uniform stress distribution [6]. Hariprasad M.P, et al. brings out the evolution of a suitable photoelastic model in dentistry, which can be analyzed and interpreted using the stress-optic law, so that the model can be used in live loading conditions. Different methods in model making are discussed along with the improvements and advantages. [13].

Fig. 2 a) Wax pattern produced without any limiting structure and soft tissue attachments b) Photoelastic model made out of the silicon mould produced by wax pattern c) Dark filed isochromatics of residual stress posterior region of the mandibular arch [13]. Author found that residual stress in the model is highly influenced by the heat dissipation during the curing process and proper methodologies are established which are found to be effective in producing suitable three dimensional photoelastic models of the human mandible. [13].

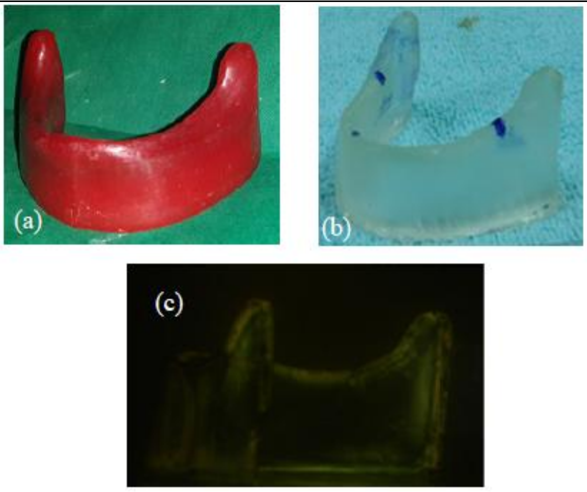

Fig. 2 a) Wax pattern attachments b) Photoelastic model c) Dark filed isochromatics

B. Aerospace

E.A. Flores-Jonson reported that Photoelastic evaluation of fiber surface-treatments on the interfacial performance of a polyester fiber/epoxy model composite. In this work the interfacial adhesion between a polyester fiber and an epoxy matrix was improved by using chemical and topological modifications on the surface of fiber. Photoelasticity method was used to measure the maximum interfacial shear strength and to find the interfacial performance in pull-out single-fiber composite specimens. An increase of the interfacial shear strength was observed when plasma-treated or surface-modified fibers were used; also, when we increase the applied load to the free fiber, the fiber treatment causes a reduction of the debonded area at the fiber–matrix interface.

Author concluded that the method of nitrogen–aniline plasma treatment and mechanical surface modification improves the interfacial adhesion. These treatment methods allow the composite material to perform better by carrying a higher load prior to interfacial failure, due to an increase of fiber– matrix stress transfer with reduced debonding at higher loads [8]

C. Civil Structures

J. Jayamohan et al. has done the photo elastic analysis for the measurement of internal Stresses in Indeterminate Structures. Author concluded that the technique of photoelasticity can be effectively explored to experimentally measure the internal stresses in indeterminate structures with complicated shape and loading. At the same time, some theoretical problems related to nonlinear optical phenomena need further investigation in order to widen the scope of the method [10]

D. Automobile

Rabah Haciane et al. studied photoelastic analysis of sphere contact problem. They have experimentally analyzed the stress field, developed in a birefringent parallelepiped model by a sphere made up of steel. The purpose was to analyze the stress field, particularly in the neighborhood of the contact zone. Author concluded that number of fringes and stresses can be calculated easily and accurately for an isolated slice with sufficient accuracy by using photoelasticity method [11]

E. Electronics

Y.C. Lee at al. studied how to find out residual stress and stress-optical coefficient for flexible electronics by using photoelasticity. In this work, a two-dimensional photoelasticity with higher measured speed and better uniformity was proposed by using a PBS connecting with two CCD cameras that are used for the purpose of capturing the intensity of right-hand and left hand circular polarization differently. Stress-optical coefficients of the PET, ITO-coated PET, and PEN substrates are measured by two-dimensional photoelasticity. These samples were exerted by increasing and decreasing tensional forces and optical retardations are calculated from tensional stresses. A linear fit was performed on the experimental data and the stress optic coefficient value can be calculated from the slope describing the fit and the sample thickness. It shows that stress-optical coefficients for these substrates in 0_ and 90_ orientations are different. [12]

III. RESULT AND DISCUSSION

Photoelastic analysis has been widely used in dentistry to study the biomechanical stress transfer in several kinds of prosthesis. The photoelastic model is a different homogeneous plastic material that simulates human bone constituted of cortical bone and cancellous bone. It shows that the magnitude of the stresses in real bone can be different from those in a model. However, the location and general standard of these stresses are similar. The technique used also facilitates a two-dimensional view of the stress concentration.

The result shows that as the isochromatic fringe pattern was obtained with circularly polarized light; two quarter wave plates were used in order to eliminate the isoclinic fringes. The isochromatic fringes are used to obtain the values of the principal stresses difference in the model along the vertical axis of symmetry, particularly in the neighbourhood of the contact zone. A close-up of the contact zone is necessary in order to determine accurately the fringe orders. Author used a white background configuration, the fringe order of the first isochromatic is N=0.5, starting from the bottom. The fringe orders increase to a maximum value of N=32.5, as they move close to the zone of maximum shear stress, whereas, at the lower part of the model, stresses were very much lower because the load is distributed over the whole area of contact of the model with the loading frame. The maximum value recorded experimentally for the principal stresses difference was about 1.53 MPa. Stresses decrease then, as author move away from the contact zone, to lower values and almost vanishes as we get close to the lower contact surface.

The superior and inferior borders of the mandible were subjected to tensile and compressive forces, respectively. With respect to the masticatory forces transmitted through the condylar process, Kessler suggested that the posterior border of the ramus on the working side is subjected to compression strain, while a tensile strain is applied along the anterior border of the condyle and below the mandibular notch.

On the surface of the reinforcement concrete specimens, it was observed that the cracks grew radically around the reinforcing steel bar and were resulted from the corrosion and expansion of the steel bar. The photoelastic images of various cracking stages were analyzed. The original isochromatic fringe images underwent separate digital image processing to obtain a global view of the stress distribution. Photoelastic stress fringe patterns around the rebar, which indicate the distribution of the maximum shear stress taken from an original photoelastic image of the cracks in the concrete specimen after the accelerated corrosion tests.

IV. CONCLUSIONS

By studying various research papers following conclusions were drawn

1. By biomechanical study, it is possible to demonstrate a correlation of some implant characteristics to the colored fringe areas of tension distribution.

2. The technique of photoelasticity can be effectively explored to experimentally measure the internal stresses in indeterminate structures with complicated shape and loading.

3. The photoelastic analysis has been a technique of great importance in health area studies, more specifically in Dentistry. Based on this method of analysis, it is possible to measure the stress distribution and deformation in structures with complex geometry as maxilla and mandible.

4. For the purpose of producing a suitable 3-D photoelastic model of the human mandible the procedure adopted using the wax pattern was found to be effective. This model was found to be very useful in analysing the

implants in the molar and incisor areas under live loading. Further, the same model can be used for the photoelastic studies with the implants placed in other areas by stress freezing technique.

5. Photoelasticity is used to analyze the stress field, particularly in the neighbourhood of the contact zone. It shows that photoelastic fringes and stresses can be calculated easily and accurately for an isolated slice with sufficient accuracy. One should emphasize the importance of photoelasticity to solve this kind of contact problem where the limit conditions and the application of the load in the finite elements solution is not an easy task; the shape of the surface in contact is sometimes difficult to determine because both bodies in contact can deform. Photoelasticity is still very much used in automobile industry and aeronautics to solve contact problems. [11]

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