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A Review on Photoelastic Stress Analysis

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Abstract—*Photoelasticity entails experimental techniques that use properties of light propagating through loaded or deformed components to determine and analyze the relative displacements in the material in order to establish their stress and strain fields. Photoelasticity may be applied to models in the laboratory or to prototypes in the field. Thus, it is whole field technique and it gives exact results. Photoelastic methods are used to determine the principal stress and maximum principal stress difference. This paper gives the review of basic concepts of Photoelastic stress analysis. Further applications are discussed.*

Keywords: *Photoelasticity, stresses in the model, Principal stress.*

1. INTRODUCTION

One of the oldest and most useful forms of interferometric measurements for stress analysis purposes is photoelasticity, which involves the observation of fringe patterns caused by stress-induced birefringence. The technique dates back to 1816 when Brewster made some initial observations regarding birefringence. However it was not until 1940s when polymers became available, namely Bakelite, that the technique was applied in an engineering context. The technique involves manufacturing a model of an artefact from a birefringent material, usually a transparent polymer, and applying a representative load to the model. The instrument that is used for photoelasticity is called a 'polariscope'.

Experimental photoelastic stress analysis had its real beginning with the British scientists, Coker and Filon ', who pioneer the field starting about the turn of the century, Since that time, photoelastic stress analysis has become an accepted design tool. Nearly all engineering colleges and large industrial firms are now equipped with photoelastic polariscopes and related instruments.

Photoelastic studies were started by the Bureau of Reclamation at Denver, Colorado, in 1934 to assist primarily in the problems being encountered in the planning and design of Grand Coulee Dam. Original photoelastic equipment was an 8-inch reflector-type polariscope. Since that time additional equipment has been added, existing equipment modified or replaced, and operating technique developed and perfected. At the present time instruments and equipment are available for performing a great variety of stress analysis studies not only in photoelasticity but also in related fields.

Photoelasticity: Photoelasticity is an experimental method to determine stress distribution in a material. The method is mostly used in cases where mathematical methods become quite cumbersome. Unlike the analytical methods of stress determination, photoelasticity gives a fairly accurate picture of stress distribution even around abrupt discontinuities in a material. The method serves as an important tool for determining critical stress points in a material and is often used for determining stress concentration factors in irregular geometries.

Polariscope: A polariscope is the device used to measure photoelastic effects. When a ray of plane polarized light is passed through a photoelastic material, it gets resolved along the two principal stress directions and each of these components experiences different refractive indices. The difference in refractive indices leads to a relative phase retardation between the two component waves. The magnitude of the relative retardation is given by the stress optic law:

$R = Ct\,(\sigma_1\text{-}\sigma_2)$

Where, R is induced retardation, C is the stress optic coefficient, t is the specimen thickness, σ_1 is the first principal stress, and σ_2 is the second principal stress.

The two waves are then brought together in a polariscope. The phenomenon of optical interference takes place and we get a fringe pattern one can determine the state of stress at various points in the material.

Types of Polariscope: There are two main types of polariscope in use today, Plane polariscope and the Circular polariscope**.**

(a). Plane Polariscope: The setup consists of two linear polarisers and a light source. The light source can either emit monochromatic light or white light depending upon the experiment. First the light is passed through the first polarizer which converts the light into plane polarized light.

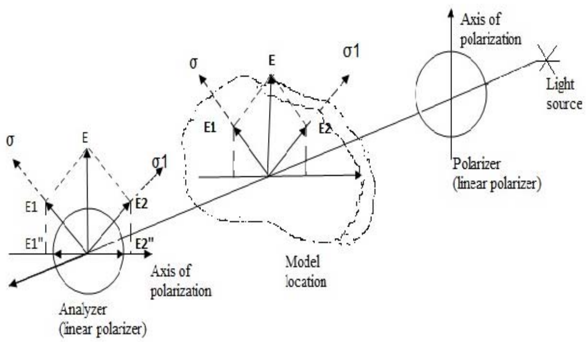

Fig. 1: Plane polariscope

The apparatus set up in such way that this plane polarized light then passes through the stressed specimen. This light then follows, at each point of the specimen, the direction of principal stress at that point. The light is then made to pass through the analyzer and we finally get the fringe pattern.

(b). Circular Polariscope: In a circular polariscope setup, two quarter-wave plates are added to the experimental setup of the plane polariscope. The first quarter-wave plate is placed in between polarizer and the specimen and the second quarter-wave plate is placed between the specimen and the analyzer. The effect of adding the quarter-wave plates is that we get circularly polarized light.

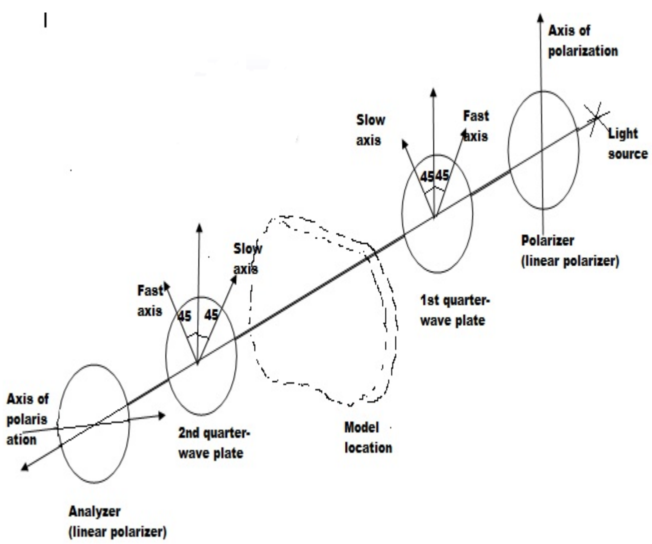

Fig. 2: Circular polariscope

There are four different kinds of arrangements for the circular Polariscope. Each arrangement produces either a dark field arrangement or a light field arrangement. In dark field arrangement, the fringes are shown by bright lines and the background is dark. The opposite holds true for the light field arrangement.

S. No.	OPTICAL SETTING	QUARTER WAVE-PLATES ARRANGEMENT	POLARIZER & ANALYZER ARRANGEMENT	POLARISCOPE FIELD	REMARKS
1	Plane Polariscope	-	Crossed	Dark	Suitable for demonstration of Isoclinics
2	Circular Polariscope	Crossed	Parallel	Light	Not Recommended
		Crossed	Crossed	Dark	Recommended
		Parallel	Parallel	Dark	Not Recommended
		Parallel	Crossed	Light	Recommended

The basic advantage of a circular Polariscope over a plane Polariscope is that in a circular Polariscope setup we only get the Isochromatics and not the Isoclinics. This eliminates the problem of differentiating between the Isoclinics and the Isochromatics.

2. RECENT INVESTIGATIONS

Table 1 shows the recent investigations and developments in photoelasticity

Table 1: Existing investigations on photoelasticity

S. No.	Author (year)	Photoelastic material (component)	Investigation
1.	Vivek C. Pathade(2013)	Araldite AY103 with hardner HY951. (Connecting rod)	Stress analysis of I.C.Engine connecting rod by FEM and photoelasticity
2.	Bhosale Kailash C. A.D.Dongare	Epoxy resin AY-103 araldite mixed with HY-951 hardener. (Helical gear)	Photoelastic Analysis of Bending Strength of Helical Gear
3.	Shetty Prajna P (2013)	Epoxy resin (Teeth)	A Fast and Economical Photoelastic Model Making of the Teeth and Surrounding Structure
4.	Mr.M.M.Dange (2014)	SAE 1030 (Bell crank lever)	Stress Analysis of Bell Crank Lever
5	E. E. WEIBEL	Bakelite And Phenolite	Studies in Photoelastic Stress Determination

6.	Vinay Kumar Singh and Prakash Chandra Gope	araldite CY 230 mixed with 9% (wt%) hardener HY 951	Photoelastic Studies of Stress Distribution Under Mixed Mode Biaxial Loading
7.	Tae Hyun Baek (2014)	Resins	Fringe Analysis for Photoelasticity Using Image Processing Techniques
8.	Pedro Americo A. M. Junior (2012)	Epoxy resin	New Numerical Method for the Photoelastic Technique
9.	Anbo Wang (1992)	Phenolite	Optical Fiber Pressure Sensor Based on Photoelasticity and its Application
10.	Seweryn J. Duda (1964)	Araldite D	The Stress around a Fault according to a Photoelastic Model Experiment
11.	Pichet Pinit (2009)	Epoxy resin	Development of Window-based program for analysis and visualization of Two dimensional stress field in digital photoelasticity

The improvements in Photoelastic stress analysis listed in Table 1 have the following conclusions:

1. Vivek C. Pathade concluded that:
i) The stresses induced in the small end of the connecting rod are greater than the stresses induced at the big end.
ii) Form the photoelastic analysis(from the fringe developed in the photoelastic model of connecting rod) it is found that the stress concentration effect exist at both small end and big end and it is negligible in the middle portion of the connecting rod.
iii) Therefore, the chances of failure of the connecting rod may be at fillet section of both ends.

2. Bhosale Kailash C.A.D.Dongare concluded that there is a good agreement between experimental and finite element results. The error in maximum bending stress is found to be 2.02 %. In helical gear the engagement between drivergear and driven gear teeth begins with point contact and gradually extends along the tooth surface. Due to initial point contact in helical gear the bending stresses produced at critical section (root of tooth) are maximum as compared to spur gear, which has kinematic line contact. The calculation of maximum stresses in a helical gear at tooth root is three dimensional problems. The accurate evaluation of stress state and distribution of stress is complex task. The stresses produced at any discontinuity are different in magnitude from those calculated by elementary formulae.

3. Shetty Prajna's article provides with a simple technique and a cost effective material to make an accurate model of the teeth. An accurate model helps provide an excellent fringe pattern to determine the stress pattern and distribution on the object of interest thus providing an optimum result.

4. Mr.M.M.Dange concluded that in effort arm it is observed that though the volume is reduce the maximum principal stresses at the corner of bell crank lever remains nearly constant and it is found to be equal to that of stresses in original model of bell crank lever. Comparison between results obtained by analytically, FEM and photoelasticity reveals that they are in close harmony with each other with minimum percentage of error.

5. E. E. Weibel concluded that the method of canceling residual stresses was not the same as that described by Dr. Baud. The extrapolation method is of value because of the extreme difficulty of adjusting parallelism of light beam and position of model so that, for example, a satisfactory image of both fillets is obtained a t the same time. Extrapolation provides a correction for the small inaccuracies at the boundary which cannot be avoided. Dr. Den Hartog's comments on the use of a rubber membrane are of considerable interest. A paper by two of his students, finds Poisson's ratio for phenolite to be 0.356. If, according to our ordinary conception of plastic strain, we assume a value of 0.5 for Poisson's ratio for the plastic strain, the over-all value of Poisson's ratio would increase with time of loading from 0.356 to a limiting value 0.5. In the two-hour tests on phenolite, strain creep in two hours was 24 per cent of elastic strain. It can be shown readily on the basis of the above assumption that the overall value of Poisson's ratio increased from 0.356 to 0.383 or 7.6 per cent.

6. Vinay Kumar Singh and Prakash Chandra Gope was concluded that there is a significant effect of boundary loading (biaxial factor, k, crack angle, α and r/a) on the state of stress ahead of the crack tip. Inclusions of higher order stress terms would improve the accuracy of the prediction of crack initiation angle.

7. Tae Hyun Baek concluded that Photoelasticity is a reliable optical technology for stress analysis in mechanics. Advance in a personal computer has facilitated use of photoelastic techniques. In this paper, image processing techniques are applied to stress analysis of fringes in photoelastic specimen. Gradient descent process is successfully used for the sharpening technique on the fringes. The fringes are multiplied twice for limited fringe order by use of dark- and light-field fringes. The fringe multiplication is confirmed with the sharpening technique of fringes. In addition, 8-step phase measuring technique is shown to separate isoclinics and isochromatics. The validity of 8 step phase measuringtechnique for separation of isoclinics and isochromatics is proved by use of photoelastic experiment.

8. Pedro Americo A. M. Junior was concluded that the equations used for phase calculation measurements with images using phase shifting technique. The new equations are

shown to be capable of processing the optical signal of photoelasticity. These techniques are very precise, easy to use, and low cost. On the basis of the performed error analysis, it can be concluded that the new equations are very good phase calculation algorithms. The metric analysis of the considered system demonstrated that its uncertainties of measurement depend on the frame period of the grid, on the resolution of photos in pixel and on the number of frames. However, the uncertainties involved in the measurement of the geometric parameters and the phase still require attention. In theory, if we have many frames, the measurement errors become very small. The measurement results obtained by the optical system demonstrate its industrial and engineering applications in experimental mechanics.

9. Anbo Wang concluded that a practical optical fiber-pressure sensor system based on photoelasticity using a novel compensation technique has been described. The system has a pressure measurement range of 0-147 KPa with a sensitivity of 10 Pa. It maintained a high accuracy of 0.2% regardless of the fiber losses up to -30 dB and regardless of the temperature changes from -10 to 42°C. The system has superior abilities to compensate for the large variations of MPD in the fibers. This sensor has been successfully applied to measure storage in a crude oil tank and a high accuracy of 0.25% has been obtained under the in situ operation conditions over the one-year test use.

10. Seweryn J. Duda was concluded that the photoelastic model experiments, with improved boundary conditions as compared with earlier mathematical models, the increase of shear stress towards the ends of a fault is confirmed. There is also no longer an infinite shear stress at the fault ends. The shear stress reaches a much higher absolute value at the left end of the slit in profile **I,** models **A, B** than on its right end. For a profile on the opposite side of the slit, the behaviour is opposite. The strain release density for the Desert Hot Springs aftershocks exhibits a similar pattern in relation to the Mission Creek fault, which may be explained by our finding. This would mean that our two-dimensional stress distribution is agood approximation to the stress field around Mission Creek fault, and also that the hypocentres do not vary much in depth. Of course, the aftershocks occur in a material with elastic afterworking, and the strain release density map shows a summary effect in time, whereas the photoelastic material used by us had to be nearly perfectly elastic.

11. Pichet Pinit was concluded that i). Since, by principle, the isochromatic parameter pertains to the stress field of (σ_1 - σ_2), the separation is needed such that the stress components σ_{xx}, σ_{yy}, and τ_{xy} or the individual σ_1 and σ_2 are retrieved. These stress components are subsequently used in the theories of failure for designing of the structural members in question. The process of separation requires unwrapped isoclinic and isochromatic data, which are readily obtained from the program. Although several researchers have proposed the separation techniques, these techniques only were just applied to the benchmark problem and they would fail when being applied to complicated models such as a model having discontinuities in the fringe field. The stress separation for complicated models should be, therefore, addressed in the future. ii). Digital photoelasticity needs the plastic model such that the fringe can be viewed; therefore, performing the real experiment may take time due to the preparation of the models. With the new technology of rapid prototyping (RP), construction of those models is then no longer tedious in that the complicated models can be simply manufactured. Applying the software to the fringe images of such models built from the RP technology could make the fringe analysis faster. This could be beneficial for engineering design.

3. CONCLUDING REMARKS

From the output of the analysis the results can be compared with numerical and FEM results, observed that results obtained are in close agreement with each other and maximum failure and stress concentration occurs at maximum bending surface. By the observation, for the complicated problems of arbitrary geometries the experimental method like photoelasticity is important because the results are very close to the reality.

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