Photoelastic Coatings

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SOCIETY FOR EXPERIMENTAL STRESS ANALYSIS MONOGRAPH NO. 3

SESA

PHOTOELASTIC COATINGS

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PHOTOELASTIC COATINGS

SOCIETY FOR EXPERIMENTAL STRESS ANALYSIS MONOGRAPH SERIES

PREFACE

This book is the third in a series of volumes published by the Monograph Committee of the Society for Experimental Stress Analysis. The Society feels that, in addition to its primary dissemination of information through publication of the journal *Experimental Mechanics*, this series of monographs is a vital means of providing the engineer with a handy and in-depth source in a specific field.

Photoelastic Coatings is written by three highly qualified authorities in the field, Felix Zandman, Salomon Redner, and James W. Dally. The material contained in this volume represents not only more than twenty years experience for each author but also research of the numerous other workers that are cited. Dr. Zandman, in particular, has extended considerable effort and devotion to ensure acceptance of and improvements in techniques involving photoelastic coatings. This commitment has resulted in lectures that have literally spanned the globe. In 1970 the SESA awarded Dr. Zandman the Distinguished Contribution Award with the citation: "For outstanding original contributions to the technology of experimental mechanics through the development of birefringent coatings." Mr. Redner's contributions range from instrument and coating developments to improvement of methods. Professor Dally's leadership in the application of the concept of photoelasticity to a wide variety of problems in experimental mechanics is well documented. The Society is fortunate to have the services of these specialists to write on this important field.

The first two chapters of this monograph are devoted to background material. Chapter 1 deals with the general theory of photoelasticity; the specific application of this theory to photoelastic coatings is covered in Chapter 2. The next two chapters discuss the materials used for coatings and the equipment employed to analyze the photoelastic patterns. In the chapters that follow, the parameters that must be considered in various applications and the specific applications themselves are discussed. The aim of this monograph is to serve as a quick reference for those already in the field; and, with the background material presented, to aid the practicing engineer in becoming proficient in this area with a minimum effort.

The Monograph Committee wishes to thank the authors who voluntarily gave their time to produce this volume. Their cooperation and enthusiasm is greatly appreciated. As usual, B. E. Rossi, Managing Director of the Society for Experimental Stress Analysis, displayed his untiring effort in assuming responsibility for editorial styling and working with the publishers.

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INTRODUCTION

Many experimental methods can be used to determine the distribution of stresses and strains in machine components and structures. Probably the most common method involves the use of resistance strain gages that are easy to install and provide precise results under a wide variety of operating conditions. Unfortunately, strain gages provide data only at the points where they have been mounted, and little is learned about other regions on the surface of the component. As a consequence, there has been a continuing interest in "full-field" experimental methods that provide data on stresses and strains over relatively large areas of the component surface.

Brittle coatings or lacquers represent one of the full-field experimental methods. These coatings are similar to a varnish except that they crack when subjected to a critical strain. The cracking of the coating is useful in locating the position and direction of the maximum stress. However, since the resin-based brittle coatings are extremely sensitive to a number of parameters such as humidity, temperature, loading time, and coating thickness, precise determination of the stress magnitude is not always possible.

Two- and three-dimensional photoelasticity also provides full-field experimental methods to determine stresses at points on the surface or in the interior of the specimen. Precise results can be obtained, although the three-dimensional method is more complex than the strain-gage and brittle-coating methods. Classical photoelasticity requires the use of models fabricated from transparent birefringent polymers and this also limits the applicability of the method.

The method of birefringent coatings, also called the method of photoelastic coatings, extends the classical procedures of model photoelasticity to the measurement of surface strains in opaque two- and three-dimensional models made of any structural material. The coating is a thin layer of birefringent material—usually a polymer—that is bonded integrally to the flat or curved surfaces of the prototype being analyzed for stress. When the prototype is loaded, the surface strains are transmitted to the coating, reproducing the prototype strain field in the coating. (For certain cases in which the prototype strain field is affected by the presence of the coating, coating-thickness correction factors are introduced to account for this effect.) To provide light reflection at the interface, the coating is bonded in place with a reflective cement. When viewed through a white-light reflection polariscope, the strained coating exhibits black isoclinic and colored isochromatic fringes. Isoclinic fringes provide directions of principal strains. Isochromatic fringes, when viewed in normal-incidence light, provide the difference of principal strains (maximum shear strains); when viewed in oblique-incidence light, they provide additional data that permit the determination of the magnitude and sign of individual principal strains. Full-field isochromatic and isoclinic patterns are directly visible and can be photographed for subsequent analysis by using simple reflection polariscopes. With more advanced equipment, the fringe patterns can be analyzed on a point-by-point basis by using a compensator to determine the fringe order, with the magnitude of the strain being displayed on a digital readout device.

The photoelastic-coating method has many advantages compared to other methods of experimental stress analysis. It provides point-by-point or full-field quantitative data, enabling the investigator to determine the complete distribution of surface strains and directly highlighting severely strained areas. The method is nondestructive and, since the coatings can be applied directly to prototype parts and structures, eliminates the need for elaborate and costly models. Both static and dynamic strains can be measured. With appropriately selected coating materials, the method is applicable over a wide range of elastic and plastic strains. The photoelastic-coating method is also very useful in converting analysis of complex nonlinear stress situations in the prototype to analysis of relatively simple linear-elastic problems in the coating; i.e., plastic and viscoelastic behavior in a prototype can be measured in terms of the elastic response of the coating. Similarly, the anisotropic characteristics of composite materials can be examined in terms of an isotropic response in the coating.

The concept of photoelastic coatings was first proposed by M. Mesnager[1] in France in 1930, and the method was reexamined by Oppel[2] in Germany in 1937. Mesnager tried to bond segments of glass to structures. The difficulties in machining glass; its high modulus, which caused significant reinforcement; and the lack of a proper adhesive for bonding the structure prevented this approach from being developed. Oppel used flat sheets of Bakelite. Here, the development of a severe "time-edge effect," lack of strong adhesives, and applicability only to flat surfaces prevented this method from being used industrially.

With the availability of epoxy resins in the 1950s, the required high-strength adhesive and a photoelastic sheet relatively free of time-edge effect could be produced. The development of the photoelastic-coating method proceeded rapidly with contributions in materials, techniques, and instruments from Fleury and Zandman[3] in France; D'Agostino, Drucker, and Liu[4,5] in the United States; and Kawata[6] in Japan.

At this time photoelastic coatings were still considered an academic curiosity by those in industry because a technique to apply coating surfaces with compound curvature had not been developed. Finally, Zandman[7] developed the contour sheet procedure for applying a constant-thickness coating to curved surfaces without introducing residual birefringence. At the same time he developed a portable reflection polariscope,[8] making the method practicable for quantitative measurements under industrial conditions. In the late 1950s Zandman, Redner, and Riegner[9] treated the problem of reinforcement by the coating and developed techniques to account for reinforcing effects, thus removing an obstacle to obtaining quantitative data when coating thickness is not negligible with respect to the thickness of the part.

Following these developments of epoxy coating materials and adhesives, sheet-contouring techniques, and analysis procedures, the method was generally accepted and considerable research followed. Investigators developed more sensitive and higher elongation coatings. Several instruments for laboratory and field use, particularly designed for coatings, were introduced. Methods were advanced for using the coatings in analysis of plasticity, thermoelasticity, vibrations, and wave and crack propagation. Also, many engineers in industry began to use the method in the solution of a wide variety of industrial design problems.

No attempt is made in this monograph to recite the individual contributions of the many investigators who improved the method. Extensive literature on this subject has appeared in the United States, France, United Kingdom, U.S.S.R., and other countries (see References). Instead, this volume is arranged to guide the experimentalist in the use of birefringent coatings toward the solution of practical stress-analysis problems. The background necessary to thoroughly understand the theory of the photoelastic-coating method is presented in Chapters 1 and 2. Materials commonly used for coatings and adhesives, along with the techniques and procedures for bonding the coating to the prototype, are described in Chapter 3. Reflection polariscopes, compensators, and calibration devices adapted for use with birefringent coatings are described in Chapter 4. Parameters affecting the behavior of the coating and correction factors for coating thickness and other effects are treated in Chapter 5. A series of case histories is presented in Chapter 6 to illustrate the application of the coating method to components fabricated from different materials and to different types of problems that occur in a wide range of industries. Finally, Chapter 7 discusses likely future developments.

DEFINITION OF SYMBOLS

β = angular position of quarter-wave plates
δ = linear retardation
Δ = angular retardation
$\epsilon_1, \epsilon_2, \epsilon_3$ = principal strains
$\epsilon_{xx}, \epsilon_{yy}, \epsilon_{zz}$ = normal strains
γ = rotation angle of the analyzer
$\gamma_{xy}, \gamma_{xz}, \gamma_{yz}$ = shear strain
ϕ, φ = isoclinic parameter, direction of principal strains
ν = Poisson's ratio
θ = angle of incidence of polarized light
λ = wavelength of light
ρ = radius of curvature
Γ = constants of integration
σ_1, σ_2 = principal stresses
$\sigma_{xx}, \sigma_{yy}, \sigma_{zz}$ = normal stresses
$\tau_{xy}, \tau_{xz}, \tau_{yz}$ = shear stress
ω = circular frequency of light
a = maximum amplitude
c = speed of light
f = frequency
f_ϵ, f_σ = material-fringe value (strain and stress)
g = thickness ratio of plastic coating to metal, h_c/h_s
h = thickness
n, n_0, n_1, n_2 = index of refraction
r = fractional fringe order
t = time
u = displacement
z = position along the axis of propagation
A = amplitude of light vector components
A_1, A_2, A_3 = light vector components
C = stress-optic coefficient
$C_{1,2,3,4,5}$ = correction factors
E = modulus of elasticity
F_ϵ, F_σ = coating fringe value
I = intensity of light
K = strain-optic sensitivity of the coating
N, N_0, N_θ = fringe order (relative retardation)
S_σ = stress-sensitivity index
T = period

SUMMARY OF BASIC EQUATIONS

1. UNIAXIAL-STRESS MEASUREMENTS ($\sigma_2 = 0$)

Measured: Fringe order in normal incidence, N
Isoclinic angle, ϕ

Coating: Thickness h, sensitivity K, fringe constant $F_\epsilon = \lambda/2hK$

Difference of principal strains: $\epsilon_1 - \epsilon_2 = NF_\epsilon$

Strains: $\epsilon_1 = N[F_\epsilon/(1+\nu)]$; $\epsilon_2 = -\nu\epsilon_1 = -N[F_\epsilon \nu/(1+\nu)]$

Stress: $\sigma_1 = E\epsilon_1 = N[EF_\epsilon/(1+\nu)]$

2. BIAXIAL-STRESS MEASUREMENTS

Measured: Fringe order in normal incidence, N_0
Fringe order in oblique incidence, N_θ
Isoclinic angle, ϕ

Coating: Thickness h, sensitivity K, fringe constant $F_\epsilon = \lambda/2hK$

Difference of principal strains: $\epsilon_1 - \epsilon_2 = N_0 F_\epsilon$

Shear strain: $\gamma_{xy} = N_0 F_\epsilon \sin 2\phi$

Separated values of strain:

$$\epsilon_x = [F_\epsilon/(1+\nu_c)\sin^2\theta_x]\ [N_\theta\ (1-\nu_c)\cos\theta_x - N_0\ (\cos^2\theta_x - \nu_c]$$

$$\epsilon_y = [F_\epsilon/(1+\nu_c)\sin^2\theta_x]\ \{N_\theta\ (1+\nu_c)\cos\theta_x - N_0\ [(1-\nu_c)\cos^2\theta_x]\}$$

$$N_\theta = [1/F_\epsilon(1-\nu_c)\cos\theta]\ \{\epsilon_x\ (1-\nu_c\cos^2\theta) - \epsilon_y\ (\cos^2\theta - \nu_c)\}$$

Difference of principal stresses: $\sigma_1 - \sigma_2 = N_0\ [EF_\epsilon/(1+\nu_c)]$

Separated values of stresses: $\sigma_{1,2} = [E/(1-\nu^2)]\ (\epsilon_{1,2} + \nu\epsilon_{2,1})$

Shear stress: $\tau_{xy} = [NF_\epsilon E/2\ (1+\nu)]\ \sin 2\phi$

3. CORRECTION FACTORS

To obtain surface strains on uncoated structure ϵ^u from the measured strains in the coating ϵ^c:

$$\epsilon_1^u - \epsilon_2^u = (1/C_n)\ (\epsilon_1^c - \epsilon_2^c)$$

C_n: correction factors shown on Figs. 5.2, 5.4, 5.5, and 5.6.

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