Photothermoelastic Investigation of Stresses Around a Hole in a Plate Subjected to Thermal Shock

Purpose of study is to determine if the presence of a hole in a thermally shocked plate acts as a significant stress raiser

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ABSTRACT—This paper contains a three-dimensional photothermoelastic study of stresses generated around the edge of a hole in a flat unrestrained plate subjected to a thermal shock uniformly applied to one face of the plate. The approach taken is experimental in nature, utilizing a newly developed three-dimensional, non-destructive photoelastic technique. An extrapolation procedure is formulated in order to determine transient fringe orders at the thermally shocked surface. For the case considered, the thermal-stress-concentration factor at the edge of the hole was found to be 1.28.

Nomenclature

\[ a = \text{thermal diffusivity (in.}^2/\text{hr)} \]
\[ E = \text{modulus of elasticity (lb/in.}^2) \]
\[ f = \text{material fringe value (lb/fringe-in.)} \]
\[ h = \text{heat-transfer coefficient (Btu/hr-ft}^2\text{-°F)} \]
\[ k = \text{thermal conductivity (Btu/hr-ft}^2\text{-°F/in.)} \]
\[ K = \text{thermal-stress-concentration factor} \]
\[ M_n = \text{eigenvalues defined by eq (7)} \]
\[ n = \text{fringe order (fringes)} \]
\[ t = \text{thickness of photoelastic model (in.)} \]
\[ T = \text{temperature (°F)} \]
\[ \Delta T = \text{temperature change (°F)} \]
\[ T_i = \text{initial temperature of model (°F)} \]
\[ T_f = \text{temperature of fluid against model boundary (°F)} \]
\[ T_s = \text{surface temperature of model (°F)} \]
\[ x = \text{arbitrary length in heat-transfer equation (ft)} \]
\[ \alpha = \text{coefficient of thermal expansion (in./in./°F)} \]
\[ \delta = \text{thickness of heat-transfer model (ft)} \]
\[ \theta = \text{time (hr)} \]
\[ \nu = \text{Poisson's ratio} \]
\[ \sigma_\theta, \sigma_\phi, \sigma_z = \text{principal stress components in cylindrical coordinates (lb/in.}^2) \]
\[ \Phi = \alpha \delta / \delta^2 = \text{parameter used in heat-transfer equations} \]

Introduction

Photothermoelasticity is a relatively new experimental technique in which thermal rather than mechanical loads are used to introduce characteristic fringe patterns in birefringent materials. The most commonly used birefringent materials are plastics, and since their material properties become increasingly time dependent at elevated temperatures, thermal loads are usually introduced by cooling.

The initial works in the field went far in developing the validity of the photothermoelastic method by comparing analytic solutions of well-known thermoelastic problems with the experimental results. New techniques were developed and the method was extended to the solution of practical stress-analysis problems, and most recently as a basis for new theories.

This paper contains a three-dimensional, experimental investigation of the stresses generated around the edge of a hole in a flat unrestrained plate subjected to a thermal shock uniformly applied to one face of the plate. The purpose of the study was to determine if the presence of a hole in a thermally shocked plate acted as a significant stress raiser.

In order to obtain the reported results, special equipment had to be fabricated, and new experimental techniques developed. The complete program is described in detail in this paper.

Models

Cemented-polariscope Technique

Due to the highly transient nature of the problem under consideration, the standard three-dimensional photoelastic techniques such as stress-freezing were not applicable. One method which might have been utilized is the scattered-light technique. Unfortunately, fringe patterns obtained with this method are faint, and difficult to evaluate. Because of the complexity of instrumentation and analysis, coupled with the relatively large experimental errors which might be expected from scattered light in a problem of this type, this approach was abandoned.

The technique adopted was one developed by Tramposch and Gerard. In this technique, polarizer and analyzer are cemented on both faces of a
piece of birefringent plastic, and the whole sandwich is then cemented into the area of interest in a three-dimensional model of the same plastic. This allows the investigator to obtain fringe information at any area of interest within a three-dimensional model without having to destroy the model or interpret overly complex fringe patterns. Main disadvantages stem from the fact that the fringe patterns are confined to a preselected area, residual fringes cannot be readily compensated, and a single model allows the investigator to study only the isochromatics or a single isoclinic. This makes separation of the principal stresses in the interior of models difficult.

Questions as to the effect of the cemented polariscope on the fringe patterns, strength of cemented joints, and applicability of the method to mechanical loadings are all discussed in detail in Ref. 2.

Tramposch and Gerard conclude that the technique is admirably suited to quantitative experimental analysis of thermal stresses in three-dimensional objects.

Reflection-polariscope Model (Model One)

Two models were fabricated: one to obtain the radial and tangential stresses around the hole, the other to obtain radial and longitudinal stresses. Both were machined from blocks of Hysol 4290 epoxy resin. Their dimensions are shown in Figs. 1 and 2. The polarizer and analyzer material used was standard Polaroid type HNCP-37 circular polarizing sheet, 0.030-in. thick. Cement used on all joints was Hysol 2038 liquid resin mixed with Hysel type C hardener.

Model One, used to obtain radial and tangential stresses, incorporated a doubling polariscope, i.e., one piece of circular polaroid sheet served as both polarizer and analyzer. A smooth surface was cast on both the top and bottom of the plate to increase its transparency. An aluminum film, 0.0001-in. thick, was vacuum deposited on the top face of the plate to serve as the reflector. Slots were milled at precise locations, and copper-constantan thermocouples of AWG-36 (0.005-in. diam) wire were located in the model at the positions shown. Dimensions indicate the center of the thermocouple bead.

Transmission-polariscope Model (Model Two)

Model Two was used to check radial and longitudinal stresses at the edge of the hole. It incorporated a conventional cemented circular polariscope. Thermocouples were of the same type as those employed in Model One. Surfaces were cast on both sides of the model, parallel to the polaroid sheet.

Test Setup and Related Equipment

In order to photograph rapidly changing fringe patterns at 1-sec intervals, a high-intensity rapid-fire light source was constructed utilizing GE photoflash 50 flashbulbs and a revolving drum. Thermocouples were of the double-bead type, one bead being imbedded in the model, the other in an ice-water reference bath. Thermocouple outputs were recorded on the Y-axis, and time on the X-axis, of three Moseley Type 3S, X-Y recorders.

The test setup used in determining radial and tangential stresses is shown schematically in Fig. 3. As can be seen, a partially silvered front surface mirror was used to alter the light path, allowing the fringe pattern of Model One to be photographed. Figure 4 shows the actual arrangement used.

Longitudinal and radial stresses were determined in a similar manner, but here, since Model Two incorporated a transmission polariscope, the front