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10 August 1967

Materiel Test Procedure 5-2-587
White Sands Missiles RangeU. S. ARMY TEST AND EVALUATION COMMAND
COMMON ENGINEERING TEST PROCEDURETHE PHOTOSTRESS METHOD OF
STRUCTURAL DATA ACQUISITION1. OBJECTIVE

The objective of this MTP is to provide a procedure for determining the magnitudes and directions of stresses in test specimens using the photostress method of structural data acquisition.

2. BACKGROUND

A knowledge of the structural characteristics of materiel is essential in determining suitability for expected usage. By determining the magnitudes and direction of surface stresses in a structural body, loaded in a manner similar to expected usage, the structural adequacy of the body can be determined.

The photostress method of stress analysis is based on the fact that certain material, e.g., plastic, become birefringent when subjected to stress, and the degree and the orientation of the birefringency is mathematically related to the direction and differences of the principal stresses acting in the material. When a thin layer of such material is applied to the surface of a test item such that the surface stresses in the test item are transferred to the plastic coating, a measure of the amount and direction of the birefringency in the plastic will allow determination of the directions and differences of the principal surface stresses of the test item. The direction and amount of birefringency in the plastic coating can be determined by passing polarized light through the plastic coating and then measuring the effect of the birefringency on the polarized light.

3. REQUIRED EQUIPMENT

Some of the items listed below are described in Appendix C.

- a. Facility to load the test specimen to stimulate service loading.
- b. Reflective polariscope
- c. Optical compensators
- d. Liquid or sheet plastic having applicable strain constraint(K).
- e. Oven for heating plastic
- f. Provisions for tracing and photographing patterns.
- g. Calibration beams
- h. Applicable hand tools for molding, applying and removing plastic.

4. REFERENCES

- A. Hetenyi, M., Handbook of Experimental Stress Analysis, John Wiley & Sons, Inc., New York, 1950.
- B. Frocht, M.M., Photoelasticity, John Wiley & Sons, Inc., New York, 1941.

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- C. McMaster, R. C., Nondestructive Testing Handbook, Vol. II, The Ronald Press Co., New York, 1959.
- D. Dove, Richard C. and Adams, Paul H., Experimental Stress Analysis and Motion Measurement, Charles E. Merrill Books, Inc., Columbus, Ohio, 1964.
- E. How to Select Photoelastic Coatings, Materials in Design Engineering, September 1964.
- F. McIver, Robert W., Structural-Test Applications Utilizing Large Continuous Photoelastic Coatings, Experimental Mechanics, January and February 1965.

5. SCOPE

5.1 SUMMARY

This MTP describes methods for performing photostress data acquisition, including: the selection, application and calibration of the plastic coating, the acquisition of photostress data using a reflective polarscope, the determination of the directions of principal stresses by the construction of stress trajectories, and the determination of the difference in magnitude of principal stresses (or maximum shearing stress).

NOTE: Many of the terms used in this MTP are explained in Appendices A and B.

5.2 LIMITATIONS

No attempt will be made to describe the analysis of stress in any specific object or structure. The procedures outlined in this MTP are of a sufficiently general nature to be applicable to most cases of two dimensional photostress data acquisition.

6. PROCEDURES

6.1 PREPARATION FOR TEST

6.1.1 Selection of Plastic

The plastic coating shall be selected using the following criterion.

- a. Sheet or liquid plastic may be used. Sheet plastic shall normally be preferred over the liquid forms since it can be bonded to the test item at room temperatures and its thickness is uniform and predetermined. However, the irregular shape of the surface or the size of the area to be tested may require the use of liquid plastic. Liquid plastic may be directly applied to the test item surface by brush or spray or it may be used to make up castings of specially shaped sheet plastic. For additional selection criterion see Reference E and F.
- b. The thickness of the plastic applied shall be the optimum relationship between being thin enough to not materially reinforce the test item and being thick enough to bring out the desired degree of photostress resolution.

c. The plastic shall have a strain constant compatible with the strains to which the test item will be subjected.

NOTE: Plastics are available in high strain and low strain types. The maximum strain values to which the plastics can be subjected without loss of accuracy are listed on the technical data sheets for plastics. See also Appendix C, Pages C-7 and C-8.

6.1.2 Preparation of Surface

The theory of photostress techniques is based on the assumption that the plastic coating be subjected to the same stress and strain as the surface of the test item. To ensure this, it is essential that a strong and continuous bond exist between the surface of the test item and the plastic coating. To ensure this bond the surface must be prepared as follows:

a. All paint and primer coatings shall be removed using a suitable stripper.

NOTE: The presence of paint may result in the non-adhesion of the plastic, the introduction of impurities into the adhesive or a tendency of the paint to creep under load. All of the above may affect the outcome of the test.

b. The surface shall then be roughened by sanding with emery paper or with a mild grit blast.

c. If the surface is not now reflective it shall be polished and then slightly roughened or painted with applicable reflective paint.

NOTE: If the plastic to be applied has a reflective backing this step may be omitted. Also this step may be omitted if the adhesive to be used is reflective, e.g., photo stress reflective bonding adhesive.

d. The surface should be covered with paper to prevent contamination prior to bonding.

6.1.3 Application of Plastic

a. Sheet Plastic

- 1) Sheet plastic shall be applied by bonding it to the test item using a special adhesive which is applied like any ordinary cement.
- 2) The adhesive shall be allowed to harden for 25 hours.

b. Liquid Plastic

- 1) The liquid plastic shall be applied to the test item by brushing, spraying, pouring or dipping.

- 2) The test item shall be heated to from 150 to 230 degrees Fahrenheit (F°) depending upon the facility used.
- 3) Allow a few minutes for the plastic to harden, then apply a second layer.
- 4) Repeat this procedure until the desired thickness of plastic is attained (usually from 0.001 to 0.060 inches).

c. Casting and molding of liquid plastic

NOTE: This procedure is discussed in detail in Reference F.

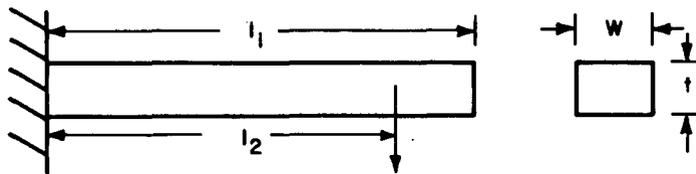
- 1) A flat sheet is made by pouring some liquid plastic and some hardner into a level mold.
- 2) The plastic is polymerized at 122°F for approximately 45 minutes, and then removed from the mold.
- 3) The resulting sheet can then be shaped over the test item and bound to it with special adhesive.

6.1.4 Calibration of the Plastic

a. Measure the thickness of the plastic on the test item by direct measure using a micrometer or a small field meter.

NOTE: To use the small field meter, focus first on the surface of the plastic surface and then on the surface of the test item. The difference in focus can be read on the micrometer attachment.

- b. Apply a similar layer of plastic to a standard testing beam.
- c. Record the dimensions of the beam as shown below:



- d. Record the following physical characteristics of the beam:
e.g., density.
- e. Load the beam as a cantilever with a known load while observing the beam with a reflective polarscope using monochromatic light.
- f. Record the photostress patterns as they develop.
- g. Repeat steps e and f with other known loads.
- h. Calculate and record principal strain for each load using the standard formula for a beam in flexure.
- i. From the data recorded in steps f and h above calculate the value of the strain constant (K) using equation 6.4.1.c.

6.2 TEST CONDUCT

6.2.1 Identification of Isoclinics

NOTE: Isoclinic lines are lines through points where the principal stresses are aligned in the same direction.

a. The quarter wave plates on the reflective polarscope shall be removed from the polarscope optical path so that the polarscope is in the plane polarized mode of operation.

b. The analyzer shall be rotated to the crossed or parallel position depending upon whether a light or dark background is desired.

NOTE: For the following discussion it will be assumed that the background is light (crossed position)

c. The test item shall be loaded in accordance with MTP 5-2-504 or other applicable MTP.

d. The test item shall be inspected and isoclinics shall be identified and their positions recorded by marking the test item, by suitable tracing or by photographic means.

NOTE: Procedures for distinguishing isoclinics from isochromatics are found in reference D. In general if monochromatic light is used, both isoclinics and isochromatics are the same color but if the plane polarscope is converted into a circular polarscope the isoclinics will disappear and only the isochromatics will remain. If white light is used the isoclinics will appear as black lines and the isochromatics will appear as bands of multi colored lines.

e. The polarscope shall be rotated 10° with respect to the test item and step (d) shall be repeated.

f. Step (e) shall be repeated until the polarscope has been rotated 180° with respect to the test item.

6.2.2 Identification of Isochromatic Fringe Order

Isochromatics are regions where at all points within the region the difference in the principal stresses are the same. Isochromatics appear as black bands when the test item is illuminated with monochromatic light. If the light is plane polarized, isoclinic lines will also appear as black bands. However, if the polarizer is rotated the isochromatics will remain stationary while the isoclinics change position and disappear. If the light is circularly polarized only the isochromatic bands will appear. If the test item is illuminated with white light the isochromatic lines will appear as colored bands. If the white light is plane polarized isoclinic lines will appear as black bands. If the white light is circularly polarized only the isochromatic bands will appear. White light is usually used when the maximum number of fringe orders is less than four. Above fringe order three the individual color fringes begin to blend and become indistinguishable.

a. The quarter wave plate shall be positioned in the polarscope optical path such that the polarscope will function in the circular polarized mode.

6.2.2.1 Monochromatic Light Method

- a. Remove all loading from the test item.
- b. Illuminate the item with monochromatic light using a standard crossed circular reflective polarscope.

NOTE: If the polarizer and analyzer are in the crossed position the background will be light with the isochromatic lines appearing as black bands. This is the preferred method. If the polarizer and analyzer are placed in the parallel position the background will appear dark and the isochromatic lines will appear light.

- c. Slowly apply the load while constantly observing the points on the test item to be analyzed.
- d. The number of alternate conditions of variations of brightness at the point shall be observed and recorded as the fringe order at that point. Motion pictures may be used.

NOTE: This is illustrated best by an example of a bar tested in compression. When the bar is analyzed with a standard crossed circular reflective polariscope with the quarter-wave plates in opposition, it will appear dark under the zero load condition when viewed through the analyzer. It must be remembered that the analyzing instrument must be a crossed circular reflective polariscope to remove the isoclinics. As a load is applied, the bar gradually will appear lighter until it reaches maximum brightness, then it will darken again. This process will continue as long as the load is increased. Under the condition of no load, the dark image represents no retardation; hence, it is the zero fringe order. At the first maximum brightness, the retardation is equal to half the wavelength; therefore, the fringe order is one half. The second dark image represents a relative retardation of one wavelength, or fringe order one. In this manner, the retardation can be obtained by determining the fringe order and by knowing the wavelength of the light used. If a parallel circular reflective polariscope is used, the black bands will represent the half order fringe.

6.2.2.2 White Light Method

- a. Apply the full load to the test item and inspect the fringe pattern for black regions.

NOTE: Black regions are where the differences in principal stress is zero and are known as isotropic regions. If

such a region is not present the fringe order can only be determined by using the method described in the section discussing monochromatic light, (6.2.2.1).

- b. The black regions will be identified as fringe order zero.
- c. Color photographs shall be taken of the fringe pattern and retained as test data.
- d. The fringe order at any desired point shall be determined and recorded using the "tint of passage" method.

NOTE: The tint of passage is the transition from the red to the blue or green. This is a sharp and easily recognized line, and it should be used for the reference fringe. The tint of passage of first order corresponds to a relative retardation of 2.27×10^{-5} inches, as stated in Reference C. The tint of passage of order one (first fringe) is the first tint of passage encountered when moving away from a black area (location of zero stress) or a fringe of zero order. It must be remembered that the analyzing instrument, as previously stated, must be a crossed circular reflective polariscope. The subsequent tints of passage are fringes two, three, etc., and the relative retardation is $2 \times 2.27 \times 10^{-5}$ inches, etc. In fringes of higher order, the blue color disappears and is replaced by green.

It must be noted that the fringe order is increasing only when the color is going from red to green in the direction in which fringes are being counted. If the color order is reversed, the operator must deduct fringe orders.

6.2.3 Removal of Plastic

Remove the plastic from the test specimen using a wedge scraper tool and a hot air gun. Any remaining bonding adhesive shall be removed with an epoxy stripper and a wooden spatula.

6.3 TEST DATA

6.3.1 Calibration of Plastic

Record the following:

- a. Thickness of applied plastic coating in inches
- b. Manufactures calibration constant

NOTE: If the manufactures calibration constant is not available or if additional calibration data is required, record the following additional data.

- c. Dimensions of cantilever as described in 6.1.4 c, in inches.

An example of this procedure is shown in Table I.

Table I. Colors and Fringe Orders

COLOR	FRINGE ORDER
Black	
Yellow	
Red	
— — — — —	1
Green or Blue	
Yellow	
Red	
— — — — —	2
Green	
Yellow	
Red	
— — — — —	3
Green	
Yellow	
Green	
— — — — —	3
Red	
Yellow	
Green	
— — — — —	2
Red	

- d. The physical characteristics of the beam, e.g., density in pounds/(foot)³.
- e. The weight in pounds of the applied load
- f. Photostress pattern for the load recorded above
- g. Repeat steps (e) and (f) above for all additional loads.

6.3.2 Identification of Isoclinics

- a. Record the isoclinic pattern for each ten degree increment of rotation of the polarscope.

6.3.3 Identification of Isochromatic Fringe Order

- a. Record the fringe order at all points where the stress difference is desired.
- b. Record the average thickness of the plastic coating in inches

6.4. DATA REDUCTION AND PRESENTATION

6.4.1 Calibration of Plastic

- a. From equations describing the standard cantilever beam determine the stress at the surface of the beam at the point under observation.
- b. Determine the fringe order at the point under investigation.
- c. Using the following equation determine the optical strain constant (K).

$$K = \frac{2st}{n}$$

Where:

- n = fringe order at point
- t = thickness of plastic in inches
- s = surface stress at point

NOTE: This equation is a special case of

$$S_1 - S_2 = \frac{Kn}{2t}$$

Where: in the case of a cantilever beam $S_2 = 0$.

6.4.2 Construction of Stress Trajectories

NOTE: Stress Trajectories (or isostatics) are lines parallel or normal to the two principal-stress directions at all points through which they pass and graphically represent the directions of the principal stresses.

- a. Superimpose the tracings of isoclinics taken at each 10 degree increment of rotation of the polariscope on one drawing and label each isoclinic with the angle of rotation associated with it. e.g., Figure 1.
- b. Pick any point A on the first isoclinic
- c. From point A draw a straight line with a slope equal to the average of the angles of the first and second isoclinic.
- d. The point where the straight line crosses the second isoclinic shall be labeled point B.

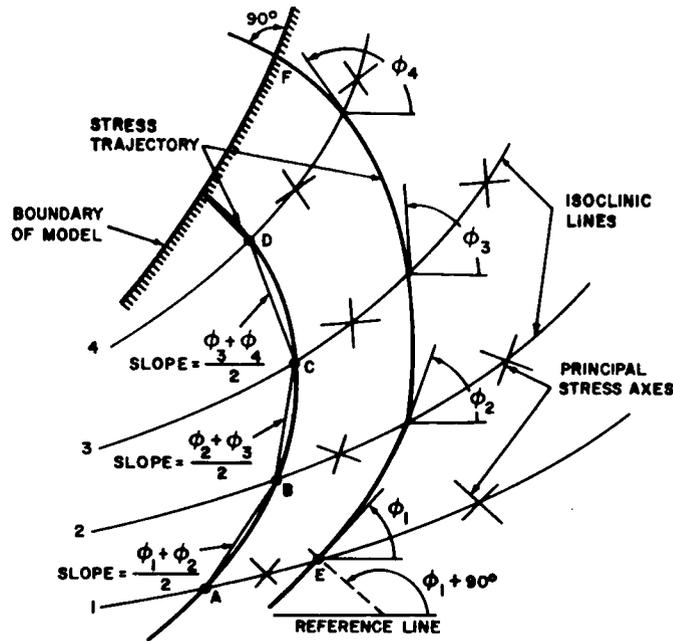


Figure 1.

- e. From point B draw a straight line with a slope equal to the average of the angles of the second and third isoclinic.
- f. The point where the straight line crosses the third isoclinic shall be labeled point C.
- g. The process shall be continued until the last isoclinic has been crossed.
- h. A smooth curve shall be scribed through all the points determined above (A, B, C, etc), such that all of the straight lines constructed form chords to the curve.

NOTE: All of the stress trajectories thus formed must form an orthogonal network (intersect only at right angles to each other and to free boundaries).

6.4.3 Determination of Stress Difference

- a. Determine the stress difference at those points where the fringe order has been determined using the following equation:

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$$S_1 - S_2 = \frac{Kn}{2t}$$

Where:

t = thickness of plastic in inches
K = stress constant in pounds/inch
n = fringe order

APPENDIX A

Polarization of Light

The terms "polarization" indicates that some control is exerted on the light vector. Light can be plane polarized, circularly polarized, or elliptically polarized.

Plane Polarization -- When the light vector is confined to a single plane, the light is said to be plane polarized, as illustrated in Figure a. The plane containing the light vector is called the plane of vibration, and the plane at right angles to it is called the plane of polarization. These planes are described in Reference A. Ordinary light may be thought of as a combination of an infinite number of plane polarized components whose planes of vibration have every conceivable orientation, as illustrated in Figure A-2.

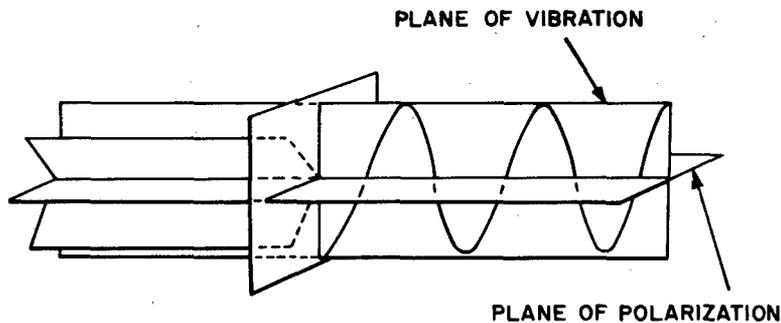


Figure A-1.

Plane Polarization

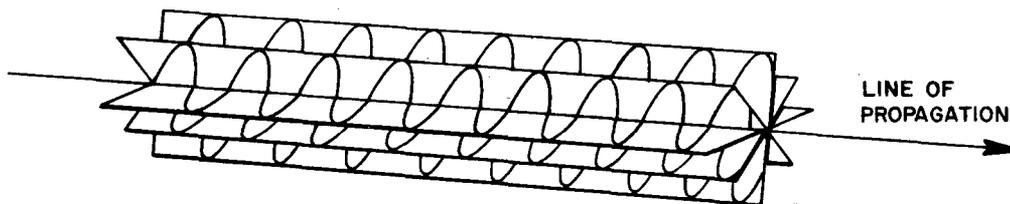


Figure A 2

Ordinary Light (No Control Over Light Vector)

Circular Polarization -- When the light vector is made to rotate about the line of propagation with its magnitude remaining constant, it is circularly polarized. If the vector is plotted at various positions along its line of propagation, the tips of the vector will form a circular helix. Circularly polarized light is illustrated in Figure A-3.

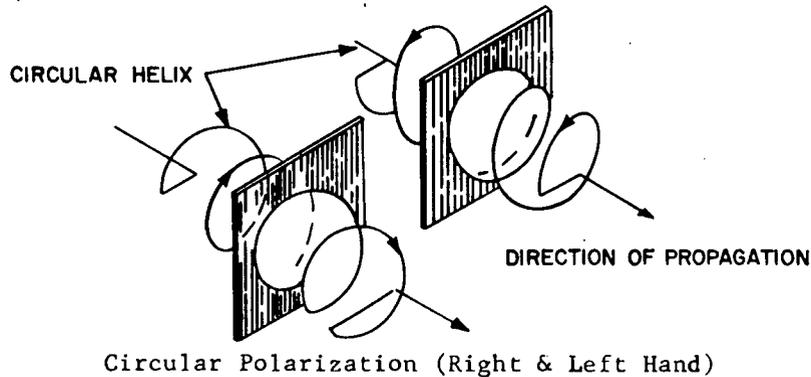


Figure A-3.

Elliptical Polarization -- Elliptical polarization essentially is the same as circular polarization, except that the magnitude of the vector changes periodically during rotation. If the vector is plotted at various positions along its line of propagation, the tips of the vector will form an elliptical helix, as illustrated in Figure A-4.

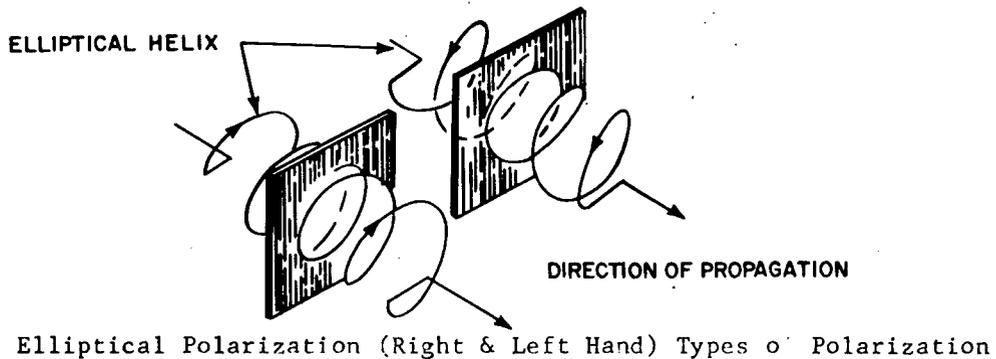


Figure A-4.

Birefringence -- Incident light passing through certain transparent crystalline materials such as calcite and mica is broken up into two beams which travel through the material at different speeds. Thus, one beam is retarded with respect to the other. This phenomena is known as birefringence or double refraction, and is illustrated in Figure 5. In addition to the

naturally birefringent materials, certain plastics become birefringent when they are under strain. A second effect of double refraction is that the two beams are plane polarized at right angles to each other. The directions of polarization corresponds to the transmission axes of the naturally birefringent material or to the directions of the principal strains in the stressed plastic. The axis which retards the beam is called the slow axis, and the other the fast axis.

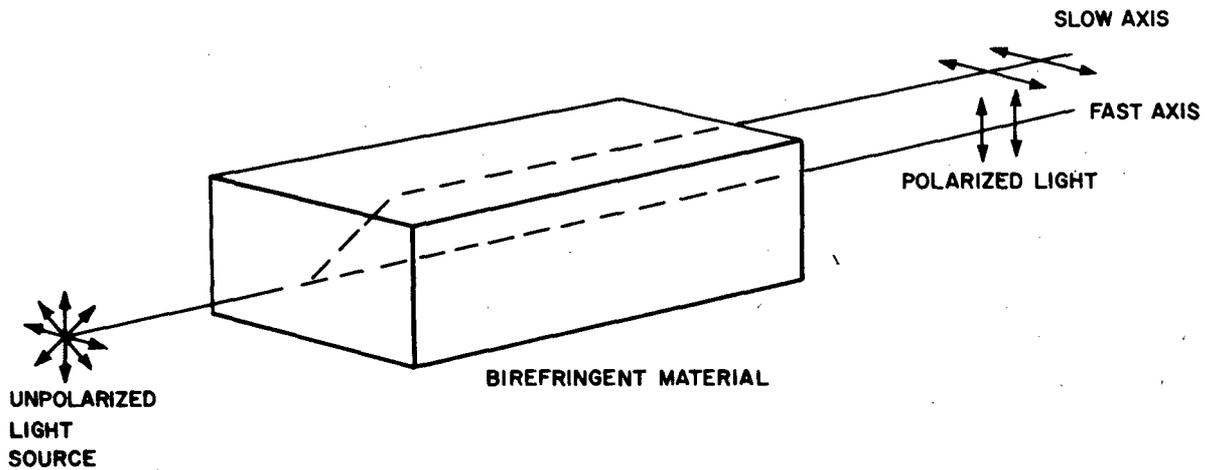


Figure 5. Action of Birefringent Material

APPENDIX B

Optical Law of Photostress

In any material which becomes birefringent when stressed, the relative retardation is related to the difference between the principal stresses by:

$$\delta n = C(\sigma_1 - \sigma_2)_p \cdot 2t \quad (1)$$

or

$$(\sigma_1 - \sigma_2)_p = \frac{\delta n}{2Ct} \quad (2)$$

Where:

- t = thickness of the photostress plastic
- C = stress optical constant
- p = photostress plastic symbol
- δn = relative retardation measured when polarized light is traversing the plastic under normal incidence
- σ_1, σ_2 = principal surface stresses

These derivations are described in Reference C. The equation uses $2t$ because the light is reflected from the work piece, passing through the plastic twice.

Hooke's law for strains states that:

$$\epsilon_1 = \frac{\sigma_1}{E} - \frac{\sigma_2}{E} \mu \quad (3)$$

and

$$\epsilon_2 = \frac{\sigma_2}{E} - \frac{\sigma_1}{E} \mu \quad (4)$$

Where:

- E = modulus of elasticity of the plastic
- ϵ_1, ϵ_2 = principal surface strains
- μ = Poisson's ratio

Therefore,

$$\sigma_1 - \sigma_2 = (\epsilon_1 - \epsilon_2) \frac{E}{1 + \mu} \quad (5)$$

and

$$(\sigma_1 - \sigma_2)_w = \frac{(\epsilon_1 - \epsilon_2)_w E_w}{(1 + \mu_w)} \quad (6)$$

$$(\sigma_1 - \sigma_2)_p = \frac{(\epsilon_1 - \epsilon_2)_p E_p}{(1 + \mu_p)} \quad (7)$$

Where:

w = workpiece symbol

Combining equations (2) and (7),

$$\frac{\sigma_n}{2tC} = \frac{(\epsilon_1 - \epsilon_2)_p E_p}{(1 + \mu_p)} \quad (8)$$

Since the plastic exactly follows the deformations of the work piece,

$$(\epsilon_1 - \epsilon_2)_p = (\epsilon_1 - \epsilon_2)_w \quad (9)$$

so that

$$(\sigma_1 - \sigma_2)_w = \frac{(\epsilon_1 - \epsilon_2)_p E_w}{(1 + \mu_w)} \quad (10)$$

$$= \frac{E_w (1 + \mu_p)}{E_p (1 + \mu_w)} \frac{(\delta n)}{2tC} \quad (11)$$

$$= \frac{E_w}{K (1 + \mu_w)} \frac{(\delta n)}{2t} \quad (12)$$

and

$$(\epsilon_1 - \epsilon_2) = \frac{\delta n}{2tK} \quad (13)$$

Where:

$$K = \frac{CE_p}{1 + \mu_p} = \text{strain optical constant} \quad (14)$$

APPENDIX C
TEST EQUIPMENT

Polariscopes

The polariscope is an optical device usually employed to produce the required polarized light and to interpret the light patterns in a photo-elastic stress analysis. A polariscope may be plane or circular, and crossed (standard) or parallel.

a. Plane Polariscope -- The plane polariscope consists of a light source and two polarizing elements arranged as shown in Figure C-1. The polarizing element nearer the light source is the polarizer, while the other one is the analyzer. When the transmission axes of the polarizer and the analyzer are parallel, the instrument is a parallel polariscope; when the two axes are at right angles to each other, it is a crossed polariscope. As the name implies, the plane polariscope produces plane polarized light.

b. Circular Polariscope -- The circular polariscope is similar to the plane polariscope, except that two quarter-wave plates are placed between the polarizer and the analyzer, as shown in Figure C-2. The quarter-wave plates are oriented so that their transmission axes are inclined at an angle of 45 degrees to the axes of the polarizer and the analyzer. The quarter-wave plates may have their fast axes at right angles to each other, or they may augment each other. The polarizer and the analyzer may be crossed as shown in Figure 3, or they may be parallel.

c. Reflective Polariscope -- The reflective polariscope is identical to the polariscopes described above except that the optical elements are arranged side by side as shown in Figure C-3. The reflective polariscope will be either circular or plane, depending upon whether the analysis is for the difference or for the direction of the principal stresses.

Optical Compensators -- The optical compensators are devices which artificially produce a fringe of a known value at any given point on the test item. They are used if the number of isochromatics is insufficient for an accurate whole-field strain difference determination. Usually, they are calibrated quartz wedges. The equipment operation manuals provide details on their use.

e. Large Field Meter -- The large field universal meter is used to analyze large areas of the test item to obtain the complete picture of stress differences and directions of the principal stresses. The large field meter is a portable instrument consisting of an illuminator equipped with a polarizer and an analyzer lying in the same plane. The illuminator may be a source of either white light or monochromatic light. The polarizer is located in front of the illuminator, and the operator observes the test item through the analyzer. The polarizer and analyzer can be rotated independently, or they can be synchronized to rotate together. The instrument also has two quarter-wave plates, one of which can be placed in front of the polarizer and the other in front of the analyzer to make the instrument a circular polariscope.

The large field meter can be used either for static or for dynamic tests. In dynamic testing, the standard illuminator is replaced, either with a stroboscope for direct viewing of the test item under alternating loads, or with a flood light for use with a high speed camera. When a camera is used, it is placed behind the analyzer.

f. Small Field Meter -- The small field meter is used to analyze small parts, or for detailed analyses at small discontinuities on large test items. It consists of a microscope equipped with a light source, a polarizer, and an analyzer. The unit can be used to measure the thickness of the plastic by focusing first on the surface of the plastic, then on the surface of the test item and reading the micrometer attachment. It can be adapted for dynamic stress analyses by attaching a photoelectric cell and an amplifier.

g. Oblique Incidence Meter -- The oblique of incidence meter is used for a point by point determination of the magnitude of each separate principal stress. An oblique incidence attachment is made for both the small field and the large field meters. Methods for using the method are found in the reference material.

h. Quarter-Wave Plates -- The quarter-wave plates are plates of a birefringent material which, for a given wavelength of light, produce a relative retardation of one fourth of a wavelength. Plane polarized light entering a quarter-wave plate with the plane of vibration inclined at an angle of 45 degrees to the transmission axes of the plate will be transformed into circularly polarized light, as shown in Figure C-4.

i. Plastic Sheets -- Commercially available plastic sheets are manufactured and are either clear or metallized on one face and are applied to the test item with cement. The sheet of plastic may be either the low strain or the high strain type. The limit of linear strain/optical response for the low strain sheet is a unit strain equal to 2.5 percent. When it is used in temperatures above 250°F, the strain can be 30 percent. The constant K is about 0.1 in the temperature range of minus 44 to plus 85°F. Above 250°F, the value of K drops to 0.03. The allowable strain for the high strain sheet is 30 percent at room temperature with a K value of about 0.02. This type of plastic is used for stress analysis of highly deformable materials such as rubber. Each plastic sheet is marked with its K value. The variations in K values with temperatures are described in detail in the technical data sheets for the plastics. The same information may be derived by calibrating the plastic at the desired temperature.

j. Liquid Plastic -- The liquid plastics also are available in both low strain and high strain forms. When the low strain liquid plastic is used at room temperature, it has a limit of strain/optical response of about three percent, with a K value of approximately 0.1. The high strain liquid plastic at room temperature has a maximum strain value of 30 to 50 percent with a K value of approximately 0.02. The k value also can be determined by calibration. Either form of liquid plastic may be applied by brushing, spraying, or dipping the test item. Also the liquid plastic cast to from special shapes of sheet plastic as explained in reference.

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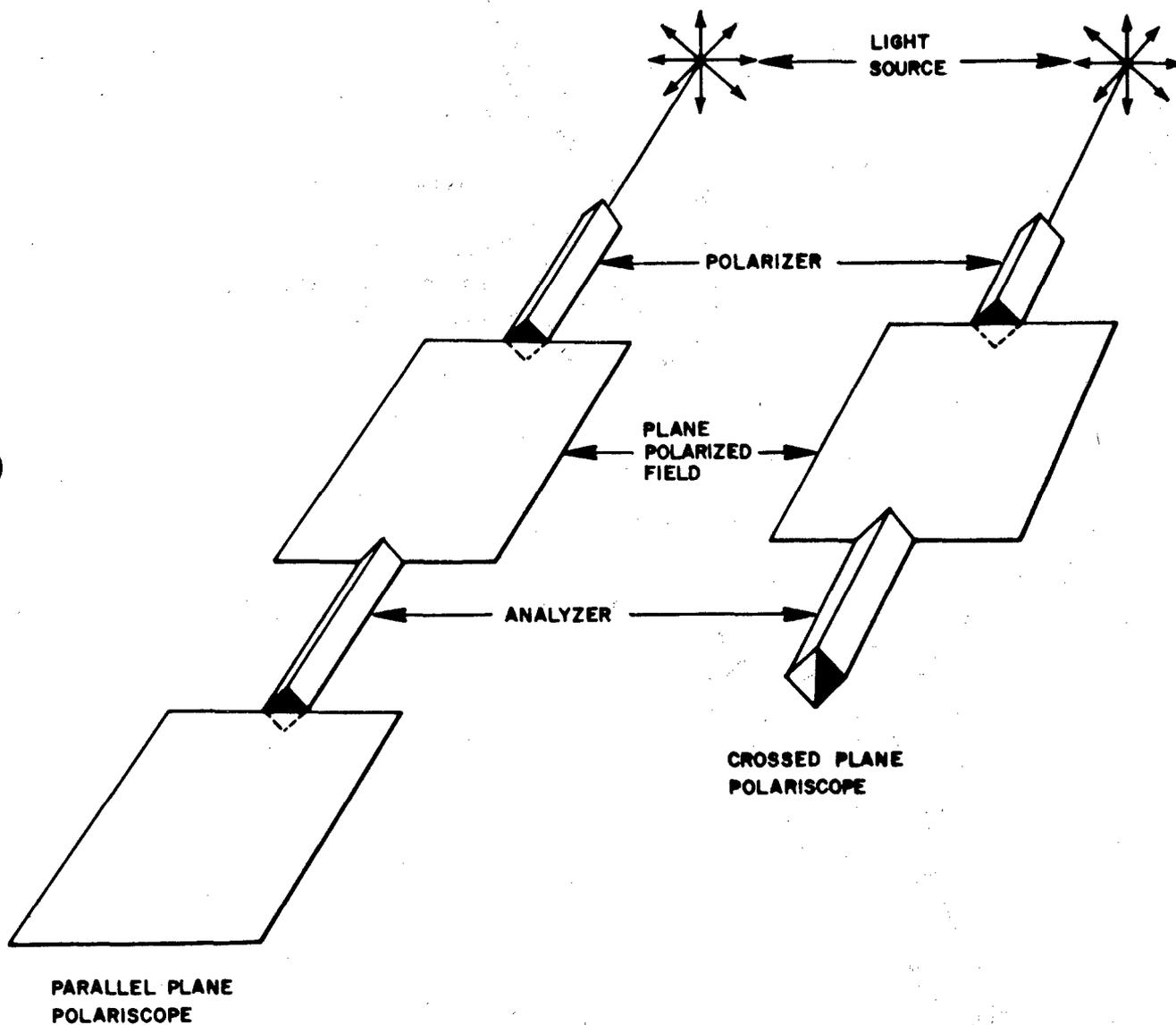


Figure C-1. Plane Polariscopes

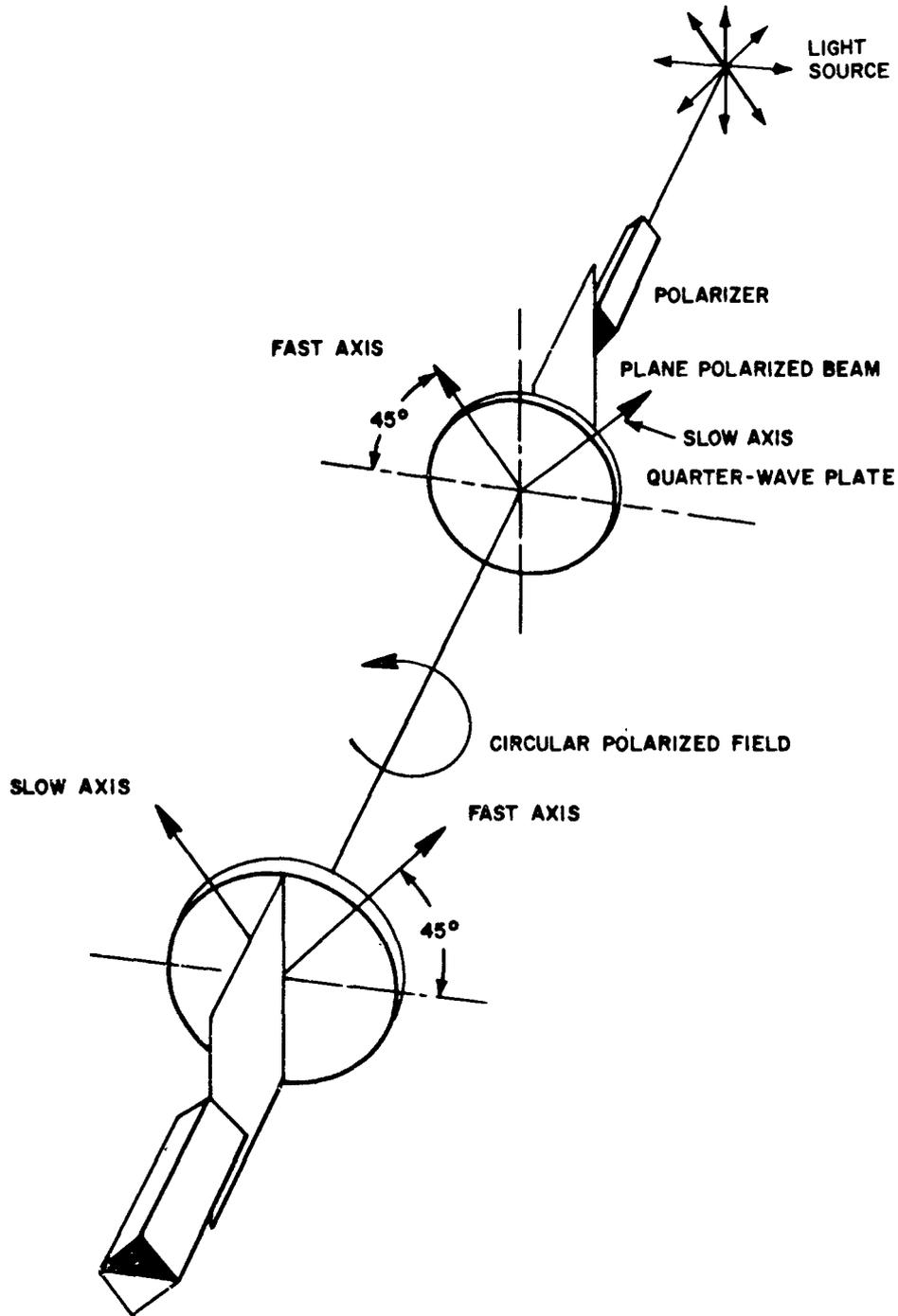


Figure C-2. Circular Polariscope

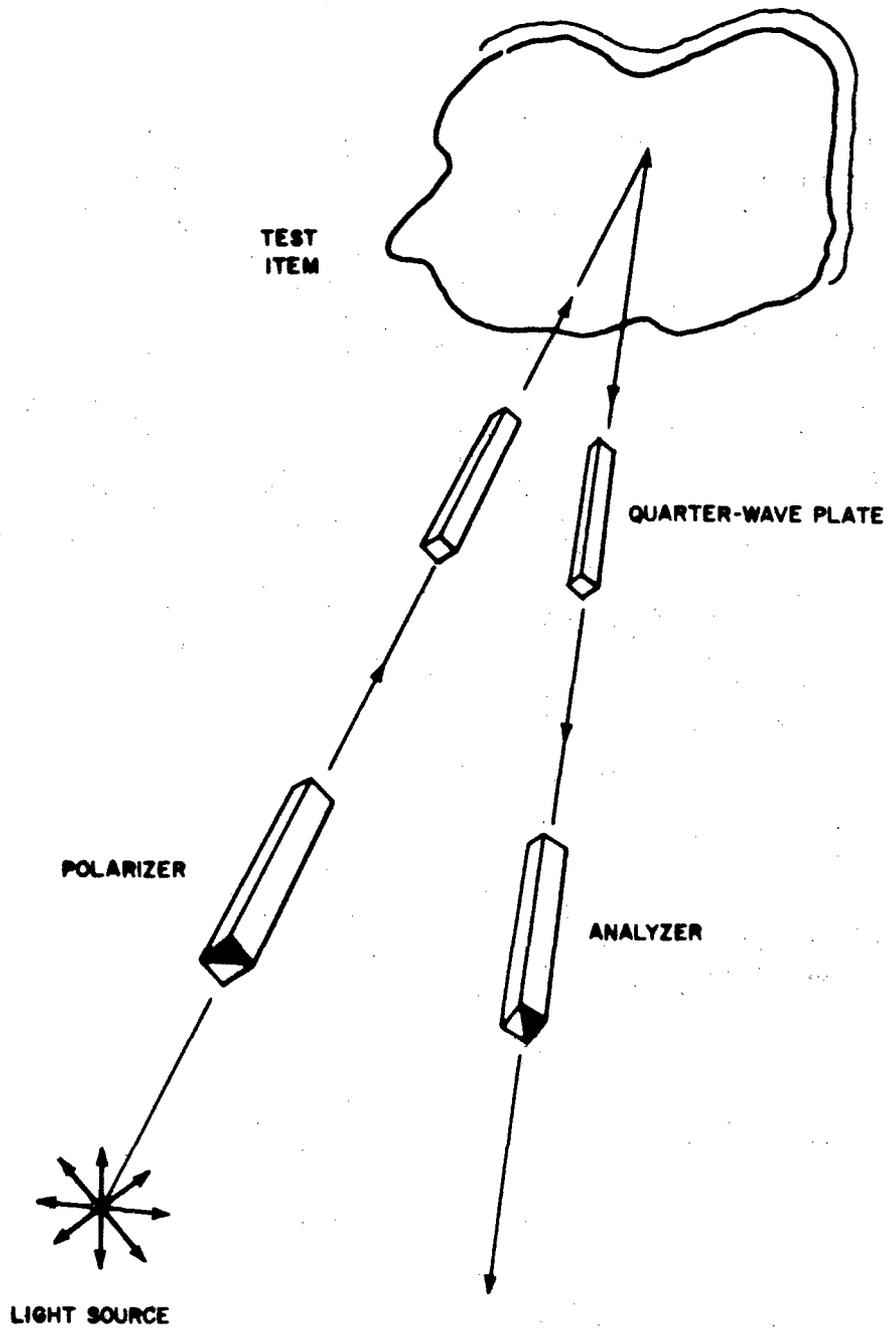


Figure C-3. Circular Reflective Polariscopes

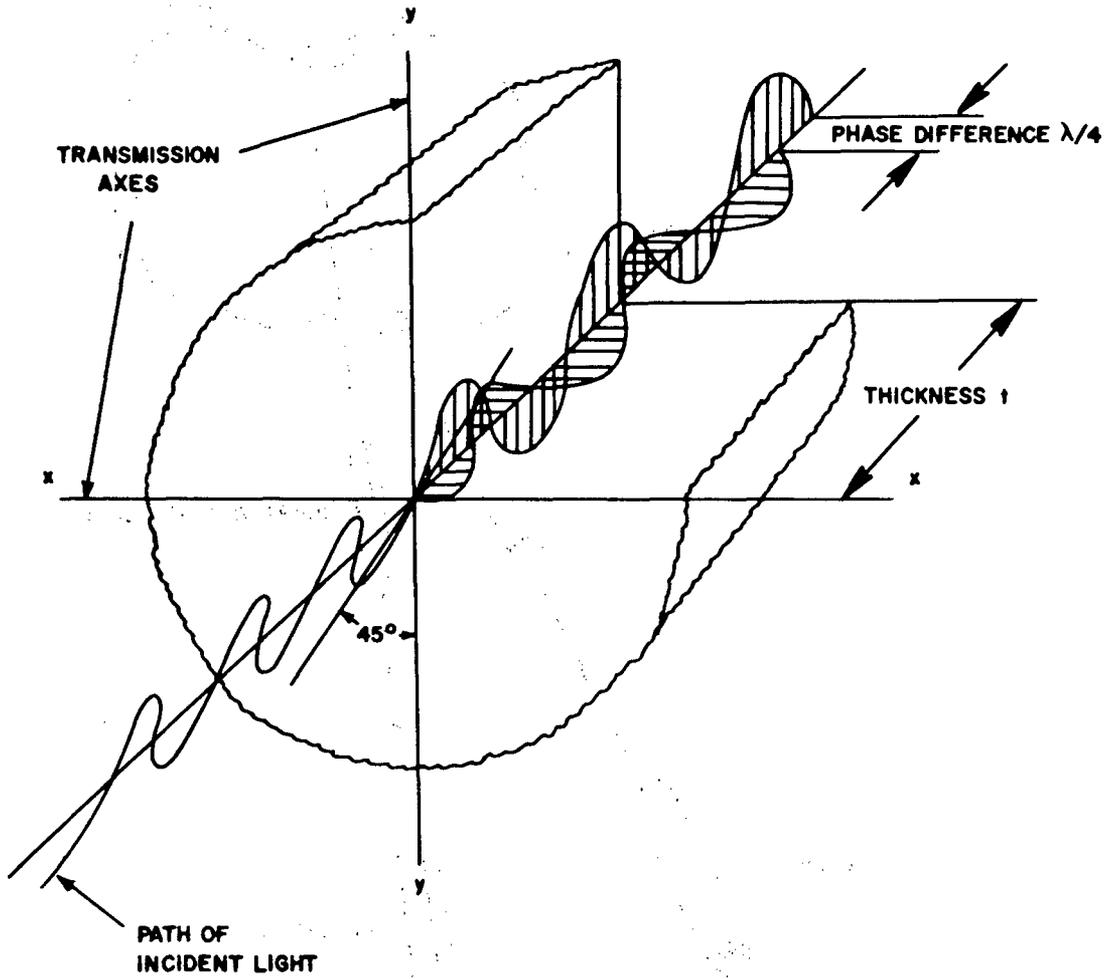


Figure C-4. Action of a Quarter-Wave Plate