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Application of the photoelastic coating method to evaluate the stress distribution on the external surface of the cap of an electrical insulator

Harijeetsinh Jagtiani

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APPLICATION OF THE PHOTOELASTIC COATING METHOD
TO EVALUATE THE STRESS DISTRIBUTION ON THE
EXTERNAL SURFACE OF THE CAP OF AN
ELECTRICAL INSULATOR

By
Harijeetsinh Jagtiani, 1943

A
THESIS

submitted to the faculty of the
UNIVERSITY OF MISSOURI AT ROLLA
in partial fulfillment of the requirements for the
Degree of
MASTER OF SCIENCE IN MECHANICAL ENGINEERING

Rolla, Missouri
1965

Approved by

Peter S. Harrison (Advisor)
E. T. Hanson
J. M. Moore
Isochromatics of a Loaded Insulator Cap
The Photoelastic Coating Method was applied to find the surface stresses on the cap of an electrical insulator. The strain distribution was observed and photographed. This color photograph indicated a visible geography of the maximum shear strain distribution in the region of the insulator where the birefringent plastic was bonded with a reflective cement.

The Oblique Incidence technique was used to determine the principal stresses from the maximum shear strain (or the principal strain difference) readings, obtained from Normal Incidence.

The critical cross-section of the insulator head was optically located, giving an initiative for the re-design of the insulator cap.

The photoelastic method was applied to determine the state of stress at this critical section.
ACKNOWLEDGMENTS

The author gratefully appreciates the constant help and guidance given him by Dr. P. G. Hansen, Professor of Mechanics, University of Missouri at Rolla, in devising the solution of this investigation. Without Dr. P. G. Hansen's thoughtful suggestions and views, this investigation would have had little value.

Thanks are due to Dr. D. E. Day, Professor of Ceramic Engineering, University of Missouri at Rolla for his expert opinions and for the procurement of data for the insulators.

The A. E. Chance Company, Centralia, Missouri, was very helpful for the supply of some equipment and materials.

Gratitude is due to Professor R. F. Davidson, Chairman of the Mechanics Department, University of Missouri at Rolla, for his interest in the author's investigation and for ordering some valuable pieces of equipment for use in certain phases of the problem.

The author thanks Mr. R. L. Pendleton, Instructor in Mechanics, University of Missouri at Rolla, for his encouragement and help.

This thesis is affectionately dedicated to the author's parents and Mrs. Opalene Tucker for their inspirations.
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<td>area of plastic in the mold</td>
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<td>$\gamma$</td>
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I STATEMENT OF THE PROBLEM

A photograph of the electrical insulator is shown in Figure 1.

It is akin to any ordinary type of insulator usually encountered on the power line poles on the streets.

The insulator is basically an assembly of a steel cap, porcelain body, stud, and portland cement as depicted in Figure 2.

This type of insulator can be used singly or in a series combination, because of the "tongue-socket" design of the stud and the cap. The insulator is axially symmetrical and is required to sustain a vertical centric load through its axis of symmetry.

The cap is coupled by a yoke to another insulator or to the power line pole. The steel loading stud is connected through a yoke to a high voltage power line or to another insulator. The main body of the insulator is made of porcelain and is the primary insulating medium. The portion of the porcelain outside the cap, called the skirt, is present primarily to prevent arcing around the insulator. It is not subjected to any mechanical load. The stud and the cap are bonded to the porcelain by use of neat Portland Cement.

The loading cap (see Figure 3), made of forged steel, is responsible for the structural rigidity of the insulator.

This thesis is primarily restricted to the optical
Figure 1  Photograph of One-Half of an Insulator
Figure 2  Half-Sectional View of Insulator
Figure 3  Full-Size Section of Insulator Cap
determination of the highest stressed horizontal section of the cap (see the frontispiece) and then to apply photoelastic methods to evaluate the state of stress at this critical section.

Upon testing such insulators with both the mechanical and electrical loads simultaneously, it was found that the failure invariably occurred due to the breaking of the porcelain, the cap being pulled off. The idea is to synchronise the failure of the porcelain and the steel cap in order to have a balanced design.

The shape of the cap also plays an important role in its design because the circular jaw-like bottom of the cap may be susceptible to opening out (radially) which may result in its slipping off from the porcelain.

Except for the coupling joint on the top of the cap, the cap is circular around its vertical axis of symmetry. In addition to this, it is slightly curved at the sides (see Figure 3) resulting in a double curvature to suit the shape and design of the porcelain inside. In view of this fact the stress distribution is three-dimensional. On the surface the state of stress is bi-axial since it is a free surface. It is also possible to prove that the stress normal to the double curvature at any point on a horizontal section of the head anywhere between sections AA and BB (see Figure 3) is negligible.

From theoretical considerations and by measurements,
it was stipulated that AA and BB were the bounding limits for the maximum tensile stress on the cap.

Such a bi-axial state of stress can easily be determined by using the photoelastic coating technique between the sections where the highest stress is suspected. This technique was considered best since the critical point or the critical section of the cap is visible and the optical readings can be restricted to the point or points of interest. This is not possible by the bonded electrical strain gage method except by the use of many gages.

The evaluation of the principal stresses from the principal strains calls for the magnitude and sign of the principal strains. The oblique incidence technique along with the normal incidence readings is very suitable in estimating the state of stress for this kind of a problem.

A photograph of the Reflection Polariscope is shown in Figure 4 and simplified in the line sketches of Figure 5.
Figure 4  Photograph of Reflection Polariscope with Telemicroscope and Oblique Incidence Attachments
(a) Crossed Plane Polariscope

(b) Crossed Circular Polariscope

P Polarizer     PC Photoelastic Coating
A Analyzer     RS Reflective Surface
Q', Q" Quarter-Wave Plates IC Insulator Cap

Figure 5 Diagrammatical Sketch of Reflection Polariscope Set for Normal Incidence
II REVIEW OF LITERATURE

No literature directly pertinent to the problem was encountered.

The idea of using Photoelasticity to study the surface stresses on actual parts of any shape is not new.

In 1930, M. Mesnager (1), working in France, proposed and investigated the use of photoelastic material bonded to the polished surface of a metal prototype. Subsequent attempts were made by Mabouix (2) in France and Oppel (3) in Germany during the 1930's.

These early attempts did not succeed for three reasons. First, the strain-optical constant K was too low. For this reason insufficient fringes were developed. Second, it was difficult to bond the photoelastic plastic to the metal in such a way that the plastic was subjected to the same surface strains as existed in the metal prototype. Third, the plastic used was not sufficiently stable with respect to time for practical use.

In March, 1954, Professor Jessop in England reported research on this subject by a British laboratory.

In July, 1954, Mylonas and Drucker (4) of the United States presented a paper in Brussels at the convention of I.U.T.A.M. on research conducted at Brown University. The technique cited could only be applied to flat parts.

In 1953, the first practical results in both elastic and plastic ranges of deformation applicable to any size
and shape (flat or curved) of part were achieved in industrial applications in France (5).

The accuracy of the results, stability in time and facility of application have caused this technique to be widely applied to industry in Europe.

The method has been applied in different industries in the United States since 1956.

Dr. Felix Zandman (6) has been very active in improving and applying several phases of the technique.

This technique is sometimes called "PhotoStress". (*)

Felix Zandman, M. Walter and S. S. Redner have written an interesting paper, "Stress Analysis of a Rocket Motor Case by the Birefringent Coating Method" (7)

Today the technique is also used for complicated stress analysis of such varied structures as: aircraft and missiles, bridges, pressure vessels, machinery, automobiles etc.

* Zandman Method
INTRODUCTION TO THE PHOTOELASTIC COATING METHOD

The rudiments of the photoelastic coating method are essentially the same as those of Photoelasticity. In fact the coating method is sometimes referred to as a logical extension of conventional Photoelasticity.

This method is basically a new quantitative stress analysis tool which converts principal strain difference or the maximum shear strain into color. It combines the functions of Photoelasticity, brittle lacquers and bonded electrical strain gages.

In optics, there are some materials which are called doubly-refractive or birefringent materials; they break up an incident ray into two components, both polarized in different but perpendicular planes, passing through the birefringent material with different velocities. It is the relative retardation of these components which appears to the eye as a color.

Some plastics also exhibit birefringence temporarily when strained. The birefringence in such plastics disappears when the loads are removed.

If a beam of white polarized light is passed through a strained model of birefringent material, a colored pattern is observed; this indicates the stress or strain distribution. This technique is called Photoelasticity.

On the other hand, the photoelastic coating technique is a method of stress analysis in which the actual
prototype to be stress analysed is coated with a photoelastic plastic. When a load is applied to the prototype the strains set up in it are transmitted to the plastic coating, through the interfacial cement bond. The plastic then becomes birefringent; this birefringence is directly proportional to the intensity of maximum shear strain of the plastic and hence of the prototype also, because of the rigid bond. If a reflective surface is provided at the interface between the prototype and the plastic bonded to it (or the interface itself a reflective cement), birefringence can be observed and measured by using a Reflection Polariscope (See Figure 4 on page 7).

When examined with the polariscope's plane polarized white light, the distribution of mechanical strains in the actual structure is revealed by black and colored fringe patterns. The polarized path of light may be made to strike the plastic normally (perpendicularly) or obliquely. These methods give different data which can be used to find each principal strain in magnitude and sign.

The black fringes, or the isoclinics, are the loci of points along which the principal strains have parallel directions. The shape of the isoclinic itself has no indication of direction; hence it should invariably be labeled by its parameter (angle in degrees). These directions are established by noting the angular position of a reference axis of the polariscope. Thus, by the rotation of the reference axis on the polariscope (from 0° to 90°) it is
possible to detect an isoclinic at any point on the surface of the subject being studied. This, in turn, makes it possible to define the directions of principal strains at each point where the plastic is coated on the prototype.

By inserting two additional optical components, quarter-wave plates, in the light path of the Reflection Polariscope, it is possible to suppress the isoclinics such that only the colored fringes remain visible in the plastic. The quarter-wave plates produce a polarized light known as circularly polarized light.

The colored fringes - called isochromatics - observed with polarized white light traversing the plastic under normal incidence, are the loci of points where the principal strain difference ($\epsilon_1 - \epsilon_2$) or the maximum shear strain (which is equal to $\epsilon_1 - \epsilon_2$) is constant ($\epsilon_1$ as used here is invariably greater, algebraically, than $\epsilon_2$).

If a black fringe is still visible with the quarter-wave plates in the field of observation, this black fringe will indicate an area where the principal strain difference is zero. An area of uniform color obviously denotes an area of uniform maximum shear strain. Color gradients correspond to shear strain gradients and color or fringe concentrations correspond to shear strain concentrations. Since the birefringence (or color) is directly proportional to ($\epsilon_1 - \epsilon_2$) it is possible to determine quantitative values of ($\epsilon_1 - \epsilon_2$) by measuring the degree of birefringence (or the fringe order) present in the plastic.
The measurement of birefringence can either be made directly by color comparison or may be accomplished by optical compensation. In the latter method some known birefringence is artificially added or subtracted from the system to get a black fringe (monochromatic light) or a "tint of passage" (white light). This "tint of passage" is a purple-red colored fringe occurring between the red and the green fringe. It is the most sensitive color to the eye. It has a precisely defined wave length. The relative retardation or the birefringence is actually defined in terms of units of wave lengths of light. Hence one wave length, corresponding to the first "tint of passage" corresponds to a retardation of one fringe. The fringe order is thus defined as the number of wave lengths that have been retarded at a certain point. The fringe order is a dimensionless number and is generally a fraction.
IV  THEORETICAL BASIS FOR THE APPLICATION OF THE METHOD
TO THE ELECTRICAL INSULATOR

(a) Normal Incidence:

Newmann's equation relates the relative retardation to
the principal stress difference by

\[ \delta_n = 2t_p (n_1-n_2) = 2t_p \varepsilon (\sigma_1-\sigma_2) \] \( \text{I} \)

Considering the strain sensitivity,

\[ \delta_n = 2t_p k (\varepsilon_1-\varepsilon_2) \] \( \text{II} \)

In both the above equations, it should be noted that
the thickness of plastic is multiplied by two because the
light reflects from the surface of the work-piece thus pas­s­
ing through the plastic twice. \((\varepsilon_1-\varepsilon_2)\) is the maximum
shear strain, identical for the plastic and the prototype.

Relative retardation is also given in terms of wave
lengths of light, by

\[ S_n = \lambda N_n \] \( \text{III} \)

as explained on page 14.

\( \lambda \) for "tint of passage" is 22.7 microinches.

From equations II and III we have

\[ (\varepsilon_1-\varepsilon_2) = \frac{\lambda N_n}{2t_p k} \] \( \text{IV} \)

Let \( f \) = fringe value of the plastic used; i.e., the
strain \((\varepsilon_1-\varepsilon_2)\) necessary to produce one fringe of
birefringence.

Then,
\[ r = \frac{\lambda}{2t_p K} \] ............................  V

The Generalized Hooke's Law states that for bi-axial states of stress,

\[ \epsilon_1 = \frac{\sigma_1}{E_s} - \frac{\mu_s}{E_s} \frac{\sigma_2}{E_s} \] ............................ VI

\[ \epsilon_2 = \frac{\sigma_2}{E_s} - \frac{\mu_s}{E_s} \frac{\sigma_1}{E_s} \] ............................ VII

And, as stated before, the state of stress in the insulator cap is bi-axial, therefore from equations IV, VI and VII it follows that

\[ \epsilon_1 - \epsilon_2 = \frac{(\sigma_1 - \sigma_2)}{E_s} (1 + \mu_s) \]

or

\[ \sigma_1 - \sigma_2 = \frac{(\epsilon_1 - \epsilon_2) E_s}{(1 + \mu_s)} \]

or

\[ \sigma_1 - \sigma_2 = \frac{\lambda N \epsilon_1 E_s}{2t_p K (1 + \mu_s)} \] ............................. VIII

Hence the principal strain difference and the principal stress difference can be determined by Normal Incidence (see Figure 5 on page 8) provided the strain-optical constant K, the thickness of the plastic and the elastic constants of steel are known.

(b) Oblique Incidence:

From the Generalized Hooke's Law for bi-axial state of
stress it is clear that

\[ \sigma_1 = \frac{E_0}{1 - \mu_s} (\varepsilon_1 + \mu_s \varepsilon_2) \] \hspace{1cm} \text{IX}

\[ \sigma_2 = \frac{E_0}{1 - \mu_s} (\varepsilon_2 + \mu_s \varepsilon_1) \] \hspace{1cm} \text{X}

It is evident that to evaluate either of the principal stresses \( \sigma_1 \) and \( \sigma_2 \) in magnitude and sign, the magnitude and sign of both \( \varepsilon_1 \) and \( \varepsilon_2 \) are involved.

After acquiring the value of \( (\varepsilon_1 - \varepsilon_2) \) from Normal Incidence, it is necessary to get another equation in \( \varepsilon_1 \) and \( \varepsilon_2 \) (with proper algebraic signs) by using the optical data obtained by making the light strike the plastic obliquely.

Figure 6 shows an element of a structure subjected to a system of forces producing strains \( \varepsilon_1 \) and \( \varepsilon_2 \). The surface of the structure is coated with birefringent plastic, thickness \( t_p \), and the axes 1 and 2 coincide with the direction of \( \varepsilon_1 \) and \( \varepsilon_2 \) at point 0. Since the plastic is bonded to the structure, the strains of both are identical.

In Normal Incidence the light propagates along axis 3 to strike at point 0 and retreat.

When the light is propagating through the plastic in Oblique Incidence, the relative retardation \( \delta_0 \) is proportional to the "secondary" principal strain difference in the plane perpendicular to the direction of propagation.

Assume the light propagation along direction 3', in the plane perpendicular to the direction 1 (Figure 7); in other
Figure 6  Oblique Incidence
Figure 7: "Secondary" Directions
words,
\[ \varepsilon_1 = \varepsilon_1' \]

The "secondary" principal strains (as they are called) in the plane perpendicular to \( 3' \) are (see Figures 7 and 8)
\[ \varepsilon_1' = \varepsilon_1 \] \text{......................... XI} \]
\[ \varepsilon_2' = \frac{\varepsilon_2 + \varepsilon_3 + \varepsilon_2 - \varepsilon_3 \cos 2\theta}{2} \ldots \text{XII} \]

Since the stress \( \sigma_3 = 0 \) (i.e. no pressure applied to the surface), we have
\[ \varepsilon_3 = \frac{\mu_p}{1-\mu_p} (\varepsilon_1 + \varepsilon_2) \] \text{........... XIII} \]

By substitution of this value into equation XII, we obtain the difference of the secondary principal strains \( \varepsilon_1' - \varepsilon_2' \), as a function of \( \varepsilon_1, \varepsilon_2 \) and the angle \( \theta \).

Also, for Oblique Incidence,
\[ \delta_0 = \frac{2t_pK}{\cos \theta} (\varepsilon_1' - \varepsilon_2') \] \text{............ XIV} \]

the thickness now being \( t_p/\cos \theta \).

Substitution of \( \varepsilon_3 \) (from equation XIII) into equation XII and the value of \( \varepsilon_2' \) thereof, into equation XIV, yields,
\[ \delta_0 = \frac{2t_pK}{\cos \theta} \left[ \frac{\varepsilon_1 (1 + \frac{\mu_p}{1-\mu_p} \sin^2 \theta)}{1-\mu_p} \right. \]
\[ - \varepsilon_2 \left( \cos^2 \theta - \frac{\mu_p}{1-\mu_p} \sin^2 \theta \right) \ldots \text{XV} \]
Figure 8 Mohr's Strain Circle
Solving equations II (page 15) and XV, simultaneously in $\varepsilon_1$ and $\varepsilon_2$ we find,

$$\varepsilon_1 = \frac{1}{2tpK (1 + \mu_p) \sin^2 \theta}$$

$$\left[ \delta_0 (1 - \mu_p) \cos \theta + \delta_n (\mu_p \cos^2 \theta) \right]$$

$$\varepsilon_2 = \frac{1}{2tpK (1 + \mu_p) \sin^2 \theta}$$

$$\left[ \delta_0 (1 - \mu_p) \cos \theta + \delta_n (\mu_p \cos^2 \theta - 1) \right]$$

The value of $\mu_p$ of the plastic used was 0.35 and the angle $\theta$ was 45°, and

$$\delta_0 = N_0 \lambda, \quad \delta_n = N_n \lambda,$$

therefore

$$\varepsilon_1 = \frac{\lambda}{2tpK} \left[ \begin{array}{c} \frac{0.68 N_0 - 0.222 N_n}{2tpK} \end{array} \right]$$

$$\varepsilon_2 = \frac{\lambda}{2tpK} \left[ \begin{array}{c} \frac{0.68 N_0 - 1.222 N_n}{2tpK} \end{array} \right]$$

If $\frac{\lambda}{2tpK} = f = \text{strain fringe value}$, then,

$$\varepsilon_1 = f \ (0.68 N_0 - 0.222 N_n) \quad \text{...... XVI}$$

$$\varepsilon_2 = f \ (0.68 N_0 - 1.222 N_n) \quad \text{...... XVII}$$

Now using equations IX and X, the magnitude and sign of $\sigma_1$ and $\sigma_2$ can be evaluated.
V EXPERIMENTAL PROCEDURE

Birefringent plastics are available in three forms. The cheapest and simplest to apply is a ready-made sheet of plastic with a standard thickness and known K. However, this can only be applied to flat surfaces or surfaces with a minimum radius of curvature of 40\". The sheets may be clear (for prototypes which are reflective or shiny, themselves) or mirror-type, one face of which is artificially made reflective. A reflective cement may also be used.

The second form of plastic is a liquid to be made into a sheet that can be contoured to a radius of curvature of about a quarter of an inch. The third form is liquid plastic to be applied with a brush or sprayed with a spray gun on the prototype and hardened by heating; this is especially suitable for complex shapes and high stress concentrations.

Because of the double curvature, it was decided that the contoured sheet would best suit the cap of the insulator.

For this purpose the author made a permanent aluminum mold with a glass plate for pouring plastic, the mold being adjustable to any required area of plastic sheet. This had to have leveling screws so that it could be leveled with a spirit level when pouring plastic molds to get a uniform thickness of the polymerized plastic.

In the selection of the plastic, the factors to be taken into consideration are maximum prototype strain, double curvature, surface of prototype - whether, or not,
reflective - rigidity of the work piece, the sensitivity of the plastic and the type of cement. L-02 plastic with a nominal K factor of 0.02 and a maximum elongation of 85% (available from the Budd Company, Phoenixville, Pennsylvania) was employed. For economy in time a new reflective cement 4HRC (also from the Budd Co.) was used; this has a drying period of only four hours.

The mold was adjusted to the required area and cleaned with a gauze pad swab first with acetone and followed by isopropyl alcohol. The mold was then covered with a Plexiglass cover and leveled by a spirit level on the remaining area of the mold glass plate.

The weight of the plastic for a certain thickness is given by the formula,

\[ W = 17 A_p t_p \]

where \( A_p \) is area of plastic in square inches
\( t_p \) is its thickness in inches
\( W \) is the weight of plastic in grams.

The plastic was weighed in a beaker and heated slowly, on a hot plate, to a temperature of 130°F (with a tolerance \( \pm 3°F \)) measured with a constantly stirring immersion thermometer. The beaker was then taken back to the weighing balance and L-02 hardener, 21% by weight of plastic, was added to it and the mixture was rigourously stirred. An exothermic reaction in the mixture followed and as a temperature of 165°F (tolerance of -0°F, +3°F) was attained,
the plastic mixture was immediately poured into the mold. To spread it evenly, the mold was lifted by hand and gently swayed until the plastic had reached all the area. The mold was carefully put back to the same leveled position. It should be noted that the weighing and temperature accuracy is critical in the above procedure.

The plastic underwent successive stages of softness, polymerization and permanent hardness. At a certain semi-polymerized state, the plastic was ready to be gently taken off the mold with oily fingers and softly placed on the palm of the hand and cut into the required pieces. These shaped pieces were freely oiled with mineral oil and gently put on the doubly curved surface which had previously been oiled. The procedure is very important because of the fact that the plastic in its semi-polymerized state can be bent or shaped without introducing a residual birefringence in the plastic.

The plastic assumed the contour of the insulator cap as it hardened to a hard plastic.

After a day or so, the hardened and shaped plastic was removed from the cap and cleaned with isopropyl alcohol. The cap was cleaned and sand-blasted at the area of interest. Sometimes these caps have a foreign coating of some other material. This makes it necessary to rub the surface with a wire brush to a deeper thickness until the base metal is discernible. The area is then cleaned with acetone and isopropyl alcohol.
The 4HRCT reflective cement is then weighed and 4HRCT hardener proportionately added to it. The surfaces to be coated with the cement are again cleaned with isopropyl alcohol and dried. The cement is applied as thinly as possible taking care to remove any air bubbles.

The bond was dried for four hours and the plastic optically tested.

With each contour sheet, a small flat piece of plastic was cured and bonded like the contoured sheet itself. This flat piece was bonded to a tensile calibration bar (an aluminum alloy machined to certain dimensions) and used for calibration (determination of strain-optical constant K) of the plastic.

The insulator cap was loaded on a universal testing machine. The reflection polariscope was adjusted to a suitable height. The analyzer handle of the polariscope was kept vertical (parallel to \( \epsilon_1 \)) and the analyzer ring adjusted to a standard crossed system. This produced circularly polarized light as depicted in Figure 5 on page 8, since the quarter-wave plates were in position. The order of the fringe was so low even at the maximum load, that it was necessary to use a full-wave plate. Such a plate gives an artificial relative retardation of one wave length resulting in measurements higher than one fringe. This artificial fringe was of course deducted from the total reading.

The Tardy gonometric technique of measuring the exact
fringe order was employed. This technique is based upon the principle of changing the analyzer optic axis from the 90° standard position to an angle where a "tint of passage" is spotted on the point of interest in the plastic. This technique, having an accuracy of 0.01 fringe, is one of the greatest advantages of the large-field meter reflection polariscope used for this investigation.

The compensator, usually useful for finding the range of the estimate of the fringe order, was not of much use in this problem because the fringe order was always less than unity.

The problem was further simplified by the fact that the directions of the principal stresses always remained the same on the section studied, since the insulator is radially symmetrical and was subjected to a tensile axial load only.

The whole procedure of finding the fringe order was as follows:

(a) **Normal Incidence:**

Set the analyzer handle parallel to \( \xi_1 \) (i.e. vertical). Rotate the analyzer to its zero position. Slide in the full-wave plate. Move the analyzer ring clockwise or counterclockwise to get a "tint of passage" at the point of interest on the plastic. Record the reading. Load the insulator, recording the load also. The color should change, if the strain is fairly high, and if the cement bond is
good enough. Move the analyzer ring clockwise until the same-colored "tint of passage" appears. Record the reading. Take the difference of both the readings and that is the fringe order for the load applied.

During any of the above loadings, the light may temporarily be changed to plane-polarized light by optically removing the quarter-wave plates, and the pattern checked to ensure that a shady black horizontal elongated area of plastic along with the isochromatics is viewed; this establishes that the principal stresses have vertical and horizontal directions.

(b) **Oblique Incidence:**

The procedure was similar to the above except that the oblique incidence attachment was set and the readings were taken from the image of the point of interest in the mirror of the oblique incidence attachment. It should be noted here that the oblique incidence reading is not necessarily zero at no load.
VI SUMMARY OF RESULTS

In spite of the method being approximate compared to the classic bonded electrical strain gage method, it should be emphasized that this method not only presents a clear picture of the strain distribution, but is also an equivalence of an infinite number of strain gages kept in the field of study. The fringes are remarkably distinct and bright and they are naturally continuous.

Excellent quantitative data is obtainable and the method is unique in comparing designs, very feasibly and quickly, to surface problems of members accessible to light. Besides other advantages, the method makes it possible; to measure residual stress; to keep a photographic record of the readings; allow for temperature corrections; reinforcement (due to plastic) corrections; maintain an accuracy of a strain of 10 microinches per inch with a tolerance in isoclinics of ±2°.

The caps in such insulators have a design load of 25,000 lbs. and the author could not understand why the porcelain was designed for a load of only 15,000 lbs. Of course, the insulators are so designed that the cap hardly ever failed; yet it seems the cap is, comparatively, excessively rigid. This posed a problem in loading the insulator sufficiently to get a substantial strain in the cap, for fear of breaking the porcelain after 15,000 lbs. This was a fairly big barrier in the attempt to get a sensitive color change in the coated
plastic.

Later on, the author learned that the cap is never supposed to yield even slightly, since under such a state, the porcelain bond disengages from the steel and is almost instantly subjected to a crack failure. In such a situation, therefore, the cap should be fixed in a fixture, alone, and loaded; but this is not practicable for the design since the design includes the effect of the stud design on the stress distribution of the cap!

As assumed, the jaw-like bottom of the cap, called the lip, radially opens out before the porcelain slips and breaks. The cap, under such a state, is centrally loaded at the coupling joint at the top and the reaction is uniformly distributed around the periphery of the lip. Due to such an application of load, the cap contracts radially resulting in stresses which may be referred to as "contraction stresses" which produce circumferential compression. The fact that the porcelain does not set up a restraint at the critical section is evident if it is seen that the lip of the cap makes the porcelain take almost the entire load in compression between the lip and the stud rather than in tension at the critical section. Before the cap contracts sufficiently to cause a radial compressive stress on the internal surface at the critical section, because of the restraint from the porcelain, the porcelain slips a small amount and releases the load.

The effect of the stud design on the stress distribution of the cap was not possible to determine with the investigated
insulators (with different studs) since the caps were themselves different in shape and material.

The correction due to the reinforcement of the porcelain was neglected on account of its poor tensile properties. There is also a certain standard graph to determine whether a correction of reinforcement due to plastic is necessary; this is much pronounced in a bending member. The author thought it wise, therefore, to have a tension member for calibration to alleviate the above correction as well as to have convenience in calibration. The correction of reinforcement is based upon the ratio of the thicknesses of the plastic and the prototype as well as on the type of material used. Luckily these ratios in both, the calibration and the insulator readings, were very nearly unity.

For every contouring of plastic, care should be taken to also cut a rectangular piece of plastic while it is in its semi-polymerized state (for contouring); this piece will be later used for calibrations. It was found that if the plastic calibration piece was cut after the plastic dried, a residual birefringence was exhibited in the plastic. This residual birefringence could sometimes be accounted for when the residual strains have taken place such that the isoclinics occur in the same way as they would when no residual birefringence existed; usually because of the condition, it becomes very difficult to apply this correction. It, apparently, is wiser to make another plastic rather than make the correction.

In the beginning of this investigation the author used
pure aluminum for calibration; being soft and ductile it showed sensitive colors; but these colors were not judged to be reliable on account of the proportionality of stress with strain, for aluminum, being too low. It also yielded permanently so much that residual birefringence was very conspicuous. Later, an aluminum alloy was used without knowing its composition and elastic constants! The stiffness was determined by the slope of the stress-strain curve drawn by affixing a bonded electrical strain gage and measuring the strain by a D.C. Bridge.

Two different types of insulators were investigated. These were:

1. Albion Iron Cap No. 60-45-10 with an Atwater Stud (Single Step)
2. BTC (Brewer Tichener Corporation) Cap with a Rex Stud (Two Step)

The critical horizontal sections, as judged from the concentration of higher order color fringes, (see the frontispiece) for the above two types of insulators are 1.56" and 1.46" respectively from the bottom plane of the cap.

The following are the stress values for a BTC Cap with a Two Step Rex Stud (The detailed calculations for the insulator and the calibration of the plastic are shown in Appendices A and B): -
At a load of 15,000 lbs,
\[ \sigma_1 = 11,200 \text{ psi (tension)} \]
\[ \sigma_2 = -4690 \text{ psi (compression)} \]
\[ \tau_{\text{max}} = 7945 \text{ psi} \]

At a load of 20,000 lbs,
\[ \sigma_1 = 12,300 \text{ (tension)} \]
\[ \sigma_2 = -7150 \text{ psi (compression)} \]
\[ \tau_{\text{max}} = 9725 \text{ psi} \]

where \( \tau_{\text{max}} \) is the maximum shear stress.

From the discussion on page 30, it was stipulated that the compression at the critical section, horizontally on the surface, would increase faster than the vertical tension, with an increase of load, as is obvious from the above results of the photoelastic readings.

Because of the complexity of the shape (double curvature), the type of loading, and the restraint of the porcelain, it was considered necessary to confirm the above stress distribution by affixing two strain gages at the critical section. This compared fairly well with the photoelastic values.
VII RECOMMENDATIONS

This discussion for the stresses in the insulator has been restricted to the assumption that the stress distribution is two-dimensional. It may be possible to apply a frozen stress method to know the exact three-dimensional state of stress.

Bending effects due to eccentricity of the load on the hollow cylindrical surface have been neglected. This may have an effect on the stress distribution especially on the top of the cap where it curves down. This should be considered in any further investigation.

The author is of the opinion that since the idea is to have a rigid cap with such a stud design as not to make the porcelain slip before a stipulated load has been attained, the following procedure be adopted: with the internal porcelain and stud unchanged in dimensions, the thickness of the cap should be PURPOSELY decreased from the OUTSIDE (the inner structure of the insulator, thus, essentially remaining the same) and then the insulator loaded. This should be accomplished with different stud designs. This not only would produce much better strains from the photoelastic viewpoint but would also lead to an insight of attempting a synchronised failure of the porcelain and the cap after considering all the factors of safety.

It is suggested that a point of interest (usually the one with the highest stress) be obtained optically and two
bonded electrical strain gages be placed on the cap to measure the principal strains. This should give excellent results.

In measuring the fringe order, the operator is expected to avoid parasitic reflection - the normal reflection of the source itself, by making a small deviation from normal incidence. Such a reflection often merges with the true optical color and affects the reading. In the opinion of the author, this reflection, if away from the point where measurements are being taken, may be useful. The reflection, if only a spot, is brighter, and if on the same isochromatic as the point of interest, facilitates the determination of the fringe order. This is true, only, if the colors at the point of interest and the spot caused by parasitic reflection are the same with a change of load.
BIBLIOGRAPHY


3. "Das Polarisationsoptische Schichtverfahren zur Messung der Oberflächenspannung am beanspruchten Bauteil ohne Modell" by G. Oppel, VDI-Zeitschrift Bd. 81 Nr. 27, 3 July 1937.


APPENDICES
Theoretical Estimations:

Referring to Figure 3 on page 4, let us consider, as a very rough approximation, the insulator as made of a hollow cylinder from the shortest (in diameter) section between sections AA and BB (Figure 3) and subjected to uniaxial state of stress.

This hollow circular section has an inner diameter of 3.25", and an outer diameter of 3.625"

Annular area of cross-section

\[
A = \pi \left( (3.625)^2 - (3.25)^2 \right)
\]

\[= 2.04 \text{ sq. inches} \]

For a tensile load of 15,000 lbs.,

Tensile stress \( \sigma_1 = \frac{15000}{2.04} = 7700 \text{ psi} \)

Tensile strain \( \varepsilon_1 = \frac{\sigma_1}{E_s} = \frac{7700}{30 \times 10^6} \)

\[= 245 \text{ microinches per inch} \]

\( \varepsilon_2 = -\mu_s \varepsilon_1 = -73.5 \text{ microinches per inch} \)

Therefore,

\( \varepsilon_1 = 245 \) and \( \varepsilon_2 = -73.5 \text{ microinches per inch} \) and

\( \varepsilon_1 - \varepsilon_2 = \gamma_{max} = 318.5 \text{ microinches per inch} \).
Sample Calculations:


Critical Horizontal Section, as judged from the concentration of higher order colors, (see the frontispiece), is 1.46" from the bottom plane of the insulator cap.

The following measurements of stresses and strains are based upon this critical section:

Calibration:

**Tension Member used:** 1.340" x 0.187"

**Thickness of plastic bonded:** 0.092"

**Optical readings:**

<table>
<thead>
<tr>
<th>LOAD (in lbs)</th>
<th>FRINGE ORDER</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>1500</td>
<td>0.075</td>
</tr>
<tr>
<td>3000</td>
<td>0.150</td>
</tr>
<tr>
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<tr>
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<tr>
<td>7500</td>
<td>0.365</td>
</tr>
<tr>
<td>9000</td>
<td>0.450</td>
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</tbody>
</table>

Normal and Oblique Incidence Optical Readings for Insulator:

At a load of 15,000 lbs

\[ N_0 = 0.11 \text{ fringe} \quad N_n = 0.09 \text{ fringe} \]

The graph plotted from calibration readings is shown
in Figure 9.

Slope of the straight line from the graph

\[ \frac{\text{fringes per lb}}{9000} = 0.455 \]

From equation VIII on page 16,

\[ \sigma_1 - \sigma_2 = \frac{\lambda N_n' E}{2t_p K(1 + \mu)} \] .............. (a)

where \(N_n'\) is the value of the fringe order of the plastic on the calibration bar.

For this bar \(\sigma_2 = 0\), therefore from equation (a)

\[ \sigma_1 = \frac{P}{A} = \frac{\lambda N_n' E}{2t_p K(1 + \mu)} \]

where \(P\) is the load applied and \(A\) the area of the cross-section.

\[ K = \frac{\lambda E A}{2t_p(1 + \mu)} \left( \frac{N_n'}{P} \right) \]

The quantity in the parenthesis is given by the slope of the straight line of the calibration graph shown in Figure 9.

The Modulus of Elasticity \(E\), as determined from the slope of the stress-strain curve for the calibration aluminum alloy, is 13.4 x 10^6 psi.

\[ K = \frac{22.7 \times 10^{-6} \times 13.4 \times 10^6 \times 1.34 \times 0.187 \times 0.455}{2 \times 0.092 \times 1.3} \times \frac{9000}{9000} \]

\[ = 0.0161 \]

From equations XVI and XVII on page 22,

\[ \epsilon_1 = f (0.68 N_0 - 0.222 N_n) \]
Figure 9 Calibration Curve for Plastic
\[ \varepsilon_2 = f (0.68 N_0 - 1.222 N_n) \]

\[ f = \frac{\lambda}{2t_{pk}} = \frac{22.7 \times 10^{-6}}{2 \times 0.092 \times 0.0161} = 7650 \times 10^{-6} \]

Therefore,

\[ \varepsilon_1 = 7650 \times 10^{-6} (0.68 \times 0.11 - 0.222 \times 0.09) \]

= 420 microinches per inch (tension)

\[ \varepsilon_2 = 7650 \times 10^{-6} (0.68 \times 0.11 - 1.222 \times 0.09) \]

= 268 microinches per inch (compression)

The principal stresses are given by (refer to equations IX and X on page 17)

\[ \sigma_1 = \frac{E_s}{1 - \mu_s^2} (\varepsilon_1 + \mu_s \varepsilon_2) \]

\[ \sigma_2 = \frac{E_s}{1 - \mu_s^2} (\varepsilon_2 + \mu_s \varepsilon_1) \]

Assuming \( E_s = 30 \times 10^6 \) and \( \mu_s = 0.3 \)

\[ \sigma_1 = \frac{30 \times 10^6}{0.91} \left[ \frac{420 + 0.3 (-268)}{0.91} \right] \times 10^{-5} \]

= 11,200 psi (tension)

\[ \sigma_2 = \frac{30 \times 10^6}{0.91} \left[ \frac{-268 + 0.3 (420)}{0.91} \right] \times 10^{-5} \]

= - 4690 psi (compression)
VITA

Mr. Harijeetsinh Jagtiani was born in Karachi, India, on May 23, 1943. Having completed his primary education in various Convent schools in West India, he passed his Matriculation examination (with technical courses) in 1957. He entered the University of Bombay, India, for his first year at college and then went to Anand, India for his engineering studies. He acquired the Bachelor of Science degree in mechanical engineering from Sardar Vallabhbhai University, Anand, in June 1963, after which he served as a Lecturer in the Mechanical Engineering Department in Sir Bhavsinhji Polytechnic Institute, Bhavnagar, India for a little more than a year. Besides this teaching job, he was a consulting engineer to Satyavijay Iron Works, Bhavnagar, India, a firm specializing in the manufacture of upright and radial drilling machines.

He came to Rolla in September, 1964 to earn the Master of Science degree in mechanical engineering.