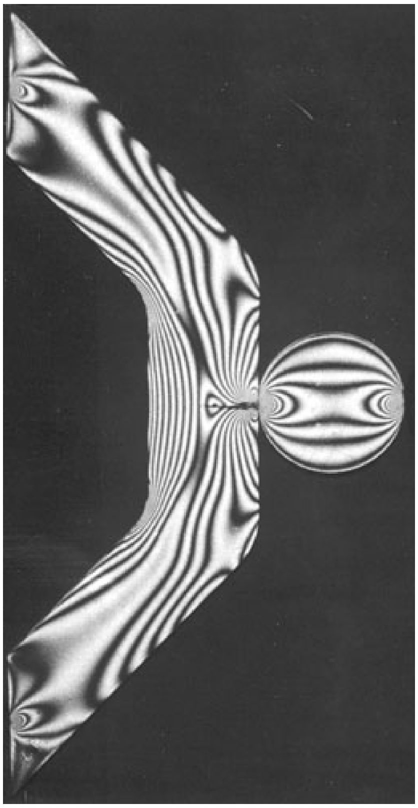
# Optical Methods in Experimental Mechanics
## Part 36: Photoelasticity VIII—Recording and Numbering Isochromatic Fringes

### REVIEW AND PURPOSE

The observables in photoelasticity, isoclinic fringes and isochromatic fringes, have been defined in recent articles in this series, and their relationships with the state of stress in the photoelastic model have been established. Polariscope systems for creating, observing, and recording these fringe patterns were described in the previous segment.

Now, we begin to learn how to record and interpret the fringe patterns to obtain information about the stress field, beginning with isochromatic patterns. After recording the isochromatic fringes, correctly assigning numerical orders to them is a critical intermediate step.

There are many methodologies to record and interpret isochromatics, some of which are very sophisticated. Since this is a "Back to Basics" series of articles, only the simplest direct approach is discussed here. With the advanced technologies available nowadays, experimental mechanicians suffer the temptation to treat the instrumentation as a "black box" and accept the results without question. Better to learn to analyze isochromatic patterns by hand, mind, and eye, after which advanced techniques will be thoroughly understood, and the results will be trustworthy. At the very least, one can scan the final results and decide if they make sense.



**Light-field isochromatic fringe pattern in an arch. A loaded disc is included for material calibration. High-pressure sodium illumination at 589 nm. Digital scan of photo by Dr. Gary Cloud, Michigan State University, ca. 1972. A high-definition file of this photo can be downloaded at www.egr.msu.edu/∼cloud/arch_isochromatics.jpg**

*This article describes the recording and numbering of isochromatic fringes as the first steps in obtaining quantitative stress information from photoelasticity.*

*The photoelastician should be wary of the "black box" approach because it can lead to undetected errors. The direct approach should be understood even if more sophisticated methods will be used in an experiment.*

### RECORDING ISOCHROMATIC FRINGE PATTERNS

Obtaining valid permanent records of isochromatic patterns is easy and hardly requires discussion at this point on our training program. The steps are as follows:

1. Set up the circular polariscope in the monochromatic dark-field arrangement discussed in the previous article (see Part 35).
2. Place the photoelastic model in the loading device and use a light meter to figure out the exposure time and f-stop for whatever camera you have available.
3. Apply the appropriate load, which you have estimated ahead of time, and wait the interval you have chosen to take care of creep effects (see Part 30).
4. Record a photograph.
5. Immediately rotate the analyzer 90° in one direction or the other to convert to the light-field arrangement and snap another picture. It is usually a good idea to record two or more extra photographs for each analyzer setting while you are at it, using exposure times that are twice and one-half that suggested by the light meter. These extra photos provide insurance and sometimes can be useful in interpreting the fringe patterns.

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*The series, Optical Methods—Back to Basics, is written by University Distinguished Professor Gary Cloud of Michigan State University in East Lansing, Michigan. It began by introducing the nature and description of light and will evolve, with each issue, into topics ranging from diffraction through phase shifting interferometries. The intent is to keep the series educationally focused by coupling text with illustrative photos and diagrams that can be used by practitioners in the classroom, as well as in industry. Unless otherwise noted, the graphics in this series were created by the author.*

*The series author, Prof. Gary Cloud (SEM Fellow), is internationally known for his work in optical measurement methods and for his book, Optical Methods of Engineering Analysis.*

*If you have comments or questions about this series, please contact Jen Tingets, journals@sem1.com.*

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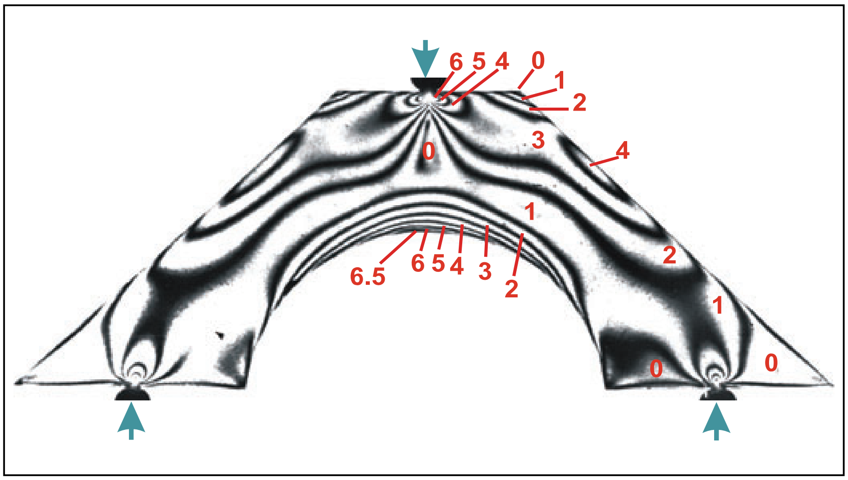
6. Remove all or most of the load on the model, but leave it in the loading frame if you are able. You will likely need to observe visually the isochromatics in white light and/or as you apply small loads in order to figure out the fringe orders in your photographs.
7. Finally, print some large paper copies of the light- and dark-field fringe patterns so you can scribble on some and include clean ones in the report you will be writing.

*To record isochromatic fringe patterns:*
- *set up the circular dark-field polariscope with monochromatic light,*
- *place the model in the load device and determine the correct photo exposures,*
- *apply the load and wait the selected time interval,*
- *record the dark-field photo,*
- *rotate the analyzer 90° to convert to light field,*
- *record the light-field photo,*
- *remove the load on the model, but leave it in the load frame if possible,*
- *print some copies of the fringe photos for analysis.*

*A light-field photo of a loaded arch is used to demonstrate the fringe numbering procedure. It also illustrates some common set-up errors.*

## A SAMPLE RESULT

Below is a light-field isochromatic pattern for a loaded arch that was obtained during a demonstration experiment. This example is a digital scan from a contact print of an 8 in. × 10 in. negative recorded in about 1967 via a Linhof scientific view camera with a Zeiss lens—a combination rarely seen in experimental mechanics labs anymore. To save space, the fringe orders are shown in red as they were established by the methods outlined in the next sections.




One reason for using this particular photograph, which is a less-than-perfect trial result, is that it contains illustrative evidence of some poor lab procedures that serve as warnings, namely:

1. Most of the fringes change direction sharply as they approach the boundary of the arch. This behavior is caused by a time-edge effect, also called rind effect or skin effect. It results from moisture migration at the raw edges of models that were machined a considerable time before being studied. Additional stress is thereby induced in the boundary layer, and this stress causes local perturbations of the isochromatics.
2. A slight lack of symmetry in the fringe pattern is apparent. It was caused in this case by applying the upper load at a slight inclination because of careless set-up of the dead-weight loading frame.
3. Some edges of the specimen are not sharply defined. This problem suggests that the camera aperture was not exactly at the focal point of the field lens, the focus was not carefully adjusted, and/or the model was not perpendicular to the optical axis of the system.
4. The field was not uniformly illuminated.

Still, this product is somewhat typical of those obtained in everyday photoelasticity, it gives useful results, and it serves well for instruction, partly because the fringe orders are on the low side and therefore are easy to discern in this reduction.

## SOME METHODS FOR ESTABLISHING FRINGE ORDERS

In order to obtain quantitative stress information from the fringe photograph, the fringe orders must be determined (review fringe pattern topics in Parts 4 and

33). This task is not trivial, a point that was mentioned early in this series of articles (e.g. Part 2) and several times since.

The most skillful photoelasticians have difficulty in establishing fringe orders from a pair of light-field and dark-field fringe photos, let alone from a single pattern such as the one presented above. If monochromatic light is used in this interferometry, then a high-order fringe in a highly stressed area looks the same as one in an area of low stress. How can we tell them apart so as to define the actual fringe orders and obtain accurate stress measurements? There is no one single magical approach; rather, we utilize knowledge of deformable body mechanics, experience, and some tricks of the trade to establish fringe orders. Much of the problem is solved if the areas of highest and lowest stress and the general direction of the stress gradient can be discerned. Some of the most useful rules and procedures are as follows:

1. Recall that the fringes that match the background are whole-order fringes. In dark-field, the whole orders are black.
2. Keep in mind that isochromatic order at a point is proportional to the difference between the principal stresses (i.e. twice the maximum shear stress) at that point.
3. Use white light in a qualitative observation to assist the quantitative work. The colors of the high-order fringes are less saturated than the low-order fringes (see Part 7).
4. Watch the isochromatics form and spread as the load is increased from near-zero. The isochromatics start from highly stressed areas and spread to areas of lower stress.
5. The zero-order fringe might disappear, followed by successive orders, into areas known as sinks, so one cannot be certain that the low-order fringes are even present.
6. The stresses in an unloaded projecting corner are zero, so the fringe order there is zero.
7. Fringes orders are high at load points, but these points might not exhibit the highest fringe orders in the field.
8. Between adjacent fringes, the fringe order changes by +1 or −1, but it might stay the same.
9. Use knowledge of simple and related stress fields from elasticity and experience. Such information is especially useful in determining the directions of stress gradients.
10. Isotropic points might appear in the field. Such a point has equal normal stress in all directions, the Mohr circle reduces to a point, the maximum shear stress is zero, so the fringe order is zero. Do not assume that the principal stresses are zero at such a point even though the fringe order is zero. But, if an isotropic point is located on a free boundary, the principal stresses are zero there.
11. Use the indentor method. Press a pointed device such as a pencil into a free edge of the loaded model. The resulting direction of motion of the fringes near the edge that results from the addition of the small normal stress serves to establish the sign of the boundary stress and helps to fix the direction of the stress gradient. Sketch the Mohr circles for this situation to sort it out.

*Some important rules and procedures for ordering the isochromatics are summarized as follows:*

- *fringes that match the background are whole-order fringes,*
- *isochromatic order is proportional to the maximum shear stress at any point,*
- *use white light observation to assist in assigning order,*
  - *the colors of high-order fringes are "washed-out,"*
- *watch the fringe pattern develop as the load is increased,*
  - *isochromatics start from points of high stress and spread to areas of low stress,*
- *the low-order fringes might disappear,*
- *the stresses in a projecting free corner are zero, so the fringe order there is zero,*
- *fringe orders at load points are large, but might not be the largest in the field,*
- *between adjacent fringes, the order changes by +1 or −1 or zero,*
- *use knowledge of related stress fields, particularly to establish the direction of the stress gradient,*
- *isotropic points might appear in the field, for which,*
  - *the principal stresses are equal,*
  - *the fringe order is zero,*
  - *the maximum shear stress is zero,*
  - *the principal stresses are not necessarily zero,*
- *push an indentor onto the edge of the loaded model,*
  - *the motion of the adjacent fringes yields information about the sign of the boundary stress and the direction of the stress gradient.*

## FRINGE ORDERS IN THE EXAMPLE

Because we are not in the lab, techniques 3, 4, and 11 in the above list are not applicable to our problem, which is a handicap because they are the most powerful approaches, in particular 3 and 4. Also, we do not have the dark-field pattern at hand, which is another disadvantage. Let us attack as best we can to figure out the fringe orders from scratch. The train of thought is outlined below. It seems tedious at first, but the procedure goes quickly when one gets the hang of it. The term "stress" is used loosely in the following sequence.

1. We need to study only one side of the arch because symmetry applies well enough.
2. This is a light-field pattern, so the light fringes are the whole orders.

*Some of the rules and procedures given are employed to establish the fringe orders in the example.*

3. There is clearly an acute projecting corner at the outside bottom. Label the light area in this corner as fringe order 0. This corner is superfluous material, and it could even be drastically rounded off without affecting the strength of the arch. One of the advantages of photoelasticity is that it immediately tells the designer where material can be removed.
4. The top outside corner is somewhat projecting, and the tiny light area there is probably also a 0-order fringe.
5. The arch wing is in a combination of compression and bending. Likely the stresses are small in the interior of the wing and increase towards the outside edge. Further, the stress will be higher near the middle of the outside edge of the wing and lower near the corners mentioned above. This reasoning, drawn from knowledge of basic mechanics, leads us to number the fringes along the outside edge of each wing as shown, and these extend into the interior and along the top edge in a reasonable way.
6. The light fringe that extends from near the bottom load point to near the top load point is a problem. The only possible orders are 3, 2, or 1 because it is adjacent to fringe order 2. It does not join 2 anywhere, so it must be 3 or 1. Given the state of bending stress mentioned above, it is probably 1.
7. The bending stress along the top edge increases toward the load point, so the fringes are numbered in sequence to a maximum at the load point. The highest order we can see near the load is 6.
8. The closed loop below the upper load point most likely surrounds the isotropic point that exists beneath such singularities, but it might be a sink. We tentatively assign 0-order to that light oval fringe because it is consistent with the numbering trend and our knowledge of elasticity.
9. The rest is easy. High stress is expected in the bottom edge of the semicircular inner boundary. It is like a curved beam. The light fringes in this area are numbered successively 2 through 6.
10. We see what looks like the beginning of a dark fringe right at the inside edge, so it would be order 6 1/2. A large-scale print of this pattern shows that order 7 is just forming at this location.
11. The bottom inside corners can be only 1 or 0, but some darkness projects into the corner, so the bending and compression might extend this far. The order is probably between 0 and 1, so call it 1/2, but keep in mind that there might be a pile-up of skin effect that is distorting the orders at this corner.

*We note that photoelasticity indicates immediately where material can be removed to save weight without affecting strength or stiffness.*

All this reasoning seems correct, but are the results correct? At least they are internally consistent, an important consideration. Little more can be ascertained with the single isochromatic pattern at hand. Certain advanced optical methods could be used in the lab to verify or disprove the ordering. The easiest and best way is to use white light and/or load changes as mentioned above in techniques 3 and 4, which is the reason we try to leave the model in the load frame until this numbering process is completed.

*The results of the analysis seem correct and are internally consistent, but some uncertainty remains because of the handicaps of not being in the lab and having only one isochromatic pattern to work with. Use of white light or changing the load would confirm or improve the result.*

## DO IT YOURSELF

The photograph appearing at the head of this article shows a digital scan of a dark-field isochromatic pattern in an arch-type structure that is similar to the example treated above, except that some of the corners are rounded, the proportions are different, the applied load is larger, less time-edge effect is apparent, and the setup met reasonably high standards. The load was applied to the arch through a disc of the same photoelastic material that was used to make the model. Thus, the experiment is self-calibrating in that an object with known stress field was included in the field so that the stress-optic coefficient of the material could be determined directly for the wavelength used (see Part 30). The original pattern was recorded during a laboratory demonstration by the author in about 1972. Polaroid film and the Linhof scientific camera mentioned above were used.

*A similar photoelastic pattern can be downloaded to provide an exercise in fringe numbering.*

It is suggested that the methods described in this article be employed to determine the fringe orders for this example. The digital file, which may be used to print the photo in large size, can be downloaded from the author's website using the link: www.egr.msu.edu/~cloud/arch_isochromatics.jpg. File size is about 1 Mb.

## WHAT IS NEXT?

The next article will complete the interpretation of isochromatic patterns. The fringe orders will be converted to stress, and a simple method of reporting the most significant data will be described. ■

*In the next article of this series:*

- *fringe orders will be converted to stress,*
- *a simple technique for reporting results will be demonstrated.*