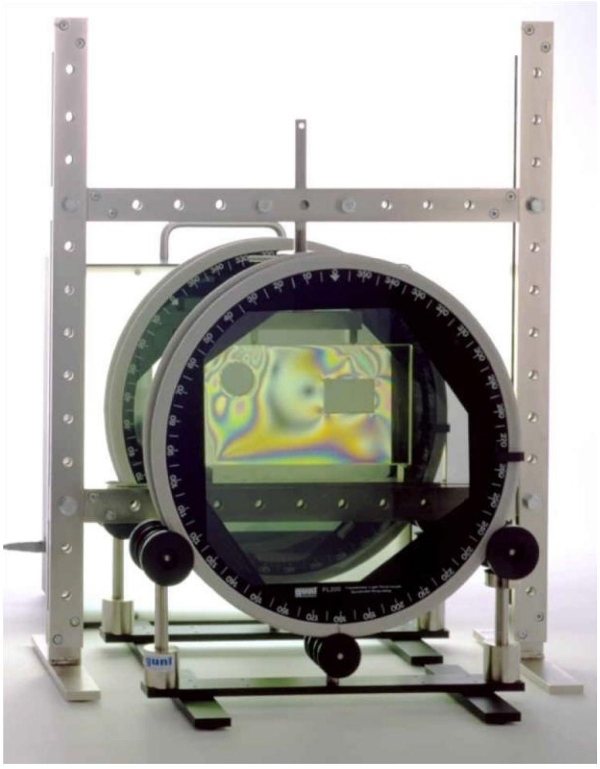
Laboratory 5

Photo-elasticity Experiment



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Contents

1. Objectives:

1. Generation of planar stress states in various models under load
   - bending, tensile load, compressive load
2. Investigation of diffusion of stresses with plane or circular polarized light
3. Interpretation of photoelastic fringe patterns
   - stress concentrations, zero points, neutral fibers, areas of constant stress, stress gradients
4. Determination of occurring stresses and strains graphically and arithmetically

2. Introduction:

Transmission polariscope device enables you to perform basic experiments in photo- elasticity.

Photo-elasticity is a tried and proven method of analyzing and recording mechanical stresses and strains in components. It is deployed for quantitative measurement and to demonstrate complex stress states.

Light (polarized and monochromatic) is used to make mechanical diffusion of stress visible in photo-elastic sensitive material.

3. Equipment description:

The transmission polariscope device is made up of independent components, which allows very flexible experimental layouts to be achieved.

The structure is divided into four areas:

- Light source (8).
- Polarizer (6, 7).
- Load frame (3) with model (4).
- Analyzer (1, 2).

The individual test pieces are clamped in the load frame.

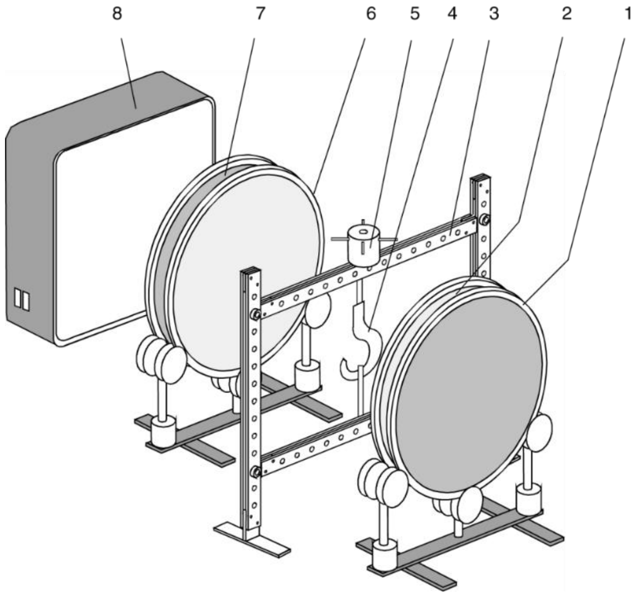


Fig. 5.1 Schematic illustration of experimental system

1	Polarization filter
2	Quarter wave filter
3	Load frame
4	Model
5	Load application device
6	Quarter wave filter
7	Polarization filter
8	Light source

a. Light Source

The light source for the unit consists of a lamp box with white diffuser. Two different types of light can be produced:

- White light from a fluorescent tube, which is supported by two bulbs to achieve uniform light diffusion.
- Monochromatic light produced by a sodium vapor lamp.

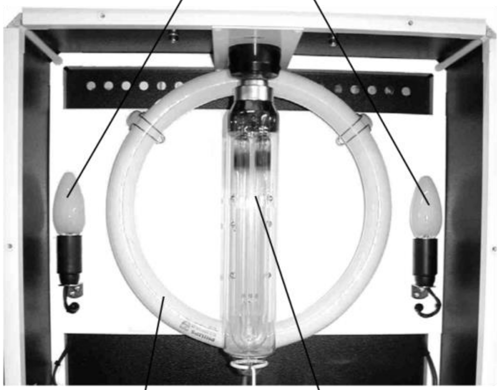


Fig. 5.2 Light source

The light source is turned on and off using two switches (one for the monochromatic light and the other for the white light) on the side of the housing. Both light sources can be operated simultaneously.

b. Load Frame

The frame consists of four individual sections (two side supports (3.7) with base plates (3.1) and two cross arms (3.3).

The side supports, and cross arms have holes for mounting the models or model holder.

The cross arms can be screwed onto the side supports at different heights. This means that the frame can be individually adapted to the experimental models and load mechanism.

To assemble, the clips for the cross arms (3.5) are pushed into the gaps in the side supports (3.2) and secured using through bolts (3.4) and nuts (3.6)

c. Filters

The device has four filters. The filters consist of two glass plates with the actual filter film between them. The edges of the filters are stuck together and fitted with edge protection. The polarizer is located between the light source and model, while the analyzer is between the model and the viewer. The polarizer and the analyzer each consist of a linear polarization filter (dark olive in color) and a quarter wave filter (almost colorless).

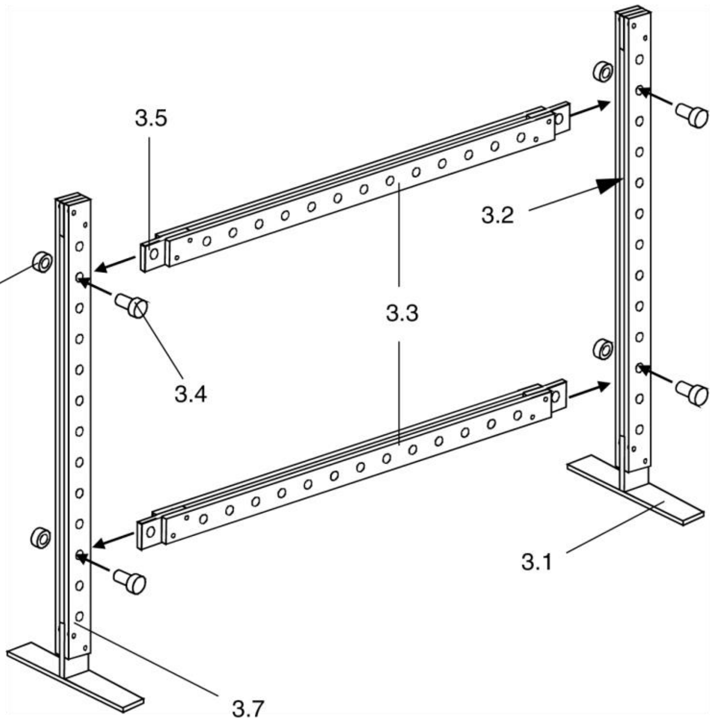


Fig. 5.3 Structure of frame

3.1	***Base plates***	***3.2***	***Gap side supports***	***3.3***	***Cross arm***
3.4	***Bolts***	***3.5***	***Clip***	***3.6***	***Nut***
3.7	***Side supports***				

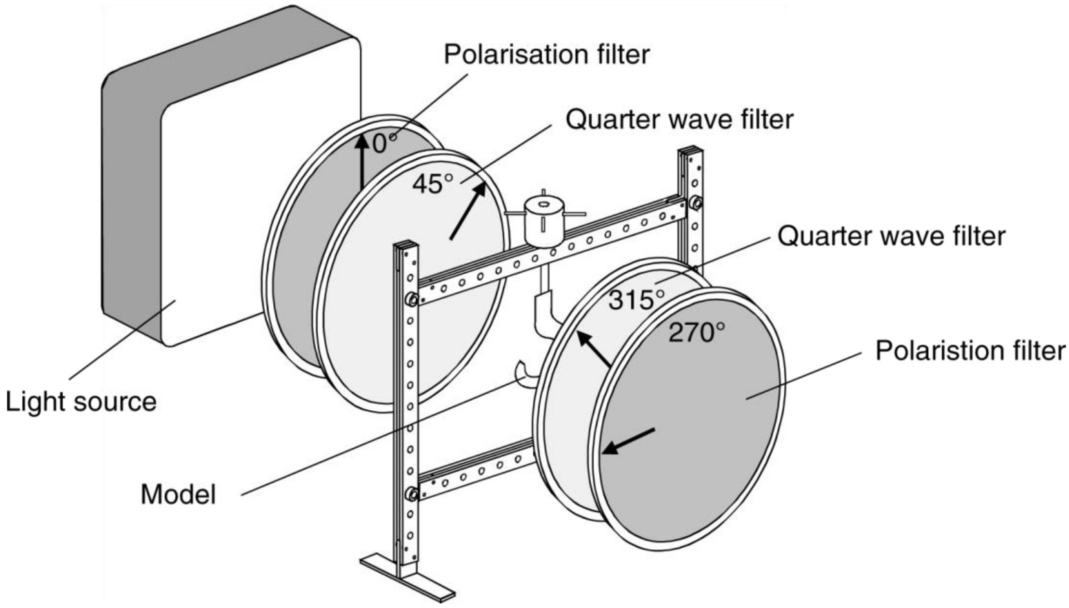


Fig. 5.4 Position of filter axes

They are arranged with a particular offset angle between their filter axes. From the light source to the viewer:

The filters are mounted in a rotating filter holder. The filter holder has a pointer on the side, which can be used to read the relative angle. The filter frame should fit into all three rollers evenly and with no clearance. The height of the two side rollers may need to be adjusted. To do this, loosen the side screw at the base and adjust the height of the retaining bar. The height of the pointer for the angle setting can also be adjusted. The pointer should be level with the center of the filter plate

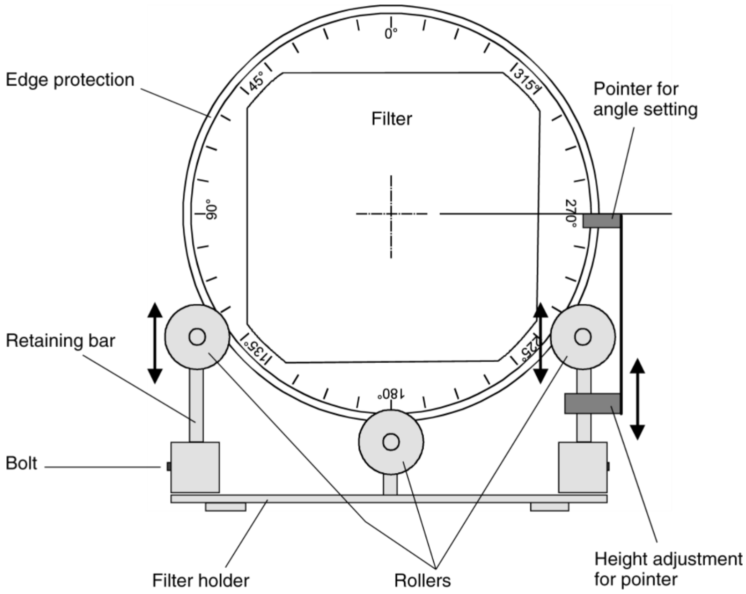


Fig. 5.5 Filter with filter holder

d. Load Spindle

The load mechanism can be fitted at any point on the load frame. Installation on the upper cross arm is preferable. However, it depends on the type of model used. For detailed instructions, refer to Chapter 3.3.

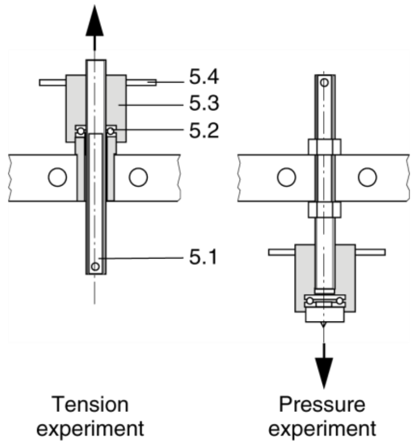


Fig. 5.6 Structure of load application device

The load application device consists of a threaded spindle (5.1) and an adjusting nut (5.3) with inserted pins (5.4). The pins allow sensitive adjustment of the nut and setting of the load. The adjusting nut has a thrust ball bearing (5.2) to minimize the friction and to rule out a transmission of moments onto the model.

- ***Generation of Tensile Forces***

1. First of all, insert the flattened pressure piece into the frame slot from above.
2. Insert the threaded spindle (5.1) into the pressure piece from above, flat side first.
3. Screw the adjusting nut (5.3) onto the threaded spindle with the ball bearing pointing downwards.
4. The model can now be fastened to the lower end of the spindle with the hole.

- ***Generation of Pressure Forces***

1. Insert the threaded spindle (5.1) into the frame slot (2) from below with the flat side and secure it from above and below with two lock nuts (3). The lock nuts should be located in the flattened part of the spindle.
2. Screw the adjusting nut (5.3) onto the threaded spindle from below with the ball bearing pointing downwards.
3. Insert the pressure piece into the adjusting nut from below.

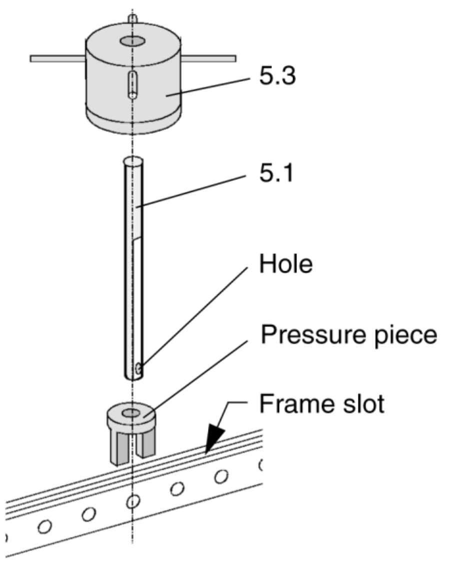


Fig. 5.7 Load application - Tensile forces

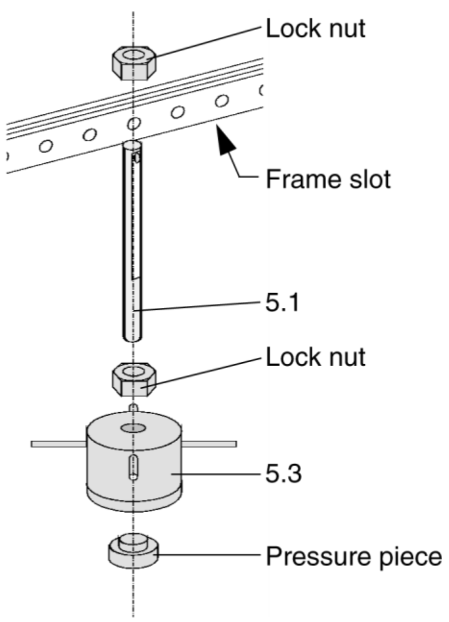


Fig. 5.8 Load application – Pressure forces

Depending on the model and the type of load (concentrated or linear load), different pressure pieces are available.

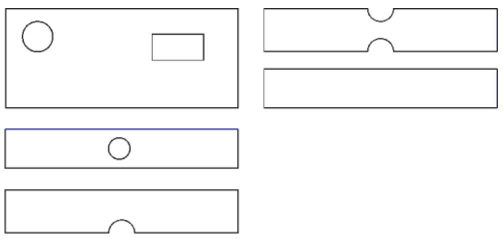
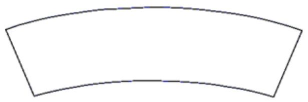
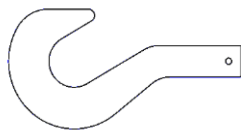
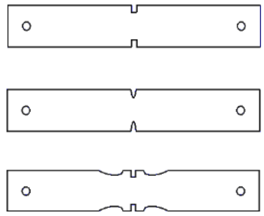
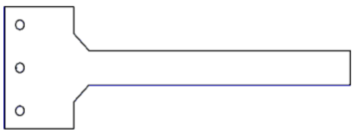
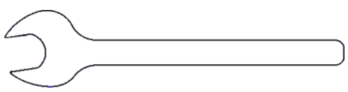
NOTICE

The pressure piece is loose and remains in the adjusting nut without being secured. It is held in position by the model.

e. Photo-elastic Sensitive Material

The basic module can be used to perform a variety of experiments in conjunction with the add-on modules. The table 5.1 show the available modules for the transmission polariscope.

Table 5.1 available modules for the transmission polariscope

	FL 200.01 Set of 5 Photoelastic Models
	FL 200.02 Model -Arch
	FL 200.03 Model Crane Hook
	FL 200.05 Set of 3 Photoelastic Models, Comparison of Notches
	FL 200.06 Model - Stresses on Weld Seams
	FL 200.07 Model - Wrench

Essentially, any double refractive material is suit- able for the photoelastic experiment. This includes glass, various transparent plastics and even gelatine. However, plastic models made of acrylic and epoxy resin are predominantly used. The acrylic is generally known as “PLEXIGLAS”. Its main advantages are that it is easy to obtain and has a low price, it can be processed using standard metal tools and it can be stored for practically an unlimited period. Its disadvantage is the low photo-elastic sensitivity. It is therefore less well suited for qualitative experiments. The models are thus made from polycarbonate, which is available in plate form under the trade name “MAKROLON”.

A carefully manufactured model plate can be used practically an unlimited number of times for qualitative demonstration purposes if handled properly.

- ### *Fitting the Models in the Load Frame - FL 200.01*

First of all, the model mounting must be inserted into the gap in the lower cross arm of the load frame. One of the models is then placed on the mounting. In order to apply a load, the load bridge must be placed on the model. The load spindle is then inserted. It must be fitted as a pressure screw for this experiment (see Fig. 3.8).

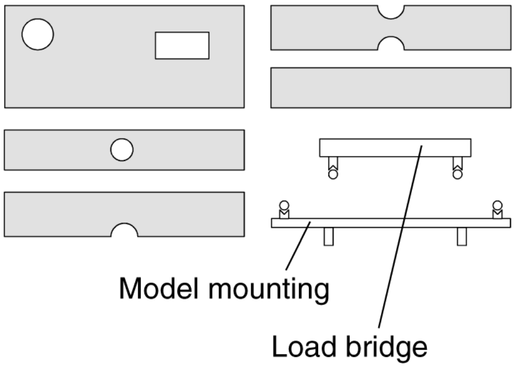


Fig. 5.9 Models

- ### *Fitting the Models in the Load Frame - FL 200.02 Model - Arch*

The model arch simulates the diffusion of stress that occurs in arches.

When fitting the model in the frame, the mounting is first placed in the gap in the lower cross arm of the frame. The model is then inserted and the load bridge with the two pressure points is then placed onto it.

The load spindle (pressure forces) can then be fit- ted and the pressure point can be used to exert a force on the model.

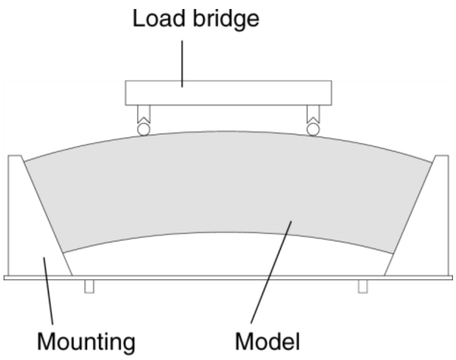


Fig. 5.10 Model - Arch

- ### *FL 200.03 Model - Crane Hook*

For the model crane hook, a tensile load must be applied (ensure correct fitting of load application device). The threaded spindle is attached to the upper end of the crane hook using two clips and two screws.

The lower end of the hook is secured with a retaining ring, which is screwed into the lower cross arm.

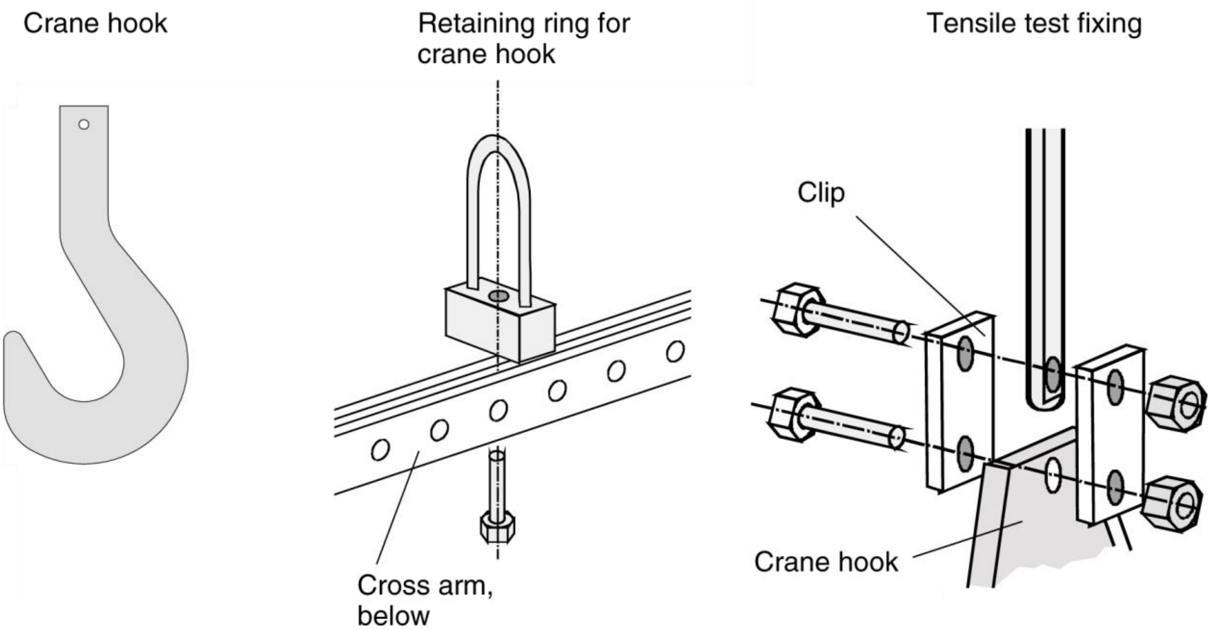


Fig. 5.11 Model – Arch

- ### *Fitting the Models in the Load Frame - FL 200.05, Comparison of Notches*

The models in FL 200.05 are placed under tension and clamped at both ends with screws.

The upper end of the model is screwed onto the flattened spindle using two clips and two screws (a).

At the lower end, the model is attached to the lower cross arm by the holder and the two screws (b).

The load spindle, which is fitted in the upper cross arm can now be used to apply the load to the model.

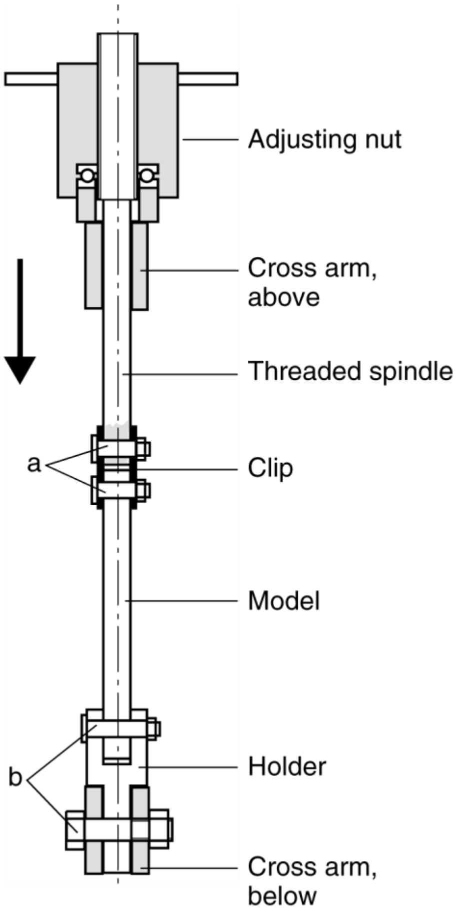


Fig. 5.12 Model - Comparison of Notches

- ***Fitting the Models in the Load Frame - FL 200.06 Model - Stresses on Weld Seams***

The model weld seam is fixed to the side support of the load frame by three screws. The load is applied by the load application device, which is fit- ted in such a way that it exerts pressure forces (see Fig. 3.8) on the free end of the model.

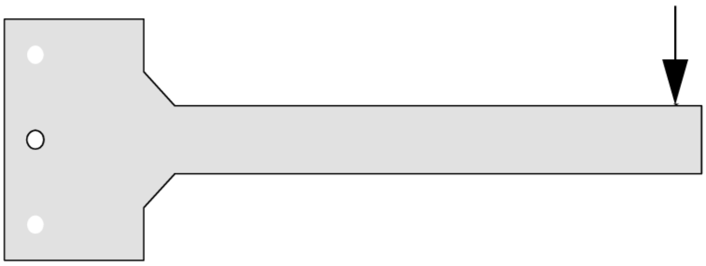
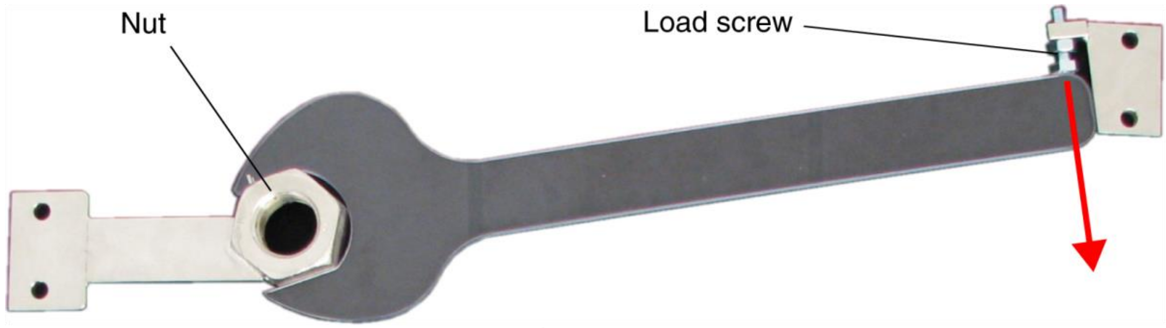


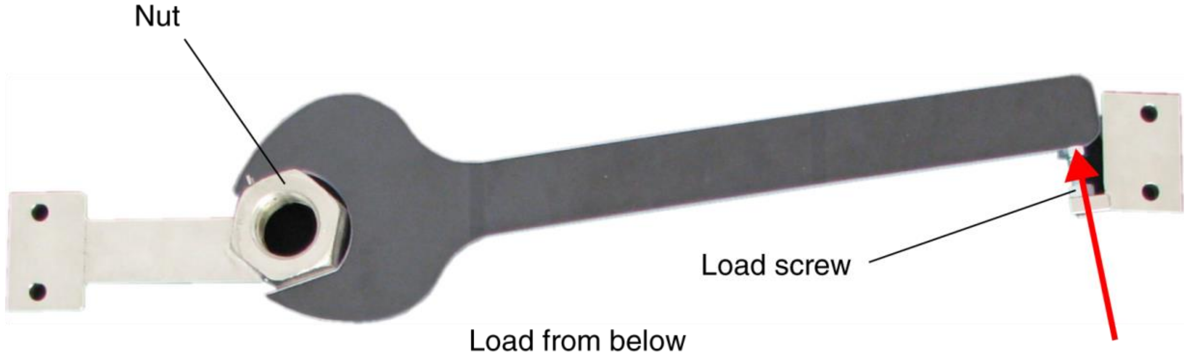
Fig. 5.13 Model - Stresses on Weld Seams

Fitting the Models in the Load Frame - FL 200.07 Model - Wrench

The nut on the model wrench is attached to the side supports of the load frame using two screws. The load is applied by one of the load screws, which are fitted in such a way that they exert pressure forces on the free end of the model.



Load from above



Load from below

Fig. 5.14 Model - Wrench

4. Safety Instructions

ATTENTION	ATTENTION Do not turn the adjusting nut more than: ½ tour for FL200.05 models 1 tour for FL200.03 models ½ tour for FL200.01 models ½ tour for FL200.02 models 2 tour for FL200.06 models

5. Formula Symbols and Units Used

Symbol	Mathematical/physical quantity	Unit
A	Light vector	
c	Light velocity in vacuum	m/s
I	Light intensity	lm
k	Proportionality factor	mm^2/N
n	Refraction index	
th	Model thickness	mm
v	Velocity	$m.s^{-1}$
δ	Path difference	
λ	Wavelength	nm
υ	Frequency	Hz
σ_x, σ_y	Direct stress	N/mm^2
σ_1, σ_2	Principal stress	N/mm^2
τ_p	Principal transverse stress	N/mm^2

6. Basic principles

The photo-elastic method has been used since 1930 and remains one of the most interesting methods in optical tension analysis, not least because of its great clarity and the relatively simple experimental layout. The photoelastic principle is particularly suited for the analysis of the distribution of stresses in flat models. However, three-dimensional models can also be analyzed at additional cost.

This review is limited to the flat state of stresses. The fundamental physical relationships and working principles of the photoelastic method are described in brief below.

The photoelastic method uses the physical property of particular transparent materials to demonstrate double refraction under stress. Double refraction, which is also familiar from natural anisotropic crystals (e.g. calcite) results from the fact that some materials that are isotropic in an unstressed state act as anisotropic if their molecular structure changes due to mechanical load.

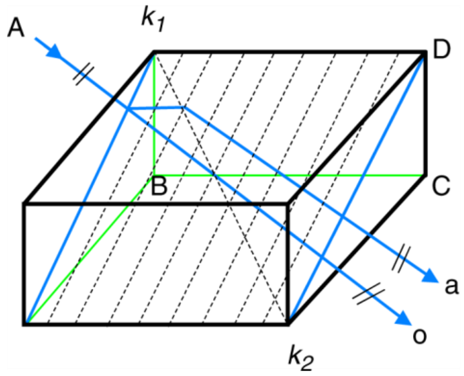


Fig. 5.15 Split-up of the wave at double refraction

The refraction index depends on the effective stresses in the material. Anisotropy can be explained as follows: If, for example, a compressive strain is acting in x direction the molecular structure is compressed in that direction. The medium becomes "optically more dense" and the refraction index increases. At the same time, however, in the y direction, perpendicular to x, the material undergoes a positive lateral strain, i.e. the molecular structure is uncompressed. In y direction, the material thus becomes "optically thinner" and the refraction index falls. The process is reversed for tensile strain and lateral contraction.

In a flat state of stresses, for each point there are two principal sections (see Fig. 5.16) lying perpendicular to one another, in which the normal stresses σ_x and σ_y have their extreme values: the principal stresses σ_1 and σ_2. This assumes that 1 is always algebraically greater. At the same time, a section below $45°$ to the principal section has the maximum shearing strain: the principal shearing strain τ_p.

With the variables σ_1 and σ_2, and the principal direction a, we can use "Mohr's circle" to graphically and mathematically determine all stresses σ_x, σ_y and τ_{xy} as well as their magnitude and direction.

The method is particularly simple for edge stresses, because one of the stresses always acts perpendicular to the edge and is therefore zero. In this case, a photoelastic experiment allows edge stresses, which are crucial for assessment in most cases, to be read directly.

In photoelasticity, light is viewed as an electromagnetic wave process, which describes transversal wave movements. In a beam of light, there are various directions of oscillation perpendicular to its propagation direction. For a photoelastic experiment, however, we require light whose vector only oscillates in a perfect direction. This result is achieved by transmitting light through a polarization filter.

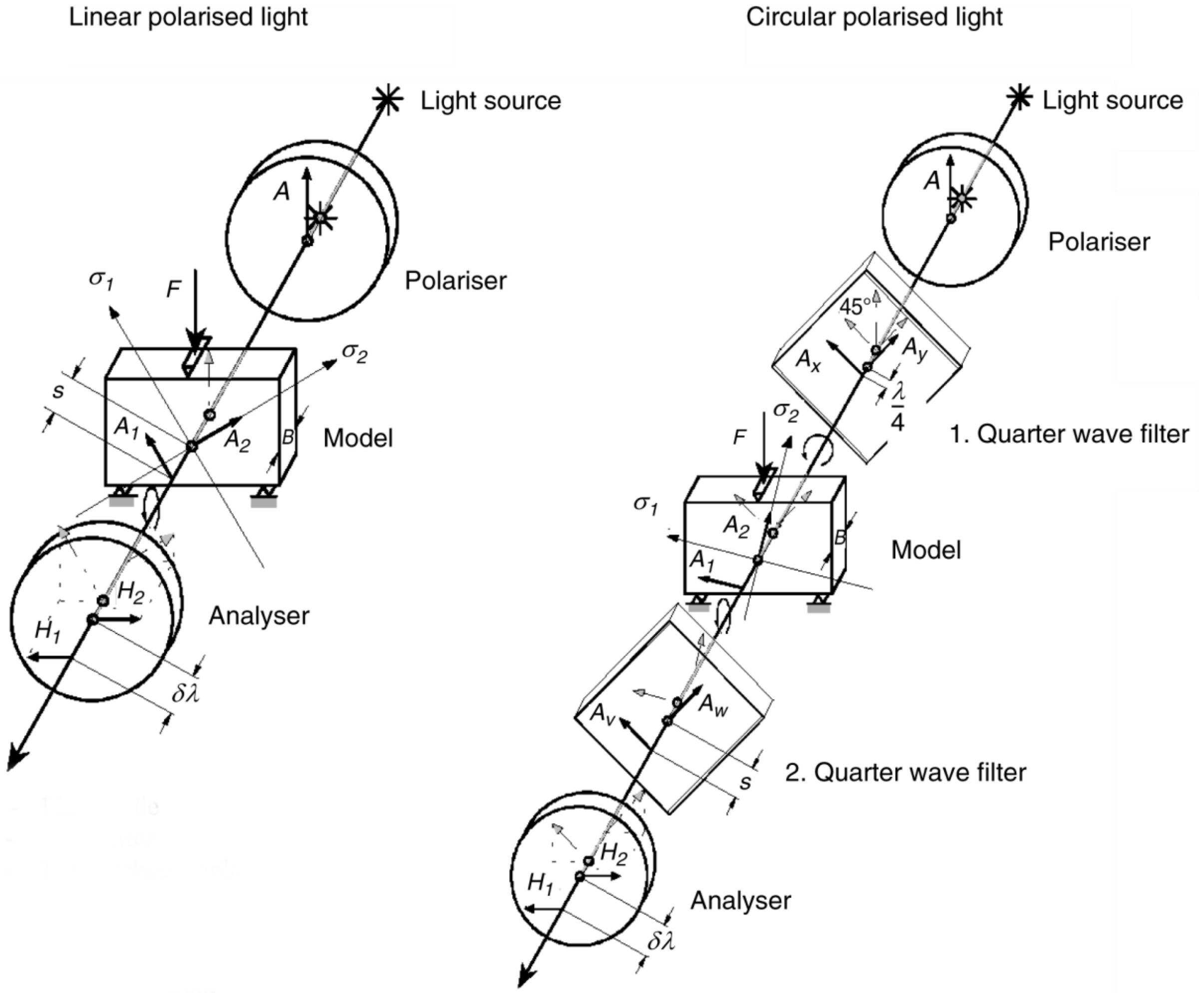


Fig. 5.16 Photoelastic beam path

Nowadays, the polarization filters used are plastic sheets whose long-chain molecules have been parallel oriented by mechanical extension and thus have a predominant direction.

After emerging from the polarization filter, the light is “linear polarized”. The second polarization filter, whose direction of polarization is exactly perpendicular to that of the first, can be used to verify this process: A dark field is obtained, i.e. all oscillations are extinguished (apart from slight stray light). For this reason, the second filter is referred to as the “analyser”. The propagation velocity of the light c in a vacuum is as follows:

$$c = 299792458 \times \frac{m}{s} \approx 3.10^{8} \times \frac{m}{s} \qquad \textbf{Eq. 5.1}$$

In other transparent materials, the velocity v is lower.

Electromagnetic radiation in the frequency range between approx. $\upsilon = 3{,}8 \times 10^{14}\ Hz$ to $\upsilon = 7{,}7 \times 10^{14}\ Hz$ is referred to as visible light and corresponds to a vacuum wavelength range of $\lambda = 390\ nm$ to $\lambda = 790\ nm$ (conversion $\lambda = c/v$)

We refer to monochromatic (‘single colored’) light, when all wave trains in a beam cluster are oscillating with the same frequency (or have the same wavelength in a medium). In the light from a sodium vapour lamp, only the two very close wavelengths of $\lambda = 589\ nm$ to $\lambda = 589{,}6\ nm$ occur in practical terms. It can therefore be approximately interpreted as monochromatic and is used accordingly in the experiment.

The ratio c/v is the refraction index n.

The refraction index is constant in homogeneous transparent bodies. In bodies that behave inhomogeneously in the presence of stresses or strain, the refraction index is a function of the principal stress or strain:

$$n_1 = f(\sigma_1) \qquad \textbf{Eq. 5.2}$$

$$n_2 = f(\sigma_2) \qquad \textbf{Eq. 5.3}$$

If a linear polarized light vector A meets a transparent body at a point P, and $1-1$ and $2-2$ are the main stress directions (Fig. 5.16), the oscillation vector splits into two polarized vectors A_1 and A_2, which oscillate in the $1-1$ and $2-2$. Depending on σ_1 and σ_2, the velocities of the two light vectors are then v_1 and v_2. The time that the two vectors require to pass through the body of thickness th is then th/v_1 or th/v_2.

This results in a relative delay or path difference between one beam and the of:

$$\delta = \frac{c.th}{v_1} - \frac{c.th}{v_2} = th.(n_1 - n_2) \qquad \textbf{Eq. 5.4}$$

According to Brewster’s law (Fig. 5.17): “The relative change in the refraction index is proportional to the difference in the principal stresses.

$$(n_1 - n_2) = k.(\sigma_1 - \sigma_2) \qquad \textbf{Eq. 5.5}$$

k is a proportionality factor that depends on the physical properties of the material and the wave- length of the light used. It is obtained from a calibration experiment on a model with constant moment. In principle, it is used to express the photoelastic sensitivity of the material.

If we combine the equations Eq. 5.4 and Eq. 5.5, we obtain the main equation in photoelasticity:

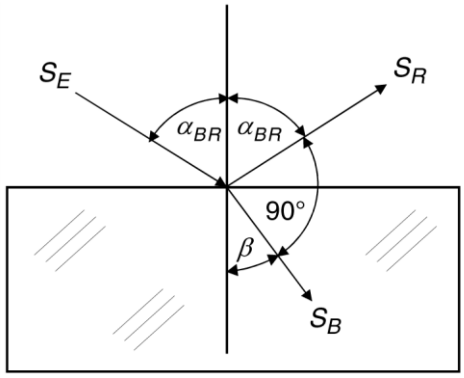


Fig. 4.17 Brewster's law

$$\delta = th.k_{(\lambda)}.(\sigma_1 - \sigma_2)$$ ***Eq. 5.6***

$$\frac{\delta}{th.k_{(\lambda)}} = (\sigma_1 - \sigma_2)$$ ***Eq. 5.7***

Between the model and the analyser, the two vectors A_1 and A_2 (see Fig. 5.16) now oscillate with the path difference δ. Superposition allows us to combine them into a single vector. The resulting vector is referred to as "elliptically polarized" because the apex of the vector moves in an elliptical spiral.

However, the same result is obtained if we continue to observe the two components A_1 and A_2 separately. The analyser only lets through those fractions of the components A_1 and A_2 that lie in its plane of polarisation H_1 and H_2 (Fig. 5.16).

H_1 and H_2 leave the analyser with the path difference δ and interfere. They are the result of the photoelastic experiment.

If the model is free of stress, there is no double refraction. The angle α and the path difference δ are zero - the model appears black. If a load is now applied and increased, a path difference results, which increases proportionally to the magnitude of the difference in the principal stresses. According to the parallelogram rule, the amplitudes of the components H_1 and H_2 depend on the gradient of the sub-components A_1 and A_2 but are always equal. The optical phenomenon now visible after the analyser depends on the composition of the fractions H_1 and H_2 or on the extent to which the oscillation caused by the onset of the path difference allows a resultant (see Fig. 5.16).

Initially, two extremes can be observed:

1. H_1 and H_2 have no path difference. They oscillate in opposite phases. This case occurs if the principal stresses are slightly higher than zero and are equal. The principal stress difference $\sigma_1 - \sigma_2$ then equals zero. As the two H fractions oscillate with the same amplitude but opposite signs, complete extinguishing is obtained for this point, i.e. darkness in the model. The same effect occurs if the path difference is the equivalent of one or multiple whole wave- lengths.
2. H_1 and H_2 have a path difference of half a wavelength. They oscillate in the same phase.

Superposition of the wave trains involved results in the oscillations intensifying at every point. After the analyser, the highest possible brightness is obtained at this point. This process is repeated in line with the accretion of the principal stress difference and thus the path difference. As the model is considered not only point by point but two-dimensionally, depending on the distribution of stresses, i.e. accretion or decay of the stress gradients, we can observe continuous lines alternating between light and dark: the isochromates.

Isochromatic are therefore lines of equal principal stress difference. Starting from the case $\sigma_1 - \sigma_2 = 0$ (path difference $\delta = 0$; total extinguishing) we can identify the isochromates by orders. Starting from the "zero-th" order ($\delta = 0$), we count the number of phase displacements of whole wavelengths (1st, 2nd, 3rd order isochromates etc.).

The arch shown is loaded with the single force like a vault. The high isochromate density can once again be identified inside the arch. This is where the highest stresses occur. In monochromatic light, the individual lines have better resolution; in Fig. 5.18 the "onion like" course of the lines below the application of the force can be discerned much more clearly.

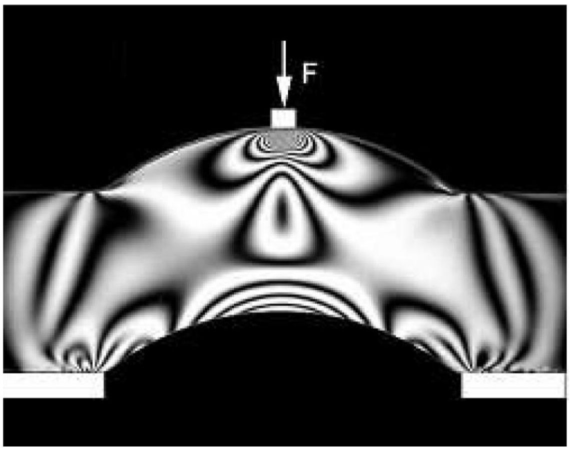


Fig. 5.18 Dark field of arch in monochromatic light

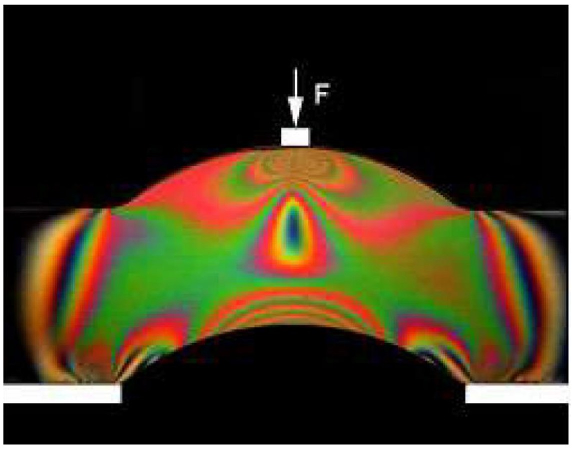


Fig. 4.19 Dark field of arch in white light

It must also be noted that these light and dark values can only be achieved with monochromatic polarized light (normally yellow or green). White light is composed of spectral colors of different wavelengths. In a photoelastic experiment, the short-wave colors (blue) achieve phase displacement a whole wavelength earlier than the long-wave colors (red). After the analyser, the relevant complementary colors then remain visible as "lines of the same color" (isochromates). Only the zero order isochromate is dark here.

When observing the model in white light, however, other dark lines can be made out that are not isochromates. They can be explained as follows: If one of the two principal stress directions coincides with the plane of polarisation, there is no double refraction at that point. The light beam therefore passes unhindered through the model and is then extinguished by the analyser. Of course, it is not only individual dark points that can be identified here, but contiguous continuous lines for all points with equal principal stress direction: the isoclines.

Of course, there is a different isocline line for each change in the plane of polarisation compared to the model. If the two filters are simultaneously rotated gradually by 90° (e.g. in 10° increments) from the initial position, a new isocline line is obtained for each filter position, which result in an isocline family when plotted together. With a degree of graphic skill, this isocline family can be used to construct a trajectory diagram for the principal stresses σ_1 and σ_2. However, this aspect is too complex for practical tuition in vocational school classes and analysis is too time consuming. By contrast: The isoclines interfere with analysis of the isochromate diagram.

To eliminate the interfering isoclines, we use the quarter wave plate. The first quarter wave plate breaks down the polarized light vector A into two orthogonal components, similar to the behaviour of the photoelastic model. The difference is that the phase displacement of the two vertical fractions is exactly $\lambda/4$ of the wavelength of the light used. As its amplitude is the same, superposition of the oscillation of the two components results in a circuit, in which the vectors move. We therefore refer to circular polarized light. The photoelastic layout is referred to as a light or dark field circular polariscope depending on the position of the analyser. The second quarter wave plate, rotated by 90°, raises the defined phase displacement applied from $\lambda/4$ again, so that linear polarized light again exits the analyser.

Compared to the stresses in the model, the circular polarized light arising due to the 1st quarter wave plate does not have a perfect direction, which means that two uniform orthogonal components always meet the photoelastic model. If these should be acting in the same direction as the principal normal stress, they are not broken down further, but are subjected to the path different δ caused by the internal stresses, which is responsible for occurrence of isochromates. The interfering effect of the isoclines when observing isochromates is thus eliminated.

The light intensity therefore no longer depends on the direction of the main axis and can be described in the following form for a dark field arrangement:

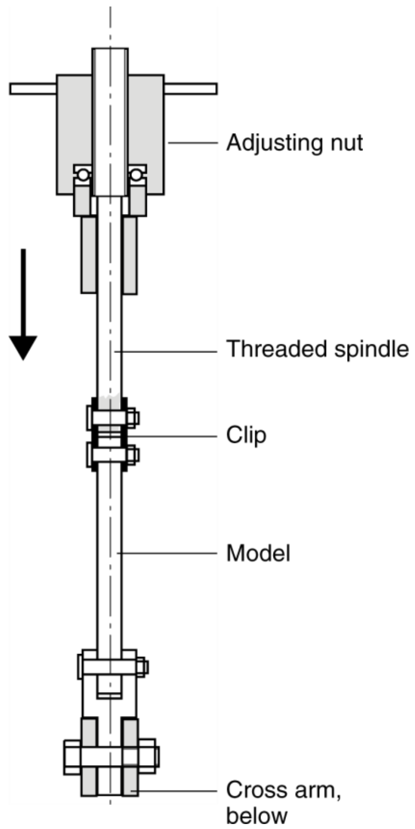
$$l(n) = l_1 + l_2.\sin^2(\pi.n) \qquad \textbf{\textit{Eq. 5.8}}$$

7. Experimental Procedure

Before commencing the experiment, all components must be inspected for damage and a check must be made as to whether the filters are in the specified angle position.

NOTICE

As the sodium vapour lamp requires up to 7 minutes to warm up, it should be turned on in good time.



Installation for FL 200.05

To start the experiment, the desired model (3) can be fitted as described in paragraph 3 and a force exerted on it using the adjusting nut. The model is fixed to the threaded spindle by a double clip and to the lower cross arm by the mounting.

By slowly and carefully rotating the adjusting nut, the formation of the isochromates can be observed.

This Fig. 5.21 to Fig. 5.23 show possible arrangements of the isochromates in monochromatic and white light.

This makes it clear that the individual isochromate orders can be distinguished and enumerated better in monochromatic light.

Enumeration always begins at the outer edge of the model and moves inwards (Fig. 5.24). The model in this example therefore has isochromates of the order 0 to 5.

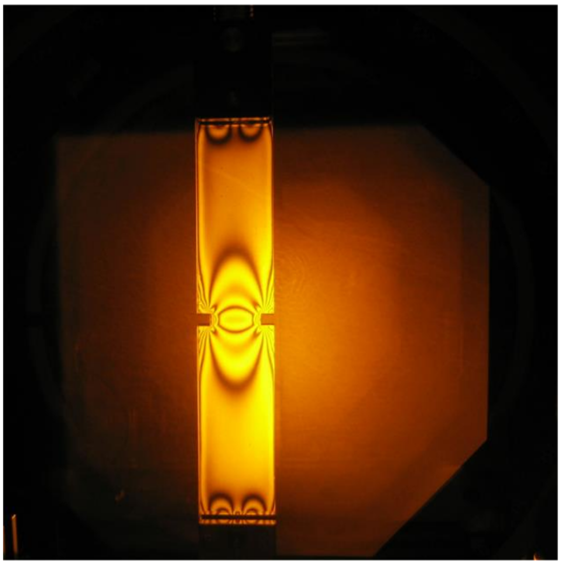


Fig. 5.21 Overall view of FL 200.05 in monochromatic light

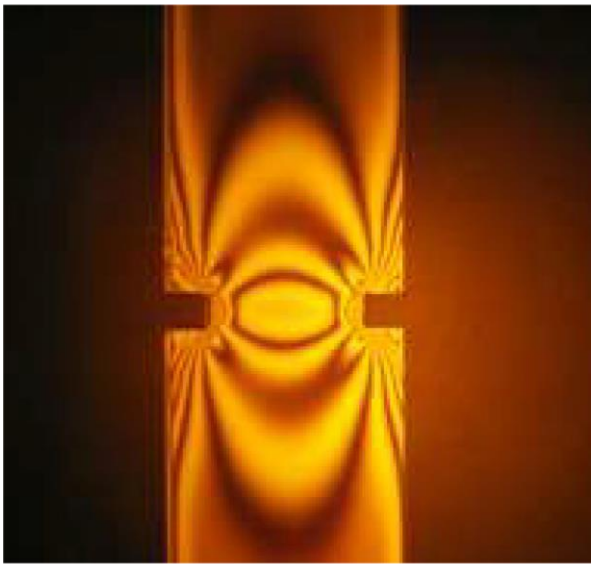


Fig. 5.21 Detail view of FL 200.05 in monochromatic light

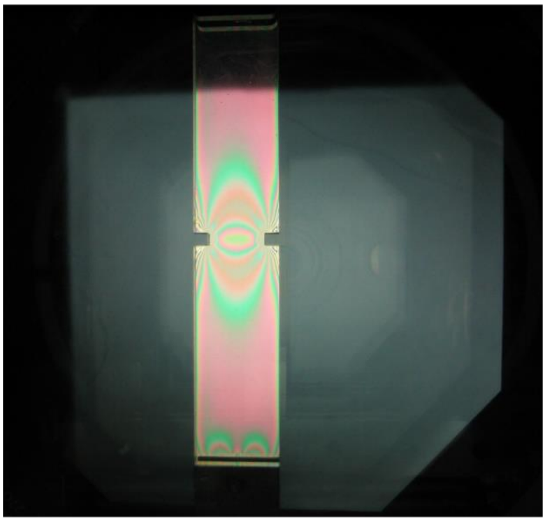


Fig. 5.22 Overall view of FL 200.05 in white light

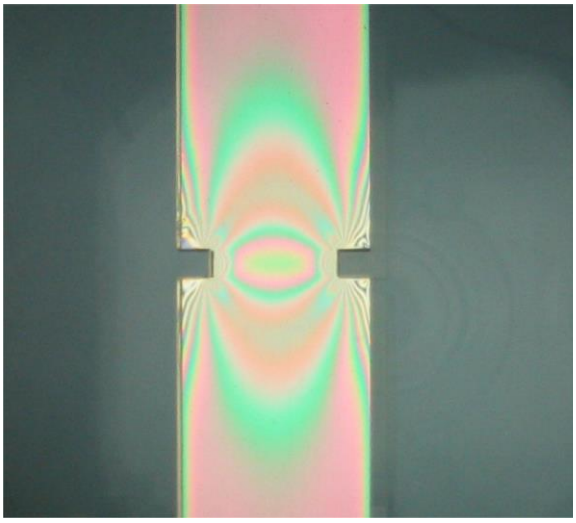


Fig. 5.23 Detail view of FL 200.05 in white light

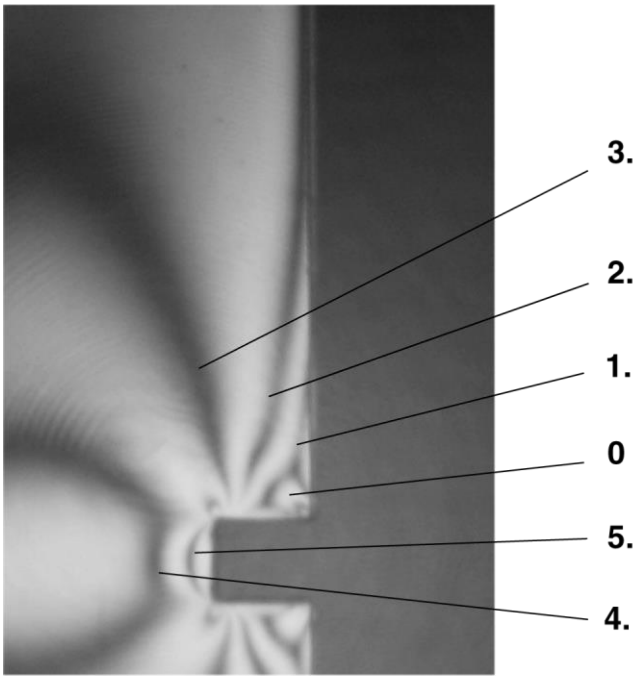


Fig. 5.24 Enumeration of isochromate orders

NOTICE

The appearance of dark strips does not necessarily mean that there is a neutral fibre or undistorted zones.

There is another possibility that can cause darkness to appear even in extended test pieces: For example, if the polarisation direction of the incident light is rotated parallel to one of the main directions of extension (e1 or e2), there is no component of polarisation on the other main direction of extension and therefore no 2nd partial wave that would allow a phase shift to be detected. The wave thus remains in its original linear polarised form and is extinguished by the crossed analyser, i.e. the method fails in this case.

8. Questions

1- Do the experiment as described in paragraph 7 for the models listed in Table 5.1, and, and plot stress distribution of each model.
2- Discuss the obtained experimental results and give your evaluation of the relationship of the stress distribution and the loading and model shape.

9. Results