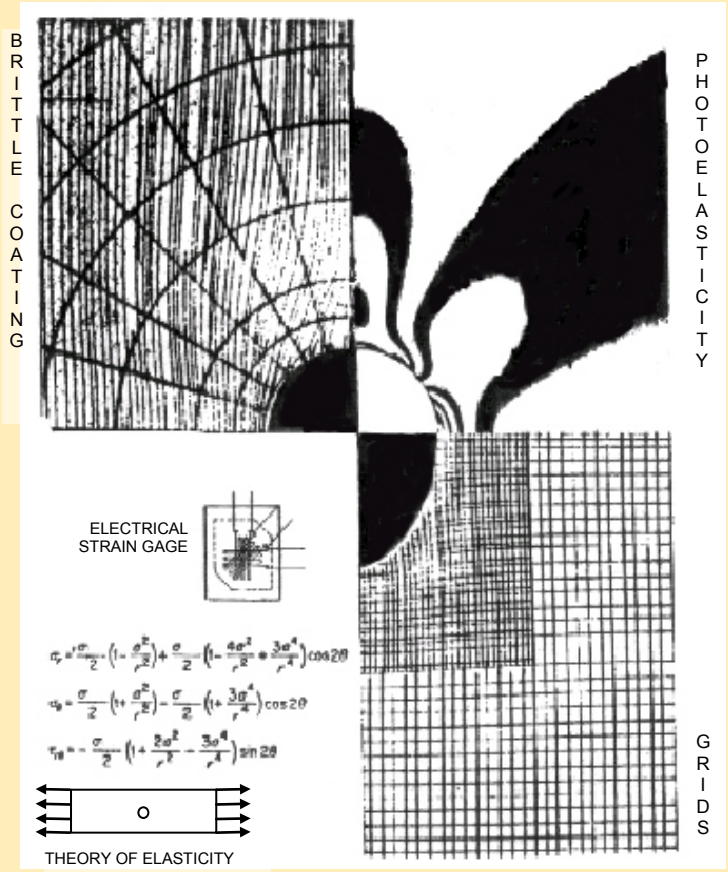
Experimental Stress Analysis
Laboratory Manual
(Revised 2014)



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We have attempted to make this document complete, accurate, and useful, but we cannot guarantee it to be perfect. When we discover errors or omissions, or they are brought to our attention, we endeavour to correct them in succeeding editions of the manual. IIT Madras or Prof. K. Ramesh is not responsible for any direct or indirect damages or loss of business resulting from inaccuracies or omissions contained herein.

Revisions

In 2014 additional experiments 11 and 13 are added. Details on handling Agilent series oscilloscope is given as a separate entity titled “Signal Acquisition with Auto Triggering, for the Agilent 5462x Series”.

Contents

Miscellaneous Topics

Brief Biographies of Some Scientists

Preface

Welcome to the exciting world of Experimental Mechanics. This booklet has experiments on Strain Gauge Technique and Photoelasticity. An experimental technique by itself may not give complete information of all the 15 unknowns (six components of stress, six components of strain and three components of displacements at a point) of a general elasticity problem. In many instances of pragmatic design one does not require all the 15 unknowns. A few key components only at selected points are required to develop a workable design. A large number of day to day design problems could be solved by a judicious choice of photoelasticity and strain gauges. The optics required for photoelasticity is simple and hence easy to establish and use of strain gauge technique is quite popular because of its versatility.

Photoelasticiy has the advantage of providing whole field information of the stress field. Several problems could be studied just by observing the whole field nature of the stress field. Fringe density is a useful tool to identify zones of stress concentration and also zones where material need to be removed for reducing the weight! The technique is very simple to employ if one has to evaluate stress concentration factors and hence ideally suited for structural optimization studies. Photoelasticity has played a very significant role in the developments of Theory of Elasticity. It is theory of elasticity that has shown that in the case of bending of beams, near the load application points the shear stress distribution is no longer parabolic – a deviation from strength of materials. The mathematics involved to arrive at this result is quite cumbersome, whereas, it is quite simple to demonstrate this by photoelasticity.

Strain gauge is a precision technique and to get reliable results it requires extreme care in carrying out the recommendations of the manufacturer. The most crucial but dull part is strain gauge pasting. In this laboratory you are given an exposure on how to follow the various steps but you can be a certified strain gauge installer (look out for the ad by BSSM in this booklet) only if you paste at least fifty more strain gauges!

The advent of computers has influenced all fields of science and engineering. Experimental techniques are not left behind. The role of computers in automating data acquisition for strain gauging and photoelasticity is included as demos.

Several postgraduate students of this laboratory have enthusiastically participated in the preparation of this booklet and also setting up the experiments listed here. My special thanks are to these students and also to the laboratory staff namely Mr. A. Sadasivam, Mr. A. Antony Raj, Mr. T. S. Elumalai and Mr. L. Kannan, project mechanic, in helping me to set up the experiments.

Prof. K. Ramesh

July 2003

General Guidelines

- Please read the details of the experiment given in the booklet thoroughly before you come for the laboratory class.
- Come prepared with tables to enter raw data pertaining to your experiment. Necessary guidelines to prepare the table for raw data is mentioned in this booklet.
- The table of raw data should be extensive and should contain all details of the experiment including the initial readings so that any error in measurement could be checked even at a later date.
- Raw data is to be entered in ink and at the end of the experiment get the signature of the lab-incharge on it.
- There will be one report per group.
- One person has to write it and the other two must check it. Doing correct calculations is important in this lab course. Otherwise one will not be able to draw right conclusions. Difference of 10% in results is easily acceptable in experimental work. Any mistake in calculation means – heavy penalty to checkers only.
- If you miss a lab, you will have to do the experiment separately and write the report separately too.

Lab Report :- Lab report has to be formal, neatly written on good sheets in legible handwriting.

(i) **Flower Garland Analogy** :- A technical write-up can be compared with a flower garland whose flowers are figures, graphs, pictures and equations. Your text works as a thread. So, prepare your tables, figures and graphs before you start writing.

(ii) **Graphs** :- They are the most important elements of the report. A reader can easily grasp the results through well prepared graphs. Graphs, figures and photographs must be numbered as Fig.1, Fig.2, etc. with appropriate captions. The axes should be defined completely. If there are more than one line on the graph, each line should be identified clearly. Each figure should be called by the text.

Tables : Tables are also to be numbered and for each table give a title. Moreover a table should be readable. Do not bring unnecessary details from the raw data.

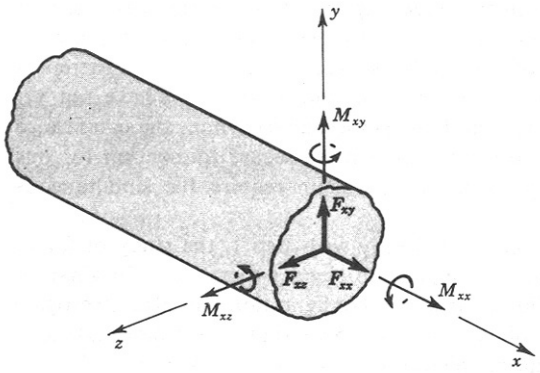
Precise and to the point : A report should be precise but complete. Theory and experimental details should be to the point. I do not want to see essays in theory and experimental details

Units : Only S.I. units please. There is a separate unit for a quantity. Force should be represented in N, stress in MPa and modulus generally in GPa.

Tampering with data : Biggest crime in technical work is if you tamper with data. I will accept any absurd data and still give you good marks. May be our instrument has gone bad on that particular day and you are getting faulty readings. However, if I find you cheating – all the members of the group will get zero in that report.

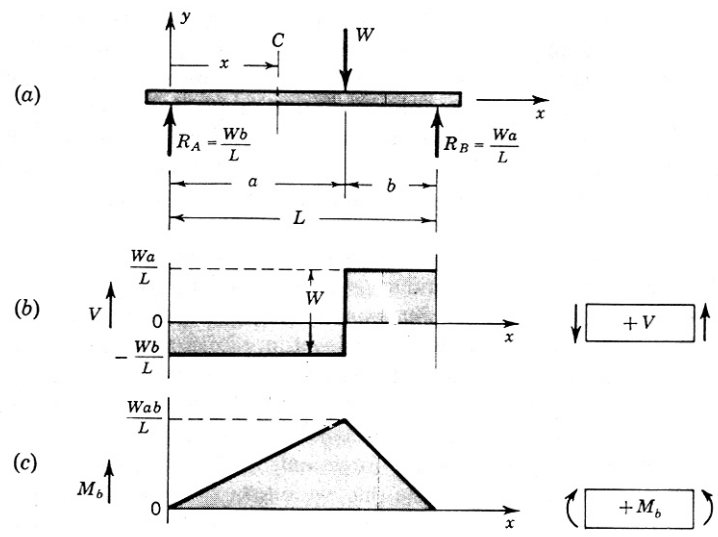
Sign Convention

Imagine a *hypothetical cut* or *section* across the slender member. If either part of the member is considered as an isolated free body, the force and moment required at the section to keep that part of the member in equilibrium can be obtained by applying the conditions of equilibrium. In general, there will be both force and moment acting across the section as shown in the figure below.



The notation F_{xx} , …, etc., of the components in the figure is used to indicate both the orientation of the cross section and the direction of the particular force or moment component. The first subscript indicates the direction of the outwardly directed normal vector to the face of the cross section. The cross-sectional *face* is considered *positive* when the outward normal points in a positive co-ordinate direction and *negative* when its outwardly directed normal vector points in the negative coordinate direction. The second subscript indicates the coordinate direction of the force or moment component. The equations presented in this booklet follow the above sign convention.

In drawing the shear force diagram and bending moment diagrams various sign conventions are used by different authors. The following sign convention is adopted in this booklet and the flexure formula needs to be interpreted based on this sign convention.



Force or moment in the positive direction on the positive face is positive and on the negative face the negative direction of these is considered positive. This sign convention is in tune with the general sign convention mentioned previously.

In some books you may find one of the sign conventions for either shear force or bending moment will be same as shown in the figure and the other would be just the reverse. This may modify the final equation. Always make it a habit to show the sign convention adopted along with the SFD or BMD as shown above.

1. Strain Gage Installation

1.1 Surface Preparation

Strain gages can be bonded satisfactorily to almost any solid material if the material surface is properly prepared. The purpose of surface preparation is to develop a chemically clean surface giving a roughness appropriate to the gage installation requirements, a surface alkalinity of correct pH, and visible gage layout lines for locating/orienting the strain gage. Surface preparation for aluminum alloys and steels require five basic operations:

- Solvent degreasing
- Surface abrading
- Application of gage layout lines
- Surface conditioning
- Neutralizing

To ensure maximum cleanliness and best results, the following should be avoided in all steps:

- Touching the surface with the fingers
- Wiping back and forth or reusing swabs or sponges
- Dragging contaminants into the cleaned area from the uncleaned boundary of the area
- Allowing a cleaning solution to evaporate on the surface

Allowing partially prepared surface to sit between steps in the preparation process or a prepared surface to sit before bonding

Solvent Degreasing

Fig. 1 Solvent Degreasing

- Degreasing is performed to remove oils, greases, organic contaminants, and soluble chemical residues. Degreasing should *always* be the first operation.
- Degreasing can be accomplished using a solvent such as CSM_1 Degreaser/Acetone. Spray applicators are preferred to avoid back-contamination of the parent solution.
- Use a clean gauze sponge to clean the entire specimen, if possible, or an area covering *100 to 150 mm* on all sides of the gage location.

Surface Abrading

The surface is abraded to remove any loosely bonded adherents (scale, rust, paint, coatings, oxides, etc.), and to develop a surface texture suitable for bonding. For rough or coarse surfaces it may be necessary to start with a grinder, disc sander, or file, but for most specimens a suitable surface may be produced with only silicon-carbide paper of the appropriate grit.

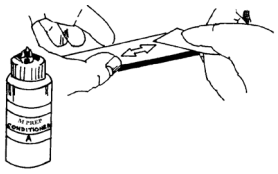


Fig. 2 Surface Abrading

- Place a liberal amount of M-Prep Conditioner A (conditioner is an acid based solution) in the gaging area and wet-lap with clean 320-grit silicon-carbide paper for aluminum, or 220-grit for steel at 45^{o} in two mutually perpendicular directions to the orientation of strain gauge. Add Conditioner A as necessary to keep the surface wet during the lapping process.
- When a bright surface is produced, wipe the surface dry with a clean gauze sponge. A clean surface of the gauze should be used with each wiping stroke.
- A sufficiently large area should be cleaned to ensure the contaminants will not be flagged back into the gaging area during the steps to follow.
- Repeat the above step, using 400-grit silicon-carbide paper for aluminum, or 320-grit for steel.

Layout Lines

The desired location and orientation of the strain gage on the test surface should be marked with a pair of crossed-perpendicular reference lines. For aluminum, a medium-hard drafting pencil (5H) is satisfactory. For most steels, a ball-point pen or a tampered brass rod may be used. All residue from the burnishing operations should be removed in the following step.

Surface Conditioning

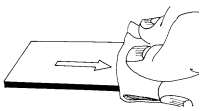


Fig. 3 Surface dried by a single stroke of gauze sponge

- After the layout lines are marked, Conditioner A should be applied repeatedly, and the surface scrubbed with cotton-tipped applicators until a clean tip is no longer discolored by scrubbing.
- The surface should be kept constantly wet with Conditioner A until the cleaning is completed.
- When clean, the surface should be dried by wiping through the cleaned area with a *single* slow stroke of a gauze sponge.
- The stroke should begin inside the cleaned area to avoid dragging contaminants in from the surrounding area.

- Throw the used gauze away, and with fresh gauze make a *single* slow stroke in the opposite direction. Throw the second gauze away.

Neutralizing

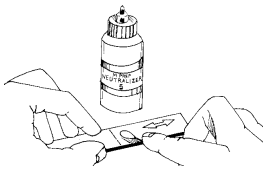


Fig. 4 Scrubbing the surface with cotton tipped applicator

- To provide optimum alkalinity for Micro-Measurements strain gage adhesives, the cleaned surfaces must be neutralized.
- This may be done by applying M-Prep Neutralizer- 5 (Ammonia water) liberally to the cleaned surface, and scrubbing the surface with a clean cotton-tipped applicator.
- The cleaned surface should be kept completely wet with Neutralizer 5 throughout this operation.
- When neutralized, the surface should be dried by wiping through the cleaned area with a *single* slow stroke of a clean gauge sponge.
- Throw the gauze away and with another fresh gauze sponge, make a *single* stroke in the opposite direction. Always begin within the cleaned area to avoid recontamination from the uncleaned boundary.

If the foregoing instructions have been followed precisely, the surface is now properly prepared for gage bonding. *The gages should be installed within 30 minutes on aluminum or 45 minutes on steel.*

1.2 Strain Gage Bonding

The electrical resistance strain gage is capable of making accurate and sensitive indications of strain on the surface of the test part. Its performance is absolutely dependent on the bond between itself and the test part. The procedures outlined below will help ensure satisfactory bonds when using M-Bond 200

Handling and Preparation

Micro-Measurements strain gages are specially treated for optimum bond formation with all appropriate gage adhesives. No further cleaning is necessary if contamination of the prepared bonding surface is avoided during handling. (Should contamination occur, clean with a cotton swab moistened with a low residue solvent such a *M-LINE* Neutralizer 5 or isopropyl alcohol. Allow the gage to dry for several minutes before bonding.) *Gages should never be touched with the hands.*

- Remove the strain gage from its acetate envelope by grasping the edge of the gage backing with tweezers, and place on a chemically clean glass plate (or empty gage box) with the bonding side of the gage down.
- Place the appropriate terminals (if any) next to the strain gage solider tabs, leaving a space of approximately 1.5 mm between the gage backing and terminal.

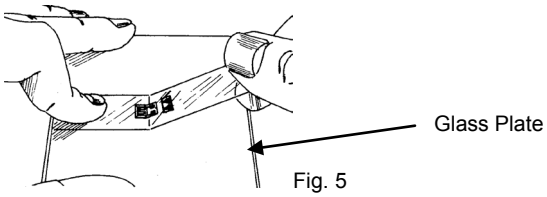


Fig. 5

- Using a 100-to-150 mm length of *M-LINE* PCT-2A cellophane tape, anchor one end of the tape to the glass plate behind the gage and terminal.

Wipe the tape firmly down over the gage and terminals. Pick the gage and terminals up by carefully lifting the tape at a shallow angle (30 to 45 degrees) until the tape comes free with the gage and terminal attached. (The shallow angle is important to avoid over-stressing the gage and causing permanent resistance changes.)

Caution: Some tapes may contaminate the bonding surface or react with the bonding adhesive. Use only tapes certified for strain gage installations.

- The strain gage is now prepared for positioning on the test specimen. Position the gage/tape assembly so the triangle alignment marks on the gage are over the layout lines on the specimen.
- Holding the tape at a shallow angle, wipe the assembly onto the specimen surface. If the assembly is misaligned, lift the tape again at a shallow angle until the assembly is free of the specimen. Reposition and wipe the assembly again with a shallow angle.

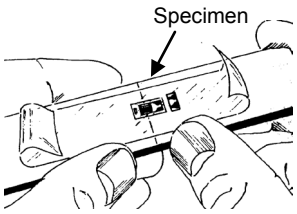


Fig. 6

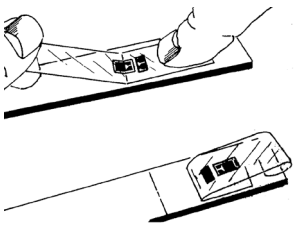


Fig. 7

- In preparation for applying the adhesive, lift the end of the tape opposite the solder tabs at a shallow angle until the gage and terminal are free of the specimen.
- Tack the loose and of the tape under and press to the surface so the gage lies flat with the bonding side exposed.

Bonding with M-Bond 200

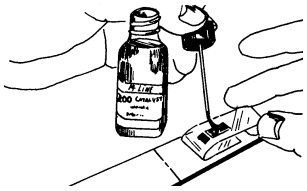


Fig. 7 Catalyst application (Step 1)

- M-Bond 200 Catalyst should be applied sparingly in a thin uniform coat.
- Wipe the brush against the lip of the bottle approximately ten times to remove most of the catalyst.
- Set the brush down on the gage and swab the gage backing by sliding - not brushing in the painting style – the brush over the entire gage surface.
- Move the brush to an adjacent tape area prior to lifting from the surface.
- Allow the catalyst to dry at least one minute under normal ambient laboratory conditions.
-

The next three steps must be completed in sequence within three to five seconds. Read these steps before proceeding.

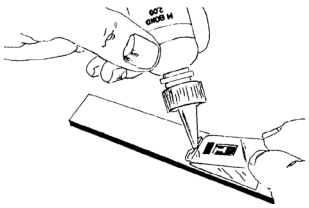


Fig. 8 M-Bond application (Step 2)

- Lift the tucked-under tape. Holding the gage/tape assembly in a fixed position, apply one or two drops of M-Bond 200 Adhesive at the junction of the tape and specimen surface, about 13 mm outside the actual gage installation area.
- *Immediately* rotate the tape to approximately a 30-degree angle so that the gage is bridged over the installation area.
- Holding the tape slightly taut and beginning from the tab end of the gage, slowly and *firmly* make a single wiping stroke over the gage/tape assembly with a clean gauze sponge to bring the gage back down over the alignment marks on the specimen. Release the tape.
- Immediately upon completion of the above step, *discard the gauze* and apply firm thumb pressure to the gage and terminal area.

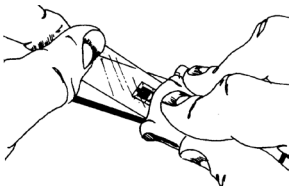


Fig. 9 Bonding (Step 3)

- This pressure should be held for at least one minute. Wait two minutes before the next step (tape removal).

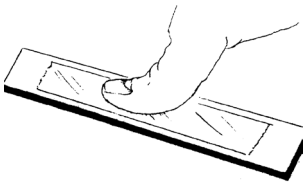


Fig. 10 Application of thumb pressure (Step 4)

- The gage and terminals should now be bonded to the specimen. To remove the tape, pull it back directly over itself, peeling it slowly and steadily off the surface.

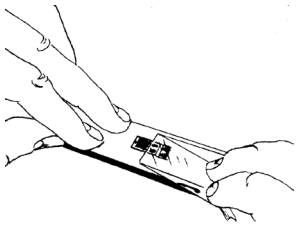


Fig. 11 Removal of cello tape (Step 5)

1.3 Soldering Technique

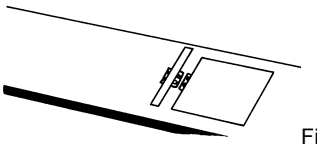


Fig. 12 Masking the Gage

- Mask the gage grid area with drafting tape, leaving only the tabs exposed.
- After the soldering iron has reached operating temperature, clean the tip with a dry gauze sponge and tin it with fresh solder.

Tinning Tabs and Terminals

Tinning helps to ensure surface wetting and good heat transfer during the soldering operation.

- Hold the soldering pencil in a nearly horizontal portion (<30 deg.) with the flat surface of the tip parallel to the solder tab or terminal.
- Place the rosin-core solder wire flat on the gage tab, and press firmly with the tinned hot soldering tip for about one to two seconds while adding approximately 3mm of fresh solder at the edge of the tip.
- Simultaneously lift both the soldering pencil and solder wire from the tab area.
- A bright, shiny, even mound of solder should have been deposited on the tab. If not, repeat the process.

Note:

a. Lifting the soldering iron before lifting the solder may result in the end of the solder wire becoming attached to the tab:
b. Lifting in the reversed order can leave a jagged (spike) solder deposit on the tab.

Fig. 13 Soldering (Step 2)

Tinning the Leadwire

- For a three-conductor lead-in wire, separate the individual leads for 20mm. Strip away 13mm of insulation on both side of each end of the wire 13mm from the ends and quickly pulling off the insulation.

Warning: Do not use a knife or other blade to cut the insulation.

- The ends of stranded wires are to be twisted tightly before tinning.
- Remove excess solder from the soldering tip using a dry gauze sponge. Then melt fresh solder on the hot tip to form a hemisphere of molten solder about the twice diameter of the wire to be tinned.
- Slowly draw the base wire through the molten solder while continuously adding fresh solder to the interface of the wire and soldering tip.

Lead wire attachment

- Holding the tip of a finger on the tip of the tinned wire for safety, cut each wire with diagonal wire cutter leaving 3mm of exposed, tinned wire.
- Lead wires should be formed and routed to the strain gage or terminal strip, then firmly anchored to the test-part surface with drafting tape so that the tinned end of the wire is spring-loaded in contact with the solder bead before making the soldered connection.
- Attempting to route the lead wires after completing the solder joint will often result in damage to the gage or terminals.
- Clean and re-tin the soldering iron tip with fresh solder.
- The temperature of the iron should be adjusted so that the solder is easily melted without rapidly vaporizing the flux.
- Hold the soldering pencil nearly horizontal, firmly press the flat surface of the tip on the junction while adding approximately 3mm of fresh solder at the edge of the tip.
- Simultaneously lift both the soldering pencil and solder wire from the area.

Cleanup & Inspection

- Any traces of residual flux can cause gage instability and drift and will inhibit bonding of the installation protective coating.
- Incompletely removed soldering flux is the most common cause of degraded performance in strain gage installation.
- Soldered connections should be smooth, shiny and uniform in appearance. If not re-solder and remove flux.
- Apply rosin solvent liberally to the solder joints. Drafting tape may be removed by loosening the mastic with rosin solvent. Remove all solvent with a gauze sponge, using a dabbing action.

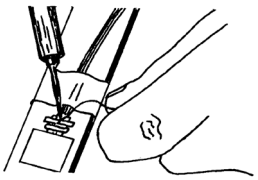


Fig. 14 Soldering (Step 3)

- Secure the lead-in wires to the specimen by tape or dental cement to prevent the wires from being accidentally pulled from the tabs.
- A stress relief ”loop” should be placed between the tape and the solder connections.
- Apply a protective coating over the entire gage and terminal area. For most laboratory uses, M-Coat A will provide adequate long-term protection. The coating should be continuous up to and over at least the first 3mm of leadwire insulation.

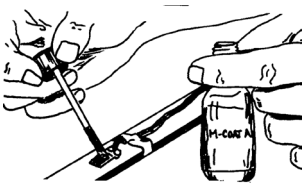


Fig. 15 Application of protective coating

- The properly installed strain gage will have a resistance to ground of at least 10000 to 20000 mega ohms.
- Checking leakage resistance with the Model 1300 Gage Installation Tester is highly recommended.

1.4 Strain Gage Installation Testing

Test for Voids in Bonding System

- Take a soft rubber eraser. Using this tap or press the gage installation. Observe the effect on strain indicator.
- If the strain reading is noted, the gage bonding is not satisfactory and voids exist between strain gage and specimen.

Test for Complete Curing of Adhesive by Strain Cycle/Temperature cycle

- Give a small strain cycle to the specimen bonded with strain gage.
- Strain gage installations with completely cured adhesives when cycled to 1000 με. will exhibits zero shifts less than 2 με.
- If strain cycle is not possible, a temperature cycle can be given.

- If there is a zero shift, it indicates incomplete bonding.

Use of Model 1300 Gage installation Tester to Test Insulation Resistance and Gage Installation

- Connect the strain gage to Model 1300 as directed in the instrument.
- Press BATT Button: It indicates whether battery is to be replaced or not. If the instrument is being used for the first time in weeks, it may be also necessary to exercise the switches to obtain stable readings. This can be done by pressing each of the buttons approximately six times (particularly M Ω and 1% switch).
- It can be used to measure the insulation resistance between gage and specimen. Press MΩ button. Meter will indicate the insulation resistance between gage foil and specimen. A properly installed gage should read above 10000 MΩ at ambient temperature. Readings below this indicate trapped foreign matter, moisture, flux or partial failure of the backing.
- Press Ω: Meter will indicate the normal gage resistance in ohms on upper scale. A shorted or open gage will indicated by a zero or infinity reading.
- Press 5%, 1%: Indicate % deviation of gage resistance from normal or reference.

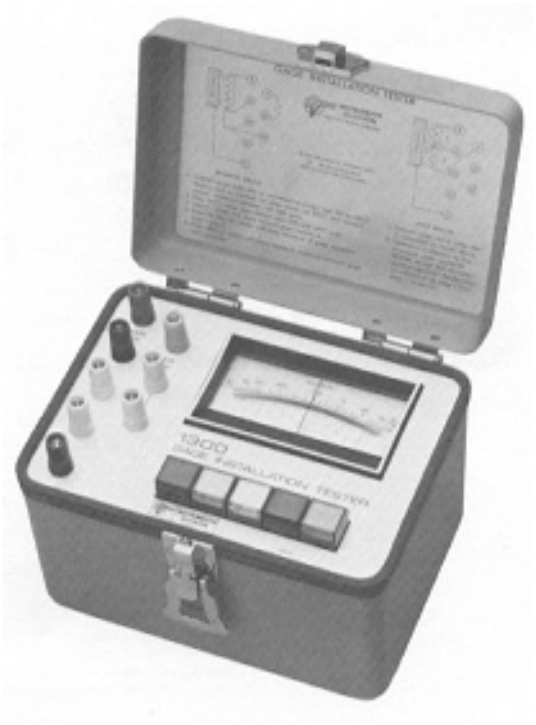


Fig. 17 Model 1300 strain gage installation tester

BSSM The British Society for Strain Measurement

CERTIFICATION

BSSM Strain Measurement Certificates are recognised throughout industry as the vocational/ professional qualifications for all personnel involved in the installation and use of electrical resistance strain gauges. The Certification Scheme operates at three levels, constent with the European Standard EN473:1993.

Demonstrate your competence by a BSSM Certificate in Strain Measurement

Level 1 The basic qualification for strain gauges installers. The standard is broadly similar to NVQ2

Level 2 The qualification for personnel who install strain gauges, supervise the installation of gauges, and use gauges to make measurements. The standard is broadly similar to NVQ2

Level 3 The qualification for senior strain measurement personnel involved in the design of strain gauge installation and the analysis of measurement data. The standard is broadly similar to NVQ4.

Seminars Two weeks prior to the event, preparation seminars will be held at each examination venue. Arranagements can also be mae for seminars and examinations to be hld at an employer's premises.

The next examinations are:

Level 1	27 March	Oxford Brookes University
	03 July	Oxford Brookes University
	31 July	Strathclyde University, Glasgow
	30 October	Measurements Group UK, Basingstoke
Level 2	27 March	Oxford Brookes University
	11 September	Oxford Brookes University
Level 3	02-03 July	Oxford Brookes University

Booklets, registration forms and further details can be obtained from: Mr D.H.Mitchel, Asst Secretary BSSM, 11 Wolfridge Ride, Alveston, Bristol BS35 3RA. Tel/Fax: 01454 412991 email: dmitch@bssm92.freeserve.co.uk

2. Measurement of Stress due to Bending Using a Strain Gage

Objective

Using Strain gages, find the stress on the top surface of a cantilever, near to fixed end, when loaded at free end.

Apparatus

Strain gage, Specimen bar (Al), Bar holder with provision for loading, Strain Indicator model P-3500, Multimeter.

Setup

The general setup is shown in Fig. 1. The strain gauged cantilever is attached to a 'holder' having a micrometer to give deflection in steps of 0.5mm. Leadwires from the strain gauge are attached to the P-3500 which then displays the strain.

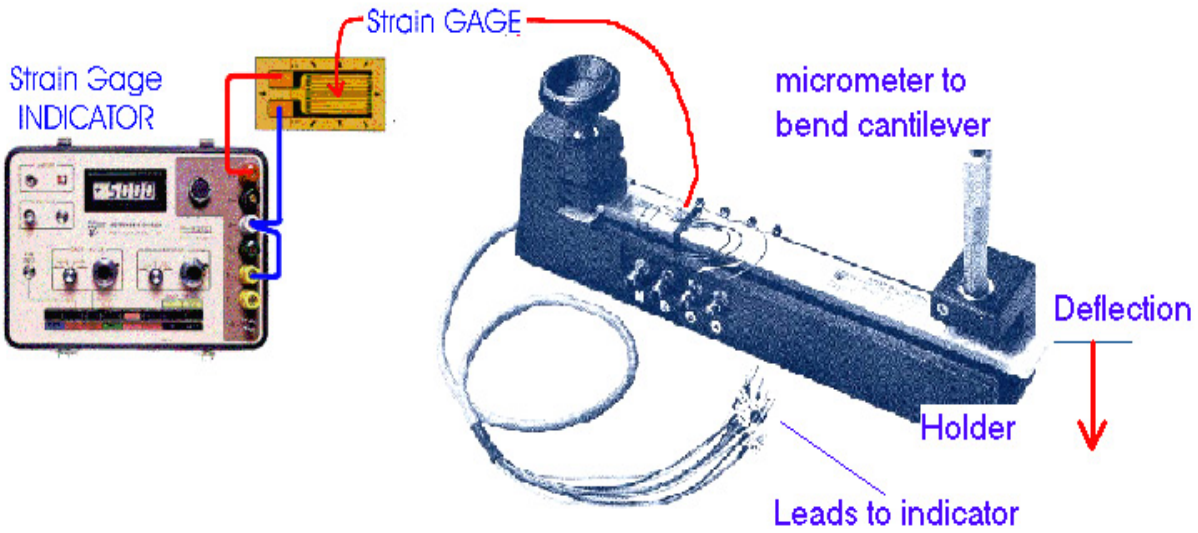


Fig. 1 General setup for experiment

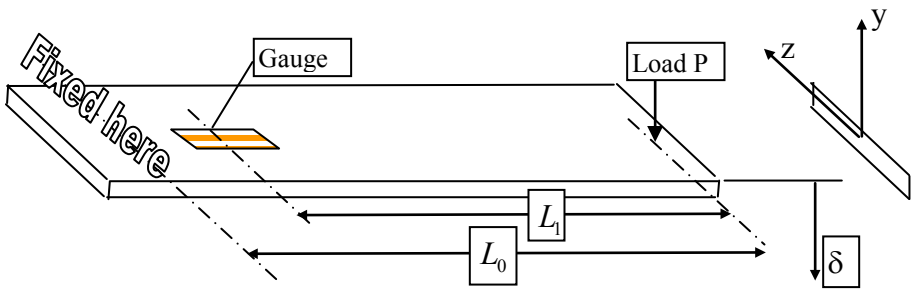


Fig. 2 Important dimensions and Co-ordinate system axes

Theory

Resistance strain gage is based on the phenomenon that the electrical resistance in a piece of wire is directly proportional to the length and inversely to the area of the cross section. If a resistance strain gage is properly attached onto the surface of a structure whose strain is to be measured, the strain gage wire/film will also elongate or contract with the structure, and as mentioned above, due to change in length and/or cross section, the resistance of the strain gage changes accordingly.

This change of resistance is measured using a strain indicator (with the Wheatstone bridge circuitry), and the strain is displayed by properly converting the change in resistance to strain. Every strain gage, by design, has a sensitivity factor called the gage factor which correlates strain and resistance as follows

$$\text{Gage factor } (S_G) = \frac{\Delta R / R}{\varepsilon}$$

Where R is resistance of un-deformed strain gage, ΔR is change in resistance of strain gage due to strain, and ε is strain.

Experimentally one measures strain. Stress can be computed by invoking the stress-strain relations. The stress-strain relations to the present case reduces to

$$\sigma_{xx} = E\varepsilon$$

The stress induced due to bending can be evaluated analytically using flexure formula. The flexure formula is

$$\frac{M_b}{I_{zz}} = -\frac{\sigma_{xx}}{y} = \frac{E}{\rho}$$

where M_b is the bending moment applied, I_{zz} is the moment of inertia of the beam cross-section, σ_{xx} is the normal stress acting on plane x in the direction x, y is the distance of the fiber from the centroidal axis, E is the Young's Modulus of the beam material and ρ is the radius of the curvature of the bent beam.

The beam is bent by applying a known deflection at free end. This can be converted to the free end load P by knowing the free end deflection analytically.

For a cantilever beam with end-load, the free-end deflection δ (in y direction) $= \dfrac{PL_0^3}{3EI_{zz}}$

$$\text{So, } P = \frac{3EI\delta}{L_0^3}$$

$$\text{Moment at gage location } M_t = -PL_1$$

Test procedure

1. Set the specimen bar (beam) to the bar holder so that the bar acts as a cantilever beam. Measure the important dimensions- L_0, L_1, breadth b, and thickness t.

   The bar should not be loaded now, and for the following steps 2-7.

2. Measure the resistance of the strain gage using the multimeter and note it down
3. Connect the two ends of the strain gage as a QUARTER bridge as shown on the inner side of the strain indicator's lid (Fig. 5).
4. Depress the GAGE FACTOR button and set the (initial) gage factor to 2.005 or 2.06. *This value is supplied by the strain gauge manufacturer*. *Please refer the gauge spec sheet for this value*. Use the small four-position 'range selector' knob first and then the bigger potentiometer. Lock the potentiometer.
5. Depress the AMP ZERO button (amplifier)- the display should be +/-0000. else use the 'fingertip control' knob to bring +/- 0000.
6. Balance the circuit (still beam is not loaded). Depress the RUN button (with all other buttons OFF) and see the display. The present strain gauge actual output will be shown. Using the BALANCE knob, set the display to a convenient value (zero or any other value). Since the readings are going to be relative with respect to a point, it does not make any difference if the initial setting is zero or not as long as it is taken into account. If the initial setting is not zero, the initial value should be subtracted from the reading value. (You may have to use both the smaller and the bigger knobs). Lock the potentiometer.
7. With no load on cantilever, take the 1st set of readings. Note down the indicated strain.
8. For next step, make a deflection of 0.5mm with the micrometer handle. Add deflection in 0.5 mm steps, to a max of 5 mm. Repeat the measurements.

Note: Weight of the beam itself does contribute to the strain and may also be considered. However, since we zeroed instrument under the load of the beam weight it is irrelevant for our measurements.

Sample Table

Initial reading of the strain indicator:_____

Sl no.	Deflection, mm	(□), micro strain		Strain (based on Beam theory)	% difference
		Display value	Strain (Experimental)		

Points for Discussion

2. Estimate the stress using stress-strain relations. Compare it with that predicted by beam theory.
3. If you have to consider the weight of the beam, how would you modify the experimental procedure?
4. If you have to account for the self-weight of the beam analytically how would you proceed?

Measuring Strain on A Surface Through A Resistance Strain Gauge

A resistance strain gage is bonded to the surface of a component so well that it becomes an integral part of the component. Note that a strain gage is capable of measuring only the normal strain (tensile or compressive along the axis of the gage). Strain is supposed to be measured at a point but experimentally a strain gage measures an average strain over an area.

Bridge excitation, gage resistance, gage length, gage backing etc. influence the strain measurement. Wheatstone bridge is the most commonly used circuit for strain measurement.

Strain Measuring Bridge

Figure 3 shows a Wheatstone Bridge circuit. Initially E is adjusted to be zero by arranging the resistances such that $R_1 R_3 = R_2 R_4$. If, after this initial adjustment there are small changes in the values of the resistances, then the voltage output ΔE of the bridge can be obtained as:

$$\Delta \mathrm{E} = V \frac{R_1 R_2}{\left(R_1 + R_2\right)^2} \left[\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} \right] \tag{1}$$

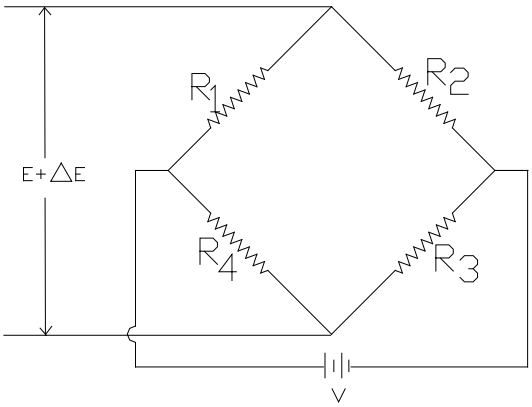


Fig. 3 Wheatstone Bridge

For optimum sensitivity it is recommended to have

R1 = R2 = R3 = R4

R1, R2, R3 and R4 can either be active strain gages or dummy strain gages.

The Eq. (1) can be interpreted as like strains in adjacent arms cancel but in opposite arms add. This aspect is judiciously used in strain measurement for temperature compensation or for doubling or quadrapling signal in transducer applications.

Applications of Wheatstone bridge to strain measurement

1. Single-arm bridge / Quarter Bridge Circuit

One of the arms of the bridge say R_1 is replaced by a strain gauge. With the initially balanced bridge, any change in resistance due to strain of the gauge causes a change in E. The output voltage obtainable from Eq.(1) is,

$$\Delta E = V \frac{R_1 R_2}{\left(R_1 + R_2\right)^2} \left[\frac{\Delta R_1}{R_1} \right] \tag{2}$$

In general, ΔR_1 can be due to both strain and temperature change. In order to measure the change in ΔR_1 only due to strain, the change in resistance due to temperature has to be cancelled. This is known as temperature compensation. Temperature compensation is critical for static measurements where the strain reading needs to be monitored for a long period of time.

2. Two–arm bridge / Half Bridge Circuit

A Wheatstone bridge that has two similar gauges in place of R_1 and R_2, while R_3 and R_4 built into the strain indicator, is termed as a Half bridge circuit. The output E is given by,

$$\Delta E = V \frac{R_1 R_2}{\left(R_1 + R_2\right)^2}\left[\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2}\right]$$

If both the gauges are in similar temperature environments, then the measurement is automatically compensated for temperature effects. In strain measurement it is *always recommended to use at least a half bridge circuit*. The strain sensitivity can be increased to two fold if choice of strain gage location are so selected such that R_1 and ΔR_2 experience opposite but equal strains.

3. Four-arm Bridge / Full Bridge Circuit

In this case all the four arms of the bridge are formed of similar strain gauge elements outside the strain indicator.
The strain sensitivity can be increased up to four times by judicious choice of pasting the strain gauges on the specimen and connecting them appropriately to the bridge.

Direct Reading – Strain indicator

A schematic diagram of the circuit element employed in a direct reading strain indicator is Fig. 4.

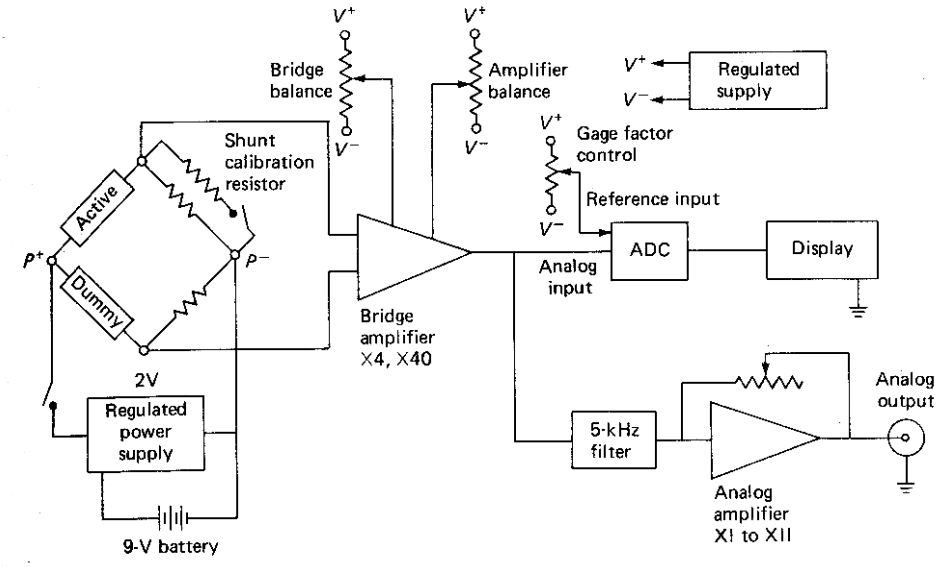
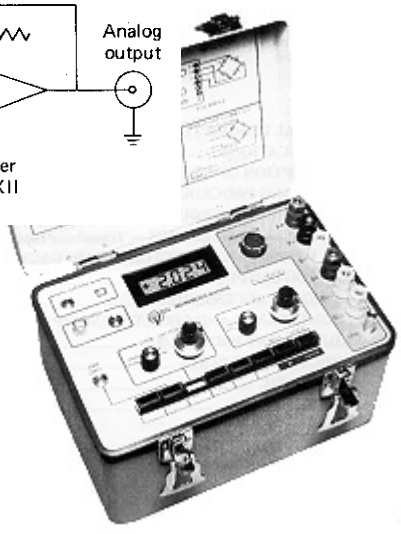


Fig. 4

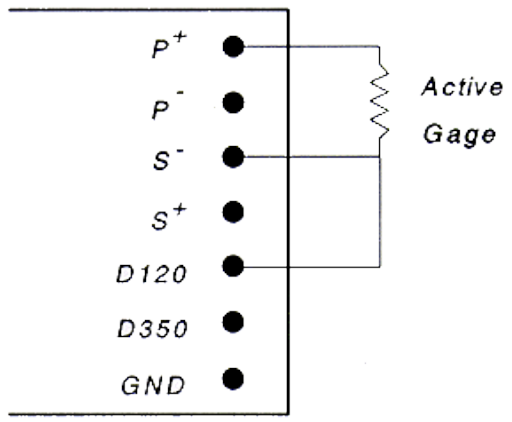
- One can read directly the strain value and also take the output as an analog signal.
- Bridge is powered by a 2V dc supply.
- Shunt resistors produce a calibration indication of 5000 με when the gage factor is set at 2.
- The output of the bridge is an input to an instrument amplifier
- A potentiometer is to balance the bridge. Note



Model P-3500 Strain Indicator

that this is used to adjust the voltage on the instrument amplifier rather than resistance on an arm of the bridge.

- Gage factor is adjusted through a potentiometer which controls the reference voltage of the analog-to-digital converter.



P-3500 Specification

Make : Measurements Group - Instruments division
Model : P 3500
Gage factor range: 0.5 to 9.99
Type of strain gages: 120 Ω and 350 Ω strain gages
Operation: Battery Operated
Readings: Displays strain as micro strain (□□). Actual strain= display * 10e-6.
The instrument supports Quarter, Half and Full bridge circuits.
The display can be set to normal display (absolute value) or with a magnification of 10.

Fig. 5 Strain Measuring Bridge (instrument) Front panel, Quarter-bridge circuit connection details and P-3500 specifications.

3. Torsion of Hollow Shaft

Objective

Evaluation of angle of twist and shear strain in a shaft subjected to torsion.

Apparatus

The apparatus (Fig.1) setup consists of fixtures for holding the specimen and is provided with the lever arm and weighing pans for loading the shaft in pure torsion. The telescope and scale arrangement is to measure the twist of the shaft. The lamp is used for clear vision of the readings in the telescope. P3500 for strain measurement.

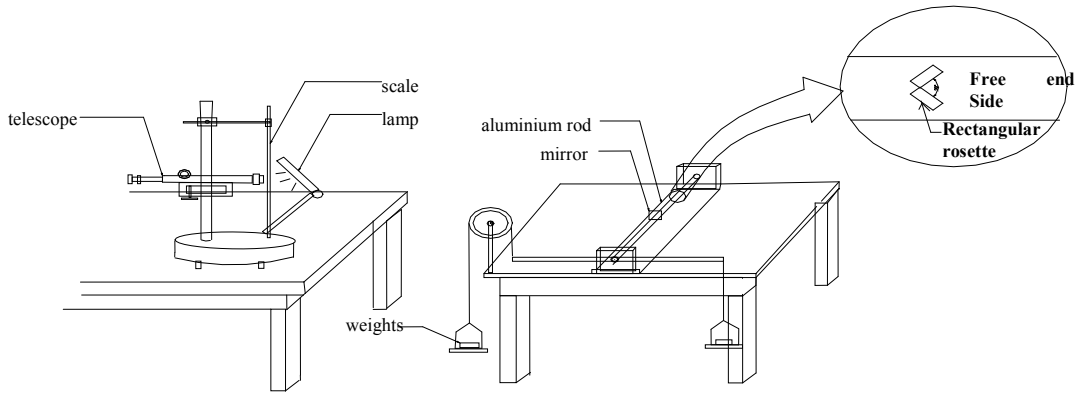


Fig. 1 Experimental setup

Theory

A slender member subjected primarily to twist is usually called a shaft. Shafts are used in the transfer of mechanical power from one point to another. In such an application, one is primarily interested in the twisting moment, which can be transmitted by the shaft without damage to the material. Knowledge of stresses that develop due to twisting (and its variation over the cross-section) is necessary to be known. In certain applications twisted shafts are used as a spring with prescribed stiffness with respect to rotation. In such a case, one is interested primarily in the relation between the applied twisting moment and the resulting angular twist of the shaft. For a circular shaft of constant diameter transmitting a uniform torque, the torsion formula is

$$\frac{M_t}{J} = \frac{\tau_{\theta z}}{r} = \frac{G\phi}{L} \tag{1}$$

where, M_t is the twisting moment applied, J is the polar moment of inertia of the cross-section, $\tau_{\theta z}$ is the shear stress developed due to torsion (Fig. 2), r is the radius of the element being considered, G is shear modulus of the material, ϕ is angle of twist (Fig. 3) and L is the length of the uniform shaft.

Specimen

Hollow Aluminium shafts with a shear strain gauge pasted.

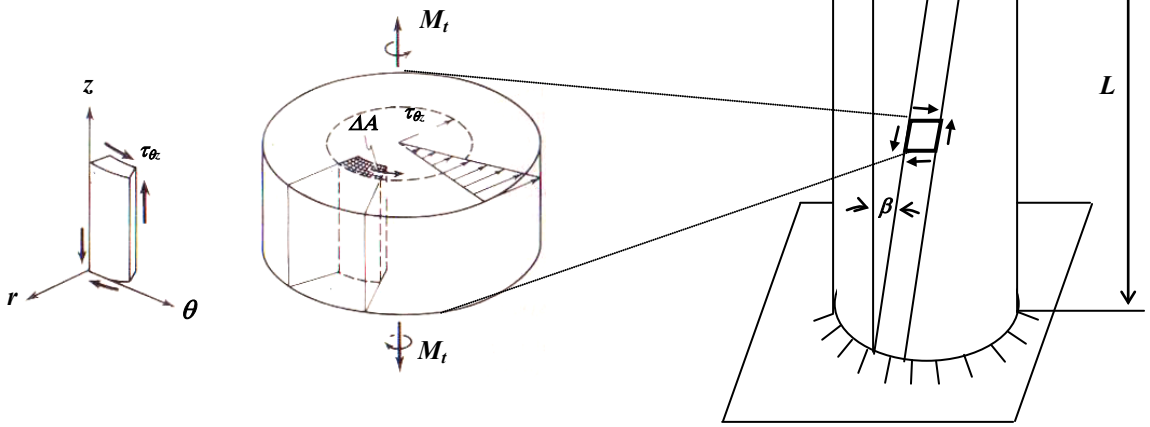


Fig. 2 Figure showing shear stress distribution

Fig. 3 Figure showing the definition of angle of twist

Procedure

1. Measure the cross sectional details of the shaft.
2. Fix the hollow aluminium shaft in the setup.
3. Adjust the telescope in such away that the image of the scale can be seen through the mirror on the shaft.
4. Measure the length of the shaft (L), distance from the fixed end to the center of the mirror (L_1), distance from the center of the mirror to the scale (L_2).
5. Note down the initial readings (x_1) of the telescope without applying any load.
6. Connect the strain gauge to P3500 to maximize the signal output.
7. Figure out how pure torsion is applied to the shaft. Apply a load of 200 g in the pan. Note: Loads should be applied simultaneously on both the weighing pans so that the setup does not get disturbed during loading.
8. Due to loading, the shaft is twisted. Note down the corresponding reading (x_2) by mirror and telescope arrangements. Also make the strain measurement.
9. Figure out how to find the angle of twist from these readings. (Hint: Since the scale is viewed through a mirror, the horizontal distance is twice the physical distance.) Verify your formula with the student representative before leaving the laboratory.
10. Load the shaft in steps of 200g until 1 kg and note down the readings as above.
11. Unload the weights in steps of 200g and record your readings.

Analysis of Results

1. Draw the free body diagram of the loaded specimen.
2. Plot a graph showing the torque versus angle of twist and torque versus maximum shear strain.

Sample Table

Shaft: Hollow shaft Dimensions: r_o = _____ , r_i =_____, L = _____,
Initial telescope reading (x_1) = _____ , Distance of mirror from scale (L_1) = _____,

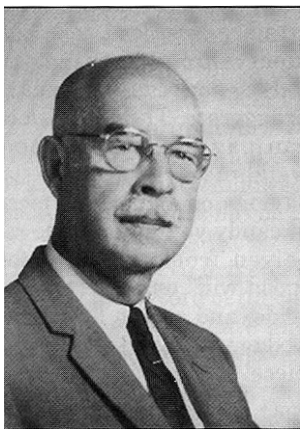
S.No	Load N	Torque N-m	Telescope readings (x_2)			(x_2 - x_1) mm	Angle of twist (radians)
			Loading Mm	Unloading mm	Average mm		

S.No	Torque Applied N-m	ϕ_{expt}	ϕ_{theory}	Percentage difference	Shear strain(expt.)	Shear strain(theory)	Percentage difference	Shear Stress(expt) $\tau_{\theta z}$ MPa	Shear stress(theory) MPa

For ϕ_{theory} use G for aluminium as = 26.6 GPa

Points for Discussion

1. If you are given two rectangular rosettes, how would you paste and connect them to get the maximum signal output? Justify your answer with neat sketches and appropriate equations.
2. How is shear modulus related to Young's modulus?
3. For a generic point on the shaft surface draw the Mohr's circle of stress
4. Discuss the reasons for deviation of experimental results with that of theory.



Arthur C. Ruge (1905-2000)

In 1936, Edward E. Simmons (EE) of California Institute of Technology working under Donald S. Clark (Met) suggested the use of a metallic wire bonded to the surface of a prismatic bar as a force measuring element. Gottfried Daetwyler (AE), his associate in the Impact Research lab., bonded insulated constantan wire to the four faces of a steel bar and measured dynamic forces in impact measurement. Thus they conceived the world's first bonded wire strain gauge load cell. The idea for constructing a strain gauge to measure strains was never thought of by them.

Prof. Ruge (CE) of MIT conceived, developed and commercialized the strain gauge.In 1937 Hans Meier (ME) joined Prof. Ruge for his doctorate to measure strain in a water tank subjected to seismic loading. In 1938 Prof. Ruge got the idea of bonding a fine wire to the surface of his test specimen. He broke apart a commercial wire-wound resistor and unwound the constantan wire to make his first bonded wire strain gauge. Meier's original topic was quickly modified into an exhaustive, detailed study of the characterization of the bonded resistance strain gauge. Hans Meier made several specimens with Elinvar wire (Isoelastic) of 0.025 mm dia and made tiny rosette strain gauges.

Ruge and Hans Meier had difficulties in their measuring system. They received some help from Prof. A.V. De Forest (ME) and got a very good galvanometer. However, they could not get a proper amplifier. On the other hand Simmons being an electrical engineer had developed a very good amplifier which could give 64.3 millivolts per 1000 micro-strain. Commercialization was done with the help of Baldwin Locomotive Works (later BLH electronics).

Simmons initially thought that his invention was too simple and obvious to patent. Baldwin-Southwark prepared the basic patent on behalf of Simmons. He got the basic patent in 1940 and Prof. Ruge got four dozen-plus improvement, development and application patents. The trademark of the new strain gauge was SR-4, indicating Simmons and Ruge and 4 denoting the team of four including Dr. Clark and De Forest.

4. Multi Channel Data Acquisition of Strain and Use of Strain Gage as Vibration Transducer

Introduction

Most of the practical applications of strain measurement need measuring strains at multiple points. To find the strain tensor at a point one needs three strain gauges. A strain rosette has three strain gauges prealigned on a single backing. Multichannel strain data acquisition is necessary in such applications. This experiment demonstrates the use of multichannel data acquisition of strain by using SB10 (Switching and Balancing Unit) in conjunction with P3500.

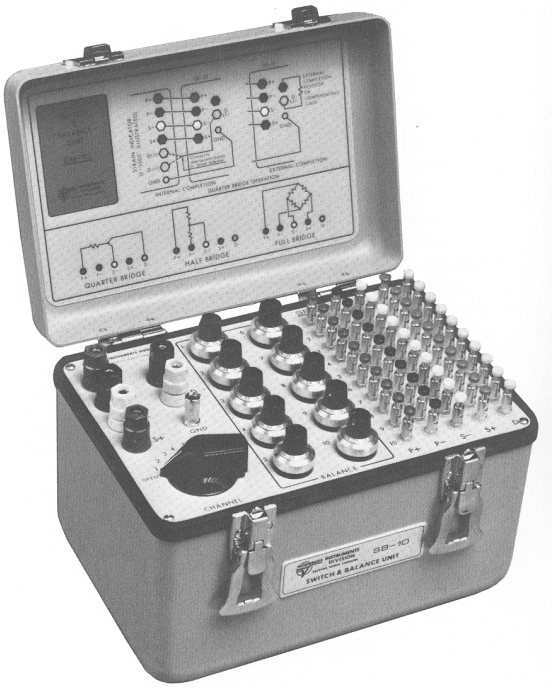
All the structures, which are having elastic property, stiffness and mass, have natural frequency with which the structure vibrates in the absence of external excitation. Measurement of natural frequency is important because when forcing frequency matches natural frequency, the structure vibrates with large amplitudes and sometimes may fail. (which is known as resonance condition) This experiment also demonstrates the use of strain gage to measure vibration characteristics namely natural frequency and damping factor. (Damping factor is a measure of the property by which how fast the vibration ceases.)

Aim

(A) Strain tensor and principal stress evaluation by using strain rosettes.
(B) To measure vibration characteristics i.e. natural frequency and damping factor of a cantilever beam.

Equipment Used

P3500, SB10, Oscilloscope, flexure apparatus, beam with strain gages, multimeter, scale, vernier caliper, protractor



Switching and balancing unit

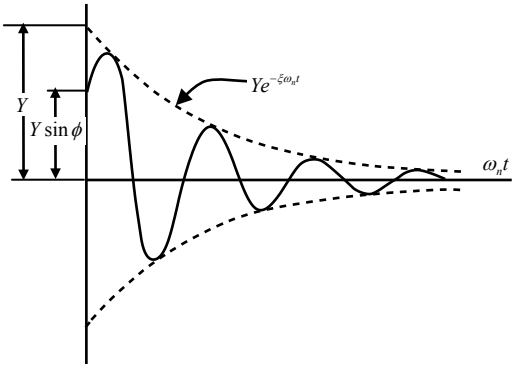
Steps

(A) Evaluation of Strain Tensor and Principal Stresses by Using Strain Rosette - An Application of Multichannel Strain Data Aquisition

- Measure the location of strain rosette and orientation of its elements (θ_A, θ_B, θ_C)
- Rigidly fix the beam in the flexure apparatus.
- Connect the strain rosette to switching and balancing unit (SB10) as shown in the circuit available on it.
- Connect SB10 to P3500 as per circuit given on the instrument.
- Balance individual channels with usual procedure with knobs provided for respective channels in SB10.
- Give an end displacement using micrometer at one end of the beam.
- Measure strains in respective channels (ε_A, ε_B, ε_C) by using the switching unit.

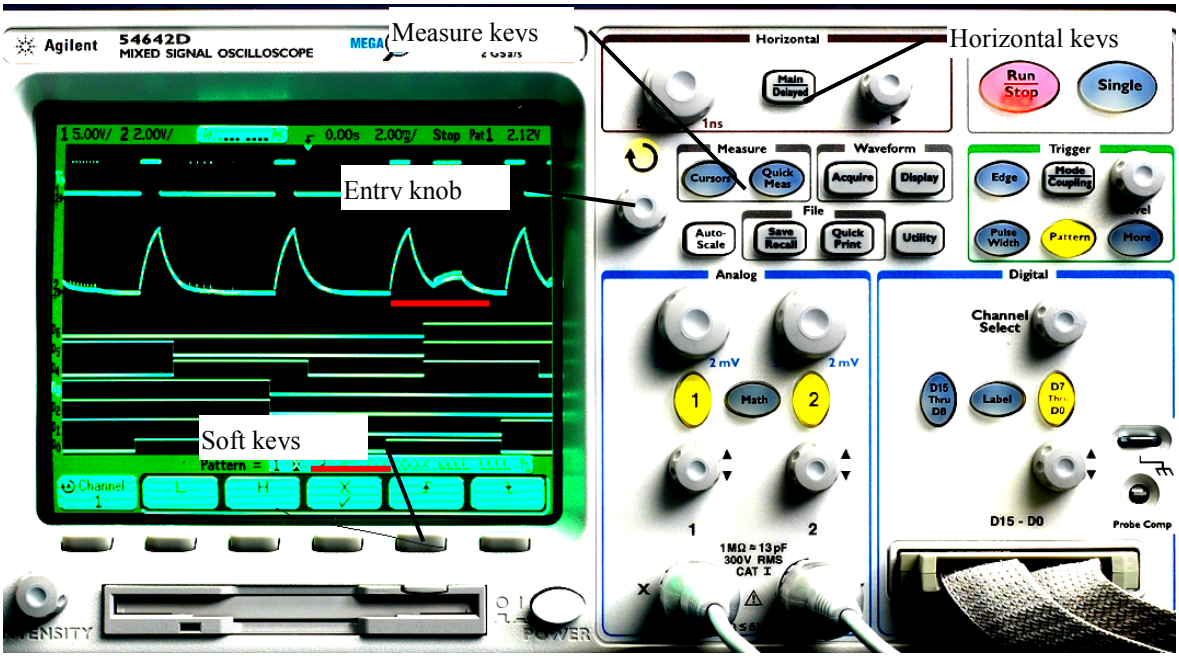
- Use the appropriate expression to calculate principal stresses. Compare your results with theory.

(B) Measurement of Vibration Characteristics



- Rigidly fix the (cantilever arrangement) beam in the flexure apparatus.
- Connect the strain gage to the strain indicator, P3500 as indicated in the circuit available on it.
- Take the output from P3500 output terminal and connect it to Oscilloscope input to any of the channels.
- Balance the strain indicator by the usual method.
- Switch on the Oscilloscope. Respective channel switch also to be pressed.
- Adjust vertical and horizontal scale knobs appropriately to get reasonable signal (amplitude and time).
- Put the oscilloscope in Run/Stop mode.
- Give an excitation to beam end.
- Captured the waveform in Oscilloscope screen.
- Call the cursor (Refer detailed instructions given at the end).
- Put X cursor on two consecutive peaks. Oscilloscope calculates $1/\Delta x$ and displays on the screen, which is natural frequency of the beam.
- Using Y cursor measure the amplitude of two consecutive peaks y1 and y2.
- Damping factor can be found by using the relation $\delta = 2\pi\zeta / \sqrt{1-\zeta^2}$ where logarithmic decrement $\delta = \log y_1/y_2$ and ζ = damping factor.

Cursor Measurements for the Agilent 5462x Series Oscilloscopes

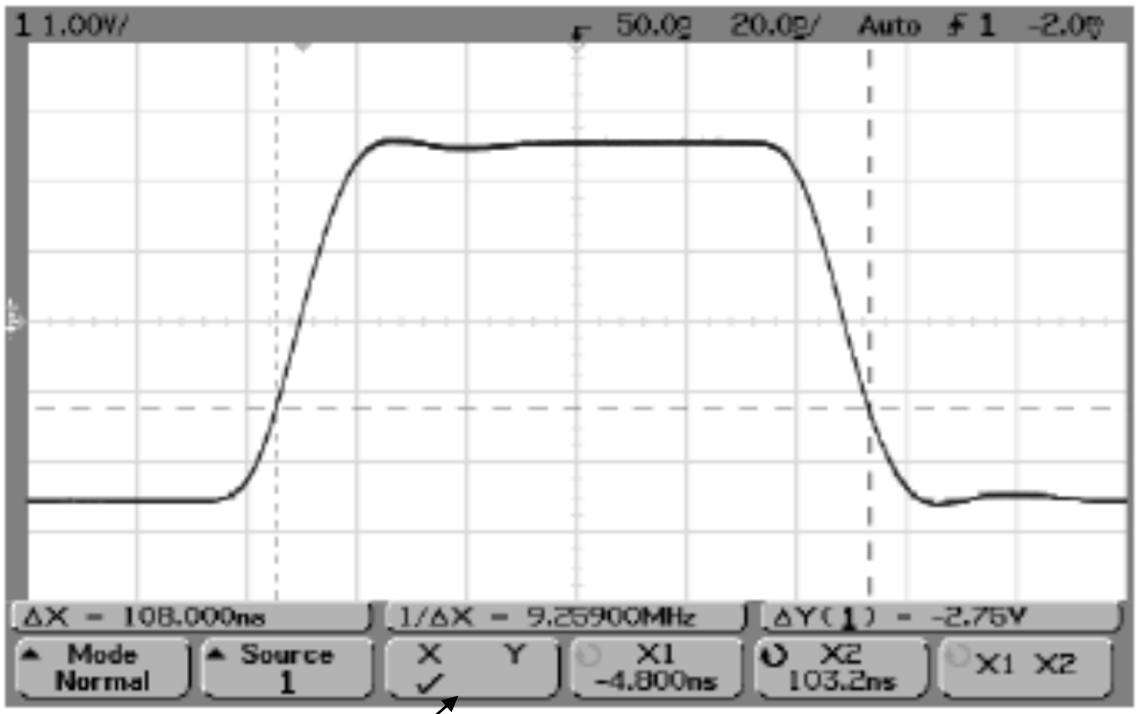


Values like frequency, period, voltage levels of waveforms (Δx, Δy etc) can be easily measured using cursors. Cursors are horizontal and vertical markers/gridlines that indicate X-axis values (usually time) and Y axis values (usually voltage) on a selected waveform.
To make cursor measurements,

1. Connect a signal to the oscilloscope and obtain a stable display.
2. Press the *Measure*/*Cursors* key; it illuminates.
3. This step (step 3) is not mandatory since we are going to use the default settings. Included only for information.
   Press the *Mode* softkey
   The three cursors modes are: Normal (default), Binary & Hexadecimal. Normal is the setting for our purpose.

Note: Repeated pressing of softkeys will toggle the options available with that softkey.
X and Y cursor information is displayed above the softkeys. ΔX, 1/ΔX, and ΔY values are displayed still above.

4. Press the *Source* softkey to select the source (channel no.) for the waveform.



ΔX =		1/ΔX =		ΔY =	
Mode	Source (channel)	*X_Y* key X/Y_selection	X1	X2	Not applicable

5. Press the X_Y softkey to decide whether to select either X cursors or Y cursors for measurement. X cursors are vertical dashed lines to measure horizontal distance. Similarly for Y cursors (voltage).
   First, we'll select X. (this being the default setting). The tick mark should be in X, as in the fig.
6. Now, press *X1* softkey.
   The gridline of X1 (*short-dashed vertical line*) is brighter now than the other gridlines. X2 is long-dashed vertical line. Now when we rotate the entry knob, the X1 gridline moves. Move this to one point of the waveform, say the peak (-4.8ns, nanosec). The

cursor values are displayed within the X1 and X2 softkeys, and the current ΔX (X1 – X2) and 1/ΔX values are shown above that.

7. Press *X2* when reaching one point of the wave. X1 will get locked at the earlier value (-4.8ns). We can move the X2 gridline now.
8. As we move along the X2 gridline, the ΔX (X1 – X2) and 1/ΔX values get changed with the X2 gridline. ΔX can give the period and 1/ΔX, the frequency. For eg., if X2 is at 103.2ns, ΔX= 108ns and 1/ΔX= 9.2MHz (frequency).
9. Press the *X_Y* softkey to measure Y distances (voltages) now. Y1 and Y2 gridlines appear. Y1 will be active now.
10. The procedure follows that of X. Δ*Y* gives Y2-Y1 once Y1 is locked by pressing the *Y2* key.
11. Finally, to turn cursors off, press this key again until it is not illuminated, or press the *Quick Meas* key.

Sir Charles Wheatstone (1802-1875)

Wheatstone was not the inventor of the bridge to which his name is associated with! It was invented by Samuel Hunter Christie in 1833. This was seven years after George S. Ohm discovered the relationship between electric current and voltage. It was first used by Wheatstone in 1843 to measure resistance in electric circuits. His inventions include stereoscope, method for measuring the velocity of electric current through a conductor etc.

5. Demo on Computer Aided Data Acquisition & Analysis for Strain Gage Instrumentation

Introduction

Any design and manufacturing process need validation tests. Most of the tests need measurements of strain and displacements. Some specific areas like Aerospace applications require temperature measurements also. System-5000 supports all the above transducers and thus at a single platform it is possible to acquire all the necessary data.

System Specifications

The Configuration of System - 5000 in Solid Mechanics Laboratory has the following features.

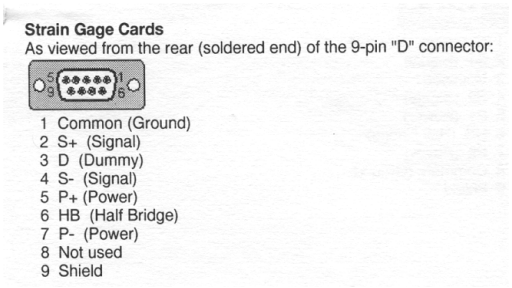
- Model 5100 Scanners - 2 Nos
- Scanner No.1 consists of 4 cards, each card has 5 strain channels - 20 Ch. of strain
- Scanner No.2 consists of 3 cards, 2 cards of 5 strain channels each - 10 Ch. of strain
  1 card of 5 LVDT channels each - 5 Ch. of disp
- Data acquisition card embedded in PC
- Pentium I or above PC with Windows-95(or above) operating system

First Measurement

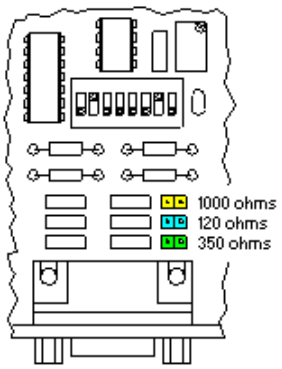
For carrying first measurement the following step by step methodology is to be used.

Hardware Settings

Strain gage leads are connected to the connector and the connector is plugged into the socket of the corresponding channel of the scanner card. Pin diagram is shown.



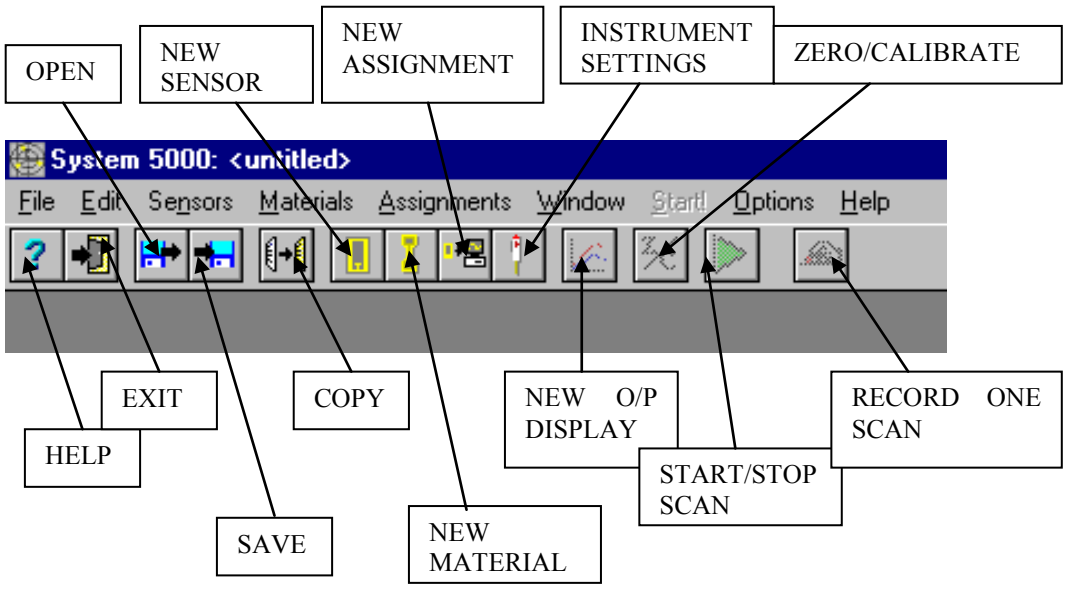
Scanner card is pulled out and the dummy resister jumper is moved to the corresponding place according to the resistance of the strain gage (120/350/1000 ohms) used. This is useful in shunt calibration



Starting System- 5000

System5000 is started by pressing the following icon which is available on the desktop of the PC. On doing this, the system initialises itself.

The following screen will appear.

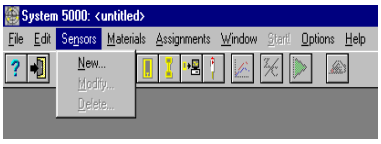


Sequence of Operations

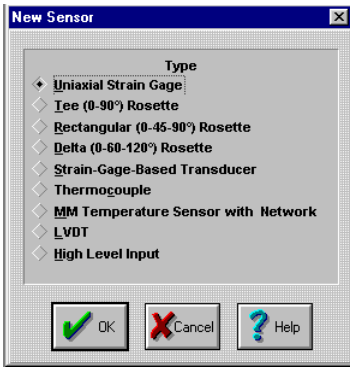
Select Sensors
Material
Assignment
Zero/Calibrate
Output Display
Scan/Stop
Record
Export

Selection of Sensors

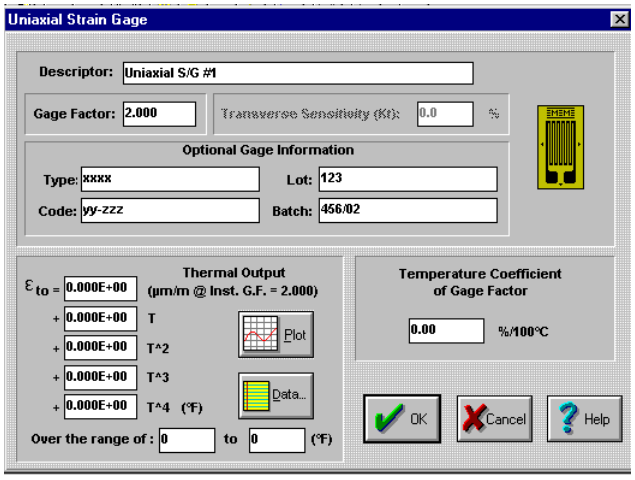
- Select the sensors menu and click on " New"



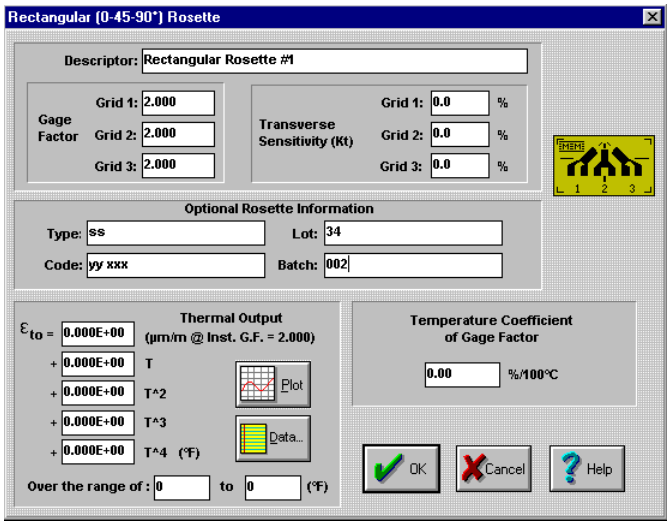
- It pops up following options. Click the corresponding sensor and press OK



- For uniaxial strain gage one gets the following screen and fields are to be filled with suitable entries. Press OK button.

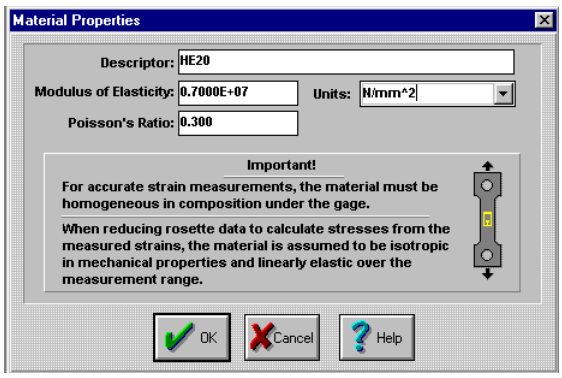


- For rectangular rosette one gets the following options. Note that advanced features such as transverse sensitivity could be assigned.



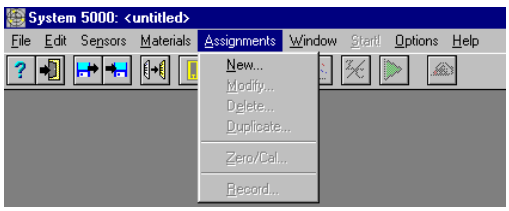
Input of Material Properties

- Click new materials button. The following window is obtained. Material properties are entered in respective fields and press OK.

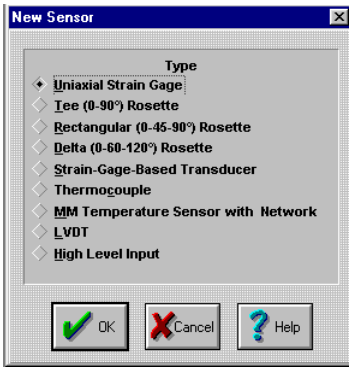


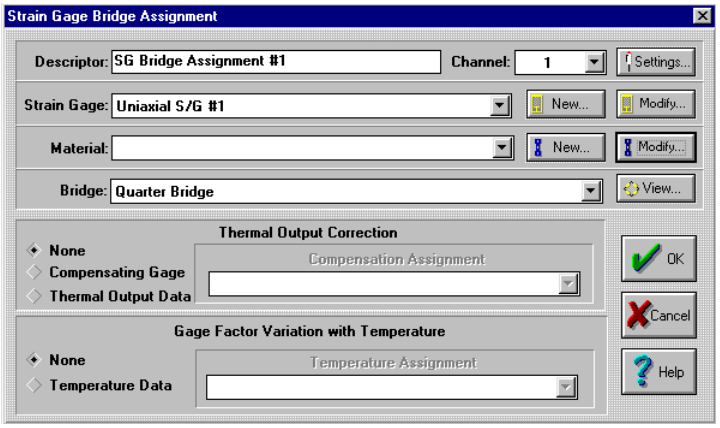
Assignment of Channels

- Select "Assignment" menu and click "New"
- Then select the sensor in the menu and click OK

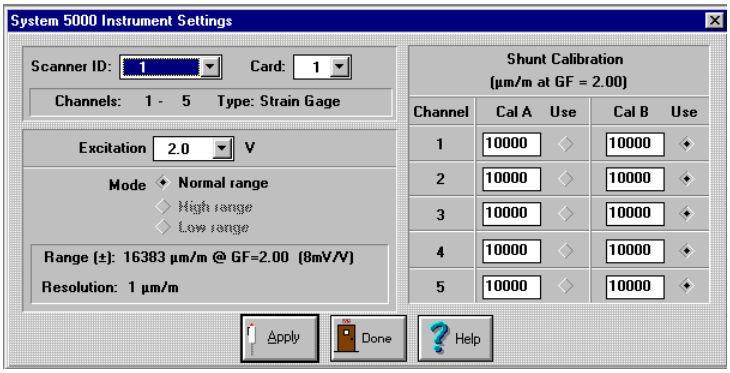


- This pops up a screen as shown. Select appropriate type of sensor. On clicking "OK" one gets the menu to fill the strain gage bridge assignment. Channel no is assigned by clicking the popup menu provided at the field “channel”. Optional information if required may be furnished for thermal output correction and gage factor variation.





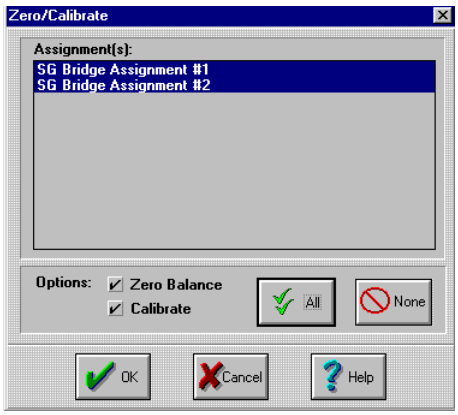
- Then “settings” option is selected. Instruments settings window will appear and the following fields are to be filled. Select CalA for 120 ohms strain gage and CalB for 350 ohms strain gage. Leave excitation and Mode as default and click DONE.



Zero/Calibration Of Channels

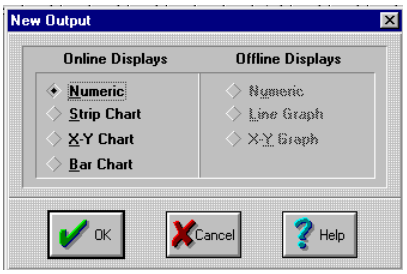
The following screen (Fig. 9) appears when zero/calibration is selected. In general do this for all channels. Press “OK”.

“Zero” operation sets the initial values of corresponding channels to zero and is similar to balancing in conventional instruments. “Calibration” simulates the strain by change in resistance through shunting additional resistance and checking for a standard value of strain.

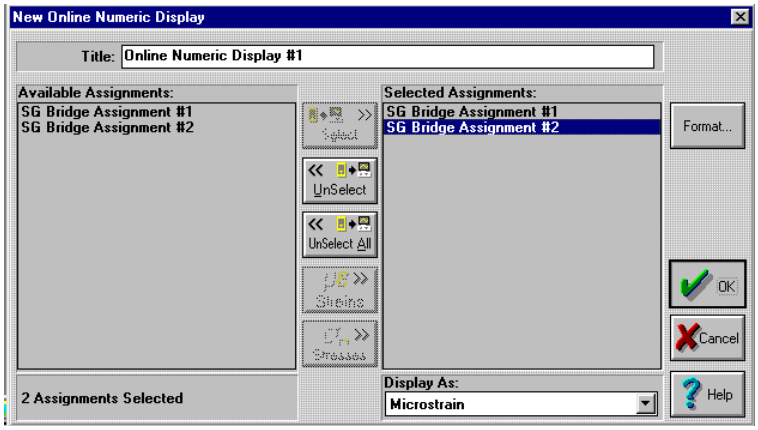


Display of Output

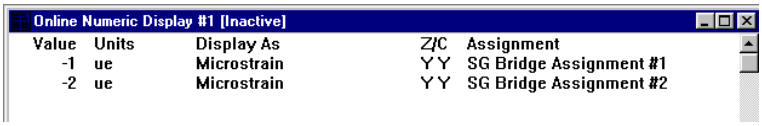
- One can select the mode of display, viz Numeric, strip chart, bar chart or X-Y chart. Click the icon "Display". The following options can be seen. Click on the type of display required and press "OK".



Then select the strain gage bridge assignments to be displayed and click OK

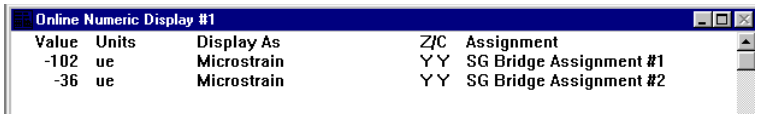


- On clicking OK one gets the following table with "inactive" as a caption



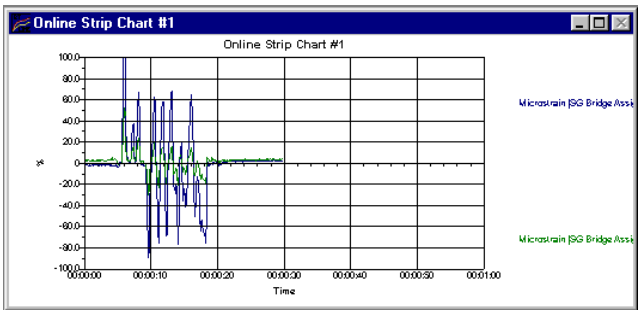
Scanning the Data

- From toolbar click the "start scan" button to initiate scanning. One gets the following table showing strain values, channel Nos. & other information with out inactive caption and the data displayed is real time data. Stopping the scan can be done by red button toggled at start button.



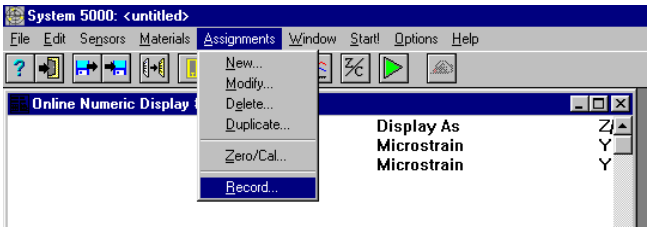
Plotting The Data

- Data can be plotted in the form of strip charts or against other variable which is also being acquired. This can be done by using the options available in display menu. A sample strip chart displayed is shown.

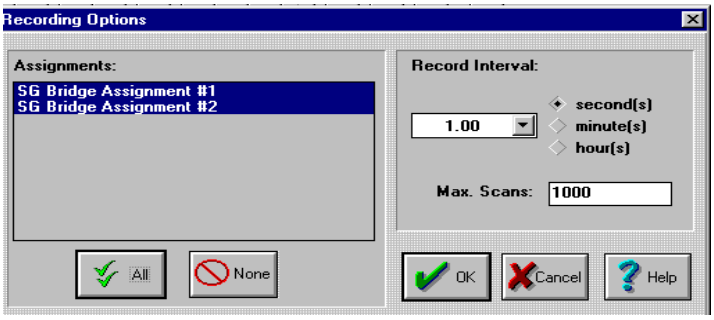


Recording the Data

Data can be recorded by clicking the "Record" in "Assign" menu.

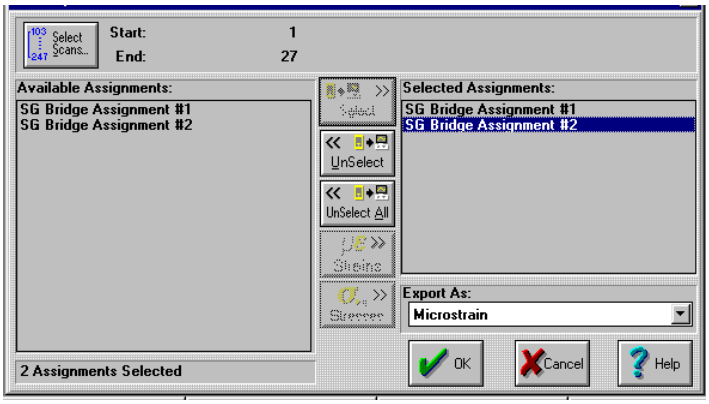


- One gets following Dialog box. Fill it with required parameters, select the assignments and click OK

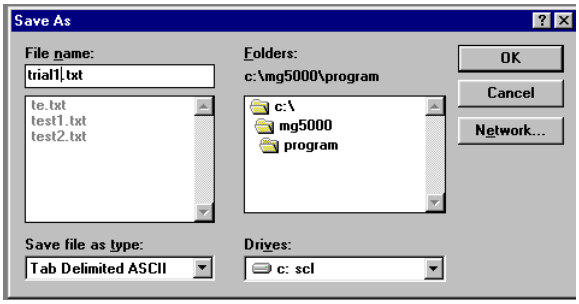


Export Data

- From File menu click "Export" option. The following window is seen. Select the assignments and press OK.

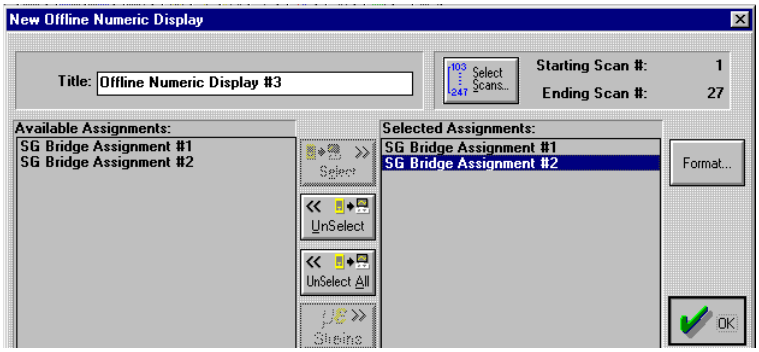


- "Save" dialog box appears. Give file name and click OK

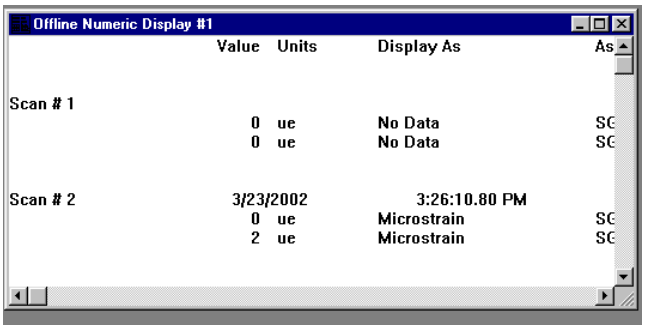


Offline Display

Click the "Display" button. Select the assignments to be displayed and press OK.



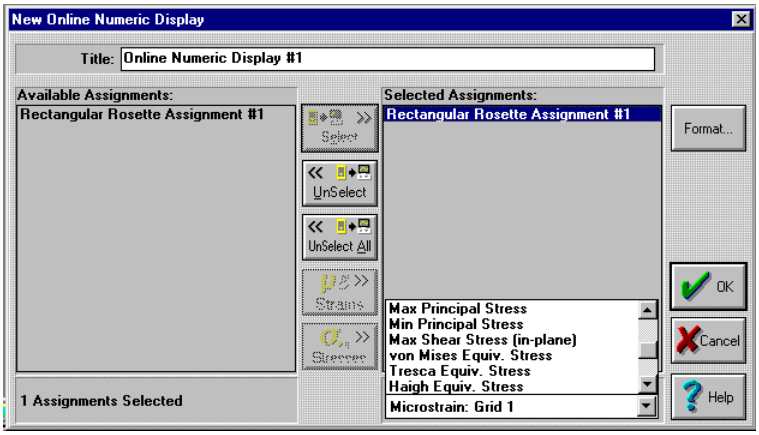
- The data in text form is obtained as shown here.



- Similarly one can get data display in the form of plots by selecting the corresponding options in display dialog box.

Principal Stresses Calculations

- System 5000 software can calculate and display principal stresses both in real time and offline when rosettes are used. This can be done by assigning the material properties also in the assignments operation. Then click the “Display” button. The following window is seen and poping up "display as" field gives various options from which maximum or minimum stresses can be selected.



- Also equivalent stresses by applying various failure criteria such as von Mises, Tresca etc. can be chosen for display. All these can be displayed as plots also.

Franz Neuman (1798 – 1895)

Famous for initiating student seminars.

Prominent students : Borchardt, Clebsch, Kirchoff, Saalschütz, and Voigt.

He derived for the first time a formula for calculating the modulus in tension for the material of a prism cut out from a crystal with any arbitrary orientation. The most important contributions made by Neumann to the theory of elasticity are included in his great memoir dealing with double refraction – stepping stone to establish photoelasticity.

He has derived for the general case of a three-dimensional stress distribution. Using simple tests he showed how optical constants can be obtained and has applied his theory to the study of the coloured patterns which Brewester observed in the non uniformingly heated glass plates and pointed out that the double refractive property of such a plate is due to stresses produced by the nonuniform stress distribution.

Neumann was the first to study residual stresses.

Voigt (1850 – 1919)

His work finally settled the old controversy over the rariconstant and multiconstant theories. The questions were these : “Is elastic isotropy to be defined by one or two constants and, in the general case, is elastic aeolotropy to be defined by 15 or 21 constants”? Voigt used thin prism cut out from single crystals in various directions in his experiments. The elastic moduli were determined from torsional and bending tests of these prisms. In addition, the compressibility of crystals under uniform hydrostatic pressure was studied. The results disproved rariconstant theory and noted that one needs 2 constants for isotropy and 21 constants for aeolotropy. The result of his work also helped in coining the term tensor! (as he dealt with tensions of crystals of various planes).

6. Calibration of Photoelastic Model Material

Objective

To find the material stress fringe value of the model material.

Theory

The stress-fringe values of model materials vary with time and also from batch to batch. Hence, it is necessary to calibrate each sheet or casting at the time of the test. Calibration is performed on simple specimens for which closed form stress field solution is known. Although the stress fields for simple tension or beam under pure bending are known, the use of circular disc under diametral compression is preferred for calibration. Circular disc is preferred, because the specimen is compact, easy to machine and it can also be easily loaded. The stress field in a circular disc cannot be obtained using principles of Strength of Materials but one has to use the principles of Theory of Elasticity. The stress field can be obtained starting from Bousinesque's solution. With the center of the disc as the origin, the stress field is obtained as

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = -\frac{2P}{\pi t} \begin{Bmatrix} \dfrac{(R-y)x^2}{r_1^4} + \dfrac{(R+y)x^2}{r_2^4} - \dfrac{1}{D} \\ \dfrac{(R-y)^3}{r_1^4} + \dfrac{(R+y)^3}{r_2^4} - \dfrac{1}{D} \\ \dfrac{(R+y)^2 x}{r_2^4} - \dfrac{(R-y)^2 x}{r_1^4} \end{Bmatrix} \quad (1)$$

Where $r_1^2 = x^2 + (R-y)^2$ and $r_2^2 = x^2 + (R+y)^2$, R denotes the radius of the disc, D represents its diameter, t is the thickness of the disc and P is the compressive load applied. The principle stress difference $(\sigma_1 - \sigma_2)$ at any point in the disc can be expressed as

$$(\sigma_1 - \sigma_2) = \frac{4PR}{\pi t} \frac{R^2 - (x^2 + y^2)}{(x^2 + y^2 + R^2)^2 - 4y^2R^2} \quad (2)$$

At the centre of the disc due to symmetry, the shear stress is zero and the principal stress difference is obtained as

$$(\sigma_1 - \sigma_2) = \frac{8P}{\pi Dt} \quad (3)$$

From Stress-Optic Law,

$$(\sigma_1 - \sigma_2) = \frac{NF_\sigma}{t} \quad (4)$$

Where N is the fringe order, t is the thickness of the model material and F_σ is the material stress fringe value in N/mm/fringe. From Equations (3) and (4) the material stress fringe value can be obtained as

$$F_\sigma = \frac{8P}{\pi DN} \quad (5)$$

N at the center of the disc is determined using Tardy's method of compensation.

Tardy's Method of Compensation

Compensation techniques are basically point-by-point techniques. The basic principle is that, by external means, the retardation provided by the model is compensated such that a fringe passes through the point of interest. The additional retardation added or subtracted is known as fractional retardation. Analyzer can be used as a compensator. The use of the analyzer as a compensator is known as Tardy's method of compensation.

Procedure for Tardy's method of compensation

Initially, the principal stress directions at the point of interest are determined using a plane polariscope. A circular polariscope is then formed such that the polarizer is kept at the isoclinic angle and all the other optical arrangements are appropriately arranged. At this stage, if the optical elements are correctly aligned, there should be no difference in the isochromatic field compared to the conventional arrangement. The analyzer alone is then rotated until a fringe passes through the point of interest. The rotation given to the analyzer can be related to the fractional retardation as

$$\delta_n = \pm|\beta| \ /180$$

Where β is in degrees and the sign is based on the physics of the problem. To determine the sign one should note down the value of the fringe order that moves when the analyzer is rotated. If a lower fringe order is passing through the point of interest the sign of β is to be taken +ve and –ve otherwise. For a circular disc under diametral compression, the point of interest is the centre of the disc and the principal stress direction are at $\theta = 0$ and $\theta = 90$. Since the basic polariscope arrangement coincides with the principal stress directions, the employment of Tardy's method of compensation simply amounts to rotating the analyzer. When the analyzer is rotated the fringe that passes through the centre forms the "figure of eight" as shown in Fig. 2.

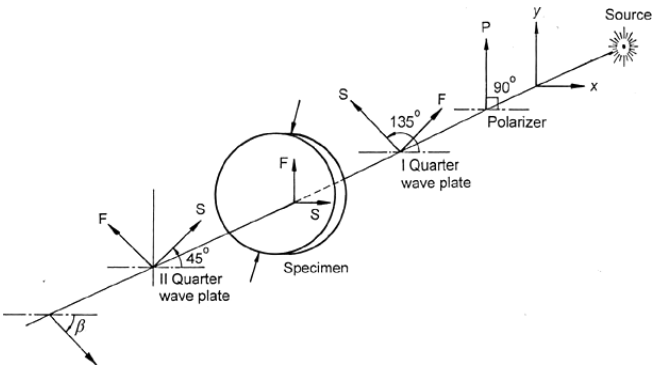


Fig. 1. Arrangement for Tardy's method of compensation

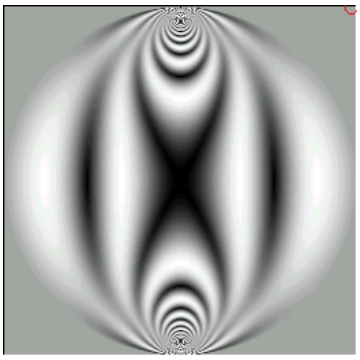


Fig.2. Fringe passing through the centre forms figure of eight

Calculations

Diameter of disk, *D* = mm
Thickness of disk, *t* = mm
Lever arm Magnification =

S.No	Load put in pan	Actual load	Analyzer rotated CW			Analyzer rotated CCW			Average N
			β	Fringe order moved	Total fringe order	β	Fringe order moved	Total fringe order	

After getting the total fringe order, using Eq. (5) the material stress fringe value is calculated. Repeat the same procedure for different loadings and get the average value of the material stress fringe value. A better approach to do this is to evaluate the material stress fringe value in a least squares sense graphically. Draw a graph between Load P and Total fringe order N. Calculate the slope P / N from the graph and use it in Eq. (5) to get the material stress fringe value.

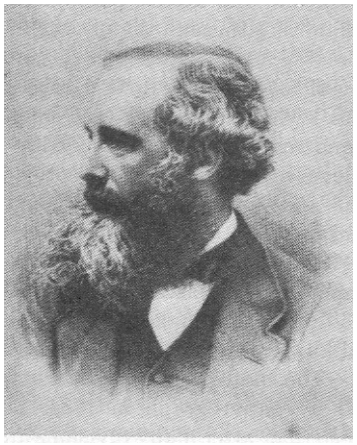
Observations & Discussion

1. You have done the experiment with analyzer rotated CW & CCW. Let the respective β values be β_1 and β_2. What is the value of $\beta_1 + \beta_2$ you have obtained and what should be its value? Can you explain the reason for deviation?

2. Each member of the team repeat the above. Have all of you got the same value of β? Can you comment on the possible errors that would have caused the difference?

3. Having done a detailed experiment on circular disc can you suggest a method to verify the alignment of polarizer and analyzer?

4. Verify the various optical arrangements to get circular polariscope and list the respective positions of the optical elements.



James Clerk Maxwell (1831 – 1879)

In the spring of 1847, James was taken to the laboratory of Nicol, the inventor of the polarizing prism, and, from that time, he became very keen on experimenting with polarized light. Nicol presented a set of the prisms he developed to James as a gift and with these he constructed an apparatus for photoelastic stress analysis.

Maxwell was the first to study the stresses developed due to centrifugal forces in rotating thin circular discs.

Maxwell was always keen on experimental verification of theoretical results. Photoelasticity was his choice for verifying the theoretical results. He recognized the use of plane and circular polariscopes and also presented a method to find the principal stresses. He also observed the possibility of stress-freezing in certain polymeric materials. Maxwell did all his important work in theory of elasticity and photoelasticity before he was nineteen years of age!

Between 1860-1865 he was elected to a chair at King's college, London and his important memoir on the kinetic theory of gases and his famous memoir on electricity were published. His great advances in theory of structures were also published during that time.

7. Virtual Polariscope

Introduction

The software P_SCOPE is a virtual polariscope, which helps to visualize and analyze the photoelastic fringes of circular disk and ring under diametral compression for various optical arrangements. This software also displays the polarization state of the light vector and the position of all the optical elements. Another information that shows on the status bar of this windows program is, fringe order and isoclinic angle at current cursor position along with the coordinates.

Plane Polariscope

The screen shot given in Fig. 1. explains how to set a plane polariscope. The menu item shown in the figure will load the dialog box where one can specify the settings relevant to a plane polariscope. A default button is available to make things easy.

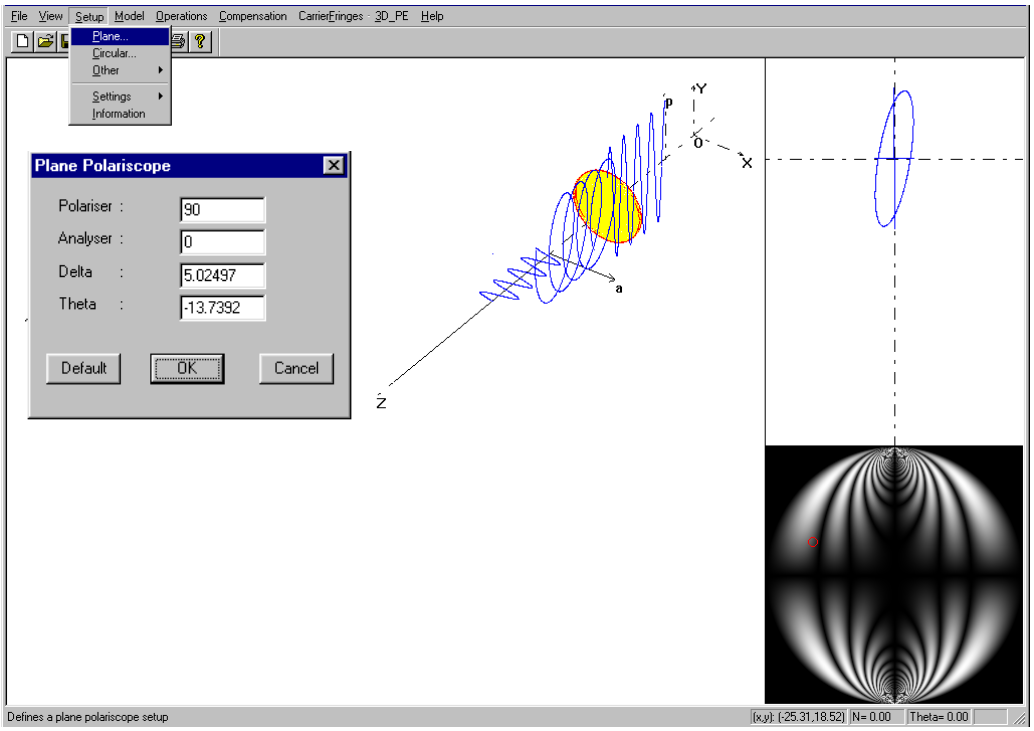


Fig. 1. Screen shot of P_Scope window

Circular Polariscope

Circular polariscope can also be set similarly. In this case, two quarter wave plates will be added. The angular position of the elements can be set using the dialog box shown in Fig. 2.

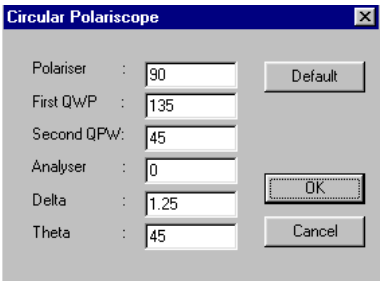


Fig. 2. Dialog box for Circular polariscope.

Changing the Load Applied

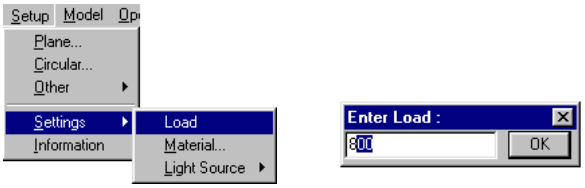


Fig. 3. Procedure for changing the load applied

Changing the Model

One can switch between circular disk and ring by the following menu and consequent dialog box. This dialog box allows one to specify the parameters of the model.

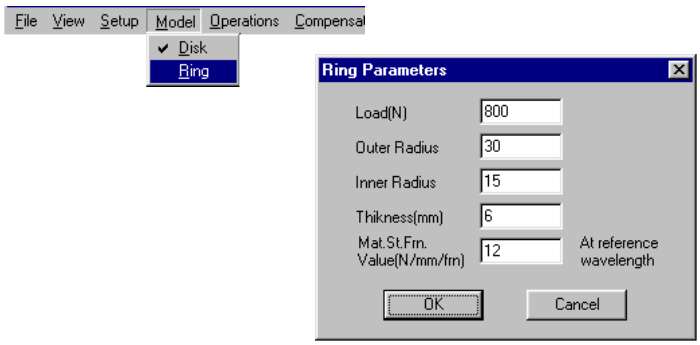


Fig. 4. Procedure for changing the model

Compensation Techniques

Various compensation techniques to determine the fractional fringe order are simulated in this software. The descriptive procedure for each compensation technique is explained below. Software will assume the current selected point as the point of interest. So, prior to clicking the menu the point of interest should be selected.

Babinet Soleil compensation

Figure 5. shows the menu item for Babinet Soleil compensation.

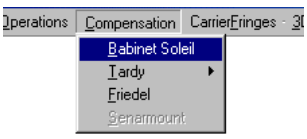


Fig. 5. Menu for Babinet-Soleil compensation

Steps

1. Find the isoclinic angle at the point of interest using the dialog box in Fig. 6. The spin buttons will increase or decrease the integer value of the angle and the slider bar contributes decimal value. These changes will virtually rotate the element and corresponding intensity value at the point of interest can be seen by pressing <Intensity> button. We can press <Refresh> button to see the current fringe pattern.

This process should be continued until the intensity value is close to zero. Then press <Next> button to proceed to second step.

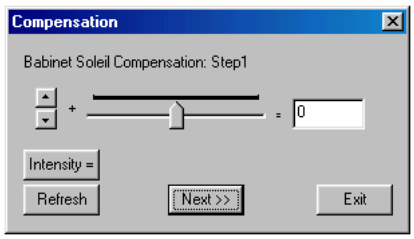
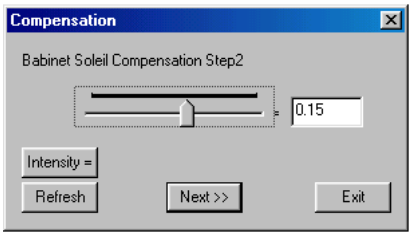


Fig. 6. Compensation (Step 1)

2. Now the software will add the compensator whose retardation can be changed using the dialog box in Fig. 7. Adjust the compensation at the point of interest using the slider bar until the intensity is close to zero.

   Note: While giving the compensation, observe whether a higher fringe order or lower fringe order moves to the point of interest. This can be done using the refresh button. Then press <Next> button.



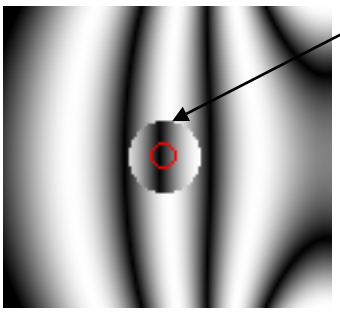


Fig. 7. Babinet Soleil compensation (Step 2)

3. Enter the integer fringe order at the point of interest and press <Add> or <Subtract> button depending on whether a lower fringe order moved or higher fringe order moved as observed in the previous step. Total fringe order will be displayed in a Message box.

Fig. 8. Compensation (Step 3)

Tardy's Method of compensation

Figure 9 shows the menu item for Tardy compensation. Manual method is exactly similar to Babinet-Soleil compensation except for the second step. Here instead of adding the compensator the analyzer will be allowed to rotate.

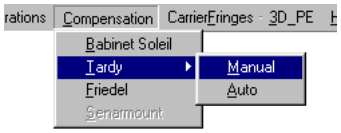


Fig. 9. Menu item for Tardy method of compensation

There is a provision to do all these processes automatically by convergence method. In this case software will test various angular positions for convergence.

Repeat step 3 as mentioned previously.

Virtual Experiments

1. Align the virtual polariscope as a plane polariscope in dark field and observe the isoclinics in steps of 10^{o} for circular disk under diametral compression and make a neat sketch of your result.

2. Repeat the same for the case of ring under diametral compression and make a neat sketch of the isoclinics.

3. For three selected points determine the total fringe order by both Babinet Soleil compensation and also by Tardy's method of compensation.

4. Provide a sketch of polarization state of the light vector after each element when the compensation is achieved by Babinet Soleil compensation and also Tardy's method of compensation.

5. What information do you get in a plane polariscope bright field? State your observation.

6. Verify the various optical arrangements to get a circular polariscope. Sketch these arrangements schematically.

---

8. Use of Photosoft_H in Fringe Ordering

1. Familiarize yourself with the software Photosoft_H using the manual provided in the laboratory. Try to use various options and also learn how to save the picture files and to load them.

2. Get the Dark-field fringe patterns of the following problems with the fringe order clearly labeled.
   a. Circular disk under diametral compensation
   b. Ring under diametral compression
   c. Plate with a hole
   d. Contact stress problem.

   Put these results in the four of default windows

3. Get the Isoclinic field in steps of 10^o for the following problems
   a. Disk under diametral compression
   b. Ring under diametral compression

4. Study the influence of change of light source on isochromatics and isoclinics for the problem of a concentrated load on a semi-infinite plate. Clearly mark the fringe orders

5. Study the influence of change of material on isochromatics and isoclinics for the problem of plate with a crack in Mode-I loading.

6. Using the zoom option, show that the fringe order is zero at a singular point.

7. Get the typical fringe pattern in the neighborhood of a crack in Mode-I, Mode-II and Mixed mode loadings.

   Investigate the role of σ_{ox} in these cases.

Max Mark Frocht (1894-1974)

Prominent Students: R.Guernsey, P. D. Flynn, L. S. Srinath, A. A. Betser.

Prof. Eli Sternberg has commented Prof. Frocht as Father of Photoelasticity. Frocht is a doctoral student of Prof. Stephen Timoshenko.

During the period from 1932 to 1946 he obtained stress concentration factors for a large variety of geometric shapes. Also extended photoelasticity to the study of statically indeterminate structures. He has developed methods for stress separation and studied the problems of stress wave propagation and finally developed Scattered Light Photoelasticity.

His books, *Photoelasticity*, Vol. I and Vol. II quickly became classics and were translated into Russian, Spanish and Chinese. These books speak a great deal about his dedication to experimental work, accuracy of experimentation, love for beautiful illustrations and photographs.

Frocht is an inspiring teacher, a resourceful and thorough researcher and has extended the scope of photoelasticity in many directions and brought three-dimensional photoelasticity to the state of perfection.

9. Photoelastic Determination of Stress Concentration Factor For a Plate With a Hole

Objective

To determine the stress concentration factor for a finite plate with hole of different sizes and combinations by Photoelastic experiment.

Theory

A structural member (Fig.1) under uniaxial tension experiences the simplest form of state of stress. The stress tensor for this case is

$$[\tau] = \begin{bmatrix} \sigma & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Fig.1. Plate without discontinuity

Where σ is easily calculated as

$$\sigma = \frac{P}{A} = \frac{P}{wh}$$

Where, σ- Stress (MPa), P- applied load (N), A- cross sectional area (mm^2), w- width of the member (mm), h- thickness of the member (mm). However, when the member contains a discontinuity such as a hole (Fig.2), notch or a sudden change in cross section, the state of stress is not a simple one but is more complicated and high-localized stresses near the discontinuity may occur. Further, the stress field in the near vicinity of the geometric discontinuity in general is multiaxial. The state of stress could only be found by principles of Theory of elasticity.

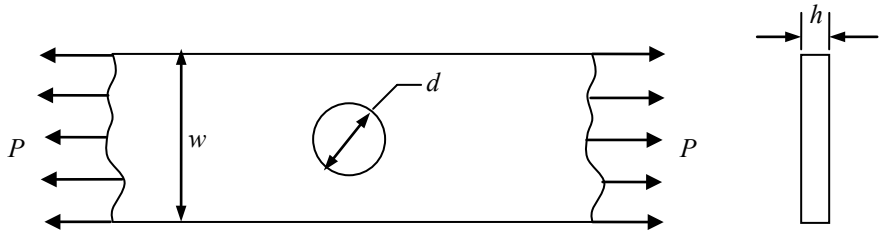


Fig. 2. Plate with a discontinuity (hole)

The stress distribution can be evaluated by Theory of elasticity for the simple case of an infinitely wide plate with a small hole subjected to tensile loading. The closed form solution of stress distributions for the plate is given by

$$\sigma_{rr} = \frac{\sigma}{2}\left[\left(1-\frac{a^2}{r^2}\right)+\left(1+3\frac{a^4}{r^4}-4\frac{a^2}{r^2}\right)\cos 2\theta\right]$$

$$\sigma_{\theta\theta} = \frac{\sigma}{2}\left[\left(1+\frac{a^2}{r^2}\right)-\left(1+3\frac{a^4}{r^4}\right)\cos 2\theta\right] \qquad (1)$$

$$\sigma_{r\theta} = -\frac{\sigma}{2}\left[\left(1-3\frac{a^4}{r^4}+2\frac{a^2}{r^2}\right)\sin 2\theta\right]$$

Where, σ is the magnitude of the remotely applied tensile stress.

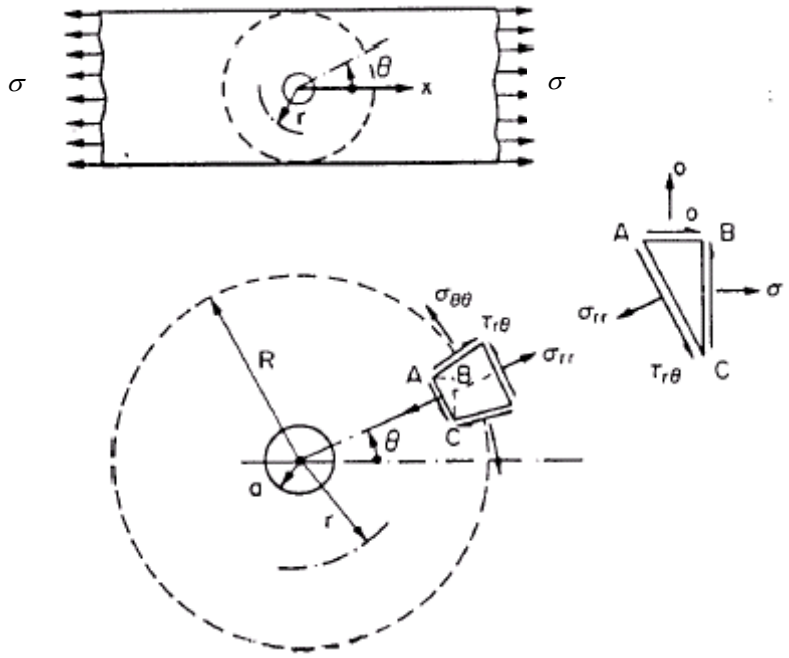


Fig.3 Stress distribution around a circular hole

The state of stress in the plate is approximately plane stress (provided the plate thickness $h<<a$), so that $\sigma_{zz} = \sigma_{zr} = \sigma_{z\theta} = 0$. The distribution of stress components at the surface of the circular hole (i.e. at $r = a$) is

$$\sigma_{rr} = 0$$
$$\sigma_{\theta\theta} = \sigma\left(1-2\cos 2\theta\right) \qquad (2)$$
$$\sigma_{r\theta} = 0$$

For $\theta = \pi/2$, the hoop stress ($\sigma_{\theta\theta}$) in Eq. (2) attains its maximum value of $\sigma_{\theta\theta} = \sigma_{max} = 3\sigma$. This corresponds to the peak of the circumferential stress distribution as shown in Fig.4 Hence we may say that the stress concentration factor (ratio of the maximum local stress to the far-field stress) for this geometry is equal to 3. Here, it is important to note that the stresses in the immediate vicinity of the hole are much higher than the far-field stress.

Consequently, failure processes may initiate locally at the edge of the hole under values of far-field stresses, which are themselves sufficiently small to preclude such failures remotely.

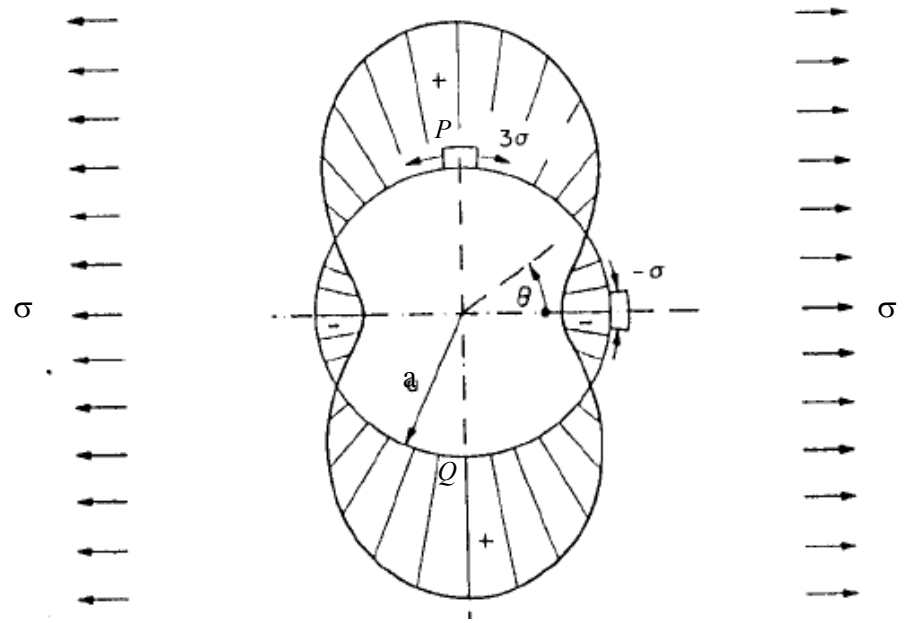


Fig. 4. Distribution of hoop stress $\sigma_{\theta\theta}$ around the circumference of circular hole in a large body

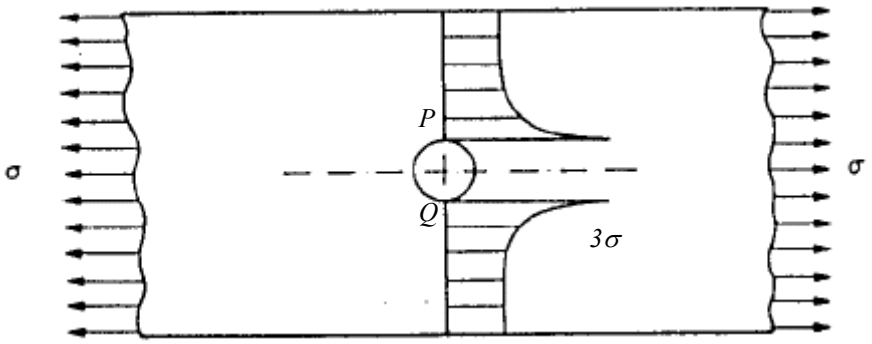


Fig.5. Radial distribution of hoop stress components $\sigma_{\theta\theta}$ along the ligament where $\theta = \pi/2$

Figure 5 shows the radial variation of $\sigma_{\theta\theta}$ along the ray $\theta = \pi/2$, emphasizes that the magnitude of the stress concentration associated with the hole decays rapidly with increasing distance from the notch. This is a clear example of St. Venant's principle, which states that the perturbations in a linear elastic field due to the presence of an isolated geometrical discontinuity of size "d" are localized within a region of characteristic linear dimension ~ 3d from the discontinuity. The stress level outside this region is therefore close to the nominal applied stress levels (unperturbed).

The above-mentioned solution is valid only for an infinite plate. For a finite plate one has to adopt an experimental approach or a numerical approach.

Photoelastic Determination of Stress Concentration Factor

The basic information one will get from photoelasticity are the fringe order N and the isoclinic angle θ. The fringe order N is experimentally related to maximum shear stress for two-dimensional problems through stress optic law as

$$\sigma_1 - \sigma_2 = \frac{NF_\sigma}{h} \tag{3}$$

Where,

N	fringe order
F_σ	material stress fringe value (N/mm/fringe)
h	specimen thickness (mm)
σ_1	maximum principal stress (MPa)
σ_2	minimum principal stress (MPa)

Photoelasticity primarily gives only principal stress difference. However our interest is to find the stress concentration factor, which needs the estimation of the maximum stress. At points P or Q (Fig.5), which lie on a free surface, $\sigma_2 = 0$ at these points and the fringe order at these locations are indicative of the maximum stress. Therefore,

$$\sigma_{\max} = \frac{N_{\max} F_\sigma}{h} \tag{4}$$

Two types of stress concentration factor definitions are found in the literature. It is important to apply the analysis consistent with the given definition. The stress concentration factor defined in Theory of elasticity literature is based on the applied stress σ and is defined as

$$K_{TE} = \frac{\sigma_{\max}}{\sigma_{far\,field}} = \frac{N_{\max}}{N_{far\,field}} \tag{5}$$

Where, $\sigma_{\max}$ is the maximum local stress at the edge of the hole and, $\sigma_{far\ field}$ is the applied far-field stress remote from the hole. In design studies, stress concentration factor is defined based on the nominal (or net-section average) applied stress σ_{nom} and is defined as

$$K_{DS} = \frac{\sigma_{\max}}{\sigma_{nom}} \tag{6}$$

Where,

$$\sigma_{nom} = \frac{P}{(w-d)h} \text{ MPa}$$

P is the applied load; w, d and h are the geometric dimensions of the specimen given in Fig. 2. Therefore the above Eq. (6) changes to,

$$K_{DS} = \frac{N_{\max} F_\sigma (w-d)}{P} \tag{7}$$

Experimental Procedure

First arrange polarizer, analyzer and quarter-wave plates for a circular polariscope arrangement. Then the Photoelastic model of plate with a hole is mounted on the loading frame. The lever arm of the loading frame should be suitably adjusted so that the straightness of the lever is maintained. If it is not straight, moving the loading frame portion by up or down by using the handle on the top can rectify it. Now the loading frame is ready for loading.

Now the specimen is loaded and one can observe isochromatic fringe patterns. Using Tardy's method of compensation total fringe order at the point (point P and Q as mentioned earlier) where maximum stress developed and far-field fringe order away from hole is to be determined. After completing the experiment, specimen is taken out from the loading frame and the geometric dimensions are measured using a vernier caliper. The experiment is to be conducted on the following four specimens (Fig. 6) of finite dimension.

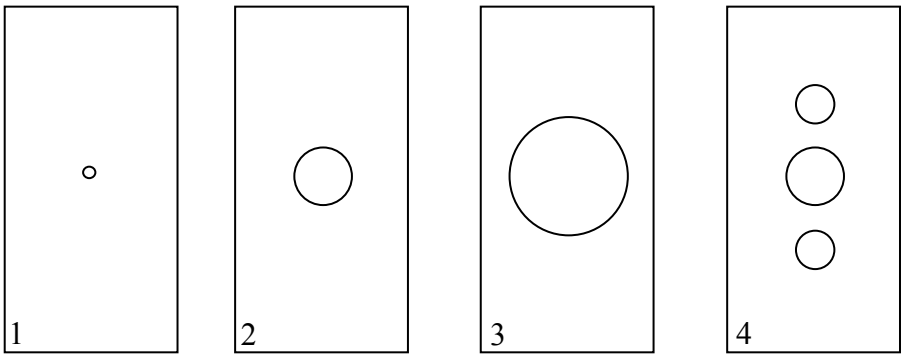


Fig. 6. Specimen geometries

Caution: Since the specimen has geometric discontinuity of varying sizes, the maximum load that can be applied for a specimen is to be less than that of the recommended value for that specimen. Consult the student in charge of the experiment before loading the specimen.

Calculation

Thickness of specimen h = mm
Width of specimen w = mm
Material stress fringe value F_σ = N/mm/fringe

S.No.	Load	N_{max}	$N_{far\text{-}field}$	σ_{max} (MPa)	σ_{ave} (MPa)	σ_{nom} (MPa)	K_{TE}	K_{DS}

Average K_{TE} = K_{DS} =

Discussion

1. For each of the specimens, compare the SCF with that of the one reported in the design handbook.
2. Draw a graph of K_{DS} versus *d/w*. Comment on your result.
3. What is the role of additional hole in the specimen 4? Comment and justify your answer.
4. Compare the effort involved in evaluating SCF for these problems by FEM.
5. Comment on the effort involved in employing Tardy's method of compensation in this problem.

---

10. Evaluation of Shear Stress Variation Over the Depth of a Beam Under Three Point Bending by Photoelasticity

Objective

Evaluation of shear stress variation over the depth of the beam under three point bending for several sections and to comment on the conventional strength of materials solution.

Theory

The shear stress (τ_{xy}) from the theory of simple bending is given by

$$\tau_{xy} = \frac{VA\overline{y}}{I_{zz}b} \tag{1}$$

where τ_{xy} is the shear stress, V is the shear force, A is the area of cross section of the beam, $\overline{y}$ is the distance from the neutral axis, I_{zz} is the moment of inertia, and b is the width of the beam.

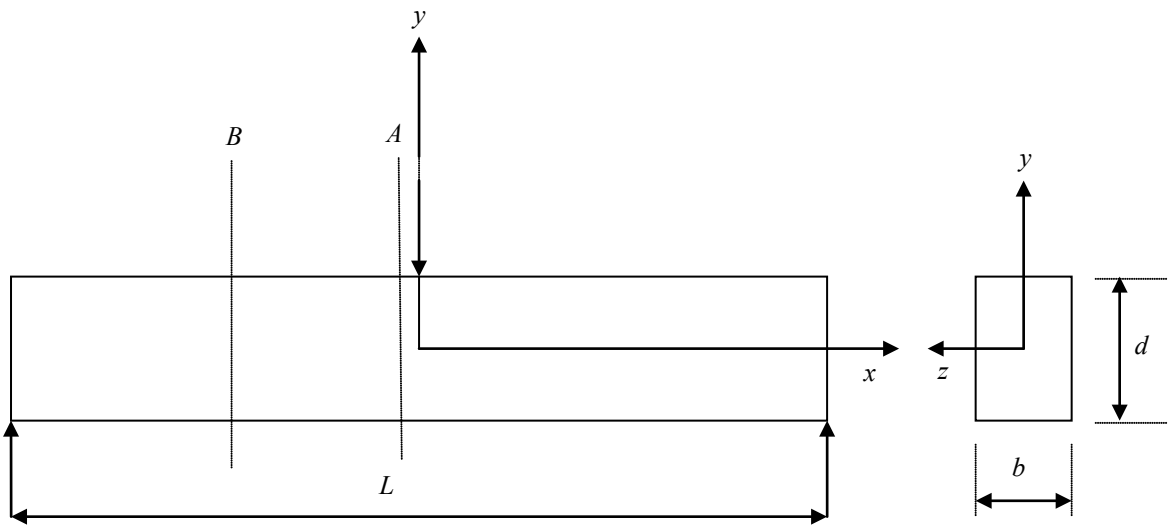


Fig. 1. Beam under three point bending

Procedure

Select two sections A and B along the length of the beam. Select the sections such that A is close to the load (5 mm or so) and B is away from both the loading points as shown in Fig. 1. Select at least seven points along each section of which two points correspond to the surfaces and one is at the geometric center of the beam depth. Load the beam and view it in plane and circular polariscope setups. Determine the isoclinic angle at each of these points. Then find out the fringe order at every point on each section using Tardy's method of compensation.

The Stress-Optic law relates principal stress difference and fringe order as,

$$\sigma_1 - \sigma_2 = \frac{NF_\sigma}{h} \tag{2}$$

Where N is the fringe order, F_σ is the material stress fringe value and h is the thickness of the beam.
Shear stress at any point over the depth is given by,

$$\tau_{xy} = \frac{\sigma_1 - \sigma_2}{2} \sin 2\theta = \frac{NF_\sigma}{2h} \sin 2\theta \qquad (3)$$

Where θ is the isoclinic angle at the point of interest.

Using Eq. (1) calculate the theoretical shear stress for all the points on the two sections A and B. Using Eq. (3) calculate the experimental shear stress for all the points on the two sections A and B. Draw the shear stress variation along the two sections A and B. Compare it with the theoretical result.

Calculations

Area of the cross section, A = mm^2
Moment of Inertia, I_{zz} = mm^4
Width of the beam, b = mm
Thickness of the beam, h = mm
Shear force, V =

Section A (closer to the load)						Section B (away from the load)					
Point of selection	$\bar{y}$ (Distance from N-A)	N	θ	$\tau_{expt.}$	τ_{theory}	Point of selection	$\bar{y}$ (Distance from N-A)	N	θ	$\tau_{expt.}$	τ_{theory}

Observations

1. Is there any difference in the shear stress variation along the two sections between theoretical result and experimental result? If so, what is it and explain the reason?
2. How can you theoretically find the stress distribution on a section close to the point of loading? Indicate the steps involved.
3. Can you develop a numerical model using FEM to solve this problem?

11. Thin and Thick Cylinder under Internal Pressure

Part A – Thin Cylinder

Objective

- To show the linearity of the strain gauges in the open and closed end cylinders.
- To evaluate the elastic properties (E, v) of the cylinder material.

Apparatus

Figure 1 shows a SM1007 thin cylinder testing apparatus. It consists of a thin walled hollow aluminum alloy cylinder of inner diameter 80 mm and wall thickness of 3 mm which is subjected to internal pressure bya manually operated hydraulic hand pump to pressurize the cylinder, pressure gauge to indicate pressure developed inside the cylinder, strain gauges pasted at different orientation with respect to axis of cylinder on the surface to measure strains, a hand wheel to adjust the cylinder to open and closed condition, digital indicator to indicate strains measured by strain gauges in micro-strains.

Open and closed configuration of the cylinder can be achieved by operating the hand wheel:

- In open condition the hand wheel is screwed in, it clamps the free-moving pistons present inside the cylinder. The frame then takes the axial (longitudinal) stress and not the cylinder wall, as if the cylinder has no ends. This allows 'Open Ends' experiments (Figure 2).
- In closed condition the hand wheel is unscrewed; the pistons push against caps at the end of the cylinder and it behaves like a closed cylinder. The cylinder wall then takes the axial (longitudinal) stress (Figure 3).

There are six strain gauges on the cylinder, arranged at various angles to allow the study of how the strain varies at different angles to the axis.

Theory

A cylindrical vessel or shell may be thin or thick depending upon the thickness of the plate in relation to the internal diameter of the cylinder. The ratio of **d/t = 20** can be considered suitable line of demarcation between thin and thick cylinders. In thin cylinders, the stress may be assumed uniformly distributed over the wall thickness. Boilers, tanks, steam pipes etc. are usually considered as thin cylinders. Thin cylinders are frequently required to operate under pressures up to 30MPa or more, for high pressures such as 250MPa or more, thick walled cylinders are used.

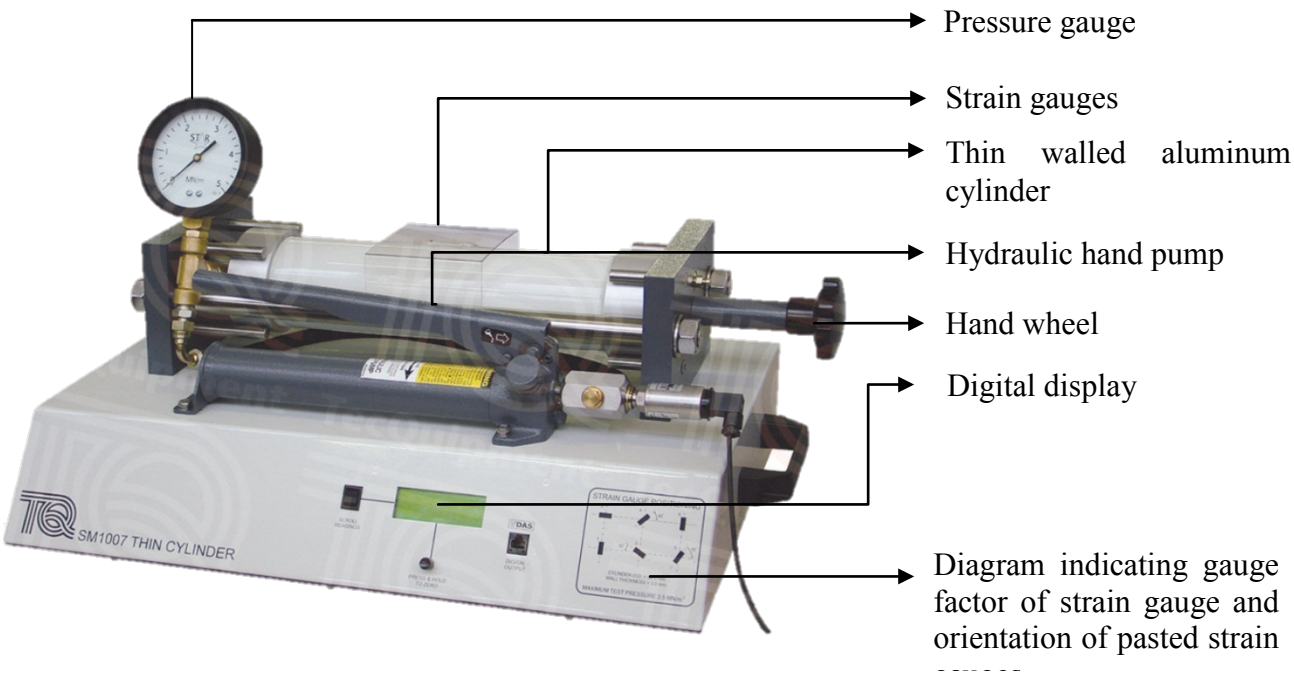


Figure 1

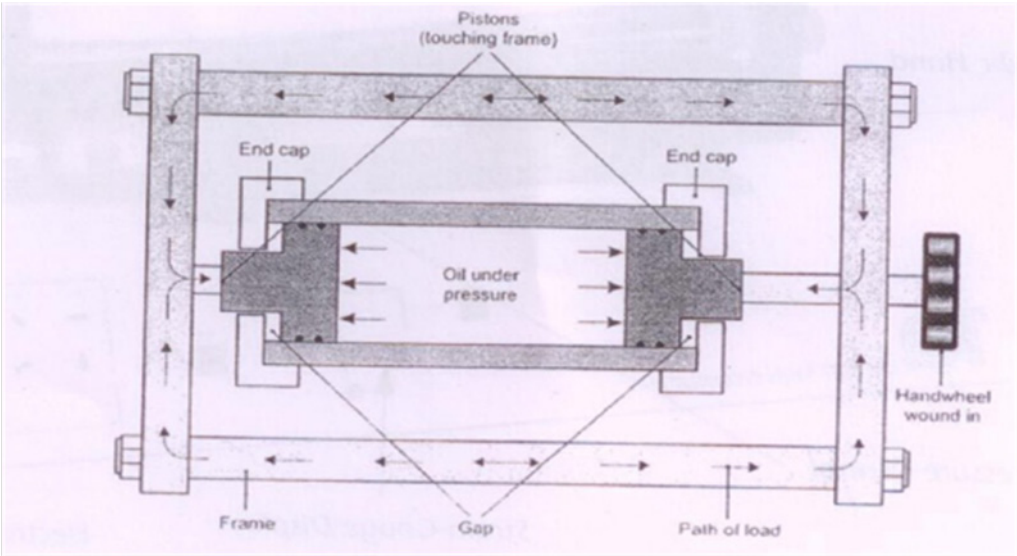


Fig.2

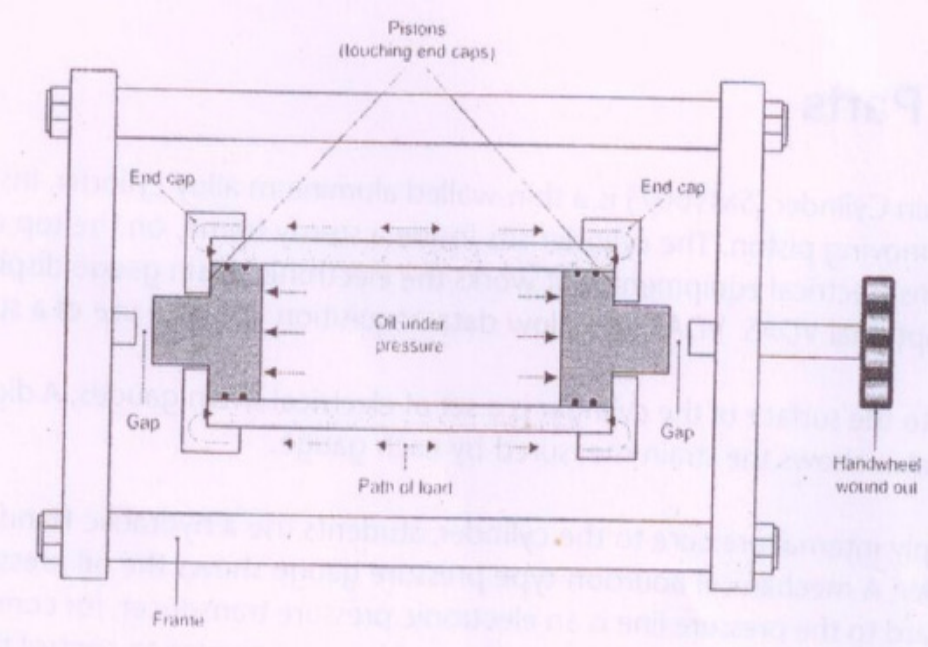


Fig.3

When thin cylinders are subjected to internal fluid pressures the following types of stresses are developed.

1. **Hoop or circumferential stresses** - These act in a tangential direction to the circumference of the shell.

   Circumferential or hoop stress,

$$\sigma_H = \frac{Pd}{2t} \tag{1}$$

   where,

   P = Appliedinternal pressure, MPa

   d = Inside diameter, mm

   t = thickness of the wall, mm

   For **open end** condition,

   Hoop strain is, $$\varepsilon_{Ho} = \frac{\sigma_{Ho}}{E} \tag{2}$$

   For **closed end** condition, (Biaxial stress state)

   Hoop strain is $$\varepsilon_{Hc} = \frac{(\sigma_H - \nu\sigma_L)}{E} \tag{3}$$

2. **Longitudinal stresses** - These acts parallel to the longitudinal axis of the shell.

   Longitudinal stress is given by

$$\sigma_L = \frac{Pd}{4t} \tag{4}$$

   For **open end** condition,

   Longitudinal strain is $$\varepsilon_{Lo} = \frac{-\nu\sigma_{Ho}}{E} \tag{5}$$

   For **closed end** condition (Biaxial stress state),

   Longitudinal strain is $$\varepsilon_{Lc} = \frac{(\sigma_L - \nu\sigma_H)}{E} \tag{6}$$

3. **Radial stresses** - These stresses acts radially and are too small for a thin cylinder. Hence theycan be neglected.

These three stresses are mutually perpendicular to each other and are principal stresses.

Procedure

1. Switch on the power to the thin cylinder and leave it for at least five minutes before doing the experiment. This allows the strain gauges to reach a stable temperature and gives accurate reading.
2. Open (turn anticlockwise) the pressure control and screw in the hand Wheel to set up the ‘open’ or ‘closed’ end conditions.
3. Shut the pressure control and use the ‘Press & hold to zero’ button to zero the strain gauge display readings.
4. Pump the hand pump until the pressure is approximately 0.4MPa and wait for a few seconds for readings to stabilize and then record the readings.
5. Carefully increase the pressure in any increments up to 3.2MPa, but do not exceed a cylinder pressure of 3.5MPa.
6. Open the pressure control to reduce the indicated pressure back to 0 MPa.

Analysis of results

1. Plot strain against pressure for all six strain gauges (Separate plots for Open end and closed end conditions).
2. Calculate the direct Hoop stress at each pressure, and plot Hoop stress against Hoop strain. Slope of the plot is the young’s modulus of the cylinder material
3. Plot longitudinal strain against hoop stress to evaluate poison’s ratio of the cylinder material.

Observations:

Open Cylinder arrangement

Sl. No.	Pressure (MPa)	Strain gauge1	Strain gauge 2	Strain gauge 3	Strain gauge 4	Strain gauge 5	Strain gauge 6

Closed Cylinder arrangement

Sl. No.	Pressure (MPa)	Strain gauge1	Strain gauge 2	Strain gauge 3	Strain gauge 4	Strain gauge 5	Strain gauge 6

Points for discussion

1. For the obtained results, draw Mohr's circle of strain.
2. Discuss the reasons for deviation of experimental results with that of theory (if there any).

Part B Thick Cylinder Under Internal Pressure

Objective

To determine the internal pressure acting on the stress frozen thick cylinder

Apparatus

1. Photoelastic model of stress frozen thick cylinder

2. Virtual polariscope software

Procedure

1. Measure the dimensions of the given thick cylinder.
2. View the stress frozen thick cylinder under a circular polariscope in dark field arrangement.
3. Measure the distance from the center of the cylinder to the point where the lowest fringe order exists on thick cylinder.
4. Use virtual polariscope to simulate photoelastic fringes in thick cylinder. Iteratively vary the pressure until the measured distance matches with the distance measured using virtual polaricope.

Points for discussion

1. How would you assign the fringe order for the fringes observed in the stress frozen sample? Discuss the reasons for the variations of fringe order along the radius of thick cylinder

12. A Demonstration on Stress Freezing in Photoelasticity

Introduction

Among the various experimental techniques, only photoelasticity offers techniques for measuring the stress field interior to the model. Success of three-dimensional photoelasticity became possible with the developments in material research, which made it possible for the use of a unique process named as *stress freezing*.

Process of Stress Freezing

In this, a model made of an appropriate epoxy is loaded and is allowed to go through a heat treatment process for locking the deformation of the model and hence the stresses. However it is termed as *stress freezing*, because the deformation locking phenomena can be explained similar to the case of a stretched spring kept in a water bath subjected to freezing in a refrigerator. At the end of freezing, water turns ice and it prevents the spring to come back to its original position even when the loads are removed.

The epoxies used for making Photoelastic models are composed of long chain hydrocarbon molecules. Some of the molecular chains are well bonded but a large number of molecules are loosely bonded. These can be termed as primary and secondary bonds respectively (Fig. 1). At the critical temperature of the polymer, the secondary bonds break and the primary bonds entirely carry the applied loads. When the temperature is lowered, keeping the loads still, the secondary bonds will re-form between the elastically deformed primary bonds and serve to lock them into their deformed positions as ice preventing the stretched spring. When the loads are removed, the primary bonds relax slightly, but a significant portion of their deformation is not recovered. Since, these deformations are locked on a molecular scale; the deformation and accompanying birefringence are maintained even in small sections cut from the original model.

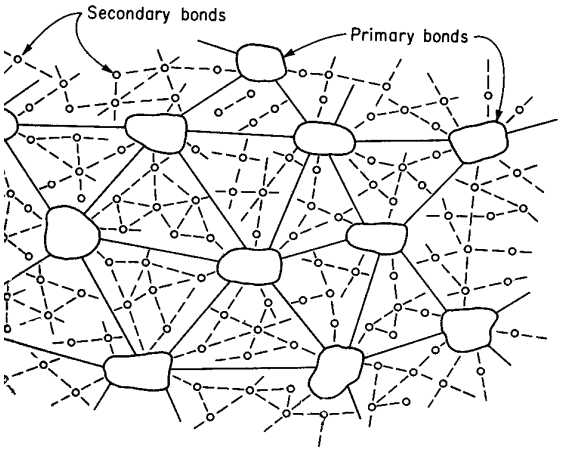


Fig. 1. Primary and Secondary molecular chains in Diphase Polymer

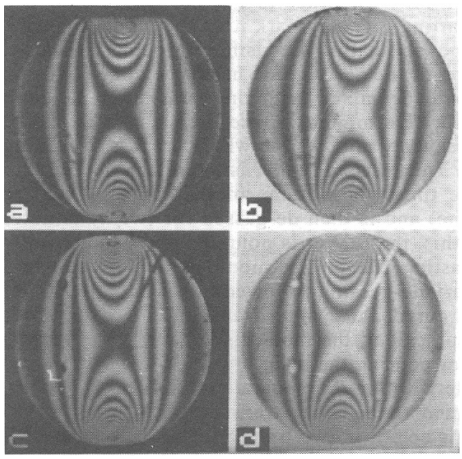


Fig. 2. Isochromatic observed for a stress-frozen disc, the fringes are not distorted after introducing two holes and slot

Analysis

After doing the process mentioned above, the model is cut into thin slices for further analysis by using the principles of two-dimensional photoelasticity. The slice cut from the model will retain the same stress distribution, as it was part of the 3-D model, provided, the slicing operation is carried out carefully so that no machining stresses are introduced (Fig. 2). This restriction is usually satisfied by using single point cutting tools

and providing appropriate coolant while cutting. Although the slice has a finite thickness and will have some variation of stresses over the thickness, their effect is usually ignored for a simplified analysis.

Microprocessor Controlled Furnace

The operation of the furnace is controlled by a microprocessor. This microprocessor can be programmed depending on the requirement of temperature and the time interval. The program can be done in different time intervals with different temperature requirements. The rate of increase / decrease in temperature for each time interval can also be programmed.

The first step in this programming is to decide the number of time segments. Once the time segments are fixed, the initial temperature and final temperature for each segment can be fed to the microprocessor. Once the program is fed, set it to run. The status of the temperature details and time left in each segment during the run can be viewed on the display.

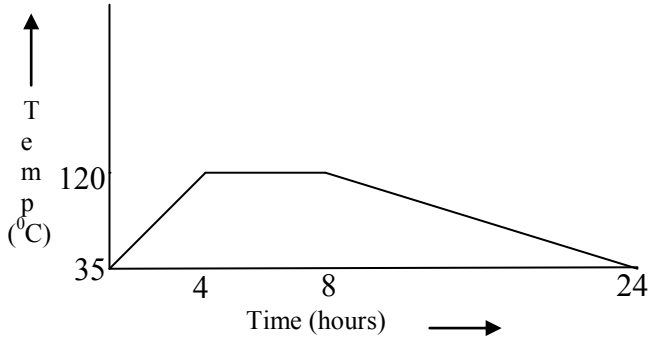


Fig. 3. Temperature Cycle for *stress freezing*

For stress *freezing* the photoelastic model, three time segments should be taken. In first segment the temperature is to be raised from room temperature (approximately 35^0C) to 120^0C over a period of 4 hours. In the second time segment, the same temperature of 120^0C is maintained for a period of 4 hours, called soaking. In the third segment it is to be cooled to room temperature at a very slow rate over a period of 16 hours (Fig. 3).

13. A Demo on Computer Aided Data Acquisition and Analysis in Photoelasiticity

Introduction

Photoelasticity has remained one of the most versatile experimental techniques. With the advancements in computer hardware playing a major role in several fields, photoelasticity has also not been left behind. The first attempts were made in the early 80s, which were confined to mimicking the manual fringe identification algorithms using digital computers. A paradigm shift in data acquisition has come about once it was realized that intensity information over the model domain could be recorded and accessed easily using CCD cameras and associated PC-based digital image processing hardware. Several methods aimed at evaluating the Photoelastic parameters based on processing the intensity information such as phase shifting, polarization stepping, load stepping and their variants have appeared. In this demo the role of fringe thinning followed by data collection and use of statistical methods for data analysis is presented.

Global Fringe Thinning Algorithm

The image of the loaded circular disc is grabbed using CCD camera and the PC-based digital image processing hardware. Generally, the fringes do not appear as thin lines, but they appear as broad bands. Early methods to measure the fringe data were manual. Photographs of the fringe pattern were magnified for facilitating better accuracy and the fringe edges were traced; midpoints between the edges along the length of the fringe bands were joined to produce the fringe lines. With the advent of the electronic revolution, photoelectric devices were used to measure the darkest points (or the minimum intensity positions) those form the actual fringe contour.

When intensity is taken into consideration, one locates the minimum intensity points forming the fringe band, which are referred to as *fringe skeleton points*. Fringe thinning involves the two steps of edge detection and fringe skeletonization. Edge detection is an important step. The better is the edge detection algorithm; the better will be the skeleton identification. For photoelastic images, a simple thresholding operation is sufficient to identify the edges. A process of semi-thresholding is implemented in the methodology. In this, for grey levels higher than the threshold, it is made white and the rest of the intensity is unaltered. This helps in identifying the edges of the fringe and also retains the intensity variation within the fringe.

For skeletonization, the fringe areas are to be identified first and within the fringe area, the skeleton point needs to be identified based on the minimum intensity criteria. To identify the skeleton point, the pixels between the edges of the fringe need to be scanned appropriately. The image is scanned row-wise (0-deg scan), diagonal-wise (45-deg scan), column-wise (90-deg scan) and cross diagonal wise (135-deg scan) as shown in Fig. 1. For each scan direction, the pixel having minimum intensity between the edges is selected as skeleton point. Thus, at the end of initial processing, one gets four images of fringe skeletons corresponding to each scan direction.

Noise points, which are scanning direction dependent, appear in each of the above scans. Further, the fringe skeleton is not continuous in one scan. The discontinuity is also scan direction dependent. The use of the logical operators shown in Fig. 1 can eliminate the fringe discontinuity and noise. The logical “OR” operation between the orthogonally scanned images helps to get a continuous fringe skeleton but the image contains noise. The noise is

scan direction dependent and is removed by the logical “AND” operation performed between the logically “OR”ed images.

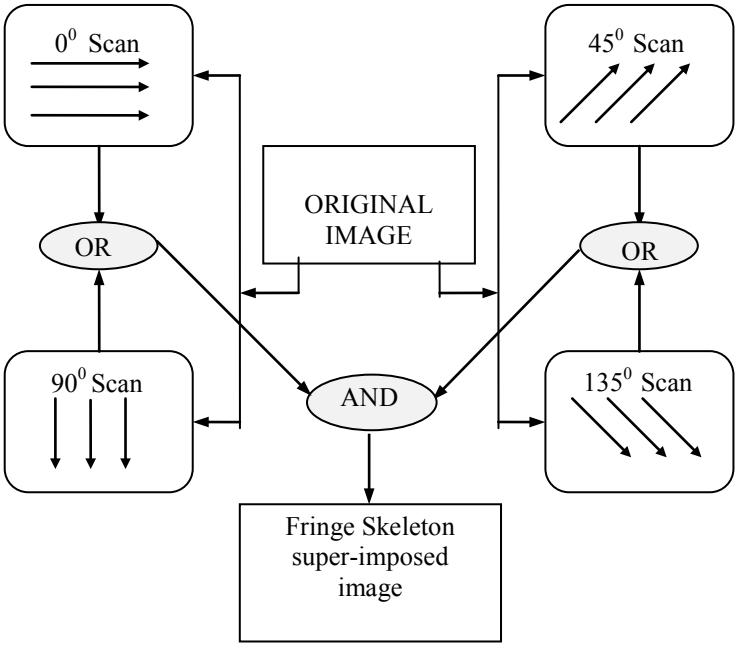


Fig. 1. The scheme of logical operators to obtain continuous fringe-skeleton

Data Acquisition and Analysis

In Photoelastic experiment, material stress fringe value is a very crucial parameter. Since this is the only parameter, which relates the optical phenomenon to the stresses, up to two or three decimal places accuracy may be required in its evaluation. Though photoelasticity is a whole field technique, data from only one point is used in the conventional method. Due to the spread of the applied loads, the agreement between the theoretical and experimental value at the center of the disc is off by about 4 percent. However in the zone r/R= 0.3 to 0.5, the theoretical and experimental results are in good agreement.

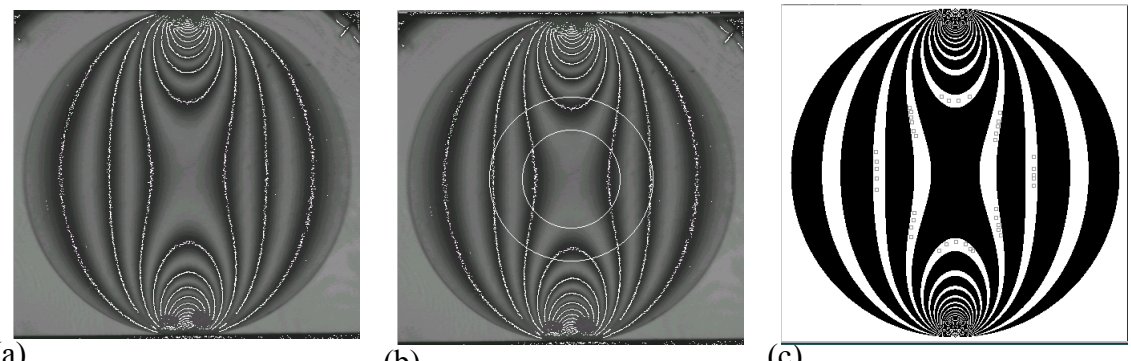
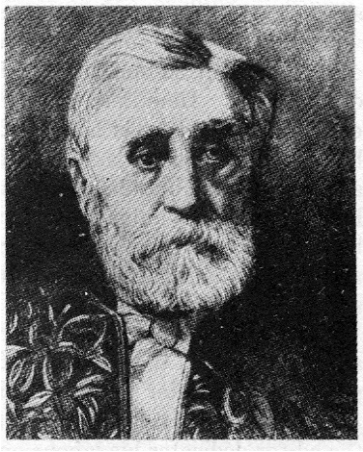


Fig. 2 (a) Skeletonized fringe pattern (b) The zone of data collection
(c) Reconstructed fringe pattern with data point echoed back

The basic idea is to use as many data points as possible from the field to evaluate the material stress fringe value. If more data points are taken, the equations available are more than the number of unknown parameters to be determined. In such cases one gets over determined set of equations. The usual method to solve such a system of equations is to obtain a new set of equations, using the least squares criteria, which are equal to the number of unknowns.

The image is skeletonized using the global fringe-thinning algorithm. The skeletonized image is shown in Fig. 2a. Data points are taken in the region of r/R= 0.3 to 0.5 (Fig. 2b). Collection of 40 data points is adequate for the material stress fringe value. Least square technique by itself does not guarantee that the result is physically admissible. Theoretical reconstruction of fringe patterns after evaluating the parameters in a least squares sense is very important and the evaluation of the parameter values is complete only if the reconstructed image fringe patterns agree well with the experimentally obtained ones. The reconstructed fringe pattern with the data point echoed back is shown in Fig. 2c.

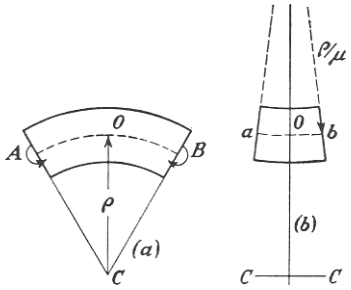


Barré de Saint-Venant (1797 – 1886)

Prominent Students Boussinesq, Lévy,

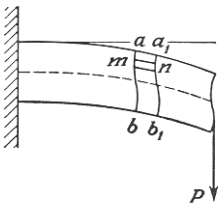
Saint-Venant believed that our knowledge can be improved only by combining experimental work with theoretical study. During the illness of Prof.Coriolis, Saint-Venant was asked to give lectures on Strength of Materials at the École de Polytechnic (France) and these lectures are of great historical interest, since some problems are mentioned which were later to become the objects of Timoshenko's scientific research. Saint-Venant was the first to try to bring the new developments in the theory of elasticity to the attention of his pupils.

Saint-Venant was the first to examine the accuracy of the fundamental assumptions regarding bending, viz., (1) that cross-sections of a beam remain plane during the deformation and (2) that the longitudinal fibres of a beam do not press upon each other during bending and are in a state of simple tension or compression.



He demonstrates that these two assumptions are rigorously fulfilled only in four-point bending. He also shows that the initially rectangular cross section changes its shape as shown in the figure having anticlastic curvatures due to lateral contraction of the fibres on the convex side and expansion on the concave side.

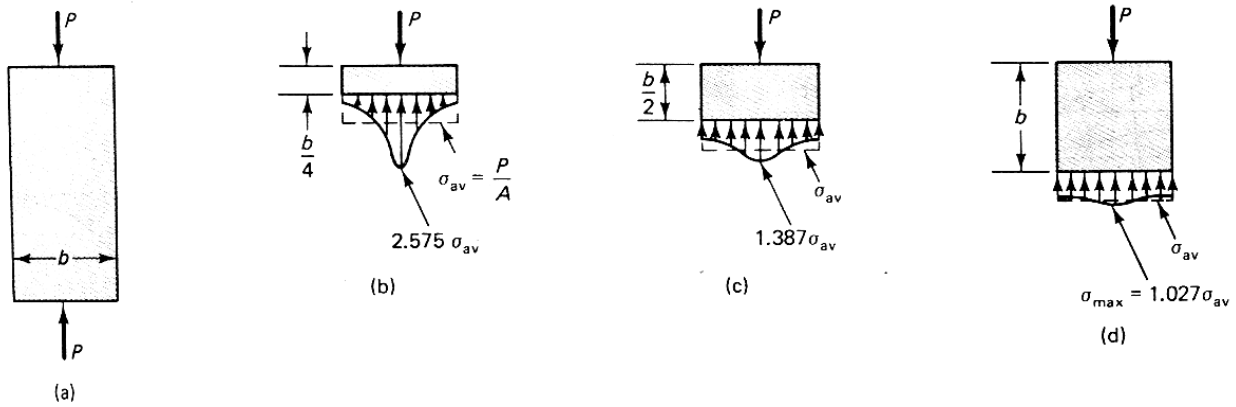
Saint-Venant was the first to study the role of shear stress in bending. He observed that for a cantilever loaded at free end, the cross-sections such as ab and a_1b_1 suffer warping as shown. Since, the warping is the same for any two cross-sections, it produces no changes in the length of the fibres and bending stress calculation by flexure formula is still exact.



Saint Venant's Principle

Saint-Venant illustrated the principle which goes by his name by experimenting on rubber bars and showed that if a system of self-equilibrating forces is distributed on a small portion of the surface of the bar, a substantial deformation will be produced only in the vicinity of these forces.

In nutshell the principle states that for the purposes of analysis the actual loading can be replaced by a statically equivalent system. The disturbance thus introduced is local and its effect diminishes at distances away from the point of loading. This could be better understood by the following.



Consider that a uniformly distributed load needs to be applied to a bar as shown. Instead a concentrated load which is statically equivalent is applied at the end. The rigorous solution to this problem by theory of elasticity reveals that the loading becomes uniform at a distance *b*, which is the thickness of the specimen. Closer to the loading one cannot estimate the stress by invoking *P*/*A*. This can be done only beyond *b*.

This principle finds wide application in the mathematical theory of elasticity and in experimental work to design loading rigs.

In 1853, Saint-Venant presented his epoch-making memoir on torsion to the French Academic composed of Cauchy, Poncelet, Piobert and Lamé.

Stephen Prokofyevich Timoshenko (1878-1972)

Prominent Students: Den Hartog, M. M. Frocht, N.J. Hoff etc.

The greatness of Timoshenko lies in the fact that his students branched out to different fields of engineering and shone as authorities in their respective fields. For example Den Hartog is an authority of vibrations, M.M. Frocht on photoelasticity and Hoff was an aeronautical expert.

Since 1903 S.P.Timoshenko worked in St.Petersburg Polytechnical Institute as senior laboratory assistant in applied mechanics and teached students statics of structures. After Quebec Bridge crash in Canada Timoshenko started working in the field of complex beams and stability analysis of frames and also developed simple methods of solving such kinds of problems. In 1922 Timoshenko moved to the USA, where he worked as an engineer in "Westinghouse" company, but later became a professor in the University of Michigan.

Timoshenko's lectures on applied mechanics in the University of Michigan attracted a great number of students and young scientisis and teachers. Such stars of science from Europe as Prandtl and Westergaard went to the USA to meet with S.P.Timoshenko. By that time he has published a number of books on materials strength, theory of elasticity and theory of stability.

Since 1936 he worked in Stanford University, where his books on technical mechanics, theory of plates and shells, dynamics were published. A great popularity was gained by his book on the history of strength of materials.

Timoshenko is considered to be the founder of the technical mechanics scientific schools in the USA. He has developed the theory of beams and plates bending taking into account shear strains (in modern structural mechanics terms “Timoshenko plate”, “Timoshenko element” are widely used), published numerous works on torsion, thrust and pivot vibration, solved the problem about stress concentration near holes (Timoshenko problem).

Report Writing

A report must be concise (but complete) and readable. Generally a report is typed but due to our limitations, it can be legibly handwritten preferably on bond papers. Attach the raw data to your report. Although this is not a general practice it helps to verify your calculation.

A laboratory report is generally divided into sub-headings like objective, theory, experimental details, results, discussion, conclusion and appendix. The objective is stated concisely in a sentence or two. For the experimental work of this laboratory, only the important definitions and theoretical results are to be presented. If you want to include a derivation, present it in an appendix and make a reference of it in the main text. The report is generally written for a technically trained person who may not be familiar with the work described in the report. Hence, some information on the background and the methodology adopted need to form part of the report. At the same time, in this busy world, one wants to reach the discussion and conclusion sections without spending too much time in knowing the background.

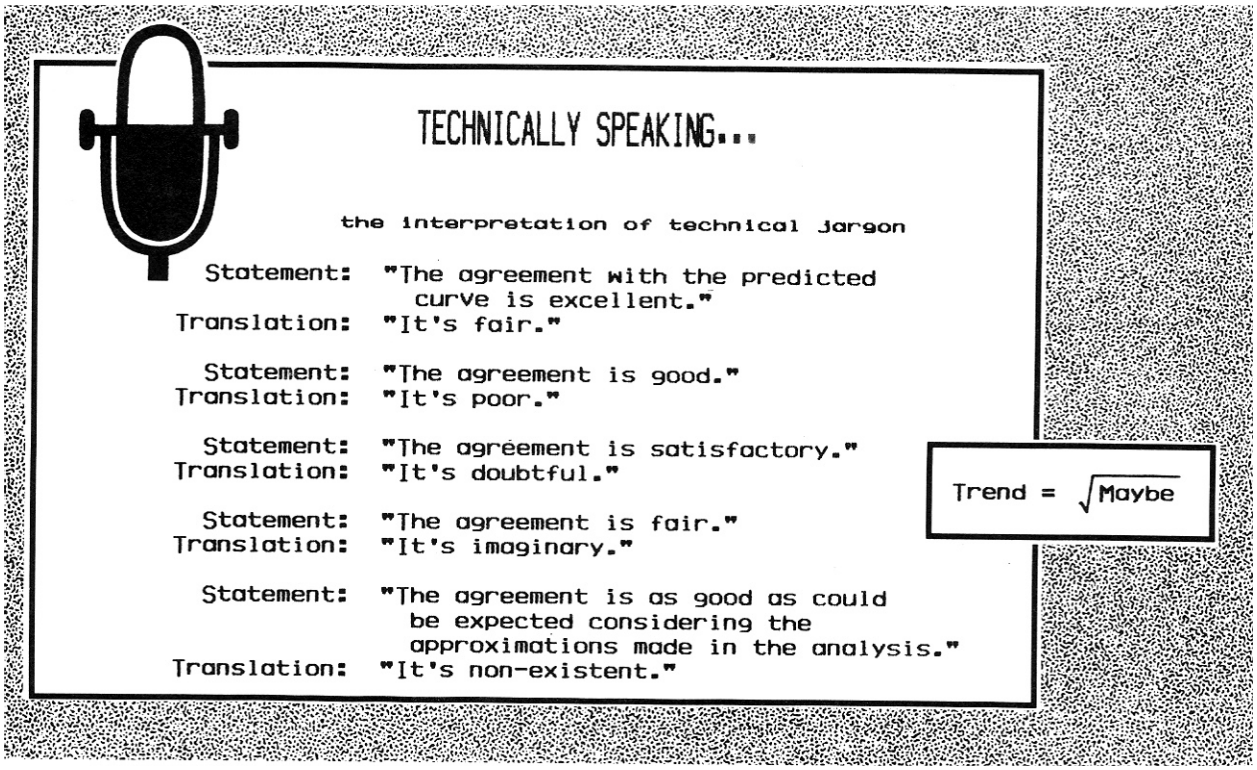
One of the best ways to discuss results is to compare them either with the results of other experimental results available in research papers or books or with theoretical predictions of a model. The comparison is generally found effective if presented in a graph or through a table.

It is very important to present the data in a readable table. Show sample calculations wherever necessary. Each table should be titled, too many columns crowd it and make it hard to read and therefore only the relevant portion of the raw data should be included. For example, initial reading of dial gauge is not carried to the formal text of the report; only the displacements are reported.

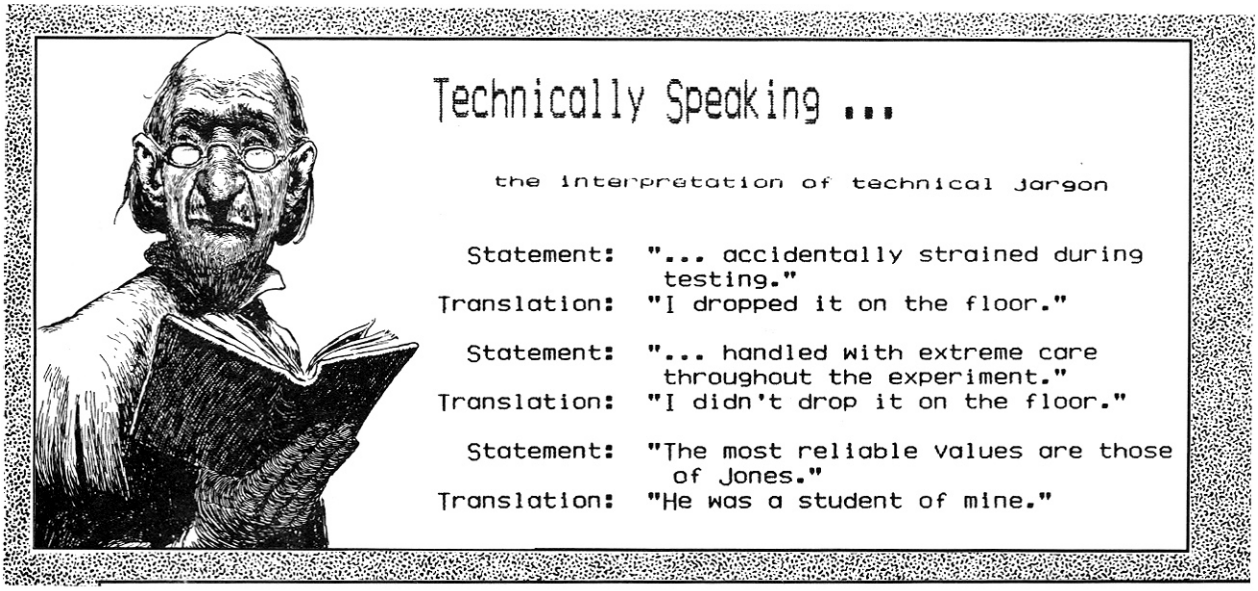
Graphs are very useful and are important features of a report to understand the results at a glance. Therefore, it pays to complete all the requirements of a graph; a suitable title should be stated clearly and if there are more than one line on the graph, each line should be identified properly. To make the graph readable, simple scales should be chosen for the axes and the axes are to be labeled with appropriate units.

Since tables and figures are the main parts of the report, they should be prepared with care and patience. All tables and figures (sketches, photographs and graphs) must be numbered, i.e., Table 1, Table 2 etc. and Fig.1, Fig. 2 etc. They do not become part of the report until they are referred to in the text. Only Figures and Tables referred in the text will be checked.

Since the writer spends hours in conducting the experiment and in reducing the data, he is in a good position to bring the highlights of the results to the attention of the reader. Also, the writer may discuss various aspects of the results such as limitations of the test equipments, problems arose during the experimentation, likely places of large errors etc.



Courtesy: Experimental Stress Analysis Note Book, Measurements Group, Inc., USA



Courtesy: Experimental Stress Analysis Note Book, Measurements Group, Inc., USA

How to Avoid Errors in Comparing Experimental Results with Theoretical Model

When you make measurements experimentally, the resulting value, if done carefully, is truth and can be used as a benchmark to test the analytical model. In many instances you may not measure force, torque or bending moment directly. You must clearly understand the functioning of the force application system and verify whether you have adjusted the necessary aspects suitably. If necessary draw the free body diagram of the system and check whether you are adopting a correct procedure in calculating the force/torque or bending moment as the case may be. If any distance measurement is involved, measure them with utmost care and always apply statistical principles in measurement. Take a few readings and use its average for any calculations.

Learn to be alert (difficult after a heavy lunch in the afternoon!) while doing the experiment. One should have a rough idea of what would be the trend of the experimental readings. For example if loading is increased, the deflection, stress or strain, should also increase in the same proportion. The results for loading and unloading should be close enough! If any deviation is observed you must make mid-course correction on the experimental procedure.

In the laboratory, the choice of dimensions of the test specimens are so chosen that it closely satisfies the assumptions made in the analytical model. Despite this, considerable deviations could exist if you do the experiment for the first time. One of the most common sources of error made by several students is the input that they feed to the analytical model. This input mainly consists of force, length, and cross-sectional details. These are to be measured and a careless approach in measurement could cost you dearly! For example if you do not measure the cross-sectional details of the specimen carefully, the error can blow up since $I = bd^3/12$ and any small error in d can blow up! On the other hand, the actual experimental measurement of deflection, strain or stress may be quite accurate yet the comparison is poor because input to analytical model is erroneous!

Instrument Characteristics - Terminologies

Readability of an instrument indicates the closeness with which the scale of the instrument may be read. The *least count is* the smallest difference between two indications that can be detected on the instrument scale. Both of these depend on scale length, spacing of graduations and parallax effects.

For an instrument with a digital readout, the terms readability and least count have little meaning.

Sensitivity of an instrument is the ratio of the linear movement of the pointer on an analog instrument to the change in the measured variable causing this motion. For example, a 1-mV recorder has a scale length of 10 cm then its sensitivity is 10cm/mV, assuming that the measurement is linear over the entire scale.

The term sensitivity does not have the same meaning for a digital instrument because different scale factors can be applied with the push of a button. Usually the manufacturer specifies the sensitivity for a certain scale setting, e.g., 100 nA on a 100 -μA scale range for current measurement.

Accuracy of an instrument indicates the deviation of the reading from a known input. It is expressed as a percentage of the full scale reading. Accuracy of the instrument needs to be monitored/improved by periodic calibration.

Precision of an instrument indicates its ability to reproduce a certain reading with a given accuracy. In actual usage, one does not know the value of the input. One is normally advised to make a few readings and the average of these is taken as the measured value. The deviation of the actual reading over this average is the precision of the instrument.

Consider that the five readings of a voltmeter reads the values 103, 105, 103, 105 and 104 V. The average value of this is 104 V and the maximum deviation is only 1 V. The precision of the equipment is then $\pm$ 1 percent. Suppose that this measurement was done for a known input of 100 V (from a well calibrated standard source) then the deviation of the instrument is high from the actual value and the maximum deviation is 5 V. Hence, the accuracy of this instrument is poor and the readings are not better than 5 percent. However, the accuracy can be made very close to the precision of the instrument by resorting to re-calibration of the instrument. Accuracy cannot be made better than the precision of the instrument. Precision of the instrument depends on various factors.

Hysteresis exists for an instrument if there is a difference in readings depending on whether the value of the measured quantity is approached from above or below.

The deviation of the actual reading from the input is the error in measurement. This error could be *systematic* or *random*. Systematic errors could be introduced due to faulty calibration of the instrument. Every effort must be made to eliminate the influence of systematic errors in measurement. Random errors – as the name indicates are truly random and every effort must be made to reduce this error. This could be due to error of parallax, poor reading of the chart and so on. Statistical methods of data analysis could reduce the influence of random errors in data interpretation.

Measurement of Deflection – Dial Gauge

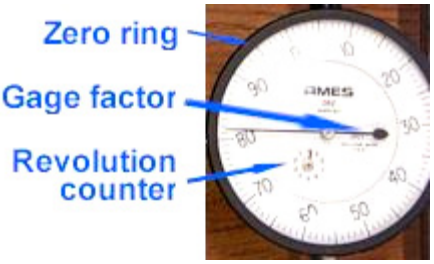
Dial Gages are used to accurately measure movements of tests in progress. They come in varying lengths and accuracies, so be sure to note gage factors and length**.**

The gage shown in the figure has a smallest increment of one thousandth of an inch (0.001), and can move 1 inch. Precision is listed as +/- 0.0005 inches.

Method to Use

Start by fastening the magnetic gage base to the equipment - simply push the button on the base in to activate the magnet.

- Adjust the holding assembly to place the tip against the object to be measured.
- Zero the gage by turning the black outside (zero) ring. Loosen locking nut first if it has one.
- As the test progresses, read the dial units. There are 100 units per revolution, so keep track of the revolutions counter as well.



- Always work in dial units and convert using the gage factor after testing. DO NOT CONVERT ON THE FLY!
- Multiply the dial units × gage factor (0.001) to calculate displacement in inches.

In this example, dial units = 41

Measurement of Force - Proving Ring

A proving ring is a device used to measure force. It consists of an elastic ring in which the deflection of the ring when loaded along a diameter is usually measured by means of a micrometer screw and a vibrating reed. The proving ring you will use in this laboratory uses a dial gauge to measure the change in diameter. The proving ring was developed by H. L. Whittemore and S. N. Petrenko of the National Institute of Standards and Technology (NIST), in 1927.

Proving ring consists of an elastic ring of known diameter with a measuring device located in the center of the ring. Proving rings come in a variety of sizes. They are made of a steel alloy. Manufacturing consists of rough machining from annealed forgings, heat treatement, and precision grinding to final size and finish.

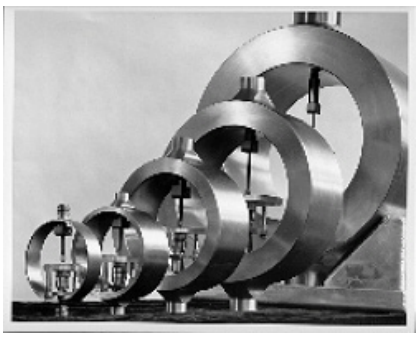


Fig. 1 Proving Rings of various sizes

Proving rings have evolved over time; however, they are still manufactured according to design specifications established in 1946 by the National Bureau of Standards (NBS), the predecessor of the National Institute of Standards and Technology (NIST). Those specifications can be found in the Circular of the National Bureau of Standards C454, issued in 1946. The concept behind the proving ring is illustrated in the diagram below.

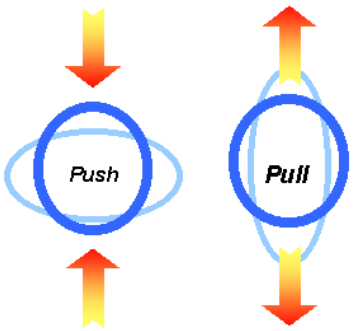


Fig. 2 Schematic diagram of the changes in the ring diameter as compression (push) and tension (pull) forces are applied.

Proving rings can be designed to measure either compression or tension forces. Some are designed to measure both. The basic operation of the proving ring in tension is the same as in compression. However, tension rings are provided with threaded bosses and supplied with pulling rods which are screwed onto the bosses.

Typically, proving rings are designed to have a deflection of about 0.84 mm to 4.24 mm. The relative measurement uncertainty can vary from 0.075 % to about 0.0125 %.

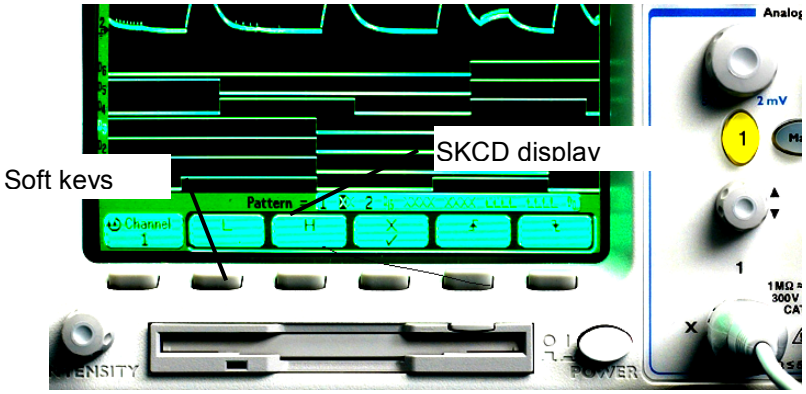
Signal Acquisition with Auto Triggering, for the Agilent 5462x Series

This note contains the following:

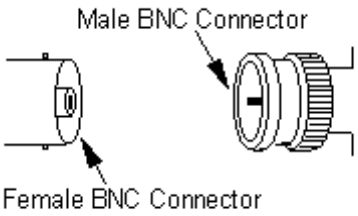
- On *connecting* the oscilloscope (signal analyzer) to the P3500 (signal generator)
- *Handling* the signal
- Understanding the oscilloscope softkey screen *display*
- *Frequency* measurement
- Signal *acquisition* (only auto triggering mode)

Notations:

SK: Softkeys (those unmarked keys whose function varies according to context)
SKCD: Softkey function displays- the lower part of the display screen shows some small windows above the SK which will show what the SK will do at this context. It also shows some additional info, like frequency, period etc.



BNC male and female ports



1 Connections

1 Connect a **BNC** cable (1.5m, white color, both ends BNC male part) between the P3500 and the oscilloscope. The cable (looks like cable TV's, only 1 pin) ports are,
   - On P3500- The '**output' port**, just below battery indicator, left side upper part of the box.
   - On oscilloscope- In the **signal input port**. Use (analog) port 1. (any of ports 1-2 may be used).

2 Switch on P3500, do standard checks/adjustments. The output port will now send the strain gauge output to the oscilloscope.

3 Switch on oscilloscope. No signal will be there in the display.

4 Press the vertical **oval** switch '1' of analog input port. It glows yellowgreen. Signal will come in screen. It is an *almost flat signal*, with occasional noise.

2 Handling the signal

1 There are 4 circular knobs to handle the signal- 2 for vertical and 2 for horizontal.

Vertical ones in the 'analog' area and horizontal, in 'horizontal' area of the oscilloscope.
Vertical bigger- zoom the signal vertically
Vertical smaller- move the signal up/down
Horizontal bigger- zoom the signal horizontally
Horizontal smaller- zoom the signal right/left (wrto time)

2 At this stage, only the following switches will be ON/glowing.
Oval switch '1'- indicating signal of port 1 is on screen.
Quick meas(ure)- factory default setting
Trigger/*edge*- factory default setting
Run/*stop*- factory default setting. 'Green': **Signal is now running on screen**

3 The oscilloscope softkey screen display, & settings.

1 Press the SK 'select:……' to bring a menu. We can select signal characteristics from the menu to be measured so that the oscilloscope will measure the signal and display it, without our help.

2 Press **'select'** continuously till freq is selected; then SKCD will be 'select: freq'

3 The info available *on the screen* are,
Pk-pk(1): peak-to-peak signal value, approx 4.5mV, of whatever signal now.
Period(1): No edges: couldn't detect a signal
Freq(1): No edges: couldn't detect a signal

4 Frequency measurement

1 We are in 'find requency' already.

Note: Getting the correct 'decaying signal' depends on the horizontal zoom knob's correct setting. Start turning the knob. Immediately the signal will take the form of a straight line. We need the line's length to be some 50% of screen width. Leave the knob.

2 Give a mild impulse/strike with a pen or light hammer. Or, press cantliver end by 5mm and release. The screen signal will reflect the impulse.

3 The measured frequency will be indicated in the screen SKCD, for a brief time, till the signal dies down, which happens almost immediately.
Frequency is approx 60Hz.

5 Damping measurement

1 Give an impulse. As we see the decaying signal, press 'Run/stop'. It'll go red.

2 Whatever signal was on screen, it was acquired and put in memory. The screen will show the saved/acquired signal now instead of the live one.

3 You should see the natural vibration characteristics of the beam now.

4 Call the cursors now and start measurement.

