J. Indian Inst. Sci., 66, Jan. 1986, pp. 1-11


# Some observations on stress freezing

P.V. REDDY AND N. SRINIVASA MURTHY
Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560 012.

Received on February 16, 1985; Revised on June 24, 1985.

**Abstract**

This paper reports investigations carried out on 6-mm thick specimens of Araldite, a photoelastic material to lock-in deformations at temperatures lower (65°C) than the current practice (130°C) employing cold-cast model material with CY230 resin and HY951 hardener or hot-cast model material with CY230 resin and HT901 hardener. The model material and the temperature range employed enable one to overcome the drawbacks and limitations of Schwaighofer's 'Extended frozen stress method'.

**Key words:** Stress freezing, photoelasticity

## 1. Introduction

In plane models, a two-dimensional photoelastic stress analysis is carried out. However, many stress analysis problems, which are three-dimensional in character exist and cannot be effectively approached by using two-dimensional techniques. It is however possible to construct and load a three-dimensional model and analyse interior planes of the model photoelastically by using either frozen-stress or scattered-light methods.

Scattered-light technique is a non-destructive one and the model can be analysed with the loads on or under live-load conditions and mechanical slicing is replaced by optical slicing and hence it is a non-destructive test. With the frozen-stress method, model deformations and the associated optical response are locked into a loaded three-dimensional model. After stress-freezing, the model is sliced and photoelastically analysed to obtain interior stress information.

## 2. Locking-in model deformation

The most commonly used conventional method of stress freezing is by heating the polymer to a critical temperature, loading it at or before it reaches that temperature, soaking it at that temperature with the load on and cooling it to the room temperature with the load on and releasing the load. This procedure locks-in the birefringence and the deformation. Presently used three-dimensional photoelastic materials have Poisson's ratio $v$ around 0.5 at the critical temperature. This introduces two limitations, the first being that since, in general, elastic solutions of three-dimensional problems depend on Poisson's ratio the solutions apply only to materials with the same Poisson's ratio as that of the model. The second limitation is that it is not possible to supplement the maximum shear information given by the birefringence measurements with mechanical or Moire' measurements because in the equations relating direct strains to normal stresses a factor $(1-2\nu)$ appears in the denominator. This makes the use of supplementary procedures necessary to separate the stresses which are inaccurate and time-consuming[1]. Thus the stress distribution is materially affected by the magnitude of Poisson's ratio as in certain problems of bending of plates, and also at critical temperature the deformations under load are large and thin members under compression buckle prematurely at the critical temperature. However, stress freezing at or higher than the critical temperature is not without advantages, the important ones being that a low load is required and the stress pattern frozen is more or less permanent and does not vanish on removal of the load. From the above it can be concluded that it is desirable to develop a material or stress-freezing method which has the following characteristics:

a. does not require a high load
b. stress freezing is possible at or about room temperature
c. the stress pattern does not relax or the fringe order does not decrease substantially on unloading
d. the duration of stress freezing is either comparable or less than that in the conventional method at the critical temperature
e. results in small deformations, a high Young's modulus and a low Poisson's ratio
f. the stress-strain relation of the material as well as the stress-fringe relation are linear.

## 3. Present practice

The normal practice is to heat the Araldite specimen under load in an oven with programmable temperature control at a rate of 10° C per hour up to 120-140° C and to soak it with the load on at this temperature. The soaking time is governed by the volume and thickness of the specimen; however, the normal duration is around 3 to 4 hours. The specimen with the load on is then cooled back to the room temperature at a rate of 3 to 5° C per hour. The slower rate of cooling is to avoid any thermal stress that could be caused if a rapid cooling is employed. Thus the entire stress-freezing cycle operation normally employed requires about 40 to 50 hours. Further, it is likely that at the soaking temperature of 120-140° C the specimen under load might undergo large local deformation especially with a point or contact load.

Schwaighofer[2] presented an extension of the well-known frozen-stress method called the Extended frozen-stress method. It uses a stress-freezing temperature of around 130° F (54.4° C) at which the modulus of elasticity of Araldite is approximately the same as that at room temperature and Poisson's ratio is 0.36. Thus if Poisson's ratio of the material of the prototype is 0.36 no corrections need to be applied to the results obtained from an extended frozen-stress study. Schwaighofer[2] identifies two regions in which the modulus of elasticity varies only slightly. One is the region with temperatures equal to or higher than the critical temperature. The other region represents the range with temperatures between 70 and 150° F, (21 and 65.5° C). The first region is the domain of the conventional frozen-stress method characterised by low modulus of elasticity, a low-fringe constant and a high Poisson's ratio. Only small loads are necessary to produce the desired photoelastic effect but the accompanying deformations are large. The second region distinguishes itself by a high modulus of elasticity, a high fringe constant (this means that the material is optically more insensitive here than in the first domain) and a low Poisson's ratio. Higher loads are necessary in order to produce a sufficiently high fringe order but the deformations are small.

The extended frozen-stress method is operative in this region. A room temperature frozen-stress investigation was carried out by Oppel[2] on phenol formaldehyde resin Dekorit. Durelli and his collaborators[3,4] also carried out stress-freezing investigations at room temperature and concluded that the creep properties increase the sensitivity of the material and allow the freezing of stresses without using the conventional heating technique. Stress freezing at room temperature on Hysol and Araldite showed that the number of frozen-in fringes decreased rapidly with a lapse of time upon unloading. The loading duration was inordinately long. However, with Hysol and Araldite it was observed that slightly elevated temperatures accelerated stress freezing. It was concluded that freezing temperatures between 130 and 140°F (54.4 and 60°C) were most suitable for Hysol and Araldite.

In order to eliminate errors due to large deformations and to make suitable corrections in the results for the Poisson's ratio at the critical temperature, stress freezing at room temperature was carried out by gamma-ray irradiation[5-7]. However, this method requires special equipment, and long freezing time, and also has radiation hazard. As the fixation is done at room temperature high loads are required. Miyazono[6] reported that the fixed fringe pattern relaxes more rapidly than in the conventional method, that is the fixed fringe pattern decreases with time after the removal of the load faster than in the usual stress-freezing method and also requires large doses of radiation. To circumvent the problem associated with large values of Poisson's ratio at the critical temperature thereby necessitating corrections for the prototype, Durelli[8] developed a material whose value of Poisson's ratio was close to that of the prototype even at the critical temperature. It was found that Epon 828 cured with Bakelite hardener ZZL 0803 could give a value of 0.4 for the Poisson's ratio at the critical temperature.

By employing the extended frozen stress method, Schwaighofer[2] had used the viscoelastic response of the material. Theocaris[9] in a discussion on the method of Schwaighofer[2] alluded to the time temperature superposition principle of Tobolsky and Andrews[9] and Leaderman[9] for the description of the mechanical viscoelastic properties of several high polymers and the description of the optical viscoelastic properties of epoxy-copolymers developed by himself[9]. By a more scientific explanation of the phenomenon he indicates the constraints under which the Schwaighofer's method[2] can be used effectively in cases in which the conventional frozen stress method fails to yield reliable and accurate results. Kuske[10] has given a general law on the mechanical and optical properties of model materials in photoelasticity using the multi-phase theory of plastics. Frocht[11] and Dally and Riley[12] have proposed models to explain the mechanism of stress freezing on the basis of the diphase theory.

## 4. Conclusions from the previous work

1. Stress freezing by gamma irradiation does not appear to be a practicable proposition.

2. Creep stress freezing needs a large load and there is a pronounced relaxation after the removal of the load.

3. Schwaighofer's method[2] operating in the temperature range 70 and 150°F (21 and 55.5°C) can be applied when in an investigation small deformations, high Young's modulus and low Poisson's ratio are desired. It has been found that for Araldite the stress-strain

relation as well as the stress-fringe relation are linear in the temperature range 70 and 150° F (21 and 65.5° C). His method can be applied to any three-dimensional problem and will directly provide results that will be sufficiently accurate for all practical purposes if the prototype consists of metals such as steel ($\upsilon = 0.3$) and aluminium ($\upsilon = 0.33$). However, his method only supplements but will not replace the conventional method. The factors that prevent this method with small deformations from acquiring first place in three-dimensional photoelasticity are the necessity of high loads, the fringe order in the model decreasing substantially on unloading and especially the amount of time involved in conducting a test.

## 5. Motivation and identification of the problem

From the conclusions it will be observed that Schwaighofer's method[2] is quite attractive excepting for the disadvantages and the drawbacks which are not insurmountable. One of the directions would be to conduct experiments on a different material. Although Schwaighofer's work was done on Araldite, it is only a general nomenclature. Since in this country most of the R&D laboratories using the photoelastic stress analysis technique invariably use the Araldite manufactured by Hindustan Ciba-Geigy, naturally the choice of material fell on Araldite CY230-Bis-A epoxy resin and hardener HY951-TETA Triethylene tetramine which could be cold-cast and CY230-Bis-A epoxy resin and hardener HT901 Phthalic anhydride which is hot-cast. Most of the experiments were carried out on specimens made with cold-cast material. All the laboratories invariably employ a temperature of 120° C for stress freezing as in the conventional method[13,16]. Hence it was of interest to explore the possibility of stress freezing at a lower temperature with all the advantages accruing thereby. This naturally appeared to be on the lines of Schwaighofer's method[2].

Preliminary tests indicated that the results and conclusions were at variance with those of Schwaighofer[2] and it appeared that the drawbacks of Schwaighofer's method were all overcome completely thereby making this method the preferred one in three-dimensional photoelastic analysis. Accompanying the question of stress freezing at a lower temperature was also the question of annealing or stress relieving at low temperature. Preliminary tests indicated that stress relieving was also possible at the same lower temperature as stress freezing. At any temperature above the room temperature one is intrigued by the question as to the variation of the elastic constants namely Young's modulus and Poisson's ratio with temperature.

## 6. Scope of the work

The investigation was taken up to answer the following questions:

a) On the lines suggested by Schwaighofer[2] is it possible to stress freeze the deformation in a loaded Araldite specimen out of CY230 and HY951 hardener?
b) Does this stress-freezing method have all the disadvantages of the extended frozen-stress method thereby making it a supplement to the conventional stress-freezing method?
c) If (b) is not true can the extended frozen-stress method enjoy the status of the conventional stress-freezing method?
d) What is the minimum temperature range where this can be applied?
e) If it is possible to stress freeze at a lower temperature is it also possible to stress relieve or anneal at or around the same low temperature?

f) On removal of load after stress freezing does the fringe order in the model get affected substantially?
g) Does the fringe order reduce substantially with passage of time over a reasonable period in an unloaded low temperature stress-frozen specimen?
h) What are the values of the elastic constants of the model material at this temperature?
i) How do the elastic constants of the model material vary with temperature?

## '. Determination of elastic constants as a function of temperature

*Motivation*

n order to try the feasibility of stress freezing at a temperature lower than the current ›ractice but at the same time overcome some or all the drawbacks of the method of ;chwaighofer[2] it was thought necessary to collect data on the variation of Young's modulus .nd Poisson's ratio with temperature. The data collected would fix the temperature range at vhich stress freezing could be carried out. For the same material as used in the present set of xperiments, Chandrashekhara *et al*[17] have determined the Young's modulus and Poisson's atio at 25 and 120° C. The reported values are $2.0685 \times 10^6$ KPa (21092 kgf/cm$^2$) and 0.35 at .5° C, 12411 KPa (126.55 kgf/cm$^2$) and 0.45 at 120° C for Young's modulus and Poisson's atio respectively. CY230 resin was 100 parts by weight and HY951 hardener was 10 parts by veight.

The value of Young's modulus at room temperature was determined by measuring the eflection of the beam under four-point bending and the Poisson's ratio was calculated by ıeasuring the change in horizontal diameter of a disc compressed along its vertical diame- ɜr[18].

In the present investigation also the values of the Young's modulus and Poisson's ratio had ɔ be determined at different temperatures. In order to get a complete picture, the determina- .on of elastic constants was carried out over the range from room temperature to 160° C.

Young's modulus was determined using an annular ring of inner/outer diameter ratio of .8 and the Poisson's ratio was determined using a disc subjected to diametral compression s indicated by Durelli[18].

## . Experimental procedure

'oung's modulus was determined by conducting tests on annular rings of ID/OD ratio of .8 and of thickness 6 mm. With the value of the Young's modulus thus obtained, tests onducted on circular discs subjected to diametral compression enabled the determination f the Poisson's ratio. The mesurements and the methods of calculation were as suggested by ›urelli *et al*[18,19]. The loaded specimen was kept in the oven and the oven temperature was set › any desired value using the temperature-controller unit. The diameters of the specimen 'ere determined using INCO Micrometer slide comparator to which a telescope was fitted. he traversing facility provided in the set-up enabled the readings to be taken to an accuracy ' 0.001 mm. Thus it was possible to make the measurements on-line.

## 8. Results and conclusions

The values of Young's modulus and Poisson's ratio as a function of temperature for the particular material mentioned earlier are plotted in fig.1.

An examination of fig.1 reveals that

a) in the neighbourhood of 35°C there is a steep fall in the Young's modulus which could be called the transition region. After about 65°C the Young's modulus reaches quite a low value of 300 kgf/cm$^2$ and attains an absolute minimum of 60 kgf/cm$^2$ around 120°C.

b) the Poisson's ratio, starting from a value of 0.35 at room temperature, shows a steep rise around 50°C and levels off close to 0.5 around 90°C.

c) Schwaighofer's method is in a domain limited by the glass transition state which for the present material appears to be in the neighbourhood of 35°C.

d) Although the Young's modulus is quite low, at about 65°C, the Poisson's ratio is around 0.42.

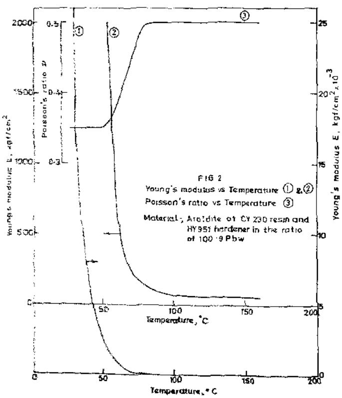



FIG. 1. Young's Modulus vs Temperature (1) & (2) Poisson's ratio vs Temperature (3).
Materials: Araldite of CY230 resin and HY951 hardener in the ratio of 100:9 Pbw.

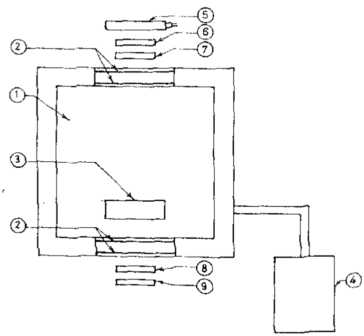


FIG. 2. Schematic diagram of the set-up.

(1) Oven (2) Glass panes (3) Loading frame (4) Temperature programme controller (5) Sodium monochromatic light source (6) Polarizer (7) 1st λ/4 plate (8) 2nd λ/4 plate (9) Analyzer.

## 9. Experimental work on stress freezing

Based on the conclusions form the first part of the investigation the temperature for stress freezing was fixed around 65° C.

The test specimens were circular discs of 40 mm diameter and 6 mm thick. The specimens were made from hot-casting Araldite CY230 resin and phthalic anhydride HT901 in the proportion 100:45 by weight and cold-casting Araldite CY230 resin and HY951 hardener in the proportion 100:9 by weight. After the machining operations the specimens were subjected to an annealing cycle to remove the residual stresses due to machining. The dimensions of the discs were recorded before the experiments. The discs were subjected to diametral compression in a loading fixture.

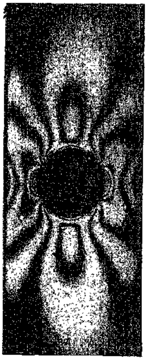
The disc was subjected to diametral compression so as to develop about four fringes for ease of counting (fig. 2). The exact value was determined by the Tardy's method. The specimen was allowed to soak at 65° C for 2 hours and cooled to the room temperature with the load on.

The stress-frozen disc, observed periodically for over 2 months, gave no evidence whatsoever of the decrease in the fringe order. Having established the feasibility of low-temperature freezing the method was extended to stress freezing of loaded tensile strips with central circular hole and an elliptical cut-out. The fringe patterns are shown in figs. 3 and 4. Figure 4 shows the fringe patterns of identical annular rings subjected to identical diametral loads stress frozen at 65 and 120° C. Though the temperature range of interest for this model material was 60-70° C, experiments were conducted all the way up to 160° C for the sake of completeness.

## 10. Other experiments

With the predetermined load imposed on the disc the temperature was increased to 65° C. The disc was allowed to soak for about 4 to 5 hours and at intervals of every half an hour the fringe order at the centre of the disc was determined including a fraction of the order by Tardy's method. If the fringe order had stabilised the disc was cooled to the room temperature by shutting off the oven. At room temperature the fringe order was once again determined. This procedure was repeated for several discs and temperatures of 50, 70, 90, 120 and 140°C were employed. The discs were preserved for a period of two months and periodically checked for the fringe order.

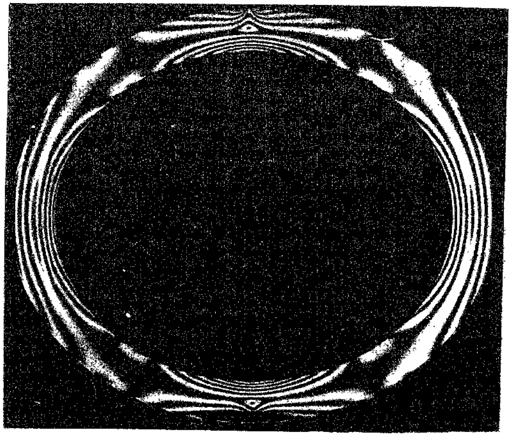
From the earlier experiments it is very clear that it is possible to stress freeze the deformation at a temperature in the neighbourhood of 65° C. It was of interest to determine whether it was possible to anneal or stress relieve also at the same temperature. For this experiment a stress-frozen disc was kept in the oven without any load. The oven temperature which was raised to around 65° C and held for about two hours was brought down to room temperature. On examination in the polariscope it was observed that the specimen was completely annealed. This was repeated several times to confirm the findings and observation. The tests, repeated on hot-cast discs, yielded almost similar results.



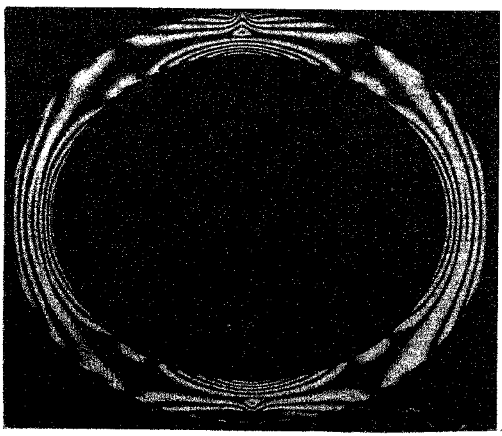
(a)

(b)

FIG. 3. Loaded tensile strips frozen around 65° C.



(a)



(b)

FIG. 4. Identical annular rings subjected to the same diametral load. Stress frozen (a) at 65° C, and (b) 120° C.

As the temperature of the oven was raised beyond 120° C it was observed that the fringe order at the centre of the disc decreased indicating an increase in the material fringe value. But as the specimen temperature was brought back to the room temperature the fringe value increased and maintained a value that was observed when the disc temperature was between 65 and 120° C. The following experiments were carried out. The oven in which the diametrally-loaded disc was kept was raised to 160° C and the disc was allowed to soak at this temperature till the fringe pattern stabilised. The fringe order at the disc centre was accurately determined using Tardy's method. The loaded disc was brought back to room temperature and the fringe order was again determined. Such experiments were conducted at several temperatures (140°, 120° C, etc.) up to 60° C. It was observed that between 60 and 120° C, the fringe order at the disc centre was more or less the same either at the higher or at the room temperature with pattern frozen.

## 11. Test results

The experimental results of the material fringe value/order against temperature are plotted in fig. 5.

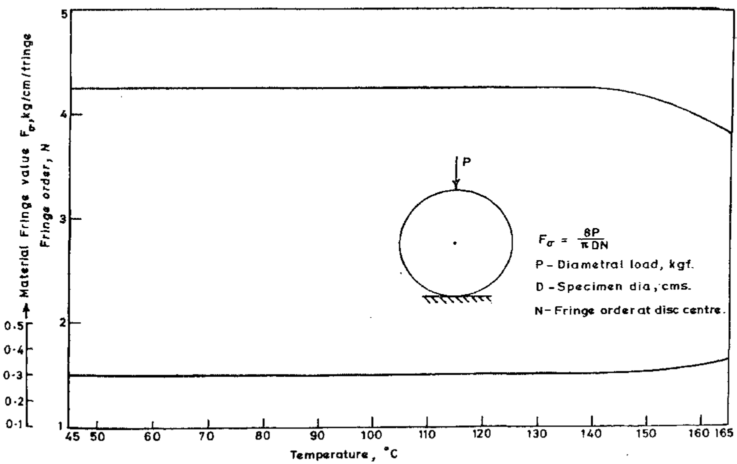



FIG. 5. Variation of material fringe value/fringe order with temperature.

The material fringe value is calculated by the well-known formula[12] for a disc subjected to diametral compression

$$f_\sigma = 8P/\pi DN$$

where

$P$ = load in kgf applied diametrally
$D$ = specimen dia, cm
$N$ = fringe order at the centre of the disc
$f_\sigma$ = material fringe value kgf/cm/fringe.

## 12. Conclusions

1. From the above investigation it appears to be reasonable and convincing to collect data on the elastic constants and the variation with temperature of the photoelastic material to be used in any problem to decide on the temperature for stress freezing.

2. There does exist a critical or a transition temperature which in the case of Araldite CY 230 resin HY951 hardener or CY230 resin and HT901 is much below the temperature for stress freezing employed in many institutions using the same combinations of resin and hardener. From the investigations carried out it has been found that temperature as low as 60 to 70°C is quite sufficient either to stress freeze or to anneal. However, the duration of soaking is dependent on the bulk of the model and also the maximum section thicknesses.

3. Since the maximum temperature of operation is now less than 70° C the cooling process can be hastened. If the bulk of the model and the maximum section thickness are not large the oven could be shut-off without any damage to the model. Against the existing practice of 40-50 hours for one stress-freezing cycle, the duration could be reduced to about 10 hours by employing lower temperatures.

4. As the ruling temperatures are quite low, the deformations, especially under contact load, due to creep, are kept down.

5. For small bulk and small sections, ovens with sophisticated programmable temperature controls may not be necessary.

## References

1. Durelli, A.J. — Complete experimental solution of 3-dimensional elastic problems, *J. Strain Anal.*, 1975, **10**(1), 42-52.

2. Schwaighofer, J. — Extended frozen stress method, *J. Engng. Mech. Div., Proc. Am. Soc. Civ. Engr.*, 1962, **86**, (EM-6), 1-12.

3. Durelli, A.J. and Lake, R.L. — Some unorthodox procedures in photoelasticity, *Proc. SESA*, 1951, 9(1), 97-122.

4. Durelli, A.J. and Riley, W.F. — Use of creep to determine the sum of the principal stresses in two-dimensional problems, *Proc. SESA*, 1957, **14**(2), 109-116.

5. TAKAHASHI, S. A survey of recent experimental mechanics in Japan, Proceedings of the 1982 joint conference on experimental mechanics, SESA, Oahu-Maui, Hawaii, May 23-28, Part I, Sessions 1-28, pp 1-6.

6. MIYAZONO, S. Some applications of fixation of photoelastic fringe patterns by gamma rays, *Expl. Mech.*, 1969, **9**, 473-477.

7. MIYAZONO, S. Fixation of photoelastic fringe patterns by gamma rays, *J. Appl. Phy.*, 1967, **38**(5), 2319-2323.

8. DURELLI, A.J. Complete experimental solution of three-dimensional elastic problems, *J. Strain Anal.*, 1975, **10**(1), 42-52.

9. THEOCARIS, P.S. Discussion on paper 'extended frozen stress method' by Schwaighofer (ref. 2), *J. Engng. Mech. Div. Proc. Am. Soc. Civ. Engr.*, 1963, **89** (EM-4), 73-77.

10. KUSKE, A. Multiphase theory of plastics, *Expl. Mech.*, 1962, 278-280.

11. FROCHT, M.M. *Photoelasticity*, 1941, No. 1, Ch. 10, pp. 339-341, John Wiley & Sons, New York.

12. DALLY, J.W. AND RILEY, W.F. *Experimental stress analysis*, 1978, Second Edition, Ch. 15, pp. 490-531, McGraw-Hill Book Company, New York.

13. ARADHYA, K.S.S. Applications of scattered light photoelasticity to study the influence of elastic constants in fracture mechanics and contact stress problems, Ph.D. Thesis, Indian Institute of Science, Bangalore, India, 1984.

14. GODBOLE, P.B. Integrated retardation method for a thermal stress problem and a new scattered light method for three-dimensional photoelasticity, Ph.D. thesis, Indian Institute of Science, Bangalore, India, 1979.

15. PATIL, V.S. A photoelastic stress analysis at the fixation of bowl-mill shaft, M.E. dissertation, Indian Institute of Science, Bangalore, India, 1985.

16. BHAVE, S.K. Personal communication.

17. CHANDRASHEKHARA, K., ABRAHAM JACOB, K., AND PRABHAKARAN, R. Towards stress freezing in birefringent orthotropic composite models, *Expl. Mech.*, 1977, **17**, 317-320.

18. DURELLI, A.J. AND FERRER, L. New method to determine elastic constants, *Mater. Res. Stand.*, 1963, **4**, 988-991.

19. DURELLI, A.J. Complete experimental solution of three-dimensional elastic problems, *J. Strain Anal.*, 1975, **10**(1), 45-52.