Solid Inclusion Stress Gage in Composite Propellant Charges

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The behavior of an inclusion in a material subjected to a stress system primarily depends on the ratio of the tangent moduli. The stress gage is an inclusion which gives an identifiable photoelastic fringe pattern which can be related to the biaxial stresses in its diametral plane—independent of host modulus when the moduli ratio is greater than 300. The study carried out to verify the use of such a gage in composite propellants is discussed. It shows the gage to be a solid inclusion, and also with a response virtually independent of Poisson's ratio. The gage is a hollow cylinder of epoxy resin whose o.d. is five times the internal diameter, and it was used in unfilled and highly filled CTPB. The principal stresses in the diametral plane of the gage are calculated from readings at 3 discrete positions in the gage. The sensitivity has been derived experimentally and theoretically. Gages were positioned from the mandrel and through the case at different depths in small solid propellant motors which had various conduit diameters and end closure shapes. The thermal stress distribution during temperature changes between −30°C and +60° were studied. After each temperature change, a gage was monitored at constant temperature to study stress relaxation.

I. Introduction

THE measurement of strain in nonlinear viscoelastic materials such as solid propellant is not easy. The conversion of measured strain into stress values is difficult, therefore it is desirable to measure stress directly. Various methods have been used to measure the stress in solid propellant motors, and the results have been reported.[1,2] The reported results are encouraging, and the work is continuing with more unusual techniques.[3]

Any transducer in a stress and displacement field will, in principle, disturb the very field that is to be measured. The calibration of such a transducer is required to determine the relationship between the output and the stress that would exist in the propellant if the transducer was not there. These problems of the inclusion effect and uncertainty in calibration are related and give rise to many practical difficulties.[4] To measure the stress, a transducer must be used which responds to stress independent of strain and produces a measurable output. Ideally, it must not itself deform or distort the local stress field.

A practical stress measuring transducer which approximates to these conditions is the high modulus inclusion gage. Hawkes[5] and Hiramatsu[6] have developed the glass inclusion gage to measure stress directly in rocket and concrete. It is being used successfully in viscoelastic materials such as rock salt and frozen ground.[7,8]

Glass is not suitable for measuring the comparatively low stress levels in propellant because of its low optical sensitivity. This paper describes a feasibility study carried out at the Rocket Propulsion Establishment with a more sensitive gage which can be used to measure stress independently of strain in low modulus materials such as composite propellant. The results from tests using these gages in small rocket motors are also described with particular emphasis on the stress relaxation during storage at various temperatures. The measured values of propellant stress relaxation times are also given.

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II. Theoretical Considerations

The stress distribution in an elastic inclusion depends on its geometry, the moduli and Poisson rates of inclusion and host materials, and the applied stress field. The effect of the moduli ratio on the stress at a position in an inclusion is determined from Hiramatsu's[6] theory and is shown in Fig. 1. The inclusion is perfectly rigid if the stress in the inclusion is independent of the host material modulus. This is the case for moduli ratios greater than 300. The other extreme of the curve shows the behavior of a perfectly soft inclusion. The stress distribution in a perfectly rigid inclusion varies only with biaxiality of the applied stress field and Poisson's ratio of the

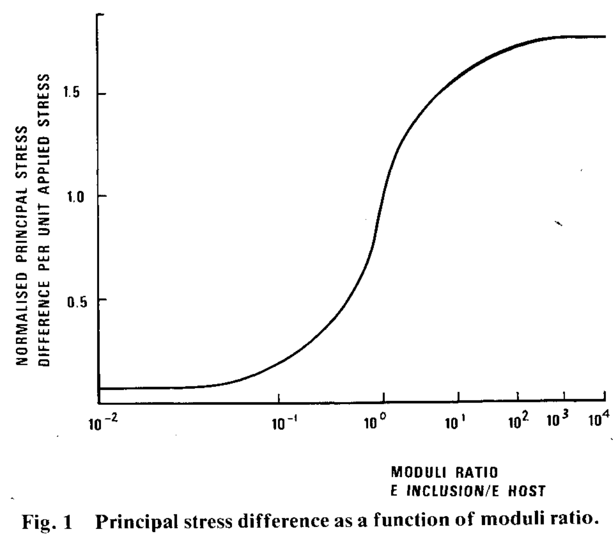

Fig. 1 Principal stress difference as a function of moduli ratio.

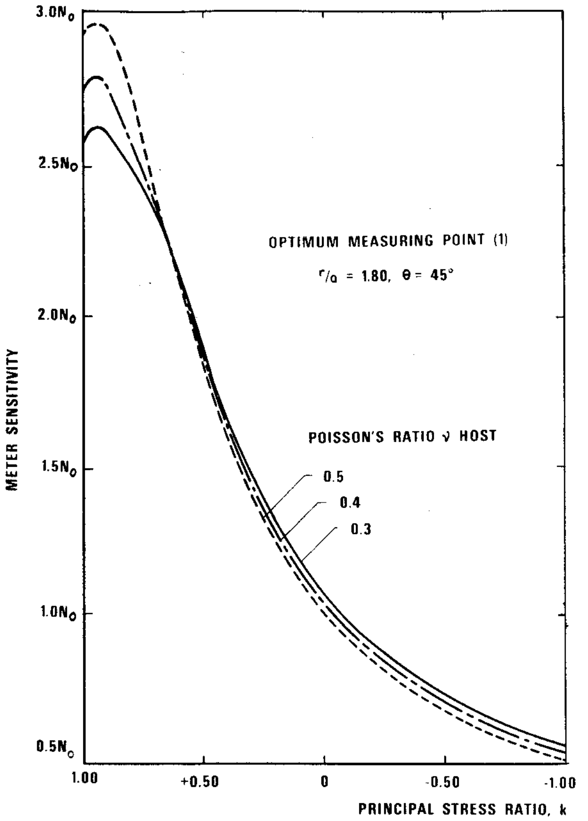

Fig. 2 Variation of meter sensitivity with Poisson's ratio of host material.

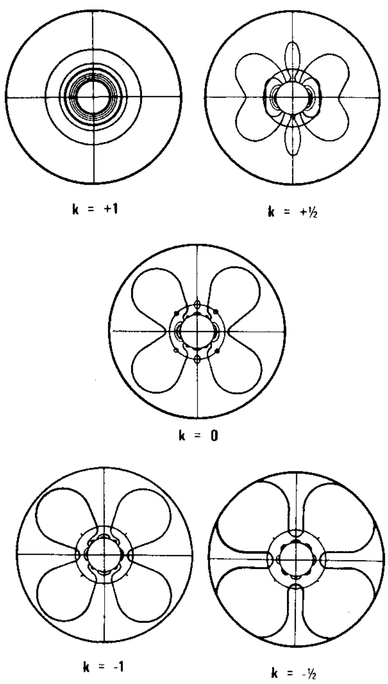

Fig. 3 Theoretical fringe patterns.

host material. The stress magnitude in the inclusion is directly proportional to the applied stress for a given ratio of applied stress.

For the range of temperatures and strain rates of practical interest, an inclusion gage of epoxy resin, modulus 3450 MPa, will give moduli ratios varying between 300 and 1300 in the propellant tested. In the annular photoelastic rigid inclusion gage, the central hole creates a stress concentration which produces identifiable fringe patterns when the host material is stressed. A diameter ratio of 5 is chosen so that the hole does not affect the stress distribution at the boundary of the gage.

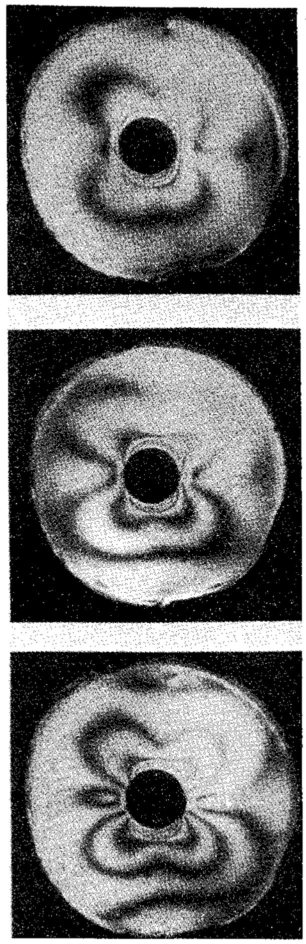

Fig. 4 Experimental fringe patterns.

The Poisson's ratio of the gage is 0.36 and that of the host is considered to be 0.5. The theoretical study indicates that even large changes in the value of Poisson's ratio of the host material does not significantly affect the gage response, see Fig. 2.

The principal stress difference in the inclusion is directly proportional to the fringe pattern produced; the proportionality constant is a function of the material stress optic coefficient and the length of the light path in the inclusion.

A numerical analysis of Hiramatsu's[6] theory gives theoretical fringe patterns for different applied stress ratios (Fig. 3). It is seen that the shape of the fringe pattern changes with biaxiality of the applied stresses and pattern recognition is an approximate method of determining the biaxiality. These shapes have been verified experimentally and a sequence of fringe patterns are shown in Fig. 4. The direction of the principal applied stress is apparent from pattern symmetry.

The stress field is identified from point readings of fringe order taken at a selected radial distance, on the 0°, 45°, and 90° axes, called optimum measuring points (OMP). For a particular applied stress ratio the major principal stress is proportional to the fringe order at any position in the inclusion. If we use Tardy compensation to determine the fringe order, the sign of the major principal stress is also obtained. The applied stress ratio can be determined from known relationships which have been previously described.[9] This ratio k may also be estimated from pattern recognition.

As the applied stress ratio changes the principal stress difference per unit principal applied stress at the optimum measuring position varies. There is an increase in gage sensitivity as the ratio k varies from $+1.0$-- -1.0. This variation is known for the optimum measuring points at 45° and 90°. Gage sensitivity N in units of kPa/fringe is expressed as a factor of gage sensitivity N_o in a uniaxial stress field measured at the 45° OMP. The sensitivity is inversely proportional to the length of the light path in the gage. The theoretical response of the gage is to the ambient host stress and not the concentration around the gage, but the concentration could cause incipient failure in the propellant at an earlier stage than normal.

III. The Experimental Feasibility Study

A series of tests were conducted using a solid inclusion gage 5 mm diam and 16 mm long and made from "photoelastic" PLM-4 material. The purpose of the testing was as follows: 1) to confirm that the value of sensitivity of the gages obtained theoretically apply experimentally in both uniaxial and biaxial stress conditions; 2) to check that the response of the gage is independent of the modulus of the host material; and 3) to verify that the gage response is independent of any creep strains provided that the stress level does not change as a result of the creep.

The gages were cast or bonded into samples of carboxyl-terminated polybutadiene (CTPB) polymer and propellant filled with 84% by weight of solids. Uniaxial tensile samples were 200 mm long, 50 mm wide, and 16 mm thick. Biaxial samples were cruciform, with each arm of these dimensions. Several uniaxial specimens were tested by loading at a constant cross head speed on an Instron testing machine. The Instron was also used for holding other specimens either at a constant load or a constant strain. Further uniaxial samples and the biaxial samples were tested in a purpose built rig.[9]

A reading instrument was produced by modifying a Zeiss Epitechnoscope into a reflection polariscope. This was provided with polarizing filters to enable isoclinics or isochromatics to be observed and for using goniometric compensation. The lens system gives a high magnification and the incident and reflected beams are almost parallel. Front face reflection from the gage made readings difficult, and this was eliminated by angling this face 5°.

To measure the sensitivity factor of a gage, the following procedure was used. It was assumed that the theoretical information with respect to the relations between principal stress ratio, the 0°, 45°, and 90° reading ratios, and the variation in sensitivity with respect to stress ratio were true. Using theoretical values and the experimental readings, the equivalent uniaxial fringe order (EUFO) was determined. This is the fringe order which would be produced at the 45° OMP by the same major principal stress acting on a gage in a uniaxial stress field. The EUFO was plotted against stress change to determine the sensitivity N_o. In a biaxial stress field the minor EUFO should change proportionally to the major EUFO in the same ratio as the applied stresses.

To verify the claim that the modulus of the test material has no effect on the gage response, calibration tests were carried out in unfilled polymer and solid propellant at various temperatures. The majority of the calibration tests were conducted at 20°C. The results confirmed that the modulus of the host material did not affect the gage response, as can be seen from Fig. 5.

Uniaxial calibration samples were also held at constant load in the Instron testing machine. Readings of fringe value were taken as the sample deformed, and under these creep conditions, the fringe order remained constant. The loading rate was varied from sample to sample without any effect on the results. Readings were taken as both the stress and strain were separately held constant. For constant stress the creep strain did not affect the gage fringe reading. For constant strain, the stress relaxation caused an expected decrease in the gage fringe order. Some of the biaxial samples were loaded uniaxially to confirm that the stress distribution at the centre was not affected by the sample geometry. These tests served as additional confirmation of the uniaxial calibration and showed that the specimen shape was suitable.

The theoretical uniaxial calibration for a gage made from PLM-4 and of length 16 mm is 132 *kPa*/fringe. Results from uniaxial tests agreed very well with this theoretical value as

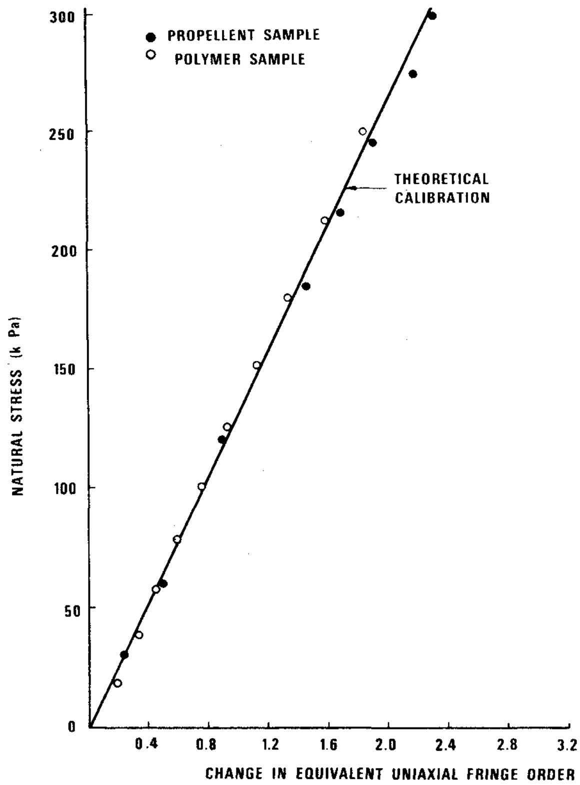

Fig. 5 Calibration graphs for uniaxial samples.

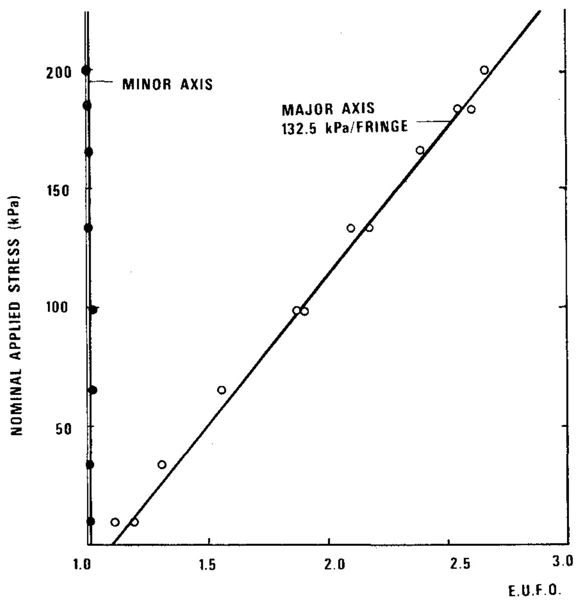

Fig. 6 Biaxial calibration related to major applied stress for $k = 0$.

can be seen from the example, Fig. 5. The results of the biaxial loading tests were also in agreement with the theoretical calibration. Figure 6 shows the response from a biaxial sample tested under uniaxial conditions of $k=0$. The corresponding plots for samples tested under applied stress ratios $k = ½$ and $k = 1.0$ are shown in Fig. 7 and Fig. 8, respectively. A histogram (Fig. 9) of sensitivity values derived from all the readings taken was developed. The mean sensitivity determined from the statistical analysis was 128.7 *kPa*/fringe. The standard deviation was 28 *kPa*/fringe, and this is largely due to erroneous readings of low-order fringe values and possible variations in the optical properties of the different batches of gage materials which was not measured. If only reading at stress levels of above 75 *kPa* are considered the mean becomes 133.9 *kPa*/fringe with a standard deviation of

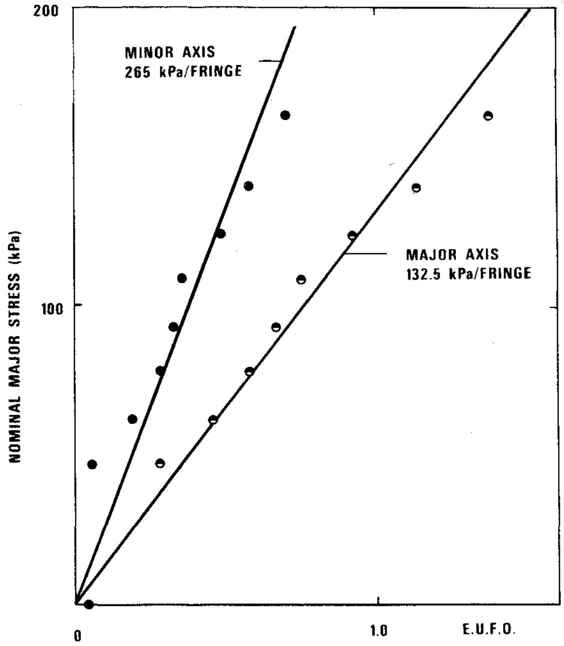

Fig. 7 Biaxial calibration related to major applied stress for $k = \frac{1}{2}$.

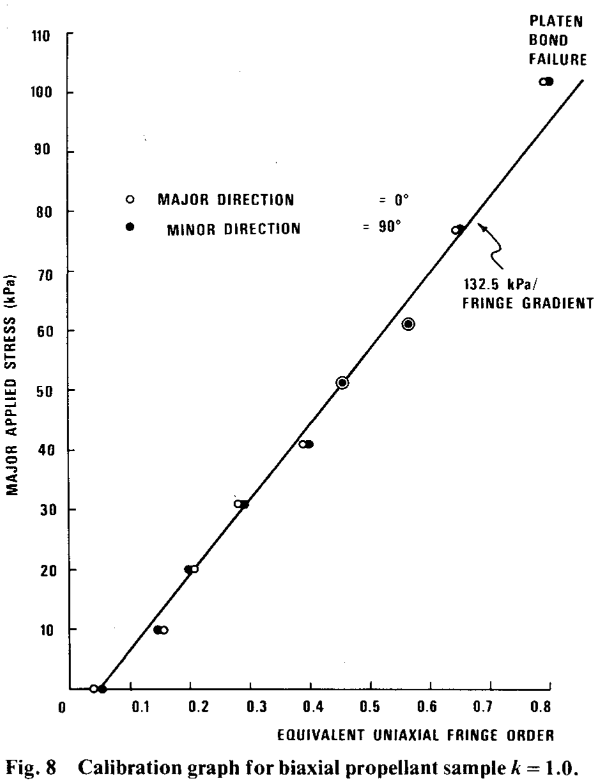

Fig. 8 Calibration graph for biaxial propellant sample $k = 1.0$.

19 *kPa*/fringe. This amount of variation is considered acceptable.

A few biaxial strip samples have been tested and the measured stress ratio was compared with the stress distribution predicted from sample dimensions.[10] The excellent agreement is shown in Fig. 10. Figure 11 shows the consistency of calibration at different temperatures.

IV. Discussion of Gage Properties

Stress is a mathematical concept which cannot be measured directly. The response of the high-modulus inclusion gage has, however, been shown both theoretically and experimentally to be dependent on changes in stress alone in the materials under consideration. By taking readings at the 0°, 45°, and 90° OMPs the sign and magnitude of the average

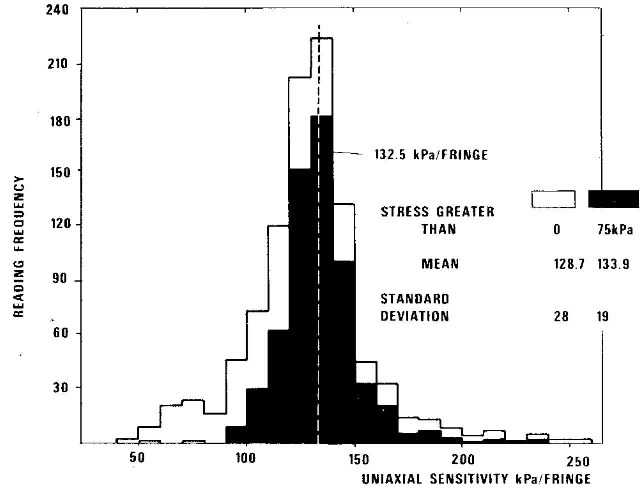

Fig. 9 Histogram of sensitivity values.

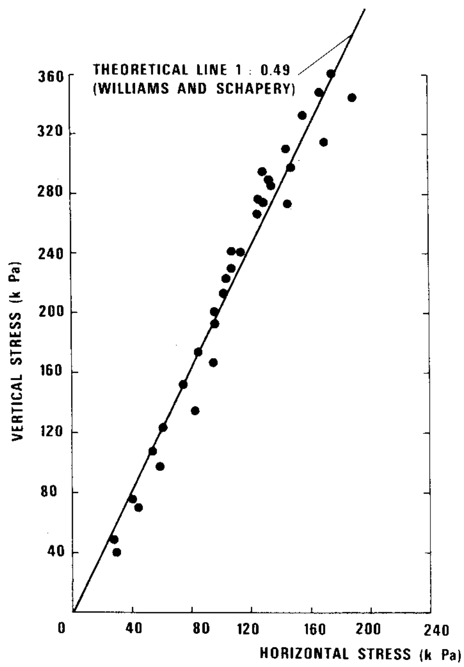

Fig. 10 Comparison of horizontal and vertical stress in strip biaxial samples.

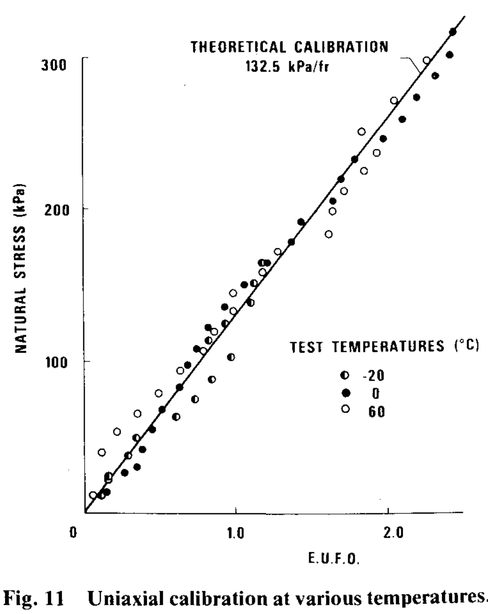

Fig. 11 Uniaxial calibration at various temperatures.

stress in the zone of influence of the gage and the biaxiality of the stress distribution can be derived. The pattern symmetry shows the direction of the secondary principal stress axes. The gage therefore can, be used to measure stress in samples of other geometry.

As with other stress indicating devices, the gage does not measure stress at a point, but within a zone of influence. As continuous recording is not available, although an automatic photocell output is theoretically possible, the technique is limited to situations in which stress is changing relatively slowly.

The importance of correctly aligning the polariscope and the manual operation of taking the readings means that remote operation of the technique is difficult if not impractical. This could limit to some extent the future application program. The sensitivity of the gage is independent of temperature within the temperature range in which propellant can be stored.

When the temperature in a motor with a stress gage changes, both the propellant and the gage will expand or contract. Because of the difference in thermal coefficients of expansion of the two materials a hydrostatic stress condition will occur in the vicinity of the gage. A further effect on changing temperature is that there will be a thermal gradient through the gage which will also produce a spurious birefringent pattern. Other work at present being carried out indicates a possible birefringent effect when moisture is absorbed by a super-dried gage. In the tests to be described, the samples had been dried previously for several days, and these effects may have been present during the tests.

Calculation of the net effect of the aforementioned parameters is difficult, if not impossible. A series of tests has therefore been carried out to determine the effect experimentally. A standard tensile test specimen with a gage centrally placed was suspended unloaded in a cooling cabinet. Readings of fringe order were taken as the sample was cooled, and various cooling rates were used.

Figure 12 shows the fringe change at different rates of cooling. For cooling slowly, there is no change in fringe order. At faster rates of cooling, a temperature is reached where there is a fringe order change, and the particular temperature at which this change starts is higher at a faster rate of cooling.

The effect due to the differential coefficient of expansion is to impose a compressive stress in the gage. Because of the viscoelastic nature of the propellant, this will relax. The relaxation will be more rapid at high temperatures than at low temperatures, and at slow cooling rates, the stress change will be negligible. At slow cooling rates, the other transient effects must be negligible or compensating; but a further study is being carried out to obtain a fuller understanding.

In the test motors presently used, the maximum rate of temperature change of propellant in the region of a gage is 1 °C in 150 sec. It follows from Fig. 12 that the temperature effect will be zero if the temperature is above −20°C. At cooling rates less than 1 °C in 200 sec, there is no temperature effect at all.

An advantage of this type of gage is its basic simplicity. It has no mechanical parts or connections which can fail during a test. The gages can be cast into position during manufacture of propellant, or bonded into holes formed or cut in the propellant. It is therefore considered that this type of gage is suitable for investigating the stresses in both propellant samples and filled rocket motors.

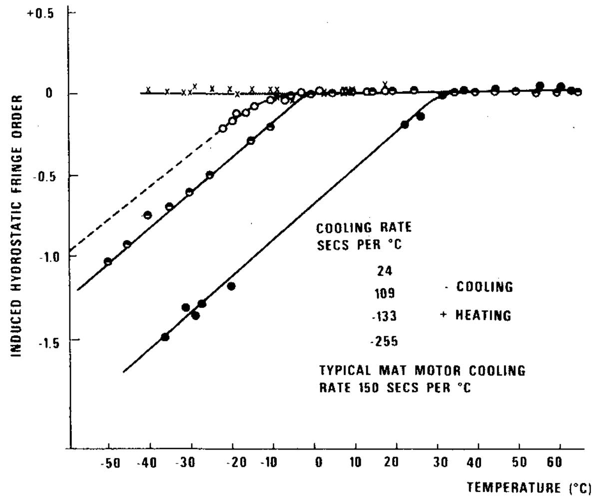

Fig. 12 Variation of induced fringe order with temperature and cooling rate.

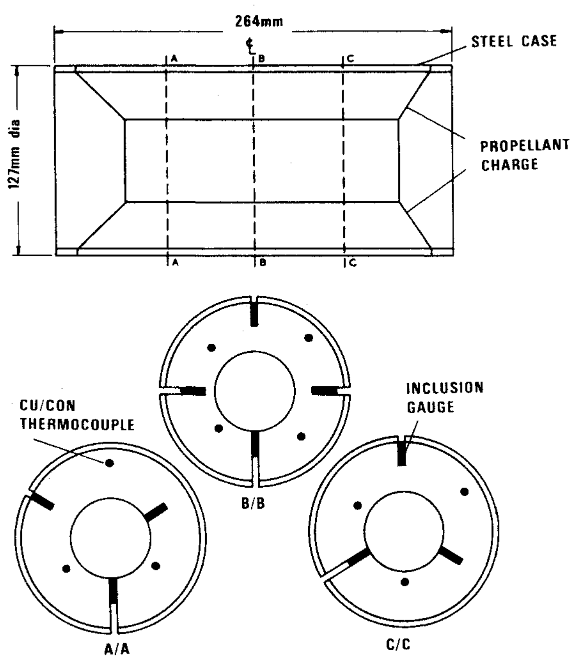

Fig. 13 Typical MAT motor gage layout.

V. Application in Structural Test Vehicles

A. Introduction

An existing small solid propellant motor 127 mm diam and 264 mm long has been adapted as a structural test vehicle, designated MAT (Motor Analogue Test). It can be cast with various diameter circular center conduits and shaped end closures and has been used to assess the gage performance under particular motor conditions.

Figure 13 shows the shape of the MAT with a typical gage layout. The gages were all cast into the MAT's, either from the center conduit or through the case. Other test vehicles had different-angled end closures and smaller center conduits.

To read the gages set from the conduit, a sighting tube attachment was fitted to the polariscope. A front surface mirror at the end of the tube enabled readings to be taken of gages set at right angles to the line of sight.

The motors were stored at various temperatures, and readings of the gages were taken as the temperature was increased or decreased. The readings indicate the stress distribution in the MAT created by the difference in the thermal coefficient of expansion of the steel case and the propellant. After a given temperature change, readings of the gages continued to be taken as the temperature remained constant, in order to assess the stress relaxation time.

This section deals with the results so far in a continuing series of tests. Definite conclusions cannot yet be drawn, but the consistency of the results is encouraging in respect to the gage response and some interesting information has been obtained.

B. Stress Distribution

When a solid propellant motor is cooled down, the

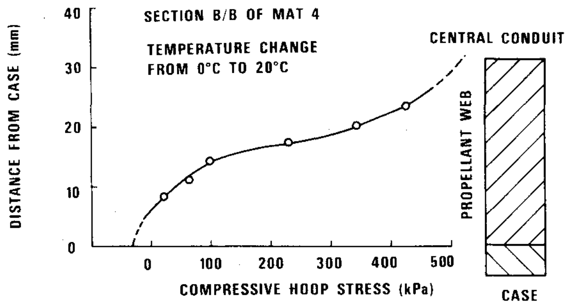

Fig. 14 Stress distribution across web.

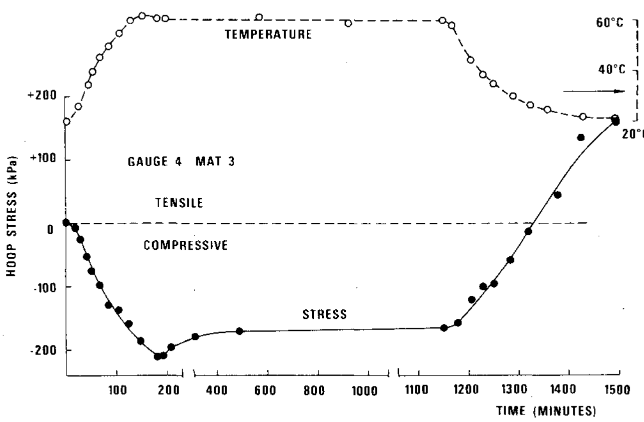

Fig. 15 Stress change on temperature cycle.

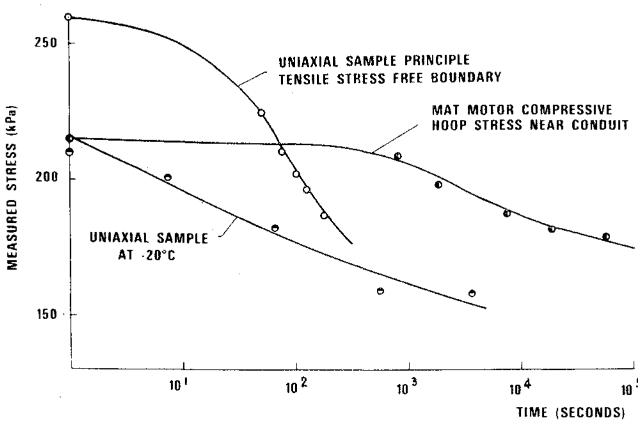

Fig. 16 Propellant stress relaxation at 60°C.

shrinkage of the propellant is greater than that of the steel case. The case, however, is stiffer than the propellant, and hence a tensile stress system is set up in the propellant. Conversely a compressive stress system is set up on heating the motor. The gages measure the average stress along their 15.8 mm length. It has been assumed in the following results that the average stress is the same as the stress at the center of the gage. To make more detailed and accurate studies where stress gradient occur, gages of different lengths will be needed. But the aforementioned assumption is acceptable at present because the primary object of the tests is to study the application of the gage. The gages measure both the hoop and the longitudinal stress and, although both values have been determined, only the hoop stress values have been studied at present.

Fig. 14 shows the stress redistribution in the center section of 'MAT 4 as the temperature was raised from 0°C to 20°C. MAT 4 has been stored at 0°C for 2 weeks before the test in order to reduce any relaxation of the tensile stress induced by cooling to a negligible value during the period of the test. The time taken to increase the temperature to 20°C was 5½ hr. The resultant compressive stresses are considerably higher near the conduit than near the case.

Figure 15 shows the stress variation at a gage as the temperature was increased from 20°C to 60°C, held at 60°C for 1000 min, and then reduced to 20°C again. The center line of the gage is 24 mm from the outside of the motor case and 8 mm from the conduit. As the temperature rises, the stress becomes more compressive, and a stress of just over 200 *kPa* was recorded at 60°C. While the temperature was held at 60°C the stress relaxed by 50 *kPa*. Reducing the temperature back to 20°C altered the stress by 320 *kPa* tensile. This is greater than the compressive stress induced by heating for two reasons. During the heating the induced stress is continuously relaxing, and as the propellant becomes hotter the relaxation rate increases, resulting in a lower stress change than for an elastic body. At the onset of cooling the compressive stress is still relaxaing, so increasing the tensile change in stress. This relaxation continues at a decreasing rate until zero stress is reached. After this point, the additional tensile stress induced starts to relax; but at lower temperatures, the rate of relaxation is less and a consequently higher tensile stress change is obtained.

C. Stress Relaxation

The viscoelastic nature of the propellant means that stress is relaxed in time. The rate of relaxation depends on the stress magnitude, the ambient temeprature, and the proximity of any restraints, such as the case. The photoelastic solid inclusion gage lends itself well to studying stress relaxation. Preliminary tests have been carried out both in uniaxial samples and in the simple motor. The tests are not sufficiently advanced to allow analysis of the results. Figure 16 however shows the results obtained from 3 tests.

The first test was carried out on a uniaxial tensile sample. This was loaded in an Instron testing machine at 60°C, and the strain level was held whilst the stress relaxed. The time taken for a relaxation of 15% of the original stress was 50 sec. The results from a similar test at −20°C are shown for comparison.

In the third test, a MAT motor was heated to 60°C, resulting in a compressive hoop stress as indicated by a gage set close to the conduit. The stress condition in the motor is biaxial and there is restraint to the relaxation afforded by the case, resulting in a slower stress relaxation. It may also be that compressive stress relaxes more slowly. The time taken for a relaxation of 15% of the original stress was 2×10^4 sec.

VI. Conclusions

The theoretical and experimental studies show that the gage has a suitable response for measuring stress in composite propellants. The response of the gage is independent of the modulus and viscoelastic behavior of the propellant.

Spurious effects can arise due to a temperature gradient in the gage produced by rapid heating and cooling. However, at rates of change of temperature less than 1°C per 200 sec, this effect is negligible. This rate is rarely exceeded in a motor under test conditions. The gage and readout instrumentation have been successfully applied for measuring stress distribution and relaxation in a structural test vehicle over a temperature range from +60°C-−20°C.

VIII. Future Program

The performance of the gage in HTPB and plastic propellants is to be assessed. A detailed investigation of the relaxation of thermally induced stress and the effect of bonded ends on the longitudinal distribution of hoop stress in structural test vehicles with conduits of various sizes has commenced. Work is planned to study the changes in stress in motors during storage and due to handling. The motors will be subjected to considerable changes in temperature. The stress distribution and stress concentration factors in motors containing star-shaped conduits have been determined by twodimensional photoelastic analysis. The magnitude of the stresses will be determined by using the solid inclusion gages in actual motors of the same design.

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