N71-37953

FINAL REPORT

NASA Grant NGR-43-003-007, Supplement 2

"Investigation of Stress Waves and Effects of Hypervelocity Impact"

Period of Grant: July 1, 1969 to November 30, 1970

DRA

Principal Investigator: Ray Kinslow, Chairman
Department of Engineering Science
Tennessee Technological University
Cookeville, Tennessee 38501

I. The major results of work accomplished under this grant are given in the following:

A. Reports that have been submitted and published as NASA Contractor Reports.

1. "Stress Waves in Multiple Laminates," R. Kinslow, March 1970, 53 pages. TTU-ES-70-1, N70-27950, NASA-CR-89880.

2. "A Dynamic Polariscope for Stress Wave Analysis," R. Kinslow, July 1970, 21 pages. TTU-ES-70-2, N71-11501, NASA-CR-108690.

3. "Stress Waves in Sandwich Plates," R. Kinslow and B. Delano, August 1970, 97 pages. TTU-ES-70-3, N71-11404, NASA-CR-108692.

Abstracts and notes concerning these are included in this report.

B. Reports that have been prepared but not submitted.

1. "A Photoelastic Investigation of Stress Wave Loading of a Crack," D. Smith, September 1970, 30 pages. TTU-ES-70-4.

2. "Dynamic Elasticity by the Theory of Characteristics," G. R. Buchanan, C-H. Phung, J-C. Huang, September 1970, 11 pages. TTU-ES-70-5.

Abstracts and notes concerning these are included in this report. Copies of the reports are also enclosed.

C. Report that is practically complete but not yet printed.

1. "Stress Wave Reflections from Intersecting Surfaces," R. Kinslow (approximately 75 pages).

An abstract is included in this report. Copies will be submitted when complete.

II. Publications, papers, and talks by the principal investigator related to this research but not supported by NASA under this grant.

A. "Properties of Reflected Stress Waves," AIAA Hypervelocity Impact Conference, Cincinnati, Ohio, 1969.

B. "Hypervelocity Impact," Graduate Mechanical Engineering Seminar, University of Florida, 1969.

C. "The Meteoroid Hazard to Space Travel," Tennessee Academy of Science, University of the South, 1969.

D. "High-Speed Impact." In <u>Encyclopaedic Dictionary of Physics</u>, Pergamon Press, 1969.

E. "High-Speed Impact Phenomena," (Editor). A book published by Academic Press, 1970.

F. "Experimental Methods in the Study of Stress Waves," ASME/SESA Conference on Experimental Mechanics, University of New Mexico, 1971.

III. Report on foreign travel supported by funds from this grant.

Permission was requested to present the report, "A Dynamic Polariscope for Stress Wave Analysis" (NASA-CR-108690, TTU-ES-70-2) at a meeting of Electro-Optics International at Brighton, England in March 1971. Permission to present the paper was granted and the use of travel funds from this grant was approved.

Attendees at the three-day conference (March 23, 24, 25) were from approximately twenty countries. The technical sessions consisted of sixty-seven papers presented by speakers from eleven countries. Fourteen of the speakers were from the United States. This paper was given in the session on "High Speed Recording of Dynamic Events." It was well received and was highly complimented by several of those in attendance. The entire program was very worthwhile.

Travel costs were as follows:

Within the U. S. $120.90 (paid by the university)

Outside the U. S. $412.59 (paid from NASA funds).

Respectfully submitted:

Ray Kinslow

Ray Kinslow, Principal Investigator

Date: July 13, 1971

Enclosures

Copy to: Mr. Burton G. Cour-Palais
NASA Manned Spacecraft Center
Houston, Texas 77058

The following abstract was published in SCIENTIFIC AND TECHNICAL AEROSPACE REPORTS, Vol. 8, No. 14, page 2680, July 23, 1970:

N70-27950 Tennessee Technological Univ., Cookeville. Dept. of Engineering Science.
STRESS WAVES IN MULTIPLE LAMINATES
Ray Kinslow Mar. 1970 53 p refs
(Grant NGR-43-003-009)
(NASA-CR-89880; TTU-ES-70-1) Avail: CFSTI CSCL20K

Fractures caused by stress waves resulting from high velocity impact are sometimes reduced and at other times are increased by the use of laminated materials. This is a theoretical study of the propagation and reflections of stress waves in laminated targets and an analysis of the effects of material properties, target geometry, and wave characteristics. The multiple reflections and transmitted components at the interfaces bounding each layer of material combine in phase so as to create stresses much greater than would have been produced in a homogeneous target.

A paper based on the preliminary results given in this report was presented at a meeting of the American Physical Society, University of Florida, November 1969.

The following abstract was published in SCIENTIFIC AND TECHNICAL AEROSPACE REPORTS, Vol. 9, No. 2, page 300, January 23, 1971:

N71-11404 Tennessee Technological Univ., Cookeville. Dept. of Engineering Science.
STRESS WAVES IN SANDWICH PLATES
Ray Kinslow and Brian Delano Aug. 1970 97 p refs
(Grant NGR-43-003-007)
(NASA-CR-108692; TTU-ES-70-3) Avail: NTIS CSCL20K

A mathematical stress wave model is formulated for use in predicting the effects of various material combinations and geometry in the design of sandwich plates that may be subjected to high velocity impact. In the experimental investigations the bounding layers were of a birefringent material and stresses were determined by means of a dynamic polariscope utilizing a high-speed framing camera. A comparison is made of the theoretical and experimental results.

A condensed version of this report was presented at a meeting of the Society for Experimental Stress Analysis, Boston, Mass., October 1970. This was published as SESA Paper No. 1653, copies of which are included with this report.

The following abstract was published in SCIENTIFIC AND TECHNICAL AEROSPACE REPORTS, Vol. 9, No. 2, page 224, January 23, 1971:

N71-11507 Tennessee Technological Univ., Cookeville. Dept. of Engineering Science.
A DYNAMIC POLARISCOPE FOR STRESS WAVE ANALYSIS
Ray Kinslow Jul. 1970 21 p refs
(Grant NGR-43-003-007)
(NASA-CR-108690; TTU-ES-70-2) Avail: NTIS CSCL20F

A polariscope for the study of the propagation of stress waves in birefringent sheets is described. Very sensitive, fast-responding photomultiplier tubes, a laser light source, and a multiple channel oscilloscope were used for the simultaneous recording of the stress-optic data at several points of the target following impact. A method of separation of stresses and the computation of displacement, strain, and stress is given.

This was presented at the Electro-Optics Systems Design Conference, New York, N. Y., September 1970 and published in the Proceedings of the conference. An invitation was received from Electro-Optics International to give this paper in Brighton, England, in March 1971. This was done and the report was published in the Proceedings of that conference. A copy is enclosed.

The following are abstracts of reports that have been completed but not previously submitted to NASA.

A Photoelastic Investigation of Stress Wave Loading of a Crack.* DALLAS G. SMITH, Tenn. Technological Univ., TTU-ES-70-4 -- Using a photoelastic technique the dynamic stress-intensity factor for the wave loading of a crack is investigated, and the dynamic polariscope is described. Five different crack lengths were considered and the pulse length was approximately constant. The dilatational wave impinged normal to the crack and the form of the incident wave was determined. The time response of the stress-intensity factor is shown for each crack length and the effect of the crack length to pulse length ratio on the maximum stress intensity is presented.

This was presented at a meeting of the Society of Experimental Stress Analysis, Salt Lake City, Utah, May 1971.

Dynamic Elasticity by the Theory of Characteristics.* GEORGE R. BUCHANAN, CHI-HUONG PHUNG, and JU-CHIN HUANG, Tenn. Technological Univ., TTU-ES-70-5 -- A characteristic analysis is presented for the equations of elasticity in Cartesian coordinates. The characteristic slope equations are derived, and it is verified that two types of waves exist. The compatibility equations are developed in relation to the direction cosines of a spherical coordinate system. A brief discussion of the method of analysis is included.

*Work supported by the National Aeronautics and Space Administration grant NGR-43-003-007.

Copies of these are included in this report.

The following abstract was published in the November 1970 issue of the BULLETIN OF THE AMERICAN PHYSICAL SOCIETY. The paper was presented on November 24 at a meeting of the American Physical Society, New Orleans, Louisiana.

Stress Wave Reflections from Intersecting Surfaces.* RAY KINSLOW, Tenn. Technological University -- Meteoroids and man-made projectiles pose potential hazards to spacecraft. Although actual puncture of the structure may not occur, reflections of tensile stress waves from free surfaces may produce damage by spallation or internal cracks. This paper presents a study of the reflection of stress waves from plane surfaces, including simultaneous reflections from intersecting planes such as occur at corners, notches, or grooves. A pressurized cavity is employed as the source of the disturbance. Reflected waves are created in "image cavities." Stress-time variations at points within the solid are determined by pressures simulating the conditions of hypervelocity impact. Results are compared with experimental observations.

*Work supported by the National Aeronautics and Space Administration grant NGR-43-003-007.

Most of the analytical and experimental studies, as well as drawings and photographs, have been completed for a NASA report. This will be finished and submitted as soon as time and funds are available.

PROCEEDINGS

of the

TECHNICAL PROGRAMME

ELECTRO-OPTICS '71
INTERNATIONAL CONFERENCE

BRIGHTON, ENGLAND 23, 24, 25, MARCH, 1971

A DYNAMIC POLARISCOPE FOR STRESS WAVE ANALYSIS

by

Ray Kinslow
Tennessee Technological University, Department of Engineering Science
Cookeville, Tennessee

Introduction

Dynamic photoelasticity has been found to be an extremely useful tool for the study of stress wave propagation. Various experimental methods have been developed to record the photoelastic fringes resulting from impact or explosions. The use of the drum camera was introduced in 1936, followed by the microflash in 1946, the multiple spark camera in 1955, and the Q-spoiled ruby laser as a light source in 1966. High speed framing cameras and image converter cameras have been employed by many investigators.

One frame of a series of photographs made with a framing camera is shown in Fig. 1. As the sheet of birefringent material was in a light-field polariscope, the half-order fringes are shown. From such photographs, the fringe order can be plotted as a function of position and the wave characteristics can be determined. If a narrow beam of monochromatic light passing through a point of such a model is monitored by a fast responding light sensor, an oscilloscope record of the time-dependent fringes can be obtained. Clark[1] was apparently the first to report the recording of propagating stress fringes by this method. The work of other investigators using this method of studying stress waves is given in references 2 - 7.

A low-power helium-neon gas laser is an ideal light source, as it provides a very narrow beam of

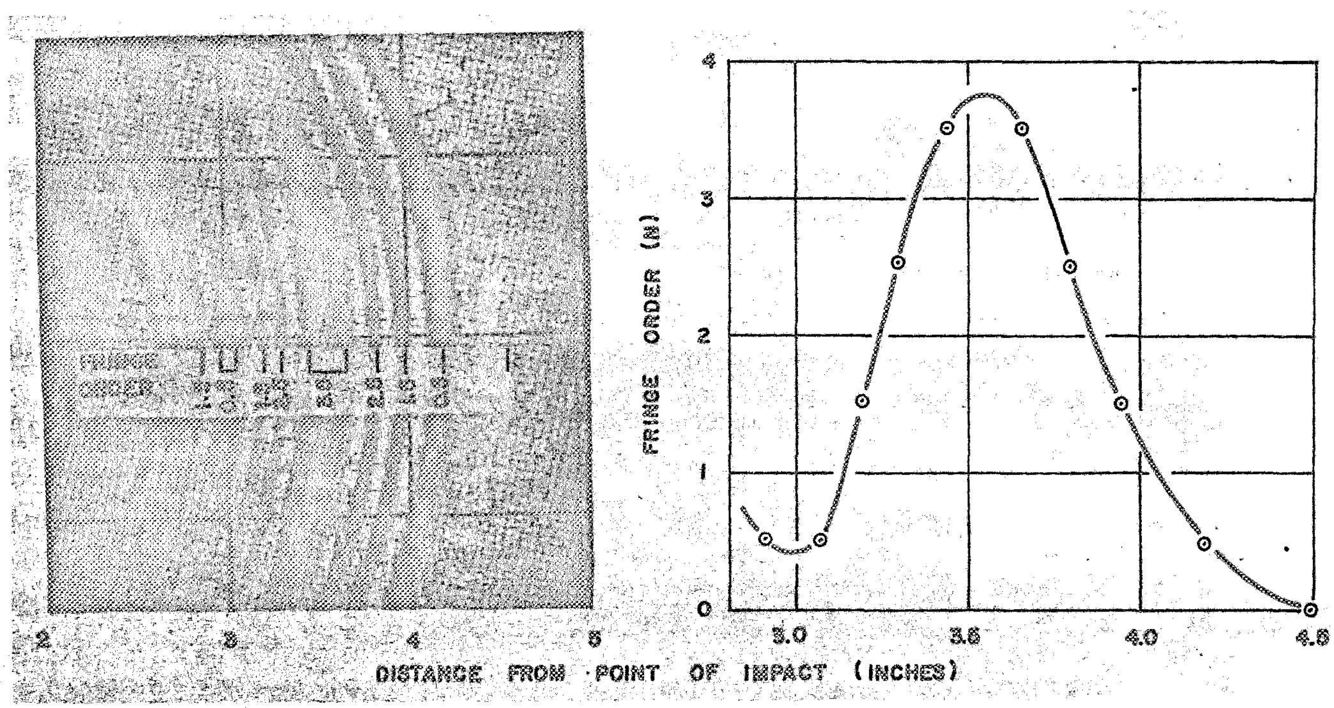
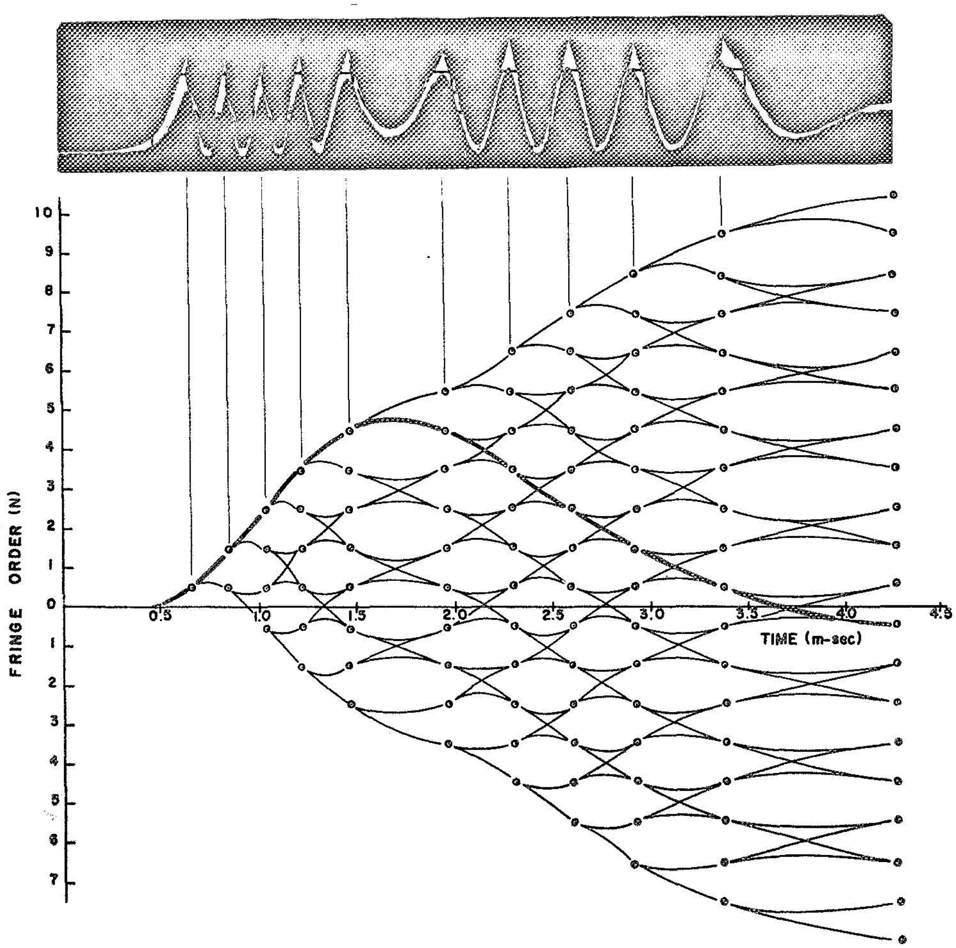


Fig. 1. Fringe order versus position as determined from photograph.

monochromatic (6328 A) light. The light sensor usually employed is a photomultiplier tube that, when connected to a high-frequency oscilloscope, makes an excellent fringe counting system. The cost of such a system is much less than the cost of a high-speed camera and intense light source. There is, however, one great disadvantage to such a system. The optical output is nondiscriminating. Not only are the fringe values absolute, detecting no changes in the sign of the stress, but one cannot be certain of the fringe order by simply counting the peaks on the oscillogram, as there is no direct way of determining whether the fringe order is increasing, decreasing, or remaining constant. This limitation is illustrated in Fig. 2. A photomultiplier response is shown at the top of the figure. The first peak gives the time of the first half-order fringe (N = 0.5) and, as this is a pressure wave, it is known to represent compression. It is assumed that the next peak represents a fringe order of three-halves (N = 1.5), but there is a possibility that it may have a value of one-half also.

As we progress across the record, it is seen that there are more than a thousand possible curves (1024 to be exact), only one of which represents the correct fringe order as a function of time. Many of the possibilities may be eliminated by simply saying that they do not look like stress waves. But are we ever sure? One would expect the two peaks representing the maximum fringe order to be spaced either closer together or farther apart than the adjacent ones. On this basis, it is believed that the fifth and sixth peaks on the oscillogram indicate the times of the maximum fringe order of nine halves (N = 4.5), and the curve drawn with the heavier line is the correct one. This clue, however, may not always be present.

Investigators using the laser-photomultiplier system generally employ some other means to verify and supplement the data. Okada, Cunningham, and Goldsmith[4] did this by taking fringe photographs.



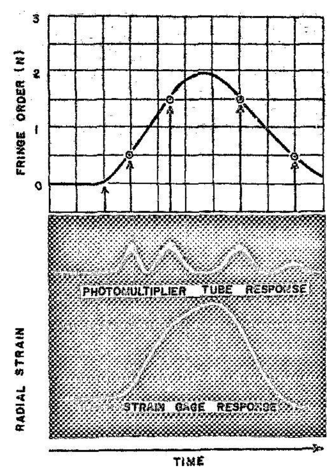


Fig. 3. Comparison of photomultiplier tube and strain gage response.

Fig. 2. Possible stress waves obtained from photomultiplier tube response.

They also fastened strain gages to the surface of the model near the point being monitored and recorded the strain gage data simultaneously with the photomultiplier output. Cunningham, Brown and Griffin[6] and Bradley and Kobayashi[7] also used strain gages to supplement their data. Such a simultaneous record is shown in Fig. 3. The strain gage response shows the approximate location of the maximum stress so that an accurate fringe order curve can be drawn by simply projecting from the oscillograph. Bohler and Shumann[8] used the oblique incidence method to separate the principal stresses.

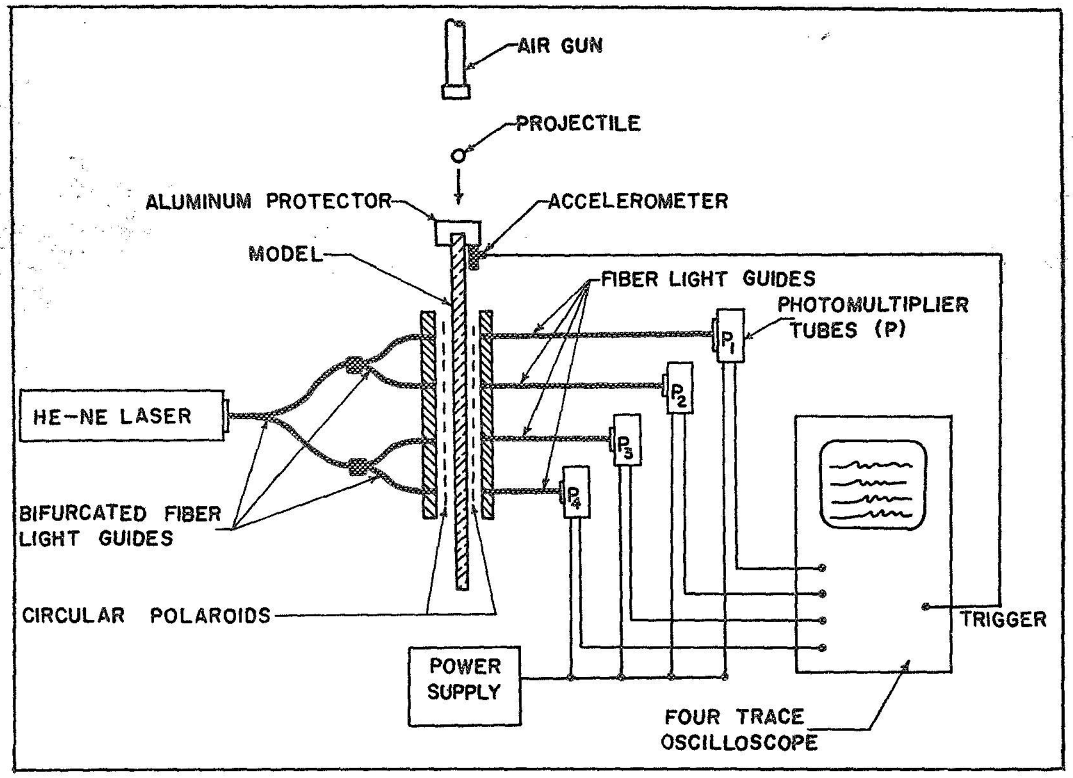


Fig. 4. Dynamic polariscope.

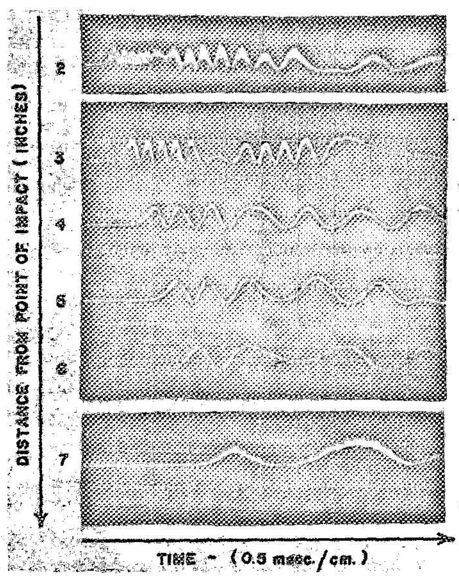


Fig. 5. Photomultiplier tube response at various distances from point of impact.

Experimental Methods and Apparatus

The target, a 12 x 12 inch sheet of 0.25 inch Hysol 4485, was placed between two sheets of circularly polarizing filters, as shown in Fig. 4. A 4-milliwatt helium-neon continuous gas laser served as the monochromatic light source. The light was directed to four points on the target, located one inch apart, by means of three bifurcated fiber light guides as shown. The light was collimated into beams 0.070 inch in diameter. The four points were in a line perpendicular to the target edge and in line with the projectile path. After passing through the target, the light was directed by fiber light guides to four photomultiplier tubes (RCA 931A), the outputs of which were connected to a Tektronix Type 3A74 four-trace amplifier plug-in Type 564 storage oscilloscope. To avoid damage to the target and to reduce the contact time of the projectile, a metallic protector was attached to the target with a thin film of wax. A miniature accelerometer of the piezoelectric compression type was attached to the protector to serve as the oscilloscope sweep trigger. Stress waves were generated by impacting the metal protector with 0.22 caliber lead pellets fired from a compressed air gun.

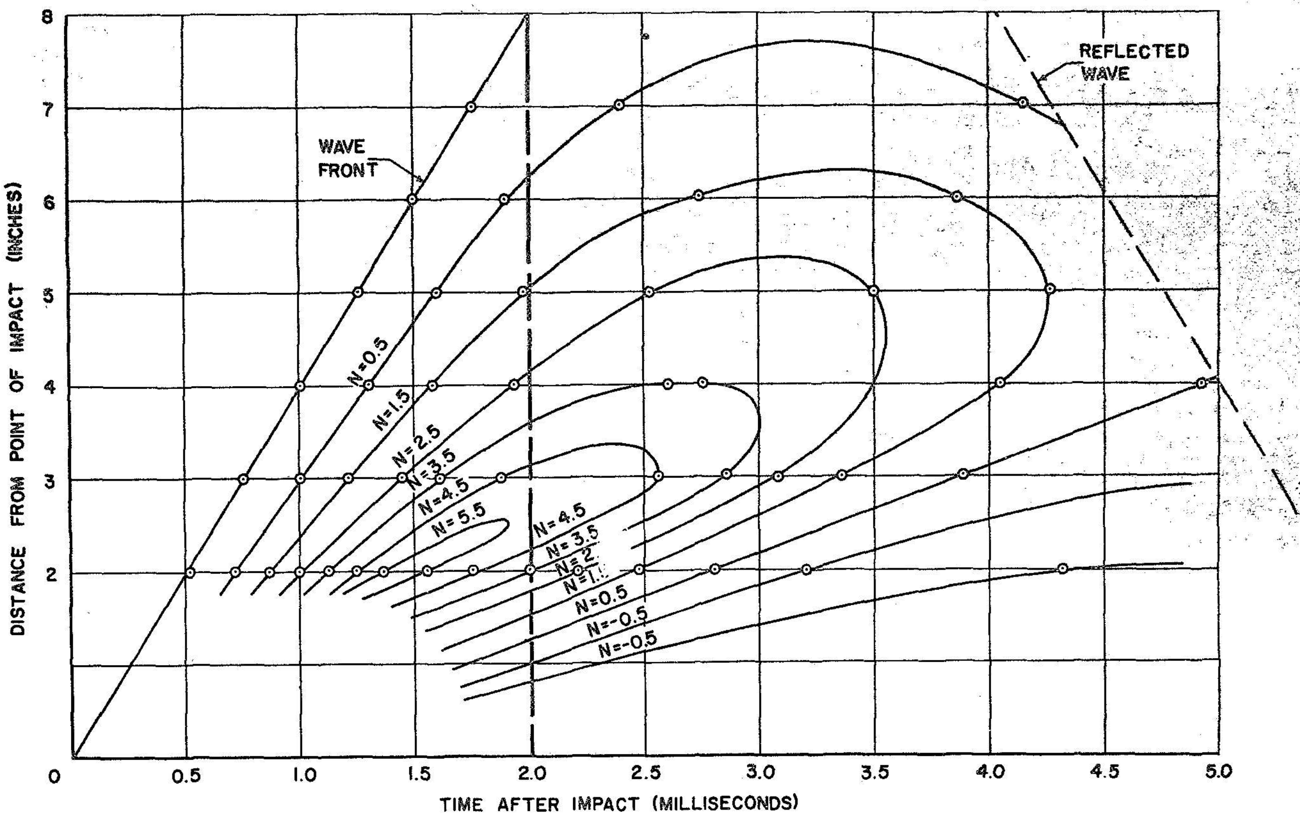


Fig. 6. Fringe-distance-time relation.

Records of the light retardations caused by the photoelastic stress fringes as detected by the photomultiplier tubes are shown in Fig. 5. Those four points located at distances of 3, 4, 5, and 6 inches from the point of impact were recorded by the four-trace amplifier. The ones at 2 and 7 inches were made by shifting the model to two other positions and repeating the shots. Excellent records could be obtained by monitoring the stress wave at eight points and recording the response of eight photomultiplier tubes on two four-channel oscilloscopes. If this were done, it would be possible to use a slower sweep for the more distant points and a faster sweep for the points near the impact in order to more accurately count and locate the various fringes. For example, if a point was located closer than two inches to the impact, a faster sweep would be necessary to distinguish the first fringes and to determine their times accurately. Likewise, if points were located farther than seven inches, it would be necessary to use a slower sweep in order to obtain information on more than one or two fringes.

Analysis of Data

It has been pointed out that one would expect the two peaks of the oscillogram that represent the maximum (or minimum) fringe order to be spaced either closer together or farther apart than the adjacent ones. In Fig. 5, it is obvious that the maximum fringe order is 4.5 at a distance of three inches from the point of impact, and at a distance of six inches, the maximum fringe order is 1.5. One would strongly suspect the maximum to be 5.5 at a distance of two inches and 2.5 at five inches. In a group of four oscillograms, there will probably be at least two or three that give this information. This can be confirmed by realzing that the peak of the stress wave moves at a velocity approximately equal to that of the fringes. By employing this fringe counting technique, additional compensating schemes are unnecessary.

By carefully determining the time of each fringe from the oscillograms of Fig. 5, the distance-time curve for each fringe can be plotted as shown in Fig. 6. If any errors were made in the fringe number, they will be detected when these curves are drawn. As the sheet of Hysol used for the target was twelve inches deep, the wave was reflected from the rear surface as shown. No points were plotted in the region of interaction of the reflected tensile wave with the pressure wave.

An analysis of the stress wave will be made for the time of two milliseconds. The intercepts of the several curves with the two millisecond line are carefully measured or projected, as shown in Fig. 7, to give the fringe order (N) as a function of position. This curve also represents the shear stress (τ), as the stress-optic relation is $\tau = \frac{Nf}{2h}$, where f is the material stress fringe value and h is the plate thickness, which in this case is 0.25 inch . Separation of the stresses is possible, since the waves in this case propagate without rotation. Stresses are developed in both the direction of and perpendicular to the direction of wave propagation. Displacement occurs, however, *only* in the direction of wave motion. The displacements are specified by

$$u_r = f(r) \quad , \quad u_\theta = 0$$

and the strain-displacement relations by

$$\epsilon_r = \frac{du_r}{dr} \quad , \quad \epsilon_\theta = \frac{u_r}{r}$$

The stress-strain equations are

$$\sigma_r = \frac{E}{1-\nu^2}\left[\epsilon_r + \nu\epsilon_\theta\right] ,$$

$$\sigma_\theta = \frac{E}{1-\nu^2}\left[\epsilon_\theta + \nu\epsilon_r\right]$$

and the shear stress has the value

$$\tau = \pm\frac{\sigma_\theta - \sigma_r}{2}$$

where E is Young's modulus and ν is Poisson's ratio.

From these relations,

$$2\tau = \sigma_\theta - \sigma_r = \frac{E}{1+\nu}\left[\epsilon_\theta - \epsilon_r\right] = \frac{E}{1+\nu}\left[\frac{u_r}{r} - \frac{du_r}{dr}\right]$$

but

$$\frac{d}{dr}\left(\frac{u_r}{r}\right) = \frac{1}{r}\left[\frac{du_r}{dr} - \frac{u_r}{r}\right]$$

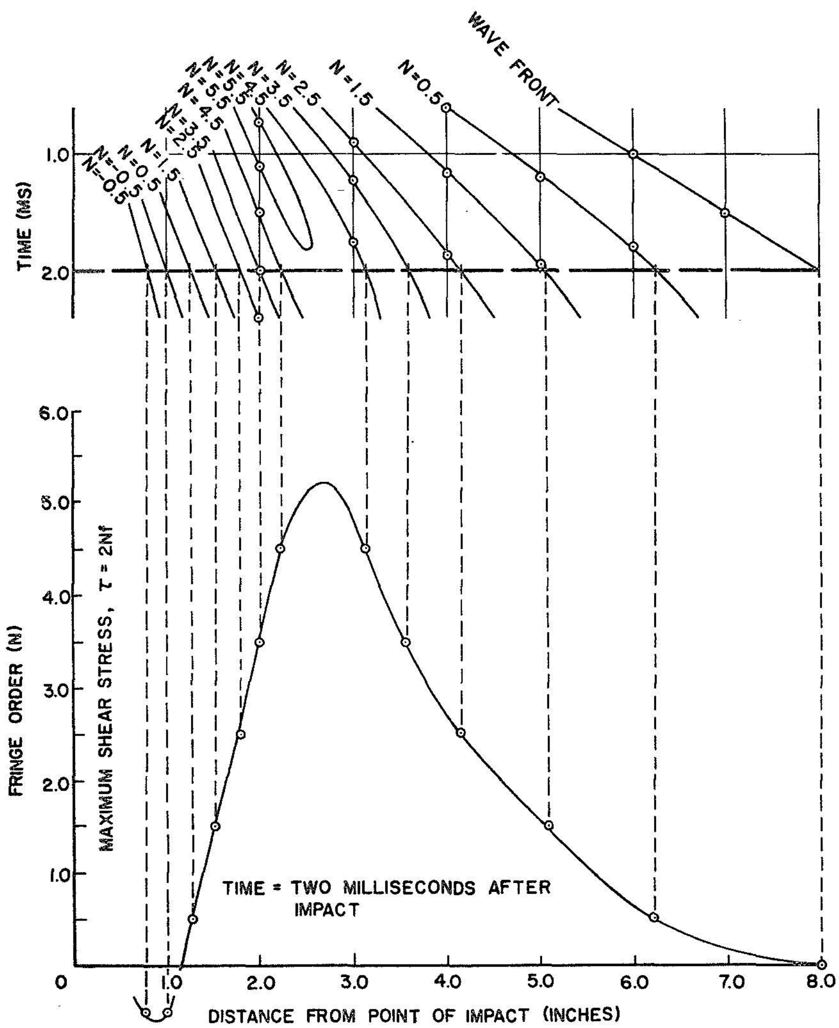


Fig. 7. Fringe order and shear stress as a function of position.

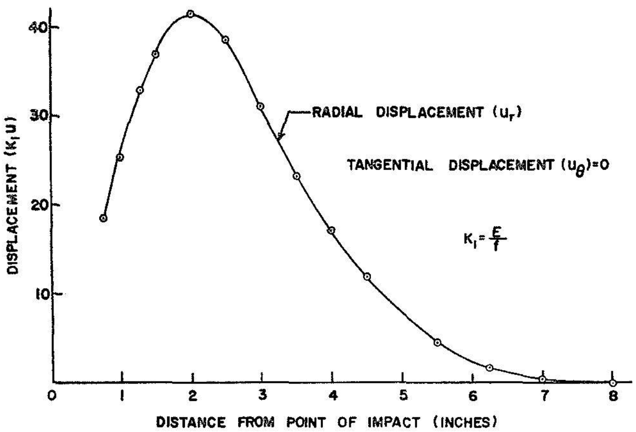


Fig. 8. Displacement.

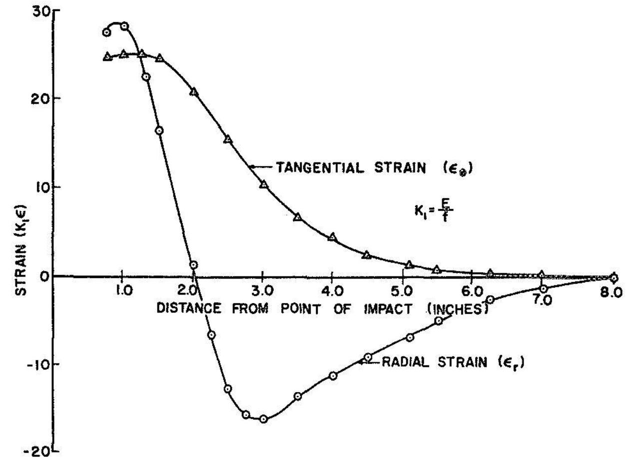


Fig. 9. Principal strains.

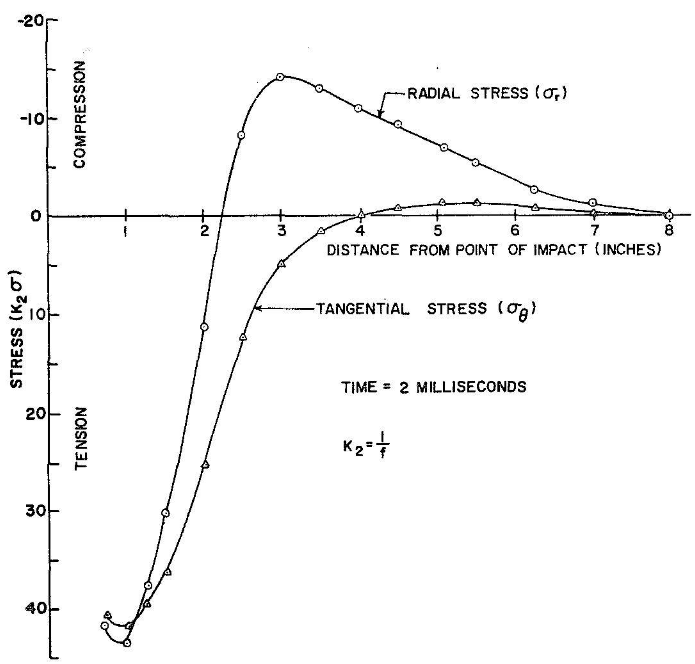


Fig. 10. Principal stresses.

So

$$\sigma_\theta - \sigma_r = -\frac{E}{(1+\nu)}\left[r\frac{d}{dr}\left(\frac{u_r}{r}\right)\right]$$

$$\frac{d}{dr}\left(\frac{u_r}{r}\right) = -\frac{(1+\nu)}{E}\left(\frac{\sigma_\theta - \sigma_r}{r}\right)$$

$$\frac{u_r}{r} = -\frac{(1+\nu)}{E}\int\frac{\sigma_\theta - \sigma_r}{r}\,dr$$

$$\epsilon_\theta = \frac{u_r}{r} = \frac{2(1+\nu)}{E}\int\frac{\tau}{r}\,dr$$

$$\epsilon_r = \epsilon_\theta - \frac{2(1+\nu)}{E}\tau = -\frac{2(1+\nu)}{E}\left[\tau + \int\frac{\tau}{r}\,dr\right]$$

The radial and tangential stresses are, therefore,

$$\sigma_r = -\left(\frac{2}{1-\nu}\right)\left[\tau + (1+\nu)\int\frac{\tau}{r}\,dr\right]$$

$$\sigma_\theta = -\left(\frac{2}{1-\nu}\right)\left[\nu\tau + (1+\nu)\int\frac{\tau}{r}\,dr\right]$$

This derivation is essentially the same as described in Reference 9.

These relations may be stated in terms of the model material properties and the fringe order.

$$u_r = -\frac{(1+\nu)f}{Eh}\left[r\int\frac{N}{r}\,dr\right] = r\epsilon_\theta$$

$$\epsilon_r = -\frac{(1+\nu)f}{Eh}\left[N + \int\frac{N}{r}\,dr\right] = \frac{du}{dr}$$

$$\epsilon_\theta = -\frac{(1+\nu)f}{Eh}\left[\int\frac{N}{r}\,dr\right]$$

$$\sigma_r = -\frac{f}{h(1-\nu)}\left[N + (1+\nu)\int\frac{N}{r}\,dr\right]$$

$$\sigma_\theta = -\frac{f}{h(1-\nu)}\left[\nu N + (1+\nu)\int\frac{N}{r}\,dr\right]$$

Values of displacement, strain, and stress may now be determined by numerical integration.

As the purpose of this paper is to illustrate a method of stress wave analysis, the values will be computed in terms of E and f. Poisson's ratio is assumed to have a value of 0.38. The results are shown in Figs. 8, 9, and 10.

Conclusion

The polariscope described in this paper provides an excellent, low-cost method for the analysis of stress waves in birefringent materials. As this system detects the changes in light retardation, it is not affected by residual stress and time edge effects that may be present in the model. By the simultaneous monitoring of several points of waves that are propagating without rotation, it is possible to separate the principal stresses and to determine their individual values without introducing additional experimental data. By using polaroids imbedded in the model, this method may be expanded to the study of spherical stress waves resulting from high velocity impact.

Acknowledgement. Research reported in this paper was supported by the National Aeronautics and Space Administration under Grant NGR-43-003-007.

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9. Dally, J.W. and Riley, W. F., "Stress Wave Propagation in a Half-Plane Due to Transient Point Load," Developments in Theoretical and Applied Mechanics, Vol. 3. Pergamon Press, p. 357-377, New York, 1967.

Ray Kinslow is Chairman of the Department of Engineering Science at Tennessee Technological University. His other positions include Principal Investigator for NASA Research on "Hypervelocity Impact and Stress Waves" and Research Consultant for ARO, Inc. and General Dynamics. Mr. Kinslow has authored more than 20 papers and reports dealing with high speed impact, stress waves and meteroid hazard to spacecraft. He edited High Velocity Impact Phenomena, Academic Press, 1970.