EXPERIMENTAL DETERMINATION OF MATERIAL PROPERTIES FOR
MATERIALS SUBJECTED TO HIGH COMPRESSIVE STRAIN RATES

by

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LIST OF PRINCIPAL SYMBOLS

C  Bar speed of sound; characteristic lines in the physical plane
E  Modulus of elasticity; as a superscript to refer to elastic quantities
i  Subscript index
m  Subscript referring to measured quantities
T  Superscript referring to quantities arising from materials test
t  Time
u  Displacement in the axial direction
v  Particle velocity
x  Axial coordinate
α  A constant along a characteristic line in the physical plane
β  A constant along a characteristic line in the physical plane
δ  An increment
ρ  Mass density
σ  Stress
1. INTRODUCTION

1.1 General

Many of the functions of modern machines and structures require that their components be subjected to a high rate of loading. It follows that today's engineer must have quantitative information available for material response at such loading rates. The conventional materials testing machines, utilizing finite cross head velocities are not capable of producing the rate of loading required and only in recent years has the science of instrumentation developed far enough to yield good quantitative data from any method involving such loading rates. However, with these advances in electronics and instrumentation, much interest has been shown recently in developing methods of obtaining such quantitative data [1].

1.2 Specific Objective

One method of obtaining information about material response to high compressive loading rates is to use the so called split Hopkinson bar scheme as described by Maiden and Green [2]. The purpose of this thesis is to describe the design, fabrication, and operation of a version of this apparatus that not only allows the determination of material response, but also allows the study of one-dimensional wave propagation problems in general.

*Numbers in brackets refer to appended references.
2. LITERATURE REVIEW

Kolsky [1] provides a good theoretical background for the study of stress waves. He develops the governing equations for waves traveling in both elastic media and plastic media as well as imperfectly elastic and viscoelastic media. He also describes experimental investigations and some results obtained before 1952 including a discussion of the original Hopkinson bar and the improved Davies bar. Dispersion investigations are also discussed in some detail and the results obtained by R. M. Davies [6] are presented.

Maiden and Green [2] investigated six materials using a medium strain rate machine and a split Hopkinson bar apparatus. They define the medium strain rate range to be from about 0.001 to 30 in/in/sec and the high strain rate range from 30 to $10^4$ in/in/sec. Their results show that stress-strain curves obtained using the split Hopkinson bar and the medium rate apparatus are in consistent agreement.

Chiddister and Malvern [3] investigated aluminum at elevated temperatures using a split Hopkinson bar technique in which measurements were made well away from the specimen faces in order to avoid reflections. The specimen lengths used were such that a length to radius ratio of one was maintained in an effort to avoid wave propagation effects in the specimen and still neglect radial friction effects at the specimen faces.

In a later work, E.D.H. Davies and Hunter [5] show that the
ratio of specimen length to radius must be at least one in order to neglect radial friction effects at the specimen faces.

Volterra and Zachmanoglou [4] present excellent summaries and results of both theoretical and experimental investigations carried out in wave propagation and mechanical responses to high strain rates. Much of the work was carried out by Volterra himself and several of his personal papers are referenced. A complete list of references is given in this work.
3. THEORETICAL BASIS FOR EXPERIMENT

3.1 Simple Wave Equation and Solution by the Method of Characteristics

Consider an axial rod of constant cross section, constant elastic modulus $E$, and constant mass density $\rho$. Let one end of the given rod experience a sudden jump in compressive stress of magnitude $\sigma_o$. The governing equation of motion for the simple compressional wave produced by the jump in stress is the simple wave equation,

$$\frac{\partial^2 u(x,t)}{\partial x^2} = \frac{1}{c^2} \frac{\partial^2 u(x,t)}{\partial t^2}, \quad (3.1)$$

where $u$ is the axial displacement, $x$ is the axial coordinate, and $C^2 = \frac{E}{\rho}$.

There are several familiar approaches to the solution of equation 3.1; however, the solution upon which this experimental work is based is obtained by applying the Method of Characteristics, hereafter referred to as the M.O.C. By the M.O.C., it may be shown that along lines of slope,

$$\frac{dt}{dx} = + \frac{1}{C}, \quad (3.2a)$$

in the $x - t$ plane,

$$\sigma - \rho Cv = 2\beta, \quad (3.2b)$$

and that along lines of slope

$$\frac{dt}{dx} = - \frac{1}{C}, \quad (3.2c)$$
\[ \sigma + \rho Cv = 2a, \]  

(3.2d)

where \( v \) is the particle velocity, \( \sigma \) is the stress, and \( a \) and \( \beta \) are constants to be determined. The lines of slope \( \frac{dt}{dx} = \pm \frac{1}{c} \) are called the characteristics, and infinitely many such characteristics appear in an \( x-t \) plane. The equations which govern the stress and particle velocity along the characteristics must be satisfied simultaneously at their intersections to yield,

\[ \sigma = a + \beta, \]  

(3.3a)

and

\[ \rho Cv = a - \beta. \]  

(3.3b)

Thus at any position \( x \) and any time \( t \), the stress and particle velocity can be determined in the rod if \( a \) and \( \beta \) are known along the characteristics which define this point in the \( x-t \) plane.

Further analysis reveals that any jump in stress or particle velocity is unchanged along the characteristics, and also that such jumps can only occur across the characteristics.

3.2 A Particular Problem

Consider the application of this solution to the particular problem shown in figure 3.1. This problem represents a split Hopkinson bar apparatus. The scheme consists of two high tensile strength steel rods of properties \( \rho_o \) and \( E_o \), between which has been placed a short specimen of another material. The steel bar on the left (figure 3.1), shown experiencing a jump in compressive stress \( \sigma_o \), is called the weighbar. The bar on the right of the
FIGURE 3.1
REPRESENTATION OF THE SPLIT HOPKINSON BAR APPARATUS FOR
THE APPLICATION OF THE METHOD OF CHARACTERISTICS
small specimen is called the anvil bar. Both of these rods have been instrumented with strain gages at positions A and D as shown. These gages record the strain-time variations at these positions which can be converted to stress-time records by means of a calibration technique described later.

Above the sketch of the bar, the physical or x-t plane has been represented. The characteristics that appear are the ones which pass through the points that correspond to the boundaries of the problem, and for which both the boundary conditions and the initial conditions are known. These characteristics are labeled $C_i^+$ or $C_i^-$, with the signs referring to the sign of the slope, and the subscript being an index.

Note that $C_1^+$ and $C_4^+$ divide the x-t plane into two regions. Below these characteristics, the stress wave has not had time to reach the position along the rod corresponding to the coordinate x. Therefore, for characteristics which begin in this undisturbed region and extend from it, the values of $\alpha$ and $\beta$ are zero.

The characteristic $C_1^+$ passes through the origin of the x-t plane corresponding to the end of the weighbar. The jump in stress at the weighbar end is $\sigma_o$, and, as shown by the M.O.C., this jump is unchanged along $C_1^+$. Consider the stress-time variation experienced by the strain gage located at position A. The stress wave will reach the gage at time $t_1$. Let the stress recorded at any time be $\sigma_{mi}^T$, the subscript m indicating that this is the measured stress, the superscript T indicating that the test specimen is be-
tween the two rods, and \( i \) being an index. Before time \( t_1 \), the strain gage records zero strain corresponding to the undisturbed region in the \( x-t \) plane. At time \( t_1 \), the gage will record a sudden jump in stress \( \sigma_{ml}^T \). Recall from the M.O.C., that,

\[
\sigma = \alpha + \beta ,
\]

and,

\[
\rho \sigma v = \alpha - \beta ,
\]
at the point indicated as 1.

From the above discussion, the jump in stress propagates along \( C_1^+ \) such that \( \sigma = \sigma_o \) (compression). Along \( C_1^- \), \( \beta = 0 \), since no jumps have occurred in the undisturbed region. Therefore, the stress at point 1 is given by equation (3.3a) as

\[
\sigma_{ml}^T = \alpha = \sigma_o ,
\]
and \( \alpha \) is determined for \( C_1^+ \). The particle velocity at point 1 is given by (3.3b) as,

\[
\rho \sigma v = \alpha = \sigma_{ml}^T .
\]

At point 2, corresponding to time \( t_2 \),

\[
\sigma_{m2}^T = \alpha + \beta = \sigma_o + \beta ,
\]
or,

\[
\beta = \sigma_{m2}^T - \sigma_o .
\]

The particle velocity at this point is,

\[
\rho \sigma v_2 = \alpha - \beta = \sigma_o - (\sigma_{m}^T - \sigma_o) ,
\]
or,

\[
\rho \sigma v_2 = 2\sigma_o - \sigma_{m2}^T .
\]

The conclusion is that along section A-A, the stress and particle
velocity can be determined from the strain-time record recorded by
the gage at A provided \( \sigma_0 \) is known.

Now consider the situation along section \( B - B \) corresponding
to the specimen and weighbar interfaces. The stress wave will arrive
at the specimen at the time corresponding to point 4 along section
\( B - B \). The values for \( \alpha \) and \( \beta \) along the characteristics \( C_1^+ \) and \( C_2^- \),
defining this point, are given by equations (3.4) and (3.6) respecti-
vately. The stress at point 4 is therefore given as,

\[
\sigma_4 = \alpha + \beta = \sigma_0 + \sigma_m^\text{T} - \sigma_o = \sigma_m^\text{T},
\]

and the particle velocity is given as,

\[
\rho C v_4 = \alpha - \beta = \sigma_0 - (\sigma_m^\text{T} - \sigma_o),
\]
or,

\[
\rho C v_4 = 2\sigma_o - \sigma_m^\text{T}.
\]

Point 5 is treated similarly to show that,

\[
\sigma_5 = \sigma_m^\text{T},
\]

and

\[
\rho C v_5 = 2\sigma_o - \sigma_m^\text{T}.
\]

The conclusion is that after the time delay \( \delta t_d \) indicated in
figure 1, the stress and particle velocity recorded by the gages
at A, is the stress and particle velocity on the specimen face.

At point 6, on the other side of the specimen, the stress is
measured by the gages at position D, and,

\[
\sigma_m^\text{T} = \alpha + \beta,
\]

and \( \beta = 0 \),
\[ \sigma_{m6}^T = \alpha. \]

Therefore, at point 7,
\[ \sigma_7 = \alpha + \beta = \sigma_{m6}^T, \]
and,
\[ \rho C v_7 = \alpha - \beta = \sigma_{m6}^T. \]

Again, the stress and particle velocity recorded by the anvil bar gages is the stress and particle velocity on the anvil bar specimen face after the time interval \( \delta t_d \).

### 3.3 Testing Machine Analogy

The above discussion has shown that the stress and particle velocity on the specimen faces can be determined from strain-time records taken on either side of the specimen. The analogy to a conventional compression testing machine is immediately evident. For example, consider a short test specimen placed in an Instron testing machine and tested in compression at a constant cross head velocity. The average strain rate over the specimen, \( \dot{\varepsilon} \), can be obtained by dividing the cross head velocity by the length of the specimen. The strain can be found at any time \( t \), by integrating the strain rate over the time interval. In this case, the strain rate is a constant and the strain at any time \( t \) is \( \frac{v t}{\ell} \) where \( v \) is the cross head velocity and \( \ell \) is the specimen length. The stress for a particular time is given by the strip chart recorder which records load as a function of time. A no-stretch curve must be obtained for the Instron in order to know the machine response to a given loading.
rate with no specimen present, and the response of the machine with the specimen present must be subtracted from this curve to obtain the actual specimen response.

The analogy with the split Hopkinson bar can now be made. The relative particle velocity corresponds to the cross head velocity, and the average strain rate can be obtained as a function of time by dividing this relative particle velocity by the specimen length. The strain rate can be integrated over time to obtain the strain as a function of time. The average stress on the specimen cross section is known directly from the strain-time records. To obtain particle velocities on the weighbar face with a specimen present it is necessary to first obtain a strain-time record of the response of the bar with no specimen present corresponding to the no-stretch curve of the Instron test. The Instron machine response is assumed to be the same for identical loading rates, whereas, for the split Hopkinson bar, identical stress waves are assumed to be produced by identical impact velocities. Thus, strain-rate versus time, strain versus time, and stress versus time curves can be determined for the specimen. Then, for a given time, the corresponding stress, strain, and strain rate are known, and points on a stress-strain curve for a particular strain rate can be filled in.

3.4 Reduction of Data

The steps for obtaining the stress-strain diagrams can be illustrated by referring to the tabular headings in figure 3.2. The
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8 $\mathcal{Q}$</th>
<th>8 $\mathcal{F}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time-$t$</td>
<td>$\sigma_o^T$</td>
<td>$\sigma_{\text{wbf}}^T$</td>
<td>$\sigma_{\text{abf}}^T$</td>
<td>$V_{\text{wbf}}$ = $\frac{2\sigma_o^T - \sigma_{\text{wbf}}^T}{\rho c}$</td>
<td>$V_{\text{abf}}$ = $\frac{\sigma_{\text{abf}}^T}{\rho c}$</td>
<td>$\varepsilon$ = $\frac{V_{\text{wbf}} - V_{\text{abf}}}{\ell}$</td>
<td>$\sigma$ = $\frac{\sigma_{\text{wbf}}^T + \sigma_{\text{abf}}^T}{2}$</td>
</tr>
</tbody>
</table>

**FIGURE 3.2**

TABULAR HEADING REPRESENTING A TABLE ILLUSTRATING THE STEPS IN DATA REDUCTION
stress waves are produced by impacting the end of the weighbar with another rod of the same material. (The physical details of the apparatus will be described later.) Two tests are conducted at the same impact velocity. The first test is conducted with a specimen made from the same material as the weighbar and anvil bar, that is, high tensile strength steel. The wave that is propagated "sees" the two rods and steel specimen as one continuous rod. Since the theory on which this experiment is based requires that the steel rods remain elastic, quantities arising from this test shall hereafter be denoted with a superscript E, and the steel specimen shall be referred to as the elastic specimen. Referring to figure 3.2, the strain-time record of the test with this elastic specimen present is divided into a finite number of time intervals which are recorded in the column designated as time - t. For each of these points in time, the stress $\sigma_o^E$ is recorded in column 2.

A second test is conducted at the same impact velocity with a specimen of the material to be tested between the two bars, and the same division of time is made on the strain-time records. The stress on the weighbar face, $\sigma_wbf^T$, and the stress on the anvil bar face, $\sigma_abf^T$, are recorded in columns 3 and 4, respectively, for each point in time from the strain-time record from this test. The particle velocities on the weighbar and anvil bar faces, $v_wbf^T$ and $v_abf^T$, is computed for each time using the theory discussed in section 3.2. This information is recorded in columns 5 and 6. The strain rate, $\dot{\varepsilon}$, is computed in column 7, by dividing the relative
particle velocity by the specimen length. This strain rate is then integrated numerically over the time increments to obtain the strain, \( \varepsilon \), which is recorded in column 8. The average stress over the specimen length is recorded in column 9, and the table is complete for one set of data.

From a number of such dual tests, the stress and strain at a particular strain rate can be read from the last three columns in figure 3.2, and points on a stress-strain curves for particular strain rates determined for the test material. In general, for one data set arising from the two tests performed at identical impact velocities, only one point on a stress-strain curve for a particular strain rate is obtained. For each data set, a considerable number of numerical computations must be made to complete one table such as is illustrated by the column headings in figure 3.2, the exact number depending upon the number of time increments chosen. Therefore, a computer program was written to perform the steps indicated in figure 3.2, and is included in the appendix of this thesis.

3.5 Review and Meaning of the Assumptions

In the development of the theory on which the experiment is based, certain assumptions were made which subject the experimental apparatus and technique to some constraints. These assumptions are of two types, being those that arise from the derivation of the simple wave equation, and those that are assumed in applying the solution by the M.O.C. to the split Hopkinson bar apparatus.
The assumptions which are made in deriving the simple wave equation are as follows:

1. The bars have a constant cross sectional area.
2. All points on a normal cross section have equal axial displacements.
3. Radial inertia effects are negligible.
4. The axial normal stress is given by \( \sigma = E\varepsilon \).
5. The normal strain is given by \( \varepsilon = \frac{2u}{2x} \).

These assumptions will be discussed briefly.

Assumption one restricts the weighbar and anvil bar to have constant cross sectional area.

Assumption two implies that a plane wave or a uniform distribution of stress across a cross section is produced. This assumption is not true near the end of the weighbar where the pressure pulse is applied, however, Volterra and Zachmanoglou [4] indicate that experiments show that a uniform distribution of stress is achieved before the pulse travels a distance of four bar diameters if the impact is axial and if dispersion effects are negligible. Axial impact is assured by giving the weighbar end a slight radius and by careful alignment.

Assumption three indicates that radial expansions and contractions are so small that any cross sectional distortion that occurs is negligible. This means essentially that dispersion is negligible. The Pochhammer-Chree solution (exact), as presented by Volterra and Zachmanoglou [4], indicates that dispersion effects are negligible for ratios of radius to wavelength less than about 0.7 for sinusoidal
pulses. R. M. Davies [6] has treated longitudinal pulses such as square waves in terms of the exact theory by performing a Fourier analysis on the periodic extension of such pulses. He has shown that dispersion is negligible for ratios of radius to pulse length which are small. Using this method, the velocity of propagation of each component of the phase velocity can be found for each term in the series, each term corresponding to a mode. Volterra and Zachmanoglou [4] have shown that higher modes are not easily excited. This fact probably accounts for little dispersion for pulses of long duration, as the primary contribution to such a pulse is the lowest mode component. Chiddister and Malvern [3] indicate that rounding of the weighbar end also reduces the high frequency content of the pulse.

Assumption four implies that the elastic limit of the Hopkinson bar must not be exceeded, and also implies that internal damping is negligible, as no internal damping term is included. In the experiments performed with the elastic bar, no attenuation of the stress wave during the first passage between the two gage positions was observable, indicating that the no-damping assumption is valid for "short" times and "long" pulses.

Assumption five is true for small displacements.

The assumptions which arise from applying the M.O.C. solution of the simple wave equation to the problem discussed in section 3.2 are as follows:

6. Reflections at the weighbar and anvil bar faces with an elastic specimen present are negligible, and the wave propagates in this test as it would in a continuous rod.
FIGURE 3.3

STRAIN-TIME RECORD OBTAINED FROM AN IMPACT TEST ON A CONTINUOUS ROD
FIGURE 3.4

STRAIN-TIME RECORDS FROM TESTS CONDUCTED

AT IDENTICAL IMPACT VELOCITIES
7. Identical impact velocities produce identical waveforms.

8. Radial friction effects at the specimen interfaces are negligible.

Assumption six means that care must be taken to insure that the elastic specimen and the Hopkinson bar interfaces are parallel and flat. In order to have some measure of the accuracy of this assumption, the data from each elastic test was compared with the results from tests conducted on an actual continuous rod. Strain-time records for one such test of a continuous rod are illustrated in figure 3.3. Any deviation in form of the strain-time records from tests conducted on the elastic specimen can be attributed to specimen misalignment and interface effects.

Assumption seven is verified experimentally. Referring to figure 3.4, strain-time records for two tests conducted at the same impact velocities of 302 inches per second, and they are seen to be essentially identical.

E. D. H. Davies and Hunter [5] have shown that assumption eight is valid if the ratio of radius to specimen length is at least one, and if a light lubricant is present at the specimen interfaces.
4. EXPERIMENTAL APPARATUS

4.1 General

A schematic drawing of the experimental apparatus is given in figure 4.1. All discussion of the physical details, and descriptions of the design, fabrication and operation of the apparatus shall refer to this figure. Photographs of the apparatus are included in figures 4.2 and 4.3.

The apparatus is composed essentially of three portions, being the air gun, the split Hopkinson bar, and the instrumentation. The operational procedure will be discussed briefly with reference to figure 4.1 in order to identify the function of each portion, and then the components themselves will be discussed in detail.

4.2 Operational Procedure

The first test is conducted using an elastic specimen. The driver bar (figure 4.1), is fired down the barrel of the air gun to impact the end of the weighbar. Near the point of impact, the impact velocity is recorded by the velocity measuring system.

As the compressive wave set up by the impact propagates along the weighbar, it passes the oscilloscope triggering device, causing the horizontal sweeps of the oscilloscope to trigger. The positioning of this triggering device is such that outputs of the strain gages mounted on either side of the specimen are displayed and recorded on Polaroid film as the wave passes.

The test is then repeated at the same impact velocity using a
FIGURE 4.1

SCHEMATIC REPRESENTATION OF THE EXPERIMENTAL APPARATUS
FIGURE 4.2

OVERALL VIEW OF THE APPARATUS AND THE ASSOCIATED INSTRUMENTATION
FIGURE 4.3

SPLIT HOPKINSON BAR PORTION OF THE APPARATUS WITH A
LUCITE MATERIAL SPECIMEN IN POSITION TO BE TESTED
test specimen.

4.3 The Air Gun

The air gun consists of the air reservoir, the barrel, and the driver bar. The air reservoir is constructed of standard 6 inch diameter steel pipe 11 inches long, one end of which is capped with a standard cast iron pipe cap. The other end is fitted with a reducer and coupling for exhausting the air through a solenoid valve. The intake of air into the reservoir is accomplished by an intake valve fitted with a Foxboro type 67 pressure regulator and pressure gage. The pressure gage serves only as an indication of the pressure within the reservoir, and is not accurate enough to allow impact velocities to be determined even by carefully controlling the pressure settings. After considerable experience, it was found that reproducible impact velocities were attained only by duplication of the firing technique for a given pressure regulator setting, and that once the pressure regulator was set to a new position, considerable difficulty was experienced in returning to the original setting.

The reservoir also contains a pressure release valve, enabling air to be released if the solenoid valve is not opened. This valve is also opened to facilitate reloading, as the reloading procedure requires that the air in the barrel be forced into the reservoir back through the solenoid valve, which will not reseat itself. If the pressure release valve is not open, this back pressure will seep
through the unseated solenoid valve causing the driver bar to move slowly down the barrel rather than remain in firing position. Once the driver bar is placed in firing position with the pressure release valve open, the solenoid valve can be reseated by operating it electrically.

The solenoid valve is an Alco type R-11 controlled by a SPDT switch. Considerable difficulty was experienced with the electromagnetic field associated with the operation of this valve. To prevent the horizontal sweep of the oscilloscope from triggering prematurely, various methods of shielding and grounding were employed unsuccessfully. The final solution of this problem was to place a 400 VDC, 250 MFD capacitor in parallel with the solenoid coil at the terminals of the coil shield.

The barrel is fabricated from a 10 foot length of commercially available cold drawn thick wall steel tubing. The inside diameter is 0.875 inches and an acceptable tolerance was obtained by reaming the length of the barrel to a uniform diameter. The driver bar was hand fitted by first shrinking on the driver bar brass bushings, and then taking light cuts on a lathe until an acceptable fit was obtained.

The driver bar is made from high tensile strength steel and is 15 inches in length, 0.75 inches in diameter, and rides on shrink fit brass bushings as pointed out above. The length of the pulse is twice the length of the driver bar or 30 inches. This length adequately insures that dispersion is negligible as discussed in
4.4 Split Hopkinson Bar

The split Hopkinson bar is made from high tensile strength steel, and the rods are both 15.0 inches in length, and 0.413 inches in diameter. The impact end of the weighbar has a slight radius for reasons discussed in section 3.6. The specimen face ends of both bars were milled flat and parallel and finally hand polished.

The elastic specimen was 0.500 inches in length, and was cut from the weighbar and anvil bar stock. Both faces of the elastic specimen were machined flat and parallel and also hand polished. Note that this specimen length satisfied the criterion for neglecting radial friction effects at the specimen and Hopkinson bar innerfaces as discussed in section 3.6.

4.5 Instrumentation

Three Baldwin SR-4 type FAP 12-12 strain gages were mounted on both the weighbar and anvil bar \( \frac{3}{8} \) inch from the ends of their respective faces. The gages were mounted in series 120 degrees apart around each bar in order to obtain the average strain over the bar surface. All gage leads were coated with SR-4 cement to prevent broken leads during the tests. Two 330 ohm precision resistors and a 10 turn 1000 ohm potentiometer completed each strain gage bridge circuit, the voltage being supplied by two 22.5 volt dry cell batteries.
Two type L plug-in preamplifiers having a rise time of 15 nanoseconds and a calibrated vertical gain of 0.005 volts per centimeter were used to amplify the strain gage outputs which were displayed on a Tektronix type 555 dual beam oscilloscope. In all cases, both time bases were operated on a horizontal sweep time of 20 \( \mu \) seconds per centimeter. This sweep speed allowed 200 \( \mu \) seconds for the display of a pulse of about 150 \( \mu \) seconds.

The single sweep of the oscilloscope was triggered from the voltage output of a phonograph crystal mounted on the weighbar about 4 inches ahead of the weighbar gages. This crystal was removed from a Philmore type CX-313 phono cartridge, and had a 3.5 volt output. The finite rise time of this crystal output allows the triggering time relative to the position of the wavefront to be controlled as much as 20 \( \mu \) seconds provided the crystal is mounted between 4 and 4\( \frac{1}{2} \) inches ahead of the first set of gages. Since each of these crystals has slightly different characteristics, this degree of control is important.

The impact velocity measuring device consists of two silver contact switches located in the barrel of the air gun near the impact point. Velocity measurement was achieved by recording the time necessary for the driver bar to travel the distance separating the two switches; the time was recorded on a Hewlett Packard model 522B electronic counter. The distance separating the switches was 2.97 inches.

The oscilloscope display was recorded on a Fairchild Oscillo-
scope camera using Polaroid type 47, 3000 speed film.

4.6 Calibration

The Hopkinson bar was calibrated by loading both the weighbar and anvil bar statically in compression and determining a curve of stress versus change in gage resistance. The Hopkinson bar was then assembled and the Wheatstone bridge balanced. A 100 K-ohm precision resistor was switched in parallel with the bridge arm containing the gages simulating a known resistance change. The resultant bridge unbalance caused a vertical deflection of the oscilloscope beam which was recorded on Polaroid film. This calibration photo was taken before each series of tests. This data allowed a constant having units of P.S.I. per centimeter deflection to be determined for conversion of the oscilloscope record into stress-time records.
5. TYPICAL RESULTS FOR A LUCITE MATERIAL

The material chosen to demonstrate the apparatus was an acrylic plastic commonly called lucite with test specimens being machined from a \( \frac{1}{2} \) inch nominal diameter lucite rod. A typical example of the data taken for the elastic tests is given in figure 5.1. In all photographs, the upper trace is the strain-time record from the weighbar gages and the lower trace is from the anvil bar gages.

For purposes of data reduction, the zero point in time is taken to be the point of the first deflection of the weighbar trace. The first time increment is taken as the time to the nearest division on the scale corresponding to the 4 \( \mu \) second divisions. Thereafter, the data is read as the deflection in centimeters at each of the succeeding 4 \( \mu \) second intervals. This method eliminates the requirement that the same triggering time relative to the position of the wave front be maintained for each test.

An example of typical data from the tests on the lucite material is given in figure 5.2. Note the finite amount of time required for the wave front to reach the anvil bar gages. The data from three elastic and three corresponding lucite tests was read into the computer program in the appendix and the output is given graphically in figures 5.3 through 5.6.

Figure 5.3 gives the average strain rate over the specimen length versus time. There is considerable fluctuation in strain rate during the early part of the curves, probably due to the high stress gradient existing in the specimen at these times. However, after
FIGURE 5.1

TYPICAL EXAMPLE OF DATA TAKEN
FROM THE ELASTIC TESTS
FIGURE 5.2

TYPICAL EXAMPLE OF DATA TAKEN FROM

THE TESTS ON A LUCITE MATERIAL
FIGURE 5.3

IMPACT VELOCITY

- 327 in/sec
- 276 in/sec
- 221 in/sec

STRAIN RATE VERSUS TIME CURVES FROM THREE SETS OF DATA FOR A LUCITE MATERIAL
about 2% strain the points form a nearly continuous curve.

Figure 5.4 gives the average stress–time variation in the specimen. Note that the curve corresponding to an impact velocity of 327 inches per second approaches the curve for an impact velocity of 276 inches per second. It is believed that this is the best indication of specimen failure, as the specimen tested at this impact velocity did fracture. For this material, fracture should probably be indicated at about 25,000 P.S.I., although more data is needed to confirm this belief.

Figure 5.5 indicates the average strain–time variation in the specimen during the test. These curves were obtained from integration of the strain–rate versus time curves.

Finally, in figure 5.6 the stress strain curve for strain rates between 400 in/in/sec and 500 in/in/sec is given. The points in circles are for strain rates below 450 in/in/sec and the points in triangles are for strain rates above 500 in/in/sec.

The results from static compression tests on lucite specimens from the same stock are also given in figure 5.6. Note the strain rate sensitive character of the material.

The failures produced by the static tests were barreling type failures or a flowing of the material. The failures from the dynamic tests were brittle type failures with the material splitting longitudinally.

Maiden and Green [2] present some curves for a lucite material for strain rates between 0.005 in/in/sec and 1210 in/in/sec.
FIGURE 5.4
STRESS VERSUS TIME CURVES FROM THREE SETS OF DATA FOR A LUCITE MATERIAL
NOTE: Calculated Values

FIGURE 5.5

STRAIN VERSUS TIME CURVES FROM THREE SETS OF DATA FOR A LUCITE MATERIAL
FIGURE 5.6
STRESS VERSUS STRAIN TAKEN FROM THE COMPUTER PROGRAM OUTPUT FOR A LUCITE MATERIAL AT STRAIN RATES 400-500 IN/IN/SEC AND THE STATIC STRESS STRAIN CURVE FOR THE SAME MATERIAL.
The curves presented here compare favorably with their curves as to shape and approximate order of magnitude. The material tested here is similar to E. I. du Pont's "Lucite" 140, based on a comparison of the static compressive strengths. Maiden and Green [2] do not specify the type of lucite they tested.
6. DISCUSSION OF THE METHOD AND THE APPARATUS

The results presented in section 5 were given to illustrate the type of information obtained from using this method and should not be taken as being completely indicative of the behavior of a lucite material at these strain rates. However, some comments on the technique and the apparatus may be made on the basis of these results.

It should be noted that the method hinges on the ability to obtain an overlap region of strain rate versus time curves. This overlap region is produced by the same strain rates occurring at different times relative to the position of the wave front during the 150 μ second pulse. It may be necessary to adjust the specimen length to obtain a more complete overlap. Decreasing the specimen length will increase the strain rates obtained for a given impact velocity. A minimum length criterion was stated in section 3.5. Correspondingly, increasing the specimen length will decrease the strain rates obtained for a given impact velocity. However, increasing the length of the specimen means that the stresses on either side of the specimen may become quite different, and the average stress will no longer be a good approximation of the state of stress within the specimen. Some of this difference will be due to the increased axial inertia of the specimen. In the case of viscoelastic materials such as lucite, the dispersion associated with plastic wave propagation would also have to be considered for longer specimens. This would also be true for testing elastic materials beyond their dynamic yield points. For the ½ inch specimens used in this investi-
igation the stresses on either side of the specimen differed by less than five percent after two percent strain had occurred.

Two possible limitations of the method may also be pointed out. First of all, a point of failure or fracture is difficult to define using this method. The best indication seems to be that when the parameter-time curves differ from the typical curves obtained for non-fractured specimens, then the specimen fractured, but the exact stress and strain at which fracture occurred cannot be discerned. This point needs more investigation.

Another possible limitation is that in order to obtain a complete stress-strain curve for a given material at a given strain rate the pulse might have to become excessive in length. This point is best illustrated by referring to figure 5.3. For example, no curves of strain rate-time could cross the 450 in/in/sec ordinate line beyond the 110 µ second abscissa line for this pulse length, and this might be required to fracture this material at this strain rate.

The approximate range of strain rates obtainable with this apparatus is from about 50 in/in/sec to about $10^4$ in/in/sec. It might also be noted that for the driver bar used in this investigation, the air gun is quite capable of buckling the Hopkinson bar and that an air reservoir pressure of about 15 P.S.I. will produce an elastic stress wave of over 50,000 P.S.I. Caution should be taken in any investigation using other driver bars to begin at low air reservoir pressures and determine the magnitude of the stress waves produced so that the apparatus is not damaged.
7. CONCLUSIONS AND RECOMMENDATIONS

The split Hopkinson bar scheme as developed here is believed to be an accurate method for obtaining material response at high strain rates. One of the most important aspects in testing materials is to be able to reproduce the testing procedures so that if statistical analysis is required for certain materials, it may be performed on the data itself without having to account for variations in the testing procedure and with confidence in the validity of the results. It is believed that the split Hopkinson bar apparatus as presented here meets this criterion.

One of the problems encountered during the course of this investigation was that considerable experience in working with the apparatus was required before data for elastic specimens corresponding to tests at identical impact velocities for test specimens could be obtained. As pointed out earlier, considerable care in conducting the tests is required in order to obtain the same impact velocity for both tests. One method of eliminating the experience and effort required, is to conduct a series of elastic tests on the continuous rod, and determine curves of strain-time versus impact velocity. Once such curves are determined, the data for the material tests can be taken without regard to reproducing impact velocities. It is believed that such a method would eliminate at least half of the effort necessary to obtain the dynamic stress-strain curves, and that tests conducted in this manner would become routine.

Study of the data from the elastic tests reveals that the pulse
shape is affected by the discontinuity in the driver bar that is necessary to accommodate the brass bushings on which it rides. It is therefore recommended that the driver bar brass bushings be eliminated, and that the driver bar be made from a solid cylindrical rod. Shorter driver bars made in this manner were used in conjunction with another study, and were found to perform well.

It is believed that this apparatus is a valuable addition to the V.P.I. laboratories, and will prove to be of significant value in the experimental study of wave propagation problems as well as material response studies.
APPENDIX A

SOLUTION OF THE WAVE EQUATION

BY THE METHOD OF CHARACTERISTICS
APPENDIX A

Solution of the Wave Equation by the Method of Characteristics

The wave equation as applied to a rod is*,

\[ \frac{\partial^2 u}{\partial x^2} = \frac{1}{C^2} \frac{\partial^2 u}{\partial t^2}, \tag{1} \]

where,

\[ u = u(x,t), \]

and,

\[ C^2 = \frac{E}{\rho}. \]

Equation (1) may be reduced to two first order partial differential equations as follows:

\[ \sigma = E \frac{\partial u}{\partial x}, \tag{2} \]

\[ v = \frac{\partial u}{\partial t}. \tag{3} \]

Rewriting equation (1),

\[ \frac{\partial}{\partial x} \left( \frac{\partial u}{\partial x} \right) = \frac{1}{C^2} \frac{\partial}{\partial t} \left( \frac{\partial u}{\partial t} \right). \]

Substituting equations (2) and (3) into the previous expression,

\[ \frac{\partial}{\partial x} \left( \frac{\partial}{\partial E} \right) = \frac{\rho}{E} \frac{\partial}{\partial t} (v), \]

or,

\[ \frac{\partial \sigma}{\partial x} = \frac{\rho}{E} \frac{\partial v}{\partial t}. \tag{4} \]

Also differentiating equation (2) with respect to time,

* For a definition of the symbols, see either the text or the list of principal symbols.
\[
\frac{\partial \sigma}{\partial t} = E \frac{\partial}{\partial t} (\frac{\partial u}{\partial x}) = E \frac{\partial}{\partial x} (\frac{\partial u}{\partial t}),
\]

and substituting from equation (3),

\[
\frac{\partial \sigma}{\partial t} = E \frac{\partial v}{\partial x}.
\]  

Equation (1) has now been reduced to the two first order partial differential equations (4) and (5).

Equations (4) and (5) may be combined as follows:

\[
(\frac{\partial \sigma}{\partial x} - \rho \frac{\partial v}{\partial t}) + \lambda (\frac{\partial \sigma}{\partial t} - E \frac{\partial v}{\partial x}) = 0 ,
\]  

where \( \lambda \) is an undetermined multiplier.

Rearrange equation (6),

\[
\frac{\partial \sigma}{\partial x} + \lambda \frac{\partial \sigma}{\partial t} = \rho \frac{\partial v}{\partial t} + \lambda E \frac{\partial v}{\partial x},
\]

and note that the left hand side looks similar to the total derivative \( \frac{d\sigma}{ds} \), and the right hand side looks similar to the total derivative \( \frac{dv}{ds} \), where \( s \) is some direction in the x-t plane.

It is possible to find the direction \( s \) such that equation (7) may be written as,

\[
\frac{d\sigma}{ds} = \frac{dv}{ds}.
\]

Consider \( \sigma = \sigma(x,t) \).

Then,

\[
\frac{d\sigma}{ds} = \frac{\partial \sigma}{\partial x} \frac{dx}{ds} + \frac{\partial \sigma}{\partial t} \frac{dt}{ds}.
\]

Comparing the coefficients of like quantities of the left hand side of equation (7) with the previous expression yields,
\[ \frac{dx}{ds} = 1, \]

and

\[ \frac{dt}{ds} = \lambda. \]  

Therefore, for the left hand side of equation (7),

\[ \frac{dt}{dx} = \lambda. \]  

Performing the same operation on the right hand side of equation it may be shown that,

\[ \frac{dx}{ds} = \lambda E, \]

and,

\[ \frac{dt}{ds} = \rho. \]  

Therefore, for the right hand side of equation (7),

\[ \frac{dt}{dx} = \frac{\rho}{\lambda E}. \]  

Equating equations (11) and (12) yields,

\[ \lambda^2 = \frac{\rho}{E} = \frac{1}{c^2}, \]

or,

\[ \lambda = \pm \frac{1}{c}. \]  

Therefore, the direction has been found such that equation (7) can be written as,

\[ \frac{d\sigma}{ds} = \frac{dv}{ds}. \]  

Multiplying both sides of equation (14) by \( dt \) yields,

\[ d\sigma \left( \frac{dt}{ds} \right) = dv \left( \frac{dt}{ds} \right), \]
where the $\frac{dt}{ds}$ associated with $\sigma$ is from equation (9), and the $\frac{dt}{ds}$ associated with $dv$ is from equation (11).

Substitution from equations (9) and (11) into equation (15) yields,

$$d\sigma(\lambda) = dv(\rho) .$$

Finally, from equation (13),

$$d\sigma (\pm \frac{1}{C}) = \rho dv ,$$

or,

$$d\sigma \pm \rho Cdv = 0 \quad (16)$$

Equation (16) is integrated along $\frac{dt}{dx} = \pm \frac{1}{C}$, to yield the result that,

$$\sigma \pm \rho Cv = \text{a constant},$$

along,

$$\frac{dt}{dx} = \pm \frac{1}{C} .$$
APPENDIX B

STATIC CALIBRATION
APPENDIX B

Static Calibration

The Hopkinson bar was initially calibrated using the following technique. The strain gages were mounted using SR-4 cement, using as thin a coat as possible. Each bar was loaded in compression statically on a Tinius Olsen testing machine and the load was cycled several times before data was taken. Load-strain data was taken for both the weighbar and anvil bar using Baldwin type switching and balancing units. The strain data was converted to change in gage resistance in the following manner. By definition, the gage factor $F$ is,

$$F = \frac{\Delta R}{\Delta \epsilon}$$

where $\Delta R$ is the resistance change, $R$ is the gage resistance, and $\epsilon$ is the strain.

Then,

$$\Delta R = FR\epsilon$$

For the gages used,

$F = 2.04$,

$R = 363.0$ ohms.

Then,

$$\Delta R = 740.0\epsilon$$

Curves of stress versus change in gage resistance were constructed as given in figure B.1. The data was treated using the method of least squares and the best slopes were determine. For the weighbar,
FIGURE B.1

STATIC CALIBRATION CURVES
it was found that,

\[ E^w_R = 3.95 \times 10^4 \text{ PSI/ohm}, \]

and for the anvil bar,

\[ E^A_R = 3.70 \times 10^4 \text{ PSI/ohm}. \]
APPENDIX C

THE COMPUTER PROGRAM FOR

DATA REDUCTION
APPENDIX C

The Computer Program for Data Reduction

The following program was written in the Fortran IV mode for the IBM 7040 digital computer in order to facilitate data reduction.

The input data needed for this program is as follows:

- **RHO**: Mass density of Hopkinson bar.
- **C**: Bar speed of sound.
- **ND**: Number of data sets (up to 10).
- **SL**: Specimen length.
- **CFW(I)**: Conversion factors for the weighbar trace for the elastic test.
- **CFWT(I)**: Conversion factors for the weighbar trace for the specimen test.
- **CFAT(I)**: Conversion factors for the anvil bar trace for the specimen test.
- **OTC(I)**: Times from the origins to the initial deflection of the weighbar trace (may be set equal 0).
- **TC(I)**: Times from the initial deflection of the weighbar trace to the nearest 4 µ second division.
- **NESPI**: Identification number of the elastic test data.
- **NTSP(I)**: Identification number of the specimen test data.
- **A(I)**: Elastic test data array from the weighbar trace.
- **B(I)**: Specimen test data array from the weighbar trace.
- **D(I)**: Specimen test data array from the anvil bar trace.

Running time on the IBM 7040 system is less than two minutes for three sets of data.
A(I)-WEIGHBAR GAGES DATA FROM PHO TO OF ELASTIC TEST (CM)
B(I)-WEIGHBAR GAGES DATA FROM PHO TO OF SPECIMEN TEST (CM)
D(I)-ANVIL BAR GAGES DATA FROM PHO TO OF SPECIMEN TEST (CM)
SIGE(I)-STRESS ON WB. FACE DURING ELASTIC TEST (PSI)
SIGWT(I)-STRESS ON WB. FACE DURING SPECIMEN TEST (PSI)
SIGAT(I)-STRESS ON AB. FACE DURING SPECIMEN TEST (PSI)
EDOT(I)-STRAIN RATE IN THE SPECIMEN (IN/IN/SEC)
VWBF(I)-PARTICLE VELOCITY ON THE WB. FACE (IN/SEC)
VABF(I)-PARTICLE VELOCITY ON THE AB. FACE (IN/SEC)
EPIS(I)-STRAIN IN THE SPECIMEN (IN/IN)
SIGMA(I)-STRESS IN THE SPECIMEN (PSI)
SL(I)-SPECIMEN LENGTH (IN)
CFW(I)-CONVERSION FACTOR FOR WB. GAGES (PSI/CM)
CFA(I)-CONVERSION FACTOR FOR AB. GAGES (PSI/CM)
OTC(I)-TIME FROM LEFT AXIS TO INITIAL DEFLECTION OF WB.
TC(I)-TIME FROM INITIAL DEF. OF WB. TRACE TO NEAREST
4 MICROSECOND DIVISION (MICROSECONDS)
NESPI(I)-IDENTIFICATION NO. OF ELASTIC PHOTO
NTSPI(I)-IDENTIFICATION NO. OF TEST PHOTO
AT(I)-TIME COUNTER FOR PROGRAM
TIME(I)-ELECTRONIC COUNTER TIME FOR IMPACT VELOCITY (NS)
RHO-MASS DENSITY OF STEEL OR ELASTIC BARS (SLUG/IN³)
C-VELOCITY OF SOUND IN ELASTIC BARS (IN/SEC)
ND-NUMBER OF DATA SETS TO BE TREATED
DIMENSION(A(380),B(380),D(380),SIGE(380),SIGWT(380),SIGAT(380),EDOT
I(380),VWBF(380),VABF(380),EPIS(380),SIGMA(380),SL(10),CFA(10),CFW
(210),OTC(10),TC(10),NESPI(10),NTSPI(10),AT(380),VDATA(10),TIME(10),CF
3WT(10))
READ(9,9)RHO,C,ND
9 FORMAT(1X,F8.6,5X,F7.0,5X,I3)
M=1
ND=ND+1
II=1
I2=32
130 READ(5,10)SL(M),CFW(M),CFA(M),QTC(M),TC(M),NESSP(M),NTSP(M),TIME(M)
   1,CFWT(M)
10 FORMAT(1X,F6.3,2F8.0,2F5.1,2I3,F6.2,F8.0)
   READ(5,15)(A(I),I=11,12)
15 FORMAT(16F5.2/16F5.2)
   READ(5,17)(B(I),I=11,12)
17 FORMAT(16F5.2/16F5.2)
   READ(5,19)(D(I),I=11,12)
19 FORMAT(16F5.2/16F5.2)
   ROC=RHO*C
C CONVERGE DEFLACTION DATA TO STRESS
D020I=I1,I2+1
SIGE(I)=A(I)/CFW(M)
SIGT(I)=B(I)/CFWT(M)
20 SIGAT(I)=D(I)/CFA(M)
C CALCULATE PV*, STRAIN RATE, AND STRESS
D030J=I1,I2+1
VABF(J)=SIGAT(J)/ROC
VWBF(J)=(2.*SIGE(J)-SIGT(J))/ROC
EDOT(J)=(VWBF(J)-VABF(J))/SL(M)
30 SIGMA(J)=(SIGT(J)+SIGAT(J))/2.
C CALCULATE FIRST STRAIN
EPIS(I1)=.500*TC(M)*EDOT(I1)*1.0E-6
L=11
I3=I1+1
C INTEGRATE STRAIN RATE
D040K=I3,I2+1
EPIS(K)=2.000*(EDOT(K)+EDOT(L))*1.0E-6+EPIS(L)
40 L=L+1
C CALCULATE IMPACT VELO. FOR SWITCHES 2,97 IN APART ONLY
VODATA(M)=2973./TIME(M)
WRITE(6,45)NESSP(M),NTSP(M),VODATA(M)
450 FORMAT(//3X,22RESULTS FROM PHOTO NO.1X,13,10H E.S. AND ,13,5H T.
1S.,6X,18HIMPACT VELOCITY = ,E10.4,2X,10HIN./SEC.//1
WRITE(6,50)
500 FORMAT(1X,4HTIME,10X,7HEL. ST.,10X,8W8F. ST.,11X,8HABF. ST.,9X,
10X,8W8F. PV.,10X,8HABF. PV./3X,6H( },8X,8H( },10X,8H( }/
2,11X,8H( },9X,8H( },10X,8H( }/
I=I1
AT(M)=OTC(M)+TC(M)
60 WRITE(6,70)AT(M),SIGE(I),SIGW(I),SIGAT(I),VWBF(I),VABF(I)
70 FORMAT(3X,F5.1,3X,5(3X,E15.8))
AT(M)=AT(M)+4.0
I=I+1
IF(I-12)60,60,80
80 I=I1
AT(M)=OTC(M)+TC(M)
WRITE(6,90)
900 FORMAT(1X,4HTIME,10X,6HSTRESS,12X,6HSTRAIN,10X,11HSTRAIN RATE/8
1X,8H( X 10 ),5X,9H( LB/IN ),10X,9H( IN/IN ),8X,13H( IN/IN/SEC )/
100 WRITE(6,110)AT(M),SIGMA(I),EPIS(I),EDOT(I)
110 FORMAT(9X,F5.1,3X,5(3X,E15.8))
AT(M)=AT(M)+4.0
I=I+1
IF(I-12)100,100,120
120 ND=ND+1
M=M+1
I1=I1+32
I2=I2+32
IF(ND.GT.1)GOTO130
STOP
END
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EXPERIMENTAL DETERMINATION OF MATERIAL PROPERTIES FOR MATERIALS SUBJECTED TO HIGH COMPRESSION STRAIN RATES

Joel Gray Bennett

ABSTRACT

The design, fabrication and operation of a split Hopkinson bar apparatus is described. The theoretical basis for the experimental determination of material properties for materials subjected to high compressive strain rates using the split Hopkinson bar is discussed along with the assumptions made and their meanings. Some preliminary results for a lucite material are used to illustrate the type of information obtained from using the method. Limitations of the method and conclusions are discussed and recommendations are made.