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Rapid Bursting of Tubular Specimens

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Synopsis

Burst tests on thin wall circular cylinders of aluminum, brass and magnesium alloys, mild steel and polymethylmethacrylate plastic are described in which stress and strain are measured at impact velocities of 14–31 ft./sec. The apparatus consists of an hydraulic cylinder and piston assembly attached to the inside of the specimen, with a falling weight producing a pressure pulse. Measurement problems inherent in the technique are analyzed: e.g., local instability leading to blister formation. An increasing amount of uniform deformation occurs in the specimen as strain rate is increased.

Introduction

The acquisition of valid data describing the mechanical behavior of materials at high rates of strain is a difficult problem, and many experimental approaches to its resolution have been made in the past. There are three essential requirements: first, development of techniques for obtaining rapid loading while reasonably approximating the desired state of stress; second, development of means of measuring the strain and strain rate at a point where the desired state of stress is obtained, and third, development of techniques for measuring the magnitude of the stress or stresses acting at this point.

These requirements seem often to conflict with one another, and the experimental techniques which have been developed to date in high strain rate testing are compromises which may satisfy one or two of the requirements at the expense of the third. Hopkins[1] has reviewed a number of these techniques. Certain of these, for example, allow one of the stresses, the strain, and the strain rate to be determined rather accurately, while leaving the state of stress in considerable doubt. Others, such as the very ingenious technique developed by Davis and his group[2] allow the state of stress to be quite well prescribed, and the strain and strain rate to be accurately determined, while leaving uncertainty as to the magnitude of the stress because of the necessity for double differentiation of the experimental displacement-time record.

The experimental technique to be described in this paper is also a compromise, but it is believed to be interesting in that it sacrifices all three requirements to some extent, and none to a great extent. In this experiment, a specimen in the form of a thin wall circular cylinder is loaded by a pulse of internal pressure. The stress system under study is the hoop stress $\sigma_{\theta\theta}$ thus induced. The stress is made approximately uniaxial by

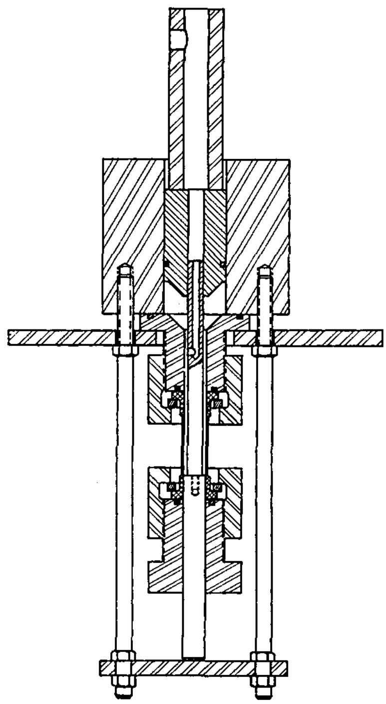

Fig. 1. First model of tube impact test fixture.

causing the longitudinal stress σ_{zz} to be carried by members other than the specimen being tested. Stresses are calculated from the measured fluid pressure, strains are observed on the specimen directly, and strain rates obtained by differentiation.

Rapid tube bursting experiments have been previously described by Clark and Duwez[3] and by Randall and Ginsburgh.[4] Clark and Duwez obtained strain rates up to about 200 in./in./sec. Randall and Ginsburgh made use of a detonation wave in a methane-oxygen mixture, and obtained strain rates up to about 900 in./in./sec. The work to be described here follows Clark and Duwez in using a piston and cylinder with falling weight for producing the pressure pulse.

Test Equipment

The first model of the tube impact test fixture is shown in Figure 1. This fixture has been designed for use with an available fifteen foot drop tower. For the preliminary tests to be described here, SAE 60 oil was used as the actuating fluid. As Clark and Duwez have pointed out, compressibility of the actuating fluid is a factor in determining the strain rates attainable, and they used mercury so as to achieve the highest possible rates. Oil was used in these experiments for the sake of convenience in spite of its greater compressibility.

Specimens

Test specimens are three-quarters of an inch in diameter at the greatest diameter, and are $1^3/_4$ in. long. The inside diameter is a nominal $^3/_8$ in. diameter, and the one inch long reduced section has an outside diameter of $^{13}/_{32}$ in. nominal, so that the nominal wall thickness is $^1/_{64}$ in. The surface finish on the inside and outside of the reduced section is 16 μin. and concentricity and out-of-roundness on the reduced section are held to within .0003 in. Wall thickness in the reduced section has been checked both mechanically and ultrasonically. To date, specimens have been made in 1100-S aluminum alloy, free-turning brass, AZ 80 A magnesium alloy and lucite.

Pressure Sensing System

The pressure-sensing system consists of a $^1/_4$ in. diameter hard aluminum alloy rod, inside the specimen and coaxial with it. This rod is strain gaged with FAP 12-12 gages, two gages being diametrically opposed at the same axial position, and aligned so as to respond to hoop strains in the rod. These gages are connected in series, and the leads brought out through a hole drilled in the rod. The rod itself is a sliding fit both at its upstream and downstream ends, to prevent axial components of the load from being transmitted to the specimen. The FAP 12-12 gages have a low transverse sensitivity factor, so that response of the pressure-sensing system to axial load components is minimized. The pressure sensing rod has a calculated sensitivity of 70 μin./in. strain/1000 psi cylinder pressure, and a natural frequency of about 500,000 cycles/sec. The low sensitivity of the pressure rod requires the use of either an external amplifier or a high gain oscilloscope preamplifier. A Tektronix Type E preamplifier has been used successfully, but limits the frequency response of the system to 60 kc.

Information regarding pressure changes at the specimen surface is transmitted quickly to the pressure cell with this arrangement. Assuming a strain of 50% in the specimen, the distance from pressure cell surface to specimen inside is about 0.156 in. The sonic velocity in the oil may be assumed to be about 50,000 in./sec., so that the transit time for a pressure wave from specimen to pressure cell is between two and three microseconds. At yield the corresponding figure is about one microsecond.

The pressure cell of the pressure sensing system was calibrated by statically pressurizing a dummy specimen, comparing pressure cell output with load indicated on the testing machine used for pressurizing.

Strain Sensing System

It is planned that ultimately the strains in the specimen will be determined from diameter measurements made by a photoelectric shadowing system. This system is represented schematically in Figure 2. Cylindrical lenses are used to image the light source as a line at the axial center of the specimen; the specimen intercepts a portion of the light and the remainder passes on to the photocell. As the specimen diameter increases, the portion of light received by the photocell decreases, and the photocell output decreases correspondingly. Imaging of the light source as a line at the axial center of the specimen guarantees that the average diameter is sensed at this axial position only.

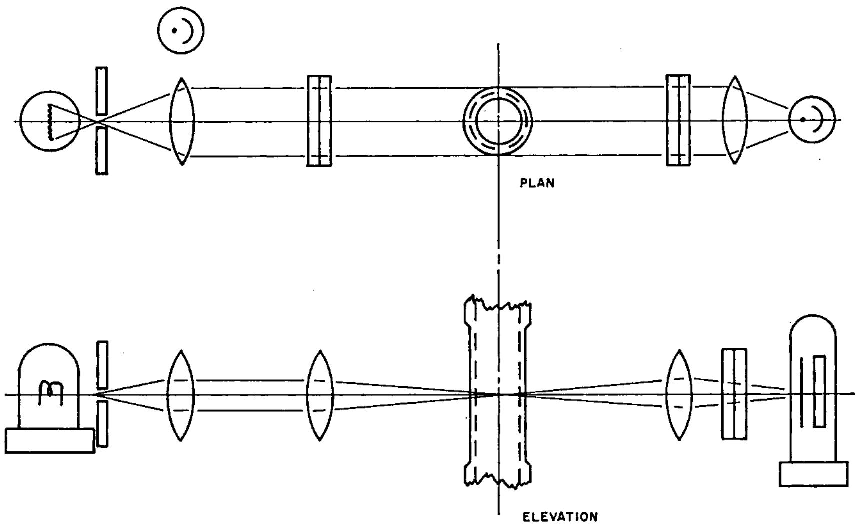

Fig. 2. Photoelectric shadowing system.

Preliminary tests with this apparatus have indicated a sensitivity of about 700 μvolt/thousandth of an inch of diameter change. At present this is not sufficiently above background noise to determine yield strengths by a 0.1% offset method. However, it is believed that further refinement of the photoelectric diameter sensing system will eventually produce a system capable of resolving yield strengths.

While development of the photoelectric system continues, preliminary testing has been carried on using a single post-yield strain gage affixed to the specimen for strain sensing. BLH PA-8 gages have been used primarily. Because of the uncertainty of the dynamic response of these gages[5] the results presented here and based upon them are considered to be tentative.

The Stress System

The design of the specimen is intended to minimize all stresses other than the hoop stress ($\sigma_{\theta\theta}$). Other stresses which are present are the radial (σ_{rr}) and axial (σ_{zz}) stress, and a shearing stress (σ_{rz}).

The radial stress varies from the inside surface to the outside surface of the specimen, being equal in magnitude to the fluid pressure at the inside, and zero at the outside. Because of the thin wall geometry, the radial stress is less than 10% of the hoop stress. It is commonly ignored in thin wall tube theory, and we will do so here.

The axial stress is due to inertial restraint. An approximation to its magnitude is made in Appendix I. To minimize this stress the mass of specimen and fittings attached to the specimen downstream from the test section must be minimized. The fittings shown in Figure 1 below the specimen are serious contributors to this unwanted stress, and have been eliminated in later tests.

The shearing stress results from the inhomogeneity in the loading in the axial direction. The transit time for a pressure pulse to travel in oil the length of the reduced section is about 20 μsec., and during this time the upstream end is in radial deformation. The shearing stress resulting may not be serious, since it must be zero or nearly zero at both inside and outside specimen surfaces, but no successful attempt has been made yet to estimate its magnitude.

Experimental Results

A typical oscilloscope record for 1100-S-O aluminum alloy is shown in Figure 3. The upper trace is cylinder pressure at 220 psi/cm., or stress

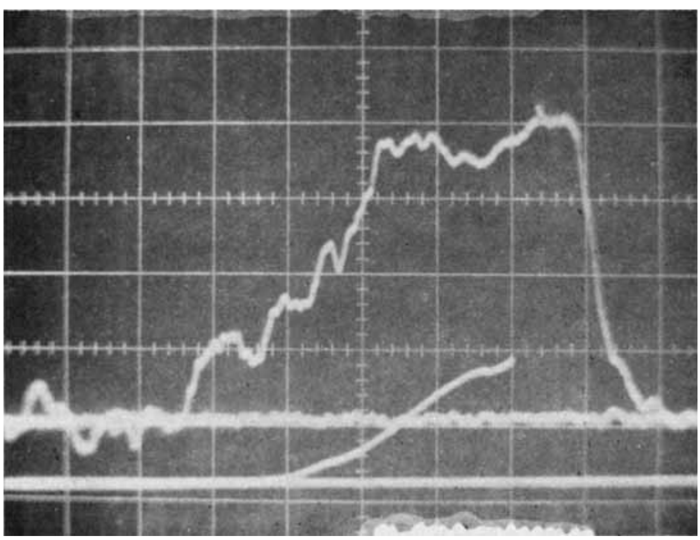

Fig. 3. Typical oscilloscope record for 1000-S-O aluminum alloy.

in the specimen at 3070 psi/cm.; the lower trace is strain in the specimen at 0.028 in./in./cm. The sweep time is 100 μsec./cm. The cylinder was pressurized in this shot by an $8^3/_4$ lb.-wt. falling thru 37 in., resulting in an impact velocity of 14 ft./sec. The average strain rate as indicated by the post yield gage is 150 in./in./sec., and the maximum strain indicated before gage failure is 4.4%.

Based on measurements of the broken specimen, the maximum uniform strain is about 17.2%, and the maximum local strain is about 45% (calculated from thickness measurements adjacent to the fracture by using the assumption that $\epsilon_{\theta\theta} = 2\epsilon_{rr}$). This straining was accomplished in approximately 540 μsec. This figure is presented with some uncertainty; the time from pressure rise to fracture is 540 μsec., but it is not obvious from the record at what stage non-uniform deformation began. This question requires further investigation. The average strain rate, based on uniform strain, is 320 in./in./sec.

Because of the uncertainty in the accuracy of the post yield gage readings, no attempt will be made to report strain or strain rate data here. However, it is believed that the pressure data is accurate, and the following tensile strength data is presented.

TABLE I
Results of First Test Series

Spec. no.	Tensile strength, psi	Time to fracture	Impact velocity, ft./sec.
3	12,000	1.6 sec.	(static test)
5	12,500	540 μsec.	14
7	12,300	350 μsec.	23
8	12,000	160 μsec.	31
11	13,700	215 μsec.	31

The tensile strength reported in Table I is an engineering stress, calculated from the peak cylinder pressure observed, the minimum measure original wall thickness, and the original specimen inside radius, by the formula $\sigma_{\theta\theta} = (P \text{ max. } r_0/t_0)$.

Two subsequent tests have been made to evaluate the mild steel test assembly. For these two tests a dummy specimen (hard aluminum alloy, 0.375 in. I.D., 0.479 in. O.D.) was used. In the first test a peak cylinder pressure of 11,000 psi was developed by an $8^3/_4$ lb.-wt. falling thru 15 ft. with no damage to the cylinder assembly and no noticeable (visual—no measurements were made) plastic deformation of the specimen. In the second test a drop of $12^1/_4$ lb. thru 15 ft. produced a peak oil pressure of 12,300 psi, resulted in the specimen blowing out to a maximum O.D. varying from 0.522 in. to 0.524 in. over the cross section, and blew the O-Ring on the downstream end of the inlet gland of the cylinder assembly. There was no other damage to the apparatus.

Discussion of Results

Because of the high natural frequency of the pressure cell, disturbance of the record by ringing is not evidenced in this test. The two predominant frequencies in the pressure record of Figure 3 are about 12 and 27 kc. Assuming a sonic velocity in oil of 5×10^4 in./sec. these frequencies correspond to transit distances of 4.1 and 1.8 in. respectively, and apparently mark transits of pressure waves from the top to the bottom of the cylinder. The sensitivity of the strain sensing system is unfortunately not great enough to resolve these transits; it will be interesting to try to resolve them with improved apparatus.

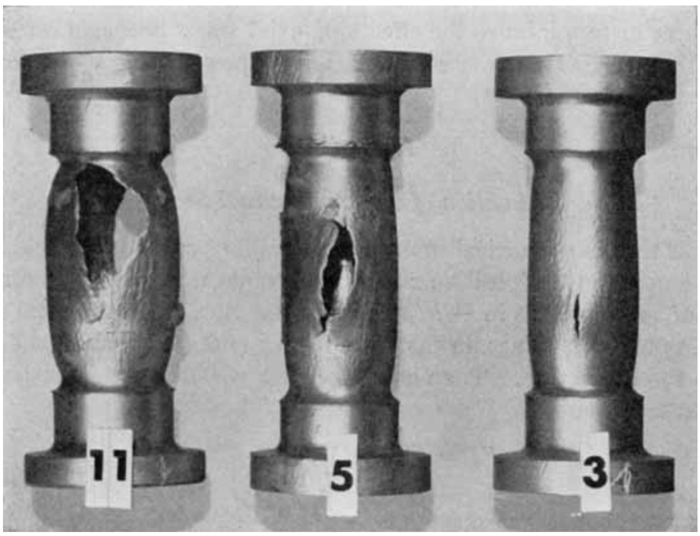

Fig. 4. Fractured specimens.

The photograph of the fractured specimens, Figure 4, shows clearly the increasing amount of uniform deformation resulting from increasing strain rate.

The use of strain gages for the measurement of strains on the specimen is not desirable, and a redesign of the photoelectric shadowing system is in process.

A photoelectric device, or any other device sensing specimen diameter, will indicate the average strain in the diameter. The situation is analogous to making measurements on a standard tensile specimen, using a gage length of about $1^1/_4$ in. Assuming deformation is uniform, it appears that the circular cross section is stable, and a diameter measurement will accurately indicate the uniform strain. This conclusion is supported by the test mentioned above, in which a dummy specimen originally 0.479 in. O.D. was blown out to a maximum O.D. varying from 0.522 in. to 0.524 in. The corresponding hoop strain varies from 9.0% to 9.4%, a variation of $\pm 2.2\%$.

Further investigation of the local instability leading to blister formation and to fracture is required. The analogue is the necking instability in a conventional tension test, and diameter measurements in the tube test lose meaning just as do measurements on a long gage length in tension. The state of stress in either case becomes different than uniaxial tension, and in either case there will be local variations in strain rate, although these are not of concern in the conventional tension test. It appears questionable that usable data can be obtained in the tube test beyond the instability point, except for fracture point data obtained from measurements on the broken specimen, and the main concern at the moment is whether the onset of instability can be recognized from pressure-diameter-time data. Work with a framing camera is believed to be the best attack on this question.

Modifications may be made in the pressurizing system to give higher strain rates or to minimize the effects of axial wave propagation or both. Systems are currently under consideration for pressurizing by explosives or by electric discharge.

Appendix I

Estimation of the Longitudinal Stress

Assume that in cylindrical coordinates the plane $z = 0$ is the midplane of the specimen and the positive z direction points upstream. The reduced section of specimen lies in $-b/2 \leqq z \leqq b/2$. Let M be the total mass of specimen plus end fittings downstream from $z = 0$. Let w be the displacement in the z direction. Then on the plane $z = 0$ at the midsection of the specimen we have

$$F_z = \int_z \ddot{w}_{(z)} dM$$

$$\sigma_{zz} = \frac{F}{A} = \frac{\int_z w_{(z)} dM}{2\pi\left(r + \frac{t}{2}\right)t}$$

where r is inner radius at $z = 0$ and t = thickness.

Assume

$$w = \epsilon_{zz}\left(z - \frac{b}{2}\right)$$

where we have assumed ϵ_{zz} is constant in z and independent of r and θ, and that $\dot{w}_{(b/2)} = 0$. Using the constant volume assumption, based on uniaxial stress, to some degree of approximation

$$\epsilon_{zz} = -\frac{1}{2}\epsilon_{\theta\theta}$$

$$w \cong -\frac{1}{2}\epsilon_{\theta\theta}\left(z - \frac{b}{2}\right)$$

$$\ddot{w} \cong -\frac{1}{2}\ddot{\epsilon}_{\theta\theta}\left(z - \frac{b}{2}\right)$$

and

$$\sigma_{zz} = \frac{\int_z -\frac{1}{2}\,\ddot{\epsilon}_{\theta\theta}\left(z - \frac{b}{2}\right) dM}{2\pi\left(r + \frac{t}{2}\right) t}$$

Further, assume $\ddot{\epsilon}_{\theta\theta}$ independent of z, and that $dM = \rho(2\,\pi)\left(r + \frac{t}{2}\right) tdz$ for all z: then

$$\sigma_{zz} = \frac{-\frac{1}{2}\,\ddot{\epsilon}_{\theta\theta}\rho(2\pi)\left(r + \frac{t}{2}\right) t \int_{-b/2}^{0}\left(z - \frac{b}{2}\right) dz}{2\pi\left(r + \frac{t}{2}\right) t}$$

$$= -\frac{1}{2}\,\rho\ddot{\epsilon}_{\theta\theta}\left[\frac{z^2}{2} - \frac{bz}{2}\right]_{-b/2}^{0}$$

$$\sigma_{zz} = \frac{3}{16}\,\rho b^2\ddot{\epsilon}_{\theta\theta}$$

Suppose $\ddot{\epsilon}_{\theta\theta}$ changes by 100/sec. in 20 μsec. and that $\rho = \frac{160}{32.2}$ slugs/ft.[3] and $b = {}^1/_2$ in. Then

$$\sigma_{zz} = \frac{3}{16}\left(\frac{160}{32.2}\right)\left(\frac{{}^1/_2}{12}\right)\left(\frac{1000}{20 \times 10^{-6}}\right)$$

$$\sigma_{zz} = 80{,}700\ \frac{\text{lb.}}{\text{ft.}^2}$$

$$\sigma_{zz} = 550\ \text{psi.}$$

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