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TRANSIENT LOADING OF THIN-WALLED CYLINDERS

By

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Stanley Anthony Mosier

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ABSTRACT

The effect of internal static loading and internal transient loading on the deformation of thin-walled tube specimens was studied for both the elastic and plastic regions. The specimens employed were six inch sections of type 304, seamless, stainless steel tubing having a nominal O. D. and wall thickness of 3/4 inch and 0.020 inch, respectively.

The transient forces were obtained from detonations of stoichiometric hydrogen-oxygen mixtures contained in a shock-type detonation tube. Each specimen was postfixed to the detonation tube and then acted as an extension of the tube. The detonation wave travelled through the system and exerted on the specimen walls a strain from either a single incident wave pressure or from an incident plus reflected wave pressure combination, depending upon the apparatus used to cap the downstream end of the specimen. Strains in the elastic region were measured with bonded electric resistance strain gages, while strains in the post-yield region were measured with a micrometer.

The static loading forces were obtained from high pressure oil fed from a hydraulic pump into the specimen.

The Young's Modulus of Elasticity for transient loading was 1.22 times greater than for static loading. Similarly, the 0.2 percent offset yield strength for the incident detonation wave transient loading case

(over)

and for the incident plus reflected detonation wave transient loading case were 1.41 and 1.50, respectively, times the static yield strength.

The results of this investigation indicated that as the time of force application decreased, the ability of type 304 stainless steel to resist deformation increased. In other words, the specimen exhibited a much higher value of toughness, elastic resilience and hyper-elastic resilience when loaded by a transient force than when loaded statically.

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I. INTRODUCTION

A. Background

In designing a homogeneous nuclear reactor, engineers are confronted with a number of complex problems. Some of these difficulties evolve from the selection of a fuel - moderator combination. If the fuel is an enriched aqueous solution of uranyl sulfate and the moderator is water or deuterium oxide, serious consideration must be given to the possibility of a detonation occurring within the system. This danger arises from the very nature of the reactor when during fission of the radioactive component a detonable mixture of hydrogen, oxygen and steam may be produced as radiation decomposition products.

There are several ways in which this hazardous situation may be handled: (1) the endangered portion of the reactor may be designed to completely withstand a detonation, (2) the reactor may be designed in such a manner to effect the arresting or dampening of any detonation that may occur, (3) the reactor may be operated out of the possible detonation range.

Under the auspices of the Reactor Experimental Engineering Division of Oak Ridge National Laboratory investigations of each of the above design propositions have been performed at Syracuse University (1, 30). This investigation is concerned with the first of

these three alternatives, that of designing to withstand a detonation.

Scores of papers have been written on the behavior of metallic bodies under stress but excluding classic static studies and the Charpy and Izod impact tests little or no general standardization of non-static studies has been postulated and accepted. This lack of systematic non-static testing of metals has necessitated that the investigator of each system in question devise a means of acquiring data for his one application. Since the primary purpose of any material of construction is to develop sturdiness, strength and durability commensurate to the application for which it is intended, it is of prime concern that the material testing technique yield exact information concerning these variables. Until a generally accepted, workable theory of the stress state is available, design data for specific applications will have to be obtained from pilot investigations of these simulated systems.

In this investigation three general bits of design information were desired: (1) a stress-strain relationship for thin-walled, seamless, stainless steel tubes subjected to internal detonative loading; (2) the effect of the reflected detonation wave on this relationship; (3) a comparison of stress properties resulting from slow static loading with those resulting from detonative loading.

The stress-strain relationship of materials is known to vary depending upon the method of specimen loading. In brief, Roark (38) has postulated the following general types: (1) short-time static loading, where the maximum load is applied so gradually that all parts at any instant are essentially in equilibrium; (2) long-time static loading, where the maximum load is applied gradually and is maintained a sufficient time to enable its probable final effect to be predicted; (3) repeated loading, where the load is applied and wholly or partially removed, or reversed many times in rapid succession; (4) dynamic loading, where the loading conditions are such that the rate of change of momentum of the parts must be considered.

To elucidate the overall picture even more dynamic loading may be subdivided into: (1) impact loading, where the subject loaded must absorb a definite amount of energy; (2) quick static loading, where the disturbing force imparts no appreciable momentum to itself or the specimen and equilibrium is considered to exist at any instant; (3) sudden loading, where a weight or "dead load", not in motion, is suddenly placed on the test specimen.

One other means of loading has become extremely important in recent years, that of transient loading. Although it may be incorporated into one of Roark's divisions, transient loading is

considered here as an entity and may be defined as dynamic loading when the time of application is of the order of microseconds. It is with this class that detonative loading will be considered. Since the methods of loading differ only in the time dependence of the applied force, it is reasonable to believe that the deformation then is a direct function of time.

B. Literature Survey

1. Impact Testing

The study of the dynamic loading of metals was for many years considered synonymous with the study of impact loading. In 1953, Committee A-3 on steel of the American Society for Testing Materials described the impact tests of steel for production purposes as follows:

An impact test is a dynamic test in which a selected specimen, machined or surface-ground and usually notched, is struck and broken by a single blow in a specially designed testing machine, and the energy absorbed in breaking the specimen is measured. The energy values determined are qualitative comparisons on a selected specimen and cannot be converted into energy figures that would serve for engineering design calculations. The notched behavior indicated in an individual test applies only to specimen size, notch geometry, and testing conditions involved, and cannot be applied to other sizes of specimens and conditions. Minimum impact requirements are usually specified only for quenched, and tempered, normalized and tempered, or normalized materials, as provided in the appropriate product specifications.

The lack of general application of the above description indicates that even today the understanding of dynamic phenomena is little better than it was in 1935 when H.C. Mann stated (31):

The object of impact testing has been to obtain a certain result for one specific purpose, which naturally led to the use of a variety of shapes and sizes of test specimens, each giving a new impression as to the interpretation of

results. This chaotic condition has unquestionably been one of the greatest influences retarding advancement to the thorough understanding of the impact test.

However, from this "chaotic" state have evolved some good ideas regarding the behavior of metals under dynamic loads.

The energy capacity of a metal is a measure of the ability of that material to absorb shock or store energy when subjected to an impact load. This measurement is designated by an elastic resilience, toughness, and/or hyperelastic resilience.

FIGURE 1

Stress vs. Strain for Mild Steel

From the above general diagram, Figure 1, the elastic resilience is represented by area X where e is the elastic limit of the material. This area designates the amount of energy that is recoverable when stress is released from the elastic limit. When

the load is released from point β in the plastic region, area Y is known as the hyperelastic resilience. Toughness is that property of a material which is related to the work required to initiate rupture and may be determined from the area under the total static stress-strain diagram.

The variation in toughness with the energy absorption rate has been studied directly and indirectly since the 1800's when the first papers on dynamic loading appeared in the literature. However, little correlating of information from these tests with static tests was made. For example in 1917 Guillery, Charpy, and Cornu-Thenard (20) conducted elaborate impact tests at velocities from 2.5 to 21.5 feet per second. Their results seemed to show that the absorption of energy was independent of impact velocity. This work was considered to have settled the question about differences in static and dynamic loading. In fact, the velocity factor was discounted as being of any importance at all.

This conclusion, however, did not appear to cause notable changes in the philosophy of investigators, since the argument concerning the effect of time on the stress state was already in its second century of progress. It began with Thomas Young in 1804 when he stated that an elastic deformation of a bar is

transmitted at a velocity corresponding to the velocity of sound in that bar. Though this was the inception of a new concept in the understanding of metallic deformation, it was many years before it was even clear what would happen if the velocity of impact were great enough to produce a strain in excess of the proportional limit. In the 1800's there was even considerable uncertainty about the elastic limit and the proportional limit.

To offset the controversies concerning the interpretation of the impact test, and to promote a more definite and intensive study of the subject, a symposium on the impact testing of materials was held in 1922 (2). However, indications were clear that a wide divergence of opinion and interpretation existed concerning the impact test. There were two significant facts that emerged from this conference, though: (1) a material has the capacity of absorbing a definite amount of energy per unit volume; (2) a material possesses a limited rate for maximum energy absorption.

In 1935, H.C. Mann (31) employed a tension form of specimen that could be tested under both static and dynamic conditions. His work led to a correlation of the two, involving

consideration of the fact that:

... a material in its initial state possesses a certain amount of inherent potential energy which, during the process of deformation, is apparently converted to kinetic energy and manifested as increased elastic strength.

Mann presented data which indicated that the mechanism of the process of deformation and rupture were essentially the same under both static and dynamic conditions. It was also Mann's opinion that since time is required for energy conversion to occur, the total energy value obtained must be dependent upon force, time, and space, and, therefore, to obtain complete knowledge of the dynamic properties of materials, the velocity of the force applied must be considered. His research verified the data of Guillery, Charpy, and Cornu-Thenard when velocities from 11 to 17 feet per second were used but showed the time dependence of deformation when velocities were increased beyond this range. Although limited by lack of impact machines producing higher velocities, Mann realized the necessity of investigating a range of velocities to obtain complete knowledge of the dynamic properties of materials.

In the following year Mann (32) investigated high velocity tension impact tests and presented data which definitely

showed that high velocity tests were essential to reveal the true dynamic properties of materials. Three significant factors were presented for consideration in the selection of materials for use under dynamic loads: (1) the transition velocity within which normal material behavior may be expected; (2) the ratio of total energy value to mass or volume of material involved; (3) the effect of surface irregularities such as tool marks, etc.. His investigations were unique since it was the first time the conclusive proof was offered illustrating the direct effect of velocity on deformation. Thus, Mann's work resulted in a pioneer contribution to the field of kinematics of stress.

In 1938 at the Second American Society for Testing Materials Symposium on Impact Testing (3), Clark and Datwyler (9) presented a paper containing some of the first experimental force-elongation diagrams for metals under tension impact loads. The results indicated that for most of the materials tested the yield forces under dynamic conditions were higher than those under static conditions. In general, they stated that the maximum dynamic forces were greater than the maximum static forces. A result of their experimental work is presented in the curve below, Figure 2, of force versus elongation for 18-8 stainless steel.

FIGURE 2

Force vs. Elongation for 18-8 Stainless Steel
Clark and Datwyler (9)

Clark and Datwyler also indicated that the physical properties of cold-worked materials in dynamic tension are superior to those in static tension. It was found that these cold-worked materials also showed considerably more elongation when loaded dynamically than when loaded statically.

Around this same time Quinney (37) designed a machine that would allow a material to be extended in tension at a fixed rate which could be made almost indefinitely slow. Quinney proposed to establish a datum by which all dynamic and present-day static tests could be based. Below is shown one of his load extension diagrams for Yorkshire Iron.

FIGURE 3

Load vs. Extension for Yorkshire Iron
Quinney (37)

From Figure 3 the yield stress and ductility were considerably lower at very low speeds, 75 hours per run, than when the test was completed in two minutes. Quinney in his paper commented on these results by making the generalization that at extremely rapid and at extremely low rates of loading the material assumed a brittle state. This comment concerning extremely rapid loading was the outcome of an unreferenced statement that when a detonated high explosive was employed as a loading agent, the ductility of the metal was remarkably low.

The status of impact loading remained about the same

for a number of years. Whittemore, Nusbaum and Seaquist (46) extensively investigated static and dynamic properties of bolts. Davis (13), Davidenkoff (12), Ginns (19), Moore (34) and others continued to observe impact loads under all conditions of loading but only stated what those investigators before them had discovered, a material could sustain an impact load when it would fail statically.

2. Electric Resistance Strain Gages

Since the discovery of Lord Kelvin, i. e. Sir William Thomson, of a strain-resistance change relationship for copper and iron wires in 1856, investigators in the field of materials testing have attempted to utilize this principal. However, it was not until 1930 that an all out effort was made to apply the phenomenon of strain sensitivity in wires to the actual measurement of strain in other bodies.

In 1930 Shamberger (40) recognizing the shortcomings of available laboratory instruments in not only static but especially dynamic work, designed a magnetic strain gage. This was somewhat of a cumbersome instrument but was employed satisfactorily for measuring dynamic strain in such structures as railroad rails, locomotive side rods, wheels, shafts, etc.

Eaton in 1931 (16) designed and used an electric resistance gage embedded in concrete to determine buckling effects. Carlson (8) improved on the work of Eaton and in 1935 presented his contribution to the growing field of electric resistance strain gages. Also contributing independently were Hathaway and Lee (22), Block (6), and Hull (25), each of whom had his own electric resistance strain gage.

In 1938 Clark and Datwyler (9) used a tension dynamometer and obtained the force-elongation diagrams for a number of steels subjected to dynamic loading. This was the first time that an investigation of this nature utilizing an electric resistance strain gage was employed. It was also noted here that the frequency response of this instrument was 16,000 cycles per second.

The present-day result of these studies is the bonded electric resistance strain gage perfected independently and almost simultaneously in 1938 by Simmons at California Institute of Technology and Ruge at Massachusetts Institute of Technology. To the advent of the Simmons-Ruge gage (commonly known as the SR-4 gage) can be attributed the wide-spread growth and application of experimental stress analysis and, indirectly, most of the significant mechanical achievements since 1940. Because of its simplicity,

size, and extremely rapid mode of response to deformation, the SR-4 gage was immediately recognized as being one of the most promising aids in the study of dynamic stress-strain relationships of materials. However, it was a few years before commercially available bonded electric resistance strain gages were to be had. It was necessary first to (1) develop satisfactory techniques for securing the strain sensitive wire to the test structure, (2) find the best wire with which to build the gages, (3) overcome calibration difficulties, and (4) establish mass production techniques.

The SR-4 gage is a very simple instrument. Essentially it consists of a thin wire cemented to a thin paper carrier to form a measuring element for the determination of superficial deformations. This is then cemented to the subject under investigation by a special cement. The movements in the surface of the object are translated through the layer of cement and paper carrier to the metal wire of the gage and hence, proportional variations in resistance are brought about that can be measured by electrical means. Details concerning the physical characteristics and means of selecting a strain gage are found well described by Lissner (29) and the Baldwin-Lima-Hamilton Corporation (5).

3. Transient Loading

With the fundamentals established by early investigators, and the new opportunities for investigation offered by the bonded electric resistance strain gage, workers in the field of experimental stress analysis could now examine more closely the dynamic properties of materials, especially under conditions of transient loading.

The imparting of a finite force to a body in other than finite time is physically impossible and may be merely approached as a limit. Transient loading is considered to encompass those methods of investigation that closely approach this limit. This differentiating of the transient phenomenon from the dynamic was made so the results of dynamic investigations could be more precisely categorized according to time dependence of the applied force and frequency response.

In 1804 Thomas Young had begun to establish the theory of elastic strain propagation in metals but had not been successful in establishing any theories concerning plastic strain wave propagation. Investigators such as Sears (39), Hopkinson (23), Moore (34), and Prowse (36) have also studied plastic strain wave propagation but, as Young, were unsuccessful in establishing any

generally accepted theories.

Then in 1941 a new light was placed on the time dependence of the stress state. Von Karman and Taylor each independently established the theory of plastic strain wave propagation in metals by considering the equation of motion of particles in the metal in relation to the stress-strain diagram. According to this concept, the velocity of propagation for a plastic strain wave will be less than for an elastic strain wave and can be expressed by:

$$c_e = \sqrt{\frac{\delta\sigma / \delta\epsilon}{\rho}} \quad (1)$$

The velocity of propagation, then, is a function of strain in the general case in which plastic as well as elastic strains are produced.

The impact velocity may be expressed as:

$$v_1 = \int_0^{\epsilon_1} c \, d\epsilon \quad (2)$$

This indicates an impact velocity, v_1 , will produce a maximum strain, ϵ_1 , that will propagate at a lower velocity than a smaller strain.

Since the most fundamental indication of the resistance of a metal to deformation is a stress-strain relations, with this added knowledge it appeared that a true stress-strain curve could

be obtained from static data and velocity measurements. However, this analysis could be applied only to long bars subjected to impact at one of the ends. Consequently, some dynamic properties of a specific material could be obtained from this latter approach but the true properties of that material in practice had to be determined from the conditions under which it was to be subjected. This latter approach, unfortunately, was exactly the same as that of the pioneer investigators in the field.

In 1943, Dohrenwend and Mehaffey (15) studied strains of both high and low frequencies. For the former they employed a potentiometric strain gage circuit which was found to reproduce the effects of the forced transient loads on their specimens very nicely.

In this same year Fehr and Parker (17) employed strain gages in the tension impact testing of cold-rolled steel at impact velocities up to 100 feet per second. They found that as the impact velocity was increased, the dynamic tensile strength likewise increased.

Transverse impact transients were studied by Dohrenwend, Drucker and Moore (14) to demonstrate that (1) usable experimental techniques did exist for such measurements, and (2) strain gages

were extremely flexible and reliable in applications such as this.

In 1945, Leal, Bisplinghoff, and Pian (26) investigated a complex problem in the stress analysis of an aircraft wing by employing SR-4 gages and an equivalent measuring system. They were concerned with the studies of transient stresses in an airplane wing model and the time history of the bending and torsional movements in the wing during impact. It was shown that although strains due to transient loading could be recorded and satisfactorily reproduced by a conventional strain gage measuring system, much improvement was necessary in the latter before strain gages could be applied to such complex problems.

Specific reference to transient loading, as defined in this section, was not found very often in the literature because of the lack of general standardization of terms in the field of dynamic loading. However, the work of many investigators, although referred to as impact, impulse, shock, or generally dynamic loading was in reality what would be considered transient loading.

As this need for transient data became more and more apparent it was necessary to first design apparatus that

would apply a desired force instantaneously. Vigness (44), Welch (45), and Armstrong (4) were primarily concerned with the design of shock testing apparatus while Hansen's efforts (21) were with a controlled impulse testing machine. These investigators were essentially trying to approach the fore-mentioned limit of loading so that a complete picture of the effect of loading velocity on deformation could be obtained.

Taylor (42), Hoppmann (24) and Clark and Wood (47) employed such improved methods of loading and measuring and continued the investigation of material properties at high rates of loading. The same general conclusion was made, however, that a material can withstand a dynamic force where it would fail statically. These repeated substantiations of previous work that now entailed a wide range of loading rates encouraged stress analysts to continue along this line.

In 1947, Shepler (41) investigated a new approach to transient loading, explosive impact tests. Shepler's apparatus employed a specially prepared bomb as the loading medium and a strain gage plus oscilloscope combination for indicating and recording the deformation of the specimen. For each of the materials tested the strength was observed to increase with the

strain rate. Then, except for C.I.T. cast steel, each of the specimens was observed to (1) increase in ductility with an increase in strain rate; and (2) increase in deformation energy with an increase in strain rate.

In 1951 Cohen and Schauer (10) measured strains on structures subjected to underwater explosions at the Norfolk Naval Shipyard. Strain distribution contours were obtained at various critical supports in naval vessels. The technique employed was a very novel application of the strain gage-oscilloscope combination.

Detonative loading as such was mentioned by Campbell (7) in 1932. Campbell used rupture disks to investigate the ratio between the unreflected detonation wave pressure and the initial gas pressure. The results of this study indicated that the disks would break at the same ultimate strength regardless of whether they were loaded dynamically or statically.

Gernstein (18) studied the detonative loading of rupture disks to determine the static versus dynamic characteristics of a material. It was concluded from this work that rupture disks may fail at a lower dynamic load than under static loading.

In 1955 Leibson (27) determined (1) the dynamic

ultimate yield stress; and (2) the effect of work-hardening on the latter, for four metals. As did Campbell and Gernstein, Leibson employed rupture disks for specimens and detonations for loading forces. The results of this study indicated that (1) the ratio of the theoretical dynamic ultimate yield stress to the rupture disk rating was greater than one (1) for all metals studied; (2) the relationship between the theoretical dynamic ultimate yield stress and the rupture disk rating was linear; (3) of the four materials tested only phosphor bronze did not dynamically work - harden.

It may be considered that these latter references and the work of Cole (11) indicate the present status of such transient loadings. All the papers and references given throughout this discussion have shown the general results that may be expected from the transient loading of metals. Since the dynamic properties of a material are very dependent upon small changes in loading velocity, physical characteristics of the specimen employed, etc., this illustrates that a fundamental approach is necessary to establish an understanding of the dynamic test and not merely the continued varying of testing techniques. Even comparing the physical properties of materials does not have

significance unless identical specimens under identical loading conditions are employed.

It is sincerely hoped that this present study will (1) provide a basis for future investigations of detonative loading; and (2) re-emphasize the need for a good fundamental study of the dynamic loading of materials.

II. APPARATUS

A. Specimen Selection

The selection of 3/4 inch O.D., 0.020 inch nominal wall thickness, type 304, seamless, stainless steel tubing as the test specimens was made for several reasons:

(1) Type 304 stainless steel or a similar type stainless steel will be used as the material of construction for reactor components.

(2) The thin-walled tubing was found to respond more satisfactorily to testing conditions than heavier-walled tubes.

The former reason is self-explanatory but the latter is the result of a preliminary investigation using heavier-walled tubes (0.035 inch nominal wall thickness). The preliminary results showed that for a constant loading force the strain was inversely proportional to the wall thickness. Thus, by using a very thin-walled tubing it was possible to employ lower detonation pressures throughout the entire range investigated without reducing the precision of measurement.

The tubing used was purchased from Superior Tube Company, and had minimum requirements shown in Appendix A.

FIGURE 4

B. Dynamic Studies

The dynamic measuring system consisted of two major parts as shown in Figure 4: (1) the loading apparatus for supplying the detonative force; and (2) the measuring apparatus for indicating and measuring the resultant deformation.

The detonating agent was a stoichiometric mixture of hydrogen and oxygen that was premixed and contained in a specially designed high pressure storage tank. The mixture was fed from this storage location through 1/4 inch O.D., 3/32 inch I.D., type 304, seamless, stainless steel pressure tubing and 30,000 p.s.i. stainless steel needle valves to the loading tube. Desired initial gas pressures in the loading tube were safely obtained by employing an elaborate filling system, Figure 5.

The loading tube, or detonation tube, was an eight foot section of seamless steel tubing with an I.D. of 0.687 inches and a wall thickness of 0.313 inches. The length of the tube was such that a stable, plane detonation wave could be established (28). Theoretically, this tube could withstand an internal pressure of 16,000 p.s.i. which was well above the theoretical maximum detonation pressure obtainable from the maximum gas pressure employed. At one end of the detonation

tube were located the specimen tube adapter, detonation tube extender, and rupture disk assembly, and at the other end were located the source of gas ignition and the gas entry tube.

The gas inlet tube was constructed of the same superpressure tubing as were the high pressure lines in the filling system. The inlet line was heliarc welded to the parent tube three inches from the end of the latter and was connected to the filling system as shown in Figure 5.

The source of gas ignition was a hot wire as shown in detail in Figure 6. It was found during preliminary detonation studies by Leibson (27) that when a spark source of ignition was employed the electrodes tended to corrode after a number of detonations had been set off and then refused to spark. This necessitated the periodic dismantling of the spark plug for cleaning purposes. With the hot wire as designed no such delay was ever necessary. Physically it consisted of a 3/4 inch heavy duty spark plug with a small coil of heavy steel wire welded on the terminals of the plug. An overload spring with a high amperage rating from a safety switch was employed for the latter. The whole plug was then threaded into the detonation tube with a copper gasket used for the pressure sealant. The direct current necessary for

FIGURE 5

Filling System for Detonable Gas Mixture

FIGURE 6
Hot Wire Igniter

heating the igniter was obtained from a common battery booster. This proved to be very satisfactory: the hot wire requiring a very short time (10 seconds) to reach a temperature sufficiently high to ignite the gas mixture.

The specimen adapter shown in Figure 7 was chosen after a number of preliminary designs were first considered. Since it was imperative that the detonation wave travel unrestricted with no discontinuities in the loading tube the adapter construction had to be such that the internal diameters of the specimen tube and the detonation tube matched up almost exactly. The specimen also had to be held flush to the detonation tube while acting as an extension of the original tube. In addition, the adapter had to be such that it retained an initial gas pressure of 287 p.s.i.g., and a reflected internal detonation pressure of around 12,000 p.s.i. By employing a double "O"-ring seal in a steel cylinder that was in turn welded to the detonation tube, a very satisfactory adapter was obtained.

The downstream specimen adapter was identical to that of the upstream except that it had a 13 inch detonation tube extender of the same diameter as the original welded to it as shown in Figure 7. The two parts comprising the whole adapter held the

FIGURE 7

specimen in place with the aid of the steel flanges and stringers.

Screwed into the end of the tube extender was a standard 3/4 inch rupture disk assembly. It was possible with this to employ weak and strong rupture disks that could be interchanged to study the effect of incident waves and reflected waves, respectively, on the specimen.

The specimens employed were six-inch sections of 3/4 inch O.D., 0.020 inch wall, seamless, type 304 stainless steel tubing. These specimens were cut from long sections of tubing with an ordinary pipe cutter so that the specimens were shaped as shown in Figure 8. The distorted openings of the tubing were then internally filed so that their diameters were identical to the I.D. of the loading tube. This design configuration was necessary for the unrestrained introducing of the specimen past the "O"-rings into the adapters.

The type of strain gage chosen for indicating the instantaneous average deformation was the Baldwin-Lima-Hamilton SR-4, type PA-3 gage shown in Figure 9. This gage is commonly known as the post-yield gage because of its ability to be deformed up to ten percent of its own length whereas all other gages deform at about one percent. Employing the strain gage as the primary

FIGURE 8

Test Specimen

FIGURE 9

The SR-4, Type PA-3 Strain Gage

measuring instrument was decided upon after some correspondence with the Navy Department who had used strain gages with great success for explosive-type loadings (35) and strain-impulse type loadings (43). It appeared from these and other sources that deformations due to detonations could be satisfactorily indicated and reproduced by SR-4 gages.

The nucleus of the dynamic strain measuring system was the Dumont 324 cathode ray oscilloscope equipped with a fixed-focus Polaroid Land Camera. The oscilloscope frequency response was flat to 100,000 cycles per second, and at a maximum sensitivity of 0.004 volts full scale it was down 30 percent at 60 kilocycles per second. The rise time was rated at 1.0 microsecond at 400 millivolts full scale and down 5 microseconds at maximum sensitivity. In addition to its "Y" axis characteristics its "X" axis sweeps were completely calibrated with 19 calibrated linear sweeps selected by front panel controls extending from one second per inch to one microsecond per inch in proportional increments.

Employed in conjunction with this oscilloscope was the Ellis Associates BA-12 strain gage bridge. This was an instrument used to complete a Wheatstone bridge circuit, with

the active and dummy (temperature compensating) strain gages that would indicate on the oscilloscope any unbalance due to a strain. The BA-12 circuit consisted essentially of a d.c. bridge supply, chopper, and an a.c. amplifier with internal provision for calibration. The frequency response of the Ellis a.c. amplifier was flat up to 25,000 cycles per second.

Since the frequency response of the strain gages when subjected to detonation loading was assumed to be above 25,000 cycles per second the amplifier in the BA-12 was not utilized. Instead, a Fairchild Decade Amplifier Model 203 was purchased for this purpose. It was rated at five cycles per second ($\pm 1/2$ db at 3.0 mc.), with a pulse response rise time less than 0.1 microsecond. The equivalent noise and hum of this instrument was 20 microvolts referred to grid input short-circuited.

To obviate the stray noise being generated from a local radio station that was causing difficulty in the reading of small strains on the oscilloscope a low pass filter was designed and placed in the recording system. A wiring diagram of this filter is shown in Figure 10. Figure 11 and Table I represent design criteria for this filter.

FIGURE 10

Low Pass Filter
(m-Derived Sections)

FIGURE 11

Frequency Response for Low Pass Filter

TABLE I

Design Constants for Low Pass Filter

$$f_c = 430 \text{ k.c.}$$

$$f_\infty = 570 \text{ k.c.}$$

$$R = \text{Load resistance}$$

$$m = \sqrt{1 - \left(\frac{f_c}{f_\infty}\right)^2}$$

$$L_k = R / \pi f_c$$

$$C_k = 1 / \pi f_c R$$

$$L_1 = mL_k$$

$$C_1 = [(1 - m^2) / 4m] C_k$$

$$C_2 = mC_k$$

C. Static Studies

The static system likewise consisted of two parts as shown in Figure 12: the loading apparatus and the measuring apparatus.

The pressure for the static loading was supplied by oil forced from an American Instruments hand-operated, hydraulic, high pressure pump rated at 30,000 p.s.i. through high pressure lines into the test specimen. The high pressure lines were constructed of 1/4 inch O.D., type 304, seamless, stainless steel superpressure tubing and 30,000 p.s.i. stainless steel fittings and needle valves. Since the maximum internal pressures considered were around 5000 p.s.i. the safety of this system against internal pressure failure was assured.

The specimens employed for static studies were of the same design as the ones used for the dynamic studies except that the ends were not filed flush with the original internal diameter.

The adapter for the static specimen was of the same general design as that employed in the dynamic studies and is sketched in Figure 13. The specimen was held between the two adapter halves each of which employed two "O"-rings for pressure sealing. The steel tube was then held in place by

Measuring System for Static Loading

FIGURE 13

Static Test Specimen Adapter Assembly

two steel flanges and four stringers that resisted any longitudinal motion due to the internal pressure.

The strain indicating and measuring system was almost the same as that used in the dynamic studies except that the Fairchild amplifier and low-pass filter were not needed. In this case the amplifier in the Ellis BA-12 was perfectly adaptable to studying static strains. The grounding system for the static studies, however, was different from that for the dynamic as seen by comparing Figures 4 and 12.

III. EXPERIMENTAL PROCEDURE

A. Dynamic Studies

1. Elastic Region

The six inch tubular specimen was prepared according to the procedure described in the previous section and an SR-4, type PA-3 strain gage was bonded to the surface in a manner described by Baldwin-Lima-Hamilton Corporation (25). The tubing sample was then inserted into the specially prepared adapters shown in Figure 7, and the stringers were tightened until just taut. In this study of the elastic region a high-rated rupture disk was employed in the assembly at the terminus of the detonation tube extender.

When the specimen was in position and the strain gage leads were connected to the measuring system both the active and dummy gages were covered with a coating of stopcock grease. This acted as a waterproofing agent for the protection of the gages. The active gage was then zeroed-out. This was accomplished by manipulating the oscilloscope, amplifier, and Ellis BA-12 until no deflection on the oscilloscope was observed with zero load on the active strain gage. The controls on the above three instruments were then set to the desired optimum levels of

operation to indicate and record the strain from the fore-coming detonation.

The detonation tube and specimen system was evacuated after which the detonable gas mixture was fed into the system as shown in Figure 5. The desired pressures were obtained by manipulating the series of control valves and reading the pressure on either the 0-60 or the 0-400 p.s.i. pressure gage.

When the detonation tube was filled with the detonable gas mixture at the desired pressure energy was supplied to the hot wire igniter for the battery booster. The strain set up in the specimen from the resulting detonation was recorded on the oscilloscope by the Polaroid Land Camera.

This procedure was applied up to the "dynamic elastic limit" of the specimen which was approximately 60 p.s.i. g. initial gas pressure for the particular specimen employed.

2. Plastic Region

The specimen for studying the plastic region was basically the same as that used for studying the elastic region. However, instead of a strain gage being applied at the center of the specimen the periphery at that point was divided into ten increments. Then the diameter at each of these points was measured with a

micrometer.

The specimen was inserted into the adapters, the stringers were made taut, and the detonation tube and specimen system was evacuated. The detonable gas was fed into the loading tube after which the hot wire was energized, igniting the gas.

The stress resulting from the detonation was from either an incident detonation wave or an incident plus reflected detonation wave combination. For the case where the former was to be studied a low-rated rupture disk was employed in the assembly at the terminus of the detonation tube extender. For the case where the latter was to be studied a high-rated rupture disk was used.

The strain created by either of the above stresses was determined by the difference in the dimension of the tube diameter at the center of the specimen before and after the detonation. This difference divided by the original outside diameter of the tube was equal to the strain set up in the tube from the detonation wave.

Loadings up to 270 p.s.i.g. gas pressure were obtained. This upper limit was the result of safety precautions in the design of the loading system.

B. Static Studies

1. Elastic Region

The specimen for this investigation was identical to the sample employed in the study of the dynamic elastic region. The tube was inserted into the special adapters as shown in Figure 13 and the stringers were made taut.

When the specimen was in position and the strain gage leads were connected to the measuring system the active and dummy gages were covered with a layer of stopcock grease for water-proofing purposes. The active gage was then balanced-out in the same manner as in the dynamic elastic study.

High pressure oil was fed through the system with plug P removed, Figure 13, until the oil was observed to be flowing from P. The plug was replaced and the pressure was increased to the desired level by manipulating the American Instruments hydraulic pump. Readings of internal pressure were made on either a 0-4000 or a 0-20,000 p.s.i.g. pressure gage. Strain readings at desired pressures were obtained from the strain gage, BA-12 and oscilloscope system as shown in Figure 12.

Readings were obtained in this manner for applied pressure versus deformation up to the elastic limit which for this particular set of circumstances and specimen was about 1300 p.s.i.g.

2. Plastic Region

Beyond the static elastic limit the specimen employed and the method for determining the strain in the specimen were basically the same as those used for studying the dynamic plastic region.

The method of applying stress to the specimens was the same as the method described for the static elastic region. Readings of applied pressure versus deformation were then taken up to the breaking pressure of the sample tubes which was 3850 p.s.i.g. These readings were then converted into nominal static hoop stress and nominal static strain in a manner described in the discussion of transient loading.

IV. RESULTS

Three primary pieces of information were obtained from this investigation: (1) a stress-strain relationship for thin-walled, seamless, stainless steel tubes subjected to internal, transient detonative loading; (2) the effect of the reflected detonation wave on this relationship; and (3) a comparison of stress properties resulting from detonative loading with those resulting from static loading.

Presented in Figure 14 are the principal results of this investigation. Curve A relates the nominal fiber hoop stress to the normal fiber strain for static loading. Curve B is plotted as nominal fiber hoop stress based on the incident detonation wave pressure against total incident plus reflected fiber strain. Curve C has as its coordinates nominal fiber hoop stress, based on the incident detonation wave pressure and incident nominal fiber strain. The data for these curves are tabulated in Tables II through VI: Tables II and III for static loading, and Tables IV, V, and VI for transient loading.

An expanded plot of nominal fiber hoop stress versus nominal fiber strain for the elastic region is presented in Figure 15. Curve A refers to the static study and Curve B to the transient.

The data for these plots are tabulated in Tables II and IV.

From the analysis of Figure 14, sufficient information was secured to construct two other curves of importance. The coordinates of each plot and the location of its tabulated data, respectively, are: Figure 16, the ratio of reflected detonation pressure to incident detonation pressure versus initial gas pressure, Table VII; and Figure 17, the ratio of nominal fiber hoop stress to static hoop stress for incident detonation waves versus nominal fiber strain, Table VIII.

The original experimental data for both the transient and static studies are found in Appendix B.

Figure 16

Figure 17

RATIO OF INCIDENT DETONATION WAVE
NOMINAL FIBER HOOP STRESS TO
STATIC NOMINAL FIBER HOOP STRESS
VS.
NOMINAL FIBER STRAIN

TABLE II

Tabulated Data for Static - Loading Elastic RegionRun A. Specimen 1

P_0 (Initial gage pressure, p.s.i.g.)	(P_0) corr. (Corrected pressure, p.s.i.g.)	σ_s (Static nominal fiber hoop stress, p.s.i.)	ϵ_s (Static nominal fiber strain, inches/ inch $\times 10^{-4}$)
100	98.5	1,748	0.8
200	197.	3,497	1.25
200	197.	3,497	1.27
300	295.	5,236	1.80
408	402.	7,136	2.45
600	591.	10,490	3.53
600	591.	10,490	3.63
610	601.	10,670	3.73
700	689.	12,230	4.30
810	798.	14,170	5.00
900	886.	15,730	5.40
1000	985.	17,480	6.00
1200	1182.	20,980	7.43
1400	1379.	24,480	8.85
1600	1576.	27,970	12.60

TABLE II (con't)

Run B. Specimen 2

P_0 (Initial gage pressure, p.s.i.g.)	(P_0) corr. (Corrected pressure, p.s.i.g.)	σ_s (Static nominal fiber hoop stress, p.s.i.)	ϵ_s (Static nominal fiber strain, inches/ inch $\times 10^{-4}$)
100	98.5	1,748	0.63
200	197.	3,497	1.32
210	217.	3,852	1.40
300	295.	5,236	1.78
330	325.	5,769	2.24
430	423.	7,508	2.51
500	492.	8,733	3.20
600	591.	10,490	3.52
730	719.	12,760	4.53
810	798.	14,170	4.82
900	886.	15,730	5.45
1000	985.	17,480	6.20
1100	1083.	19,220	6.90
1200	1182.	20,980	7.35
1300	1281.	22,720	8.28
1400	1379.	24,480	9.90
1500	1477.	26,220	11.50
1600	1576.	27,970	15.20
1700	1674.	29,710	18.30
1800	1772.	31,450	25.10

TABLE III

Tabulated Data for Static-Loading Post-Yield Region

P_0 (Initial gage pressure, p.s.i.g.)	(P_0) corr. (Corrected gage pressure, p.s.i.g.)	σ_s (Static nominal fiber hoop stress, p.s.i.)	(σ_s/E) (Post yield strain con- tribution, in/ in. $\times 10^3$)	ϵ_s (Residual strain due to σ_s , in/ in. $\times 10^3$)	$\epsilon_t = \epsilon_s + \sigma_s/E$ (Total static strain, in/ in. $\times 10^3$)
2000	1969	34,950	1.20	6.70	7.90
2500	2462	43,700	1.50	34.2	35.7
2700	2659	47,200	1.62	53.2	54.8
3000	2954	52,430	1.80	80.1	81.9
3200	3151	55,930	1.92	104	106
3500	3446	61,170	2.10	159	161
3850	3791	67,290	—	Burst	—
2200	2167	38,460	1.32	7.76	9.08
2300	2265	40,200	1.38	28.2	29.6
2900	2856	50,690	1.74	70.8	72.5
3100	3053	54,190	1.86	106	108

TABLE IV

Tabulated Data for Transient-Loading Elastic RegionRun A. Specimen 4

P_0 (Initial gage pressure, p.s.i.g.)	(P_0) corr. (Corrected gage pressure, p.s.i.g.)	(P_0) corr. (Absolute pressure, p.s.i.a.)	(P_i) det. (Incident detonation pressure, p.s.i.a.)	(P) det. - (P) atm. (Incident detonation pressure, p.s.i.)
5	2.0	16.7	326.8	312
10	7.0	21.7	424.7	410
16	13.0	27.7	543.1	527
20	17.0	31.7	620.4	606
25	22.0	36.7	718.2	704
30	27.0	41.7	816.1	801
35	32.0	46.7	913.9	899
40	37.0	51.7	1012.	997
45	42.0	56.9	1114.	1099
10	7.0	21.7	424.7	410
7	4.0	18.8	367.9	353
25	22.0	36.7	718.2	704
8	5.1	19.8	387.5	373
18	15.0	29.7	581.2	567
0	0.0	14.7	287.7	273
50	47.6	62.3	1219.	1205
55	53.2	67.9	1329.	1314
60	59.3	74.0	1448.	1434

TABLE IV (con't)

Run A. Specimen 4

σ_i (Incident nominal fiber hoop stress, p.s.i.)	ϵ_i (Incident nominal fiber strain, in/in. $\times 10^4$)
5,538	2.15
7,278	2.88
9,354	3.70
10,760	4.10
12,500	4.29
14,220	4.67
15,960	5.42
17,700	5.60
19,510	6.00
7,278	2.88
6,266	2.50
12,500	3.98
6,621	2.50
10,060	3.47
4,846	1.95
21,390	6.85
23,320	6.90
25,450	6.90

TABLE IV (con't)

Run B. Specimen 5

P_0 (Initial gage pressure, p.s.i.g.)	(P_0) corr. (Corrected gage pressure, p.s.i.g.)	(P_0) corr. (Absolute pressure, p.s.i.a.)	(P_i) det. (Incident detonation pressure, p.s.i.a.)	(P) det. - (P) atm. (Incident detonation pressure, p.s.i.)
0	0	14.7	287.7	273
7	4.1	18.8	367.9	353
10	7.0	21.7	424.7	410
15	12.0	26.7	522.5	508
20	17.0	31.7	620.4	606
25	22.0	36.7	718.2	704
30	27.0	41.7	816.1	801
35	32.0	46.7	913.9	899
40	37.0	51.7	1012.	997
45	42.2	56.9	1114.	1099
50	47.6	62.3	1219.	1205

TABLE IV (con't)

Run B. Specimen 5

σ_i	ϵ_i
(Incident nominal fiber hoop stress, p.s.i.)	(Incident nominal fiber strain, in/in. $\times 10^4$)
4,846	2.14
6,266	2.62
7,278	2.82
9,017	3.32
10,760	3.80
12,500	4.20
14,220	4.58
15,960	5.00
17,700	5.82
19,510	6.35
21,390	6.55

TABLE V

Tabulated Data for Transient-Loading Post-Yield Region
(Incident Detonation Wave Influence)

P_0 (Initial gage pressure, p.s.i.g.)	(P_0) abs. (Corrected gage pressure, p.s.i.a.)	(P_0) abs. (Absolute pressure, p.s.i.a.)	(P) det. (Incident detonation pressure, p.s.i.a.)	(P) det. - (P) atm. (Incident detonation pressure, p.s.i.)
270	281.7	284.7	5513	5498
260	271.7	274.7	5317	5302
250	261.7	264.7	5121	5107
240	251.7	254.7	4926	4911
225	236.7	239.7	4632	4618
220	231.7	234.7	4534	4520
220	231.7	234.7	4534	4520
210	221.7	224.7	4339	4324
200	211.7	214.7	4143	4128
190	201.7	204.7	3947	3933
180	191.7	194.7	3752	3737
170	181.7	184.7	3556	3541
150	161.7	164.7	3360	3345
140	151.7	154.7	2969	2954
130	141.7	144.7	2773	2758

TABLE V (con't)

σ_i (Incident nominal fiber hoop stress, p.s.i.)	(σ_i/E) (Post-yield strain contribution in./in. $\times 10^3$)	ϵ_i (Residual strain due to σ_1 , in./in. $\times 10^3$)	$\epsilon_t = \epsilon_i + \sigma_i/E$ (Total incident strain, in./in. $\times 10^3$)
97,590	2.73	57.4	60.1
94,120	2.64	50.0	52.6
90,650	2.54	45.5	48.0
87,170	2.44	40.0	42.4
81,960	2.30	26.5	28.8
80,220	2.25	23.1	25.4
80,220	2.25	24.8	27.1
76,750	2.15	22.3	24.5
73,280	2.05	14.1	16.2
69,800	1.96	12.5	14.5
66,330	1.86	8.05	9.91
62,860	1.76	6.27	8.03
59,380	1.66	3.71	5.37
52,440	1.47	2.70	4.17
48,960	1.37	2.17	3.54

TABLE VI

Tabulated Data for Transient-Loading Post-Yield Region
(Incident Plus Reflected Detonation Wave Influence)

P_0 (Initial gage pressure, p.s.i.g.)	(P_0) abs. (Corrected gage pressure, p.s.i.a.)	(P_0) abs. (Absolute gage pressure, p.s.i.a.)	(P) det. (Incident detonation pressure, p.s.i.a.)	(P) det. -(P) atm. (Incident detonation pressure, p.s.i.)
200	211.7	214.7	4143	4128
190	201.7	204.7	3947	3932
180	191.7	194.7	3752	3737
170	181.7	184.7	3556	3541
160	171.7	174.7	3360	3345
150	161.7	164.7	3164	3149
140	151.7	154.7	2969	2954
130	141.7	144.7	2773	2758
120	131.7	134.7	2577	2562
110	121.7	124.7	2382	2367

TABLE VI (con't)

σ_i (Indicent nominal fiber hoop stress, p.s.i.)	σ_i/E (Post-yield strain contribution in./in. $\times 10^3$)	ϵ_i (Residual strain due to σ_i , in./in. $\times 10^3$)	$\epsilon_t = \epsilon_i + \sigma_i/E$ (Total strain, in./in. $\times 10^2$)
73,280	2.05	46.4	4.85
69,800	1.96	31.7	3.37
66,330	1.86	21.0	2.29
62,860	1.76	13.4	1.52
59,380	1.66	10.9	1.26
55,900	1.57	7.44	0.901
52,440	1.47	4.67	0.614
48,960	1.37	3.62	0.499
45,493	1.27	1.97	0.324
42,014	1.18	1.26	0.244

TABLE VII

Tabulated Data for Figure 16

σ_i (Incident nominal fiber hoop stress, p.s.i. $\times 10^{-3}$)	ϵ_t (Total strain, in./in. $\times 10^3$)	ϵ_i (Incident strain, in./in. $\times 10^3$)	ϵ_r (Reflected strain, in./in. $\times 10^3$)	σ_r (Reflected nominal fiber hoop stress p.s.i. $\times 10^{-3}$)
73	47.0	17.4	29.6	82.0
72	42.2	16.1	26.1	79.7
70	33.5	13.9	19.6	74.9
68	26.7	11.9	14.8	70.8
66	21.5	10.0	11.5	67.5
64	17.7	8.4	9.3	65.2
62	14.8	7.1	7.7	62.8
60	12.5	6.0	6.5	61.0
58	10.5	5.1	5.4	58.7
56	8.2	4.7	3.5	48.8
54	7.1	4.4	2.7	43.2
52	5.8	3.9	1.9	38.0
50	4.8	3.7	1.1	30.6
48	4.0	3.4	0.6	24.8
46	3.4	3.0	0.4	16.0
42	2.5	2.5	0	0

TABLE VII (con't)

P_{gr} (Decaying reflected detonation wave pressure, p.s.i.)	P_{gi} (Incident detonation wave pressure, p.s.i.)	$\frac{P_{gr}}{P_{gi}}$	$P_i + P_{atm.}$ (Absolute incident wave pressure, p.s.i.a.)	P_0 (Initial gas pressure, p.s.i.)
4620	4113	1.123	4128	211
4490	4056	1.107	4071	208
4220	3944	1.070	3959	202
3989	3831	1.041	3846	197
3803	3718	1.023	3733	191
3673	3606	1.019	3621	185
3538	3493	1.013	3508	179
3437	3380	1.017	3395	173
3307	3268	1.012	3283	168
2749	3155	0.871	3170	162
2434	3042	0.800	3057	156
2141	2930	0.731	2945	151
1724	2817	0.612	2832	145
1397	2704	0.517	2719	139
901	2592	0.348	2607	133
0	2366	0	2481	127

TABLE VIII

Tabulated Data for Figure 17

ϵ_t (Total strain, in./in. $\times 10^3$)	$(\sigma_i)_{r+i}$ (Hoop stress based on incident wave, p.s.i.)	σ_i (Incident hoop stress, p.s.i.)	σ_s (Static hoop stress, p.s.i.)	$\frac{\sigma_i}{\sigma_s}$	$\frac{(\sigma_i)_{r+i}}{\sigma_s}$
2.50	42,400	42,400	31,400	1.350	1.350
5.00	50,400	57,600	34,400	1.674	1.465
7.50	54,500	62,600	36,000	1.739	1.514
10.0	57,400	65,900	37,000	1.781	1.551
12.5	60,000	68,500	37,700	1.817	1.592
15.0	62,200	70,900	38,300	1.851	1.624
17.5	63,900	73,100	38,900	1.879	1.643
20.0	65,200	75,300	39,600	1.902	1.646
22.5	66,400	77,100	40,200	1.918	1.652
25.0	67,400	79,000	40,700	1.941	1.656
27.5	68,300	80,700	41,300	1.954	1.653
30.0	69,000	82,200	41,800	1.967	1.651
32.5	69,800	83,700	42,400	1.974	1.646
35.0	70,400	85,000	43,000	1.977	1.637
37.5	71,000	86,400	43,600	1.982	1.628
40.0	71,500	87,700	44,100	1.989	1.621
42.5	72,000	89,100	44,600	1.998	1.614
45.0	72,600	90,400	45,200	2.000	1.606
47.5	73,200	91,600	45,700	2.004	1.602

V. DISCUSSION OF RESULTS

A. Consideration of Assumptions

The interpretation of the experimental results of this investigation was dependent upon the assumptions made in obtaining these results. Consequently, a great deal of thought and care were given to each supposition so that a minimum of controversial error would result.

The strain gages for the transient loading study in the elastic region were calibrated by a static strain technique having zero cycles per second frequency response as described in the Experimental Procedure. This procedure was not entirely correct however, since the gages were to be employed for the indicating of strains having a frequency response above 25,000 cycles per second. Unfortunately, at the present time there is no instrument that will allow the calibrating of strain gages at such a frequency. Even if there were there is no indication that the frequency of the specimen would remain constant at various detonation pressure loadings. This problem of frequency response versus loading rate is in itself a separate study. Consequently, it was necessary due to lack of instrument availability to statically calibrate the strain gages.

The oscillograms relating deformation as a function of time were employed to determine the transient strain when the specimen was subjected to a detonative force. As observed from Figure 18 the signal oscillations formed an envelope and appeared to vibrate about a mean that was above the datum line of the oscillogram. These large oscillatory vibrations were considered to be the result of "overshoot" created by the detonative loading force. The strain versus time line was developed by joining the points of the bisected oscillations as illustrated. The amplitude of any point on this strain line from the datum then, is a function of the strain in the specimen at the time θ . In fact this amplitude when converted to strain from the fore-mentioned calibration curve was equal to the strain for every point except that amplitude corresponding to the initial oscillation of the signal. The initial rise of the signal is a complex function of the strain and cannot be merely bisected as was done for previous oscillations.

Since the initial strain was considered to be of greatest magnitude two schemes were employed to obtain this strain-initial signal dependence. In the first the initial signal was arbitrarily bisected and the strain corresponding to this amplitude

Sample Oscillogram of Transient Elastic Strain

FIGURE 18

was obtained from the calibration curve of strain versus deflection.

This was done for each loading. The resultant plot is shown in Figure 15 with finite "X" intercept. Since a finite strain at zero stress is impossible the stress-strain line was shifted parallel to itself but fulfilling the necessary boundary condition (0, 0).

This was considered to be the true transient stress-strain plot for the elastic region. In the second scheme, the above procedure was verified. Ten consecutive oscillations from the second to the eleventh were bisected and the "best" line was drawn through these points, extrapolated to zero time. The amplitude of the point of intersection of this "best" line with the vertical axis at $\theta = 0$ was measured and was converted to strain. In every case tried the strain resulting from scheme 1, and scheme 2 were almost identical.

It was found that the SR-4 gages could not be used beyond about 60 p.s.i. initial gas mixture pressure. Above this pressure the strain signal obtained was distorted and non-intelligible. The inability of the strain gage to reproduce the strain signal was probably due to thermal failure of the special, type PA-3 bonding cement. Generally, the upper limit of this cement is around 160°F , as with all "Duco-type" cements. Above 160 p.s.i., the following

scheme was employed to obtain the instantaneous strain imparted to the specimen from a detonative force.

FIGURE 19

General Stress Versus Strain Curve

If in Figure 19 a specimen is subjected to a stress, σ_1 , beyond the elastic limit the specimen is found to have been strained ϵ_0 . The line L - ϵ_0 is parallel to the line from (0, 0) to the elastic limit. Consequently, by knowing ϵ_0 , Young's Modulus of Elasticity, E, and σ_i , any strain, ϵ_i , can be determined where ϵ_i is the instantaneous strain imparted to the specimen by the stress σ_i .

The relationship employed for calculating the nominal fiber hoop stress was

$$\sigma = PD/2t \quad (3)$$

This is the general expression indicating hoop stress for thin-

walled vessels as a function of internal pressure. From the work of McGill (33), Figure 20, the theoretical incident detonation wave pressure was known as a function of the initial hydrogen-oxygen gas mixture. Consequently, the nominal fiber hoop stress calculated throughout this study from the various initial loading pressures were based entirely on the theoretical incident detonation wave pressures.

The reflected wave most commonly referred to in detonation theory (33) is the wave established at the point of contact when an incident detonation wave impinges perpendicularly upon a rigid plane surface. As such, the wave is reflected from the rigid surface with a pressure of about 2.5 times the original incident detonation wave pressure. In this study the reflected wave pressure referred to is the decaying pressure at a point 16 inches from the point of reflection.

Due to the finite gage length of the strain gages the instantaneous strain obtained from the detonative loading force was the average instantaneous strain.

All hoop stresses referred to in this study were calculated as nominal fiber hoop stresses. As such, the specimen tubing specifications of 3/4 inch O.D., and 0.020 inch nominal wall

FIGURE 20

thickness were employed as the variables D and t , respectively, in Equation 3. The error introduced in σ by these assumptions is considered in the Discussion of Errors.

It was assumed that the incident detonation pressure although exerting a force for only microseconds initiated a state of stress in the tubular specimens that was comparable to the state developed when the internal pressure was from a static force. To establish the kinematics of stress from detonative loading was beyond the scope of this study, and therefore, this assumption was imperative. However, there is reason to believe that with further study the results of the work of Taylor and von Karman concerning elastic and plastic wave propagation could be applied to the study of the detonative loading of specimens. In this way a more exact stress relation for transient loading may be possible.

B. Interpretation of Graphs

In Figure 14 appear the essential results of this study. In each case the nominal fiber hoop stress based on the theoretical incident wave pressure increased linearly with average fiber strain up to about 24,000 p.s.i. At this point the static curve, A, began to deform very rapidly with increasing stress, whereas both of the transient stress curves, B and C, showed little deformation

over this same range of stress. Curve C with coordinates of nominal fiber hoop stress versus average strain indicated that the incident wave alone caused very little damage to the specimen up to a hoop stress of about 58,000 p.s.i. At this point the specimen deformed more rapidly with increasing stress than it had previously. Curve B showed the effect of the incident plus the decaying reflected wave on the tubular specimens. However, Curve B was prepared in somewhat of a peculiar manner and in order to interpret the curve the following sketch and explanation are first necessary.

FIGURE 21

Specimen and Detonation Tube Extender

As the detonation wave enters the test specimen an incident pressure, P_i , is exerted on the wall of the tube creating a stress σ_i and a strain ϵ_i . If the rupture disk is a high-rated disk, the detonation wave after travelling through the test section and extended

detonation tube is reflected from the rupture disk with enough force to cause it to re-enter the test specimen. This time the decaying reflected wave pressure, P_r , is imparted to the specimen creating a strain ϵ_r from a hoop stress σ_r . The total strain imparted to the specimen, ϵ_t , is the sum of ϵ_i and ϵ_r .

Curve B then shows that at a nominal fiber hoop stress of 43,000 p.s.i. the total strain begins to increase rapidly with increasing hoop stress. It also shows that as the total strain decreases Curve B approaches Curve C. At the intersection of B and C there is no significant strain contribution from the decaying reflected detonation wave. In other words at the point $(2.60 \times 10^{-3}, 43,000)$ the reflected wave has completely decayed.

The 0.2 percent offset yield strength was determined from Figure 14 for the static loading case and the two transient loading cases, Curves A, and B and C, respectively. Numerically the yield strength for each of these cases is 32,200 p.s.i., 45,400 p.s.i. and 48,400 p.s.i., respectively, or a ratio of 1:1.41:1.50. This indicates that as the time of application of the loading force is decreased the yield strength increases. Such is the case when it is considered that at one extreme, the static loading case, the tubing is strained for a finite time whereas at the other extreme,

incident detonative loading, the force producing deformation exists for only microseconds.

Between the above two limits lies Curve B which indicates that the force causing deformation here exists for a longer period of time than it does if the force were from a purely incident detonation wave. The increased time of force application is due to the decaying reflected detonation wave. This latter wave when reflected begins to attenuate spreading its pressure force over a greater area than if the wave were an incident detonation wave. The combination of a longer time of force application over a larger area causes the large deformation observed in Curve B.

Likewise indicative of the ability of type 304 stainless steel tubing to resist a greater transient load than a static load is the Young's Modulus of Elasticity (YME). By employing the statistical method of least squares it was found that the YME for the static and transient cases were, respectively, 29.2×10^6 p.s.i. and 35.7×10^6 p.s.i. From these values it is observed that per unit strain a greater resistive fiber stress is obtained for the transient case than for a static. In other words if a specimen were to be subjected to a static force and to a transient force in the elastic region the greatest design emphasis should be placed upon

resisting the static load. If this is done, protection against failure from the transient loading is automatically assured.

Although it may have been better for the sake of argument to plot merely force versus elongation rather than nominal fiber hoop stress and nominal fiber strain respectively in Figure 14, the assumptions concerning the calculations of the latter appeared valid. Using merely force and deformation for axes in the literature seemed to indicate that the authors were trying to evade discussing the stress state, and were presenting generally incomparable results.

In Figure 16 is presented a plot of the ratio of the decaying reflected detonation wave pressure to the incident detonation wave pressure versus the initial detonable gas mixture pressure. It is observed that the pressure ratio increases rapidly at first with increasing initial gas pressure. At around 175 p.s.i.g. the ratio remains at a plateau of around 1.0 and then increases slowly up to the pressure limit of the experimental study. At this limit of about 210 p.s.i.g. initial gas pressure the decaying reflected wave pressure ratio was 1.1. As was mentioned previously, at the point of incident wave reflection the theoretical ratio of reflected to incident pressure is about 2.5. Figure 16 then shows

that in a distance of 16 inches a reflected wave established from an initial gas pressure of 210 p.s.i.g. decays to the point where the reflected wave pressure is only 1.1/2.5 times its original pressure.

In Figure 17 are presented two curves that further illustrate the comparative effects of (1) the incident detonation wave and (2) the incident plus reflected detonation waves. The figure was prepared from Figure 14, Curves B and C, in the following manner. At 42,000 p.s.i. nominal fiber hoop stress there was no strain caused by the decaying reflected detonation wave pressure. Above this stress however, total strain was caused by the incident detonation wave plus the decaying reflected detonation wave. The total deformation, ϵ_t , corresponding to a give hoop stress $\sigma > 42,000$ p.s.i. is obtained first from Curve B. The horizontal distance from the "Y" axis to Curve C refers to the primary incident strain ϵ_i . The difference between ϵ_t and ϵ_i corresponds to the strain ϵ_r imparted by the reflected detonation wave. The nominal fiber hoop stress corresponding to ϵ_r was read from Curve C. This hoop stress was then assumed to be the hoop stress created by the decaying reflected detonation wave.

The interpretation of Curves A and B in Figure 17 were as follows. Curve A relates the ratio of the incident nominal fiber

hoop stress to the nominal fiber strain. As the strain increased the ratio σ_i / σ_s increased very rapidly at first and then gradually tapered off. At a strain of 47.5×10^{-3} inches per inch, the limit of available experimental data, the incident nominal fiber hoop stress was twice the static nominal fiber hoop stress. This illustrates the amazing hyper-elastic resilience exhibited by the tubular specimens when subjected to incident detonative loading. Curve B has as its coordinates the ratio σ_i / σ_s and total nominal fiber strain ϵ_t , where $\epsilon_t = \epsilon_i + \epsilon_r$. Curve B indicates that at a fiber strain of 2.5×10^{-3} inches per inch there was no effect from the reflected wave but only from the incident. As the strain increased the fiber stress increased to a ratio of about 1.65 at 25×10^{-3} inches per inch and then decreased to around 1.60 at 47.5×10^{-3} inches per inch. From this it is seen that the influence of the decaying reflected wave is quite prominent in decreasing the ability of the tubing specimens to withstand transient loads.

Figures 22, 23, and 24 are photographs of 15 specimens subjected to various primary incident detonation waves at initial gas pressures from 270 to 130 p.s.i.g., inclusively. The detonation wave travelled as shown. It is observed that the

FIGURE 22

Tubular Specimens Subjected
to Incident Detonation

← Direction of detonation wave

FIGURE 23
Tubular Specimens Subjected
to Incident Detonation

FIGURE 24
Tubular Specimens Subjected
to Incident Detonation

deformation although visible for Specimens 1-8 tends to become barely visible for the remaining seven specimens. Also, the deformation of the specimen prior to the point of its entering the downstream adapter was much greater than at any other point. This indicates that the rings or adapters restrain the free expansion of the deforming material and cause bulging at the point of restraint.

C. Explanation of Errors

The total error in this investigation is considered to be the sum of the systematic and the random errors. Random errors occur through human error in taking readings, making adjustments, etc., whereas systematic errors are generally beyond the control of the observer. Since the magnitude of the random errors is completely arbitrary and depends almost without question on the ability and technique of the investigator it is assumed that with a competent researcher the systematic errors determine the accuracy of the data from an investigation.

Listed below are what were considered to be (1) the primary systematic errors in this study, and (2) the approximate magnitudes of these errors.

1. Gage factor, F $\pm 1\%^{+}$
2. Gage resistance, R_a $\pm 1\%^{+}$
3. Oscillogram amplitude, A $\pm 5\%^{+}$
4. Calibration resistors, R_c $\pm 1\%^{+}$
5. Pressure readings, P $\pm 0.5-1\%$
6. Dial readings $\pm 1-5\%^{+}$
7. Specimen wall thickness, t $\pm 10\%$
8. Specimen O. D., D $\pm 0.5-1\%^{+}$
9. Micrometer readings $\pm 0.01\%$

Each of the values with superscript +'s were obtained from the manufacturer's specifications of that item to which the value refers. The values with no superscript +'s were obtained by considering the ratio of the first uncertain reading to the full scale capacity of the instrument and presenting it as a percentage.

In determining the error in the nominal fiber hoop stress the variables in Equation 3 must be considered. If the assumption made in the Consideration of Assumptions are accepted, the hoop stress, σ , is a function of P , D and t alone. Since the fiber hoop stress was calculated as "nominal" fiber hoop stress the errors in D and t are automatically incorporated into the term "nominal". Hence, the accuracy of the nominal fiber hoop stress depends

upon the error in P which is 0.5-1 percent.

The accuracy of the value of strain in the elastic region depends upon the error in the calibration plot of A , oscillogram amplitude, versus simulated strain. The critical variable here is the oscillogram amplitude that is accurate to only 5 percent. Consequently, the absolute error in the simulated strain is dwarfed by the 5 percent error in the value of A . In Appendix F is derived an expression for the absolute error in strain as a function of R_a , R_c and F .

The magnitude of error in the value of strain in the post-yield region was dependent upon whether the strain was in the near plastic or far plastic region. As described in Appendix D the strain was determined by dividing the difference in the average diameters of the specimen tube before and after a detonation by the original average diameter. If the numerator were very small, as in the near plastic region, the absolute error in the strain calculated would be much greater than if the strain were in the far plastic region. For an initial gas pressure of 110 p.s.i.g. an error of 0.0001 inch in both D_o and D_f would cause an error of around 22 percent in strain, while for an initial gas pressure of 200 p.s.i.g. an error of 0.001 inch would cause an error of only about 0.5 percent.

IV. CONCLUSIONS

1. The bonded electric resistance strain gage was found to be very satisfactory for indicating the transient strain in tubular specimens subjected to transient detonative loading.
2. Type 304, seamless, stainless steel tubing exhibited a phenomenal degree of toughness and hyper-elastic resilience when subjected to transient loading.
3. The distance required for the reflected detonation wave to decay was a direct function of the energy retained by the wave when reflected.
4. The ratio of Young's Modulus of Elasticity for static loading to Young's Modulus of Elasticity for transient loading was 1:1.22.
5. The ratio of the 0.2 percent offset yield strengths of static; transient, incident detonation wave influence; and transient, reflected detonation wave influence respectively, was 1:1.50:1.41.

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APPENDIX A

Specifications for Superior Type 304, Seamless, Stainless Steel Tubing

Nominal O.D. : 0.750 inches + 0.005 inches
- 0.000 "

Nominal I.D. : 0.710 inches + 0.000 inches
- 0.005 "

Nominal Wall Thickness: 0.020 inches $\pm$ 10%

Commercial Straightness Tolerance: 1/600

Analysis: (Maximum percentage of constituent present)

C	Mn	Si	P	S	Cr	Ni
0.08	2.00	1.00	0.03	0.03	18-20	8-11

APPENDIX B

Original Data

TABLE IX

Tabulated Original Data for Calibration Curve of
Signal Amplitude vs. Simulated Strain for the
Transient-Loading Elastic Region

R_c (Calibration resistance, ohms $\times 10^{-3}$)	ϵ (Simulated strain, inches/inch $\times 10^5$)	A (Strain amplitude, arbitrary units)
690	8.48	—
470	12.5	11
320	18.3	16
220	26.6	26
147	39.8	39
100	58.5	60
69	84.7	88
47	124	130

TABLE X

Tabulated Original Data for the Transient-Loading Elastic RegionRun 4 Specimen 4

P_0 (Initial gage pressure, p.s.i.g.)	(P_0) corr. (p.s.i.g.)	A (Signal amplitude, arbitrary units)	ϵ (Simulated strain, inches/inch $\times 10^4$)
5	2	20	2.15
10	7	27.5	2.88
16	13	36	3.70
20	17	40	4.10
25	22	42	4.29
30	27	46	4.67
35	32	54	5.42
40	37	56	5.60
45	42.2	60.5	6.00
10	7	27.5	2.88
12	—	—	—
7	4.1	23.5	2.50
25	22	39	3.98
8	5.1	23.5	2.50
18	15	33.5	3.47
0	0	18.5	1.95
50	47.6	69.5	6.85
55	53.2	70	6.90
60	59.3	70	6.90

TABLE X (con't)

Run 5. Specimen 5

P_0 (Initial gage pressure, p.s.i.g.)	(P_0) corr.. (p.s.i.g.)	A (Signal amplitude, arbitrary units)	ϵ (Simulated strain, inches/inch $\times 10^4$)
0	0	20	2.14
7	4.1	25	2.62
10	7.0	27	2.82
15	12	32	3.32
20	17	37	3.80
25	22	41	4.20
30	27	45	4.58
35	32	49.5	5.00
40	37	58.5	5.82
45	42.2	64	6.35
50	47.6	66.5	6.55

TABLE XI

Tabulated Original Data for the
Transient-Loading Plastic Region

(Incident Detonation Wave Influence Only)

Specimen A-1 Loading P = 270 p.s.i.g.		Specimen A-2 Loading P = 260 p.s.i.g.	
D_0	D_f	D_0	D_f
(Original diameter, inches)	(Final diameter, inches)	(Original diameter, inches)	(Final diameter, inches)
0.7514	0.7940	0.7518	0.7594
0.7512	0.7942	0.7518	0.7595
0.7515	0.7942	0.7520	0.7590
0.7517	0.7953	0.7518	0.7596
0.7515	0.7949	0.7519	0.7591
0.7514	0.7942	0.7519	0.7594
0.7512	0.7940	0.7518	0.7599
0.7515	0.7945	0.7520	0.7599
0.7516	0.7955	0.7519	0.7594
0.7516	0.7949	0.7519	0.7593
$\overline{D}_0$	$\overline{D}_f$	$\overline{D}_0$	$\overline{D}_f$
(Average original diameter, inches)	(Average final diameter, inches)	(Average original diameter, inches)	(Average final diameter, inches)
0.75146	0.79457	0.75188	0.78945

TABLE XI (con't)

Specimen A-3 Loading P = 250 p.s.i.g.		Specimen A-4 Loading P = 240 p.s.i.g.	
D_0 (Original diameter, inches)	D_f (Final diameter, inches)	D_0 (Original diameter, inches)	D_f (Final diameter, inches)
0.7518	0.7861	0.7517	0.7816
0.7515	0.7860	0.7521	0.7818
0.7514	0.7854	0.7516	0.7815
0.7515	0.7857	0.7509	0.7811
0.7518	0.7859	0.7510	0.7812
0.7518	0.7862	0.7516	0.7815
0.7515	0.7857	0.7520	0.7820
0.7514	0.7854	0.7513	0.7817
0.7515	0.7856	0.7509	0.7810
0.7518	0.7859	0.7510	0.7811
$\overline{D}_0$ (Average original diameter, inches)	$\overline{D}_f$ (Average final diameter, inches)	$\overline{D}_0$ (Average original diameter, inches)	$\overline{D}_f$ (Average final diameter, inches)
0.75160	0.78579	0.75141	0.78145

TABLE XI (con't)

Specimen A-5		Specimen A-6	
Loading P = 225 p.s.i.g.		Loading P = 220 p.s.i.g.	
D_0	D_f	D_0	D_f
(Original diameter, inches)	(Final diameter, inches)	(Original diameter, inches)	(Final diameter, inches)
0.7510	0.7714	0.7520	0.7687
0.7511	0.7715	0.7521	0.7690
0.7516	0.7715	0.7511	0.7693
0.7519	0.7715	0.7510	0.7689
0.7517	0.7710	0.7513	0.7687
0.7510	0.7711	0.7519	0.7684
0.7513	0.7715	0.7520	0.7692
0.7517	0.7718	0.7510	0.7694
0.7520	0.7714	0.7510	0.7689
0.7515	0.7710	0.7514	0.7686
$\overline{D_0}$	$\overline{D_f}$	$\overline{D_0}$	$\overline{D_f}$
(Average original diameter, inches)	(Average final diameter, inches)	(Average original diameter, inches)	(Average final diameter, inches)
0.75148	0.77137	0.75148	0.76891

TABLE XI (con't)

Specimen A-7		Specimen A-8	
Loading P = 220 p.s.i.g.		Loading P = 210 p.s.i.g.	
D_0	D_f	D_0	D_f
(Original diameter, inches)	(Final diameter, inches)	(Original diameter, inches)	(Final diameter, inches)
0.7520	0.7705	0.7525	0.7684
0.7520	0.7701	0.7525	0.7685
0.7515	0.7701	0.7515	0.7690
0.7515	0.7703	0.7510	0.7685
0.7518	0.7707	0.7513	0.7683
0.7520	0.7705	0.7522	0.7683
0.7520	0.7701	0.7524	0.7686
0.7515	0.7702	0.7513	0.7687
0.7515	0.7704	0.7510	0.7685
0.7519	0.7709	0.7515	0.7682
$\overline{D_0}$	$\overline{D_f}$	$\overline{D_0}$	$\overline{D_f}$
(Average original diameter, inches)	(Average final diameter, inches)	(Average original diameter, inches)	(Average final diameter, inches)
0.75177	0.77038	0.75172	0.76850

TABLE XI (con't)

Specimen A-9		Specimen A-10	
Loading P = 200 p.s.i.g.		Loading P = 190 p.s.i.g.	
D_0	D_f	D_0	D_f
(Original diameter, inches)	(Final diameter, inches)	(Original diameter, inches)	(Final diameter, inches)
0.7513	0.7627	0.7513	0.7610
0.7517	0.7632	0.7516	0.7611
0.7525	0.7630	0.7514	0.7609
0.7521	0.7618	0.7514	0.7606
0.7514	0.7616	0.7515	0.7608
0.7510	0.7624	0.7513	0.7610
0.7520	0.7630	0.7516	0.7611
0.7525	0.7626	0.7515	0.7608
0.7519	0.7616	0.7514	0.7605
0.7511	0.7617	0.7514	0.7608
$\overline{D_0}$	$\overline{D_f}$	$\overline{D_0}$	$\overline{D_f}$
(Average original diameter, inches)	(Average final diameter, inches)	(Average original diameter, inches)	(Average final diameter, inches)
0.75175	0.76236	0.75144	0.76086

TABLE XI (con't)

Specimen A-11		Specimen A-12	
Loading P = 180 p.s.i.g.		Loading P = 170 p.s.i.g.	
D_0	D_f	D_0	D_f
(Original diameter, inches)	(Final diameter, inches)	(Original diameter, inches)	(Final diameter, inches)
0.7512	0.7578	0.7519	0.7559
0.7512	0.7575	0.7520	0.7560
0.7515	0.7572	0.7517	0.7565
0.7518	0.7573	0.7513	0.7565
0.7517	0.7579	0.7511	0.7563
0.7513	0.7578	0.7516	0.7560
0.7513	0.7574	0.7520	0.7561
0.7516	0.7572	0.7516	0.7566
0.7518	0.7575	0.7511	0.7565
0.7515	0.7578	0.7513	0.7563
$\overline{D_0}$	$\overline{D_f}$	$\overline{D_0}$	$\overline{D_f}$
(Average original diameter, inches)	(Average final diameter, inches)	(Average original diameter, inches)	(Average final diameter, inches)
0.75149	0.75754	0.75156	0.75627

TABLE XI (con't)

Specimen A-13 Loading P = 150 p.s.i.g.		Specimen A-14 Loading P = 140 p.s.i.g.	
D_0 (Original diameter, inches)	D_f (Final diameter, inches)	D_0 (Original diameter, inches)	D_f (Final diameter, inches)
0.7511	0.7535	0.7520	0.7536
0.7512	0.7537	0.7520	0.7536
0.7515	0.7545	0.7514	0.7537
0.7516	0.7547	0.7510	0.7536
0.7510	0.7539	0.7513	0.7535
0.7510	0.7535	0.7519	0.7535
0.7513	0.7539	0.7518	0.7535
0.7515	0.7546	0.7514	0.7537
0.7515	0.7545	0.7509	0.7536
0.7509	0.7537	0.7514	0.7535
$\overline{D_0}$ (Average original diameter, inches)	$\overline{D_f}$ (Average final diameter, inches)	$\overline{D_0}$ (Average original diameter, inches)	$\overline{D_f}$ (Average final diameter, inches)
0.75126	0.75405	0.75151	0.75358

TABLE XI (con't)

Specimen A-15
Loading $P = 130$ p.s.i.g.

D_0 (Original diameter, inches)	D_f (Final diameter, inches)
0.7519	0.7533
0.7515	0.7529
0.7507	0.7524
0.7509	0.7529
0.7515	0.7530
0.7518	0.7532
0.7514	0.7527
0.7506	0.7526
0.7510	0.7529
0.7516	0.7533
$\overline{D_0}$ (Average original diameter, inches)	$\overline{D_f}$ (Average final diameter, inches)
0.75129	0.75292

TABLE XII

Tabulated Original Data for the
Transient-Loading Plastic Region

(Incident Plus Reflected Detonation Wave Influence)

Specimen B-1 Loading P = 200 p.s.i.g.		Specimen B-2 Loading P = 190 p.s.i.g.	
D_0	D_f	D_0	D_f
(Original diameter, inches)	(Final diameter, inches)	(Original diameter, inches)	(Final diameter, inches)
0.7517	0.7861	0.7519	0.7755
0.7516	0.7869	0.7518	0.7753
0.7516	0.7875	0.7517	0.7755
0.7520	0.7867	0.7516	0.7757
0.7518	0.7861	0.7518	0.7757
0.7517	0.7861	0.7519	0.7755
0.7515	0.7870	0.7517	0.7751
0.7517	0.7872	0.7515	0.7758
0.7519	0.7864	0.7516	0.7758
0.7519	0.7860	0.7518	0.7758
$\overline{D_0}$	$\overline{D_f}$	$\overline{D_0}$	$\overline{D_f}$
(Average original diameter, inches)	(Average final diameter, inches)	(Average original diameter, inches)	(Average final diameter, inches)
0.75174	0.78660	0.75173	0.77557

TABLE XII (con't)

Specimen B-3		Specimen B-4	
Loading P = 180 p.s.i.g.		Loading P = 170 p.s.i.g.	
D_0	D_f	D_0	D_f
(Original diameter, inches)	(Final diameter, inches)	(Original diameter, inches)	(Final diameter, inches)
0.7515	0.7672	0.7516	0.7613
0.7515	0.7675	0.7517	0.7614
0.7517	0.7675	0.7517	0.7615
0.7514	0.7673	0.7514	0.7618
0.7515	0.7672	0.7512	0.7618
0.7515	0.7673	0.7514	0.7613
0.7516	0.7677	0.7517	0.7613
0.7516	0.7672	0.7518	0.7615
0.7514	0.7670	0.7513	0.7618
0.7516	0.7673	0.7513	0.7618
D_0	D_f	D_0	D_f
(Average original diameter, inches)	(Average final diameter, inches)	(Average original diameter, inches)	(Average final diameter, inches)
0.75153	0.76732	0.75151	0.76155

TABLE XII (con't)

Specimen B-5		Specimen B-6	
Loading P = 160 p.s.i.g.		Loading P = 150 p.s.i.g.	
D_0	D_f	D_0	D_f
(Original diameter, inches)	(Final diameter, inches)	(Original diameter, inches)	(Final diameter, inches)
0.7515	0.7590	0.7510	0.7570
0.7509	0.7595	0.7513	0.7571
0.7509	0.7600	0.7517	0.7568
0.7510	0.7590	0.7516	0.7569
0.7516	0.7589	0.7510	0.7568
0.7512	0.7590	0.7510	0.7571
0.7508	0.7599	0.7515	0.7571
0.7509	0.7598	0.7517	0.7568
0.7509	0.7588	0.7515	0.7568
0.7515	0.7589	0.7510	0.7568
D_0	D_f	D_0	D_f
(Average original diameter, inches)	(Average final diameter, inches)	(Average original diameter, inches)	(Average final diameter, inches)
0.75112	0.75928	0.75133	0.75692

TABLE XII (con't)

Specimen B-7		Specimen B-8	
Loading P = 150 p.s.i.g.		Loading P = 140 p.s.i.g.	
D_0	D_f	D_0	D_f
(Original diameter, inches)	(Final diameter, inches)	(Original diameter, inches)	(Final diameter, inches)
0.7510	0.7570	0.7518	0.7551
0.7513	0.7571	0.7517	0.7548
0.7517	0.7568	0.7514	0.7548
0.7516	0.7569	0.7503	0.7546
0.7510	0.7568	0.7518	0.7552
0.7510	0.7571	0.7518	0.7551
0.7515	0.7571	0.7516	0.7548
0.7517	0.7568	0.7513	0.7548
0.7515	0.7568	0.7507	0.7548
0.7510	0.7568	0.7519	0.7554
D_0	D_f	D_0	D_f
(Average original diameter, inches)	(Average final diameter, inches)	(Average original diameter, inches)	(Average final diameter, inches)
0.75133	0.75692	0.75143	0.75494

TABLE XII (con't)

Specimen B-9		Specimen B-10	
Loading P = 130 p.s.i.g.		Loading P = 120 p.s.i.g.	
D_0	D_f	D_0	D_f
(Original diameter, inches)	(Final diameter, inches)	(Original diameter, inches)	(Final diameter, inches)
0.7509	0.7540	0.7520	0.7533
0.7523	0.7545	0.7515	0.7531
0.7531	0.7547	0.7512	0.7531
0.7515	0.7544	0.7517	0.7532
0.7503	0.7540	0.7521	0.7532
0.7510	0.7541	0.7520	0.7532
0.7525	0.7545	0.7514	0.7530
0.7529	0.7547	0.7513	0.7531
0.7510	0.7541	0.7517	0.7532
0.7503	0.7540	0.7521	0.7534
$\overline{D_0}$	$\overline{D_f}$	$\overline{D_0}$	$\overline{D_f}$
(Average original diameter, inches)	(Average final diameter, inches)	(Average original diameter, inches)	(Average final diameter, inches)
0.75158	0.75430	0.75170	0.75318

TABLE XII (con't)

Specimen B-11
Loading $P = 110$ p.s.i.g.

D_0 (Original diameter, inches)	D_f (Final diameter, inches)
0.7513	0.7527
0.7514	0.7525
0.7519	0.7526
0.7520	0.7527
0.7517	0.7527
0.7514	0.7527
0.7515	0.7524
0.7520	0.7526
0.7520	0.7527
0.7516	0.7527
$\overline{D}_0$ (Average original diameter, inches)	$\overline{D}_f$ (Average final diameter, inches)
0.75168	0.75263

TABLE XIII
Tabulated Original Data for the Calibration Curve
of Dial Reading vs. Simulated Strain for the
Static-Loading Elastic Region

<u>Run A</u>	R_c (Calibration resistance, ohms $\times 10^3$)	ϵ (Simulated strain, (Arbitrary units) inches/inch $\times 10^4$)	Dial
	470	1.25	025
	220	2.66	055
	100	5.85	122
	47	12.4	259
	22	26.5	554
<u>Run B</u>	470	1.25	026
	220	2.66	060
	100	5.85	125
	47	12.4	262
	22	26.5	553

TABLE XIV
Tabulated Original Data for the
Static-Loading Investigation
(Within Range of Strain Gages)

<u>Run A</u>			
P_0 (Initial gage pressure, p.s.i.g.)	(P_0) corr. (p.s.i.g.)	Dial (Arbitrary units)	ϵ (Simulated strain, inches/inch $\times 10^4$)
100	98.5	018	0.80
200	197	025	1.25
200	197	027	1.27
300	295	037	1.80
408	402	050	2.45
600	590	073	3.53
600	590	075	3.63
610	601	077	3.73
700	689	089	4.30
810	796	102	5.00
900	885	112	5.40
1000	985	125	6.00
1200	1180	155	7.43
1400	1378	185	8.85
1600	1573	263	12.60

TABLE XIV (con't)

<u>Run B</u>			
P_o (Initial gage pressure, p. s. i. g.)	(P_o) corr. (p. s. i. g.)	Dial (Arbitrary units)	ϵ (Simulated strain, inches/inch $\times 10^4$)
100	98.5	012	0.63
200	197	027	1.32
220	217	028	1.40
300	295	036	1.78
330	325	046	2.24
430	423	052	2.51
500	492	066	3.20
600	591	073	3.52
730	719	094	4.53
810	798	100	4.82
900	886	113	5.45
1000	985	129	6.20
1100	1083	144	6.90
1200	1182	153	7.35
1300	1280	173	8.28
1400	1379	206	9.90
1500	1477	240	11.5
1600	1576	316	15.2
1700	1674	381	18.3
1800	1772	522	25.1

TABLE XV

Tabulated Original Data for the
Static-Loading Plastic Region

Specimen 1		Specimen 6	
Loading P = 2000 p.s.i.g.		Loading P = 2500 p.s.i.g.	
D_0	D_f	D_0	D_f
(Original diameter, inches)	(Final diameter, inches)	(Original diameter, inches)	(Final diameter, inches)
0.7516	0.7568	0.7519	0.7779
0.7515	0.7568	0.7520	0.7775
0.7514	0.7566	0.7520	0.7769
0.7517	0.7565	0.7517	0.7771
0.7518	0.7565	0.7515	0.7779
0.7517	0.7567	0.7518	0.7780
0.7512	0.7568	0.7519	0.7772
0.7513	0.7565	0.7520	0.7769
0.7517	0.7562	0.7516	0.7773
0.7517	0.7566	0.7515	0.7779
$\overline{D_0}$	$\overline{D_f}$	$\overline{D_0}$	$\overline{D_f}$
(Average original diameter, inches)	(Average final diameter, inches)	(Average original diameter, inches)	(Average final diameter, inches)
0.75156	0.75660	0.75179	0.77746

TABLE XV (con't)

Specimen 7		Specimen 8	
Loading P = 3000 p.s.i.g.		Loading P = 3500 p.s.i.g.	
D_0	D_f	D_0	D_f
(Original diameter, inches)	(Final diameter, inches)	(Original diameter, inches)	(Final diameter, inches)
0.7518	0.8120	0.7518	0.8711
0.7517	0.8118	0.7518	0.8710
0.7517	0.8116	0.7519	0.8713
0.7516	0.8119	0.7517	0.8715
0.7514	0.8123	0.7516	0.8712
0.7518	0.8118	0.7519	0.8709
0.7517	0.8119	0.7518	0.8713
0.7518	0.8118	0.7519	0.8714
0.7515	0.8123	0.7514	0.8715
0.7517	0.8123	0.7517	0.8711
$\overline{D_0}$	$\overline{D_f}$	$\overline{D_0}$	$\overline{D_f}$
(Average, inches)	(Average, inches)	(Average, inches)	(Average, inches)
0.75169	0.81197	0.75175	0.87123

TABLE XV (con't)

Specimen 9 Loading P = 3200 p.s.i.g.		Specimen 10 Loading P = 2700 p.s.i.g.	
D ₀	D _f	D ₀	D _f
(Original diameter, inches)	(Final diameter, inches)	(Original diameter, inches)	(Final diameter, inches)
0.7517	0.8298	0.7519	0.7918
0.7518	0.8300	0.7519	0.7916
0.7518	0.8302	0.7519	0.7914
0.7514	0.8302	0.7518	0.7918
0.7516	0.8300	0.7515	0.7923
0.7517	0.8300	0.7519	0.7919
0.7519	0.8300	0.7520	0.7915
0.7516	0.8302	0.7519	0.7915
0.7514	0.8301	0.7517	0.7919
0.7518	0.8301	0.7516	0.7912
D ₀	D _f	D ₀	D _f
(Average original diameter, inches)	(Average final diameter, inches)	(Average original diameter, inches)	(Average final diameter, inches)
0.75167	0.83006	0.75181	0.79179

TABLE XV (con't)

Specimen AA-1		Specimen AA-2	
Loading P = 2200 p.s.i.g.		Loading P = 2300 p.s.i.g.	
D_0	D_f	D_0	D_f
(Original diameter, inches)	(Final diameter, inches)	(Original diameter, inches)	(Final diameter, inches)
0.7514	0.7671	0.7515	0.7724
0.7514	0.7671	0.7513	0.7723
0.7518	0.7673	0.7510	0.7724
0.7516	0.7676	0.7514	0.7728
0.7514	0.7675	0.7518	0.7729
0.7514	0.7671	0.7516	0.7725
0.7515	0.7672	0.7512	0.7723
0.7516	0.7674	0.7511	0.7725
0.7516	0.7677	0.7516	0.7728
0.7514	0.7674	0.7518	0.7720
$\overline{D_0}$	$\overline{D_f}$	$\overline{D_0}$	$\overline{D_f}$
(Average original diameter, inches)	(Average final diameter, inches)	(Average original diameter, inches)	(Average final diameter, inches)
0.75151	0.75734	0.75143	0.77259

TABLE XV (con't)

Specimen AA-3		Specimen AA-4	
Loading P = 2900 p.s.i.g.		Loading P = 3100 p.s.i.g.	
D_0	D_f	D_0	D_f
(Original diameter, inches)	(Final diameter, inches)	(Original diameter, inches)	(Final diameter, inches)
0.7517	0.8048	0.7515	0.8313
0.7515	0.8048	0.7515	0.8314
0.7513	0.8045	0.7512	0.8314
0.7514	0.8046	0.7513	0.8316
0.7516	0.8049	0.7514	0.8313
0.7517	0.8050	0.7515	0.8312
0.7514	0.8046	0.7514	0.8312
0.7513	0.8044	0.7512	0.8314
0.7514	0.8046	0.7513	0.8312
0.7517	0.8049	0.7513	0.8313
$\overline{D_0}$	$\overline{D_f}$	$\overline{D_0}$	$\overline{D_f}$
(Average original diameter, inches)	(Average final diameter, inches)	(Average original diameter, inches)	(Average final diameter, inches)
0.75150	0.80471	0.75136	0.83133

APPENDIX C

Calibration of Strain Gages

A simulated static-strain calibration technique was employed to calibrate the active strain gage. The schematic below represents the basic strain indicating system and will be referred throughout this discussion.

Simulated Strain Circuit

FIGURE 25

When a specimen to which R_a is bonded is strained, a change in resistance in R_a , ΔR , is observed. This change is caused by (1) the reduction in the cross-sectional area of the wire, and (2) the change in the resistivity of the material. The resistance change is related to the imposed strain, ϵ , by the defining equation for gage factor:

$$(1) \quad F = (\Delta R / R_a) / \epsilon$$

Rather than strain a specimen for calibrating purposes, a resistance, R_c , was added in shunt with R_a , and a strain was observed by the recording system. This relationship is seen from the following derivation:

$$(2) \quad \epsilon = (\Delta R / R_a) / F, \text{ from (1).}$$

$$(3) \quad \Delta R = (R_e - R_a)$$

$$(4) \quad R_e = (1/R_a) + (1/R_c)$$

$$(5) \quad \Delta R = ((R_c + R_a) / R_c R_a) - R_a$$

$$(6) \quad \epsilon = [(R_c + R_a - R_a^2 R_c) / R_c R_a^2] / F$$

$$(7) \quad \epsilon = [(R_a^{-2} + R_c^{-1} R_a^{-1}) - 1] / F = R_a / F(R_a + R_c), \text{ and}$$

$$(8) \quad R_c = R_a (F^{-1} \epsilon^{-1} - 1)$$

By varying R_c and knowing R_a and F , one can obtain the simulated strain, ϵ . The deflection from this strain, which was observed on the oscilloscope, was plotted against strain. The resulting plot was the calibration curve of the PA-3 strain gage which was being employed. For the dynamic measurements, the deflection due to a strain was obtained by measuring directly on the resultant oscillogram, the vertical distance of the deflection. For static measurements the degree to which a "strain dial" was rotated to zero-out the deflection was taken as a measurement of that

deflection. Henceforth, oscilloscopic deflections resulting from the strain gage could be converted into strain by employing a plot of strain in inches per inch versus deflection in arbitrary units.

APPENDIX D

Stress and Strain Determinations

The procedure for determining (1) the nominal fiber hoop stress, and (2) the nominal fiber strain from experimental data is presented for each of the following four regions:

1. Elastic region - static loading
2. Plastic region - static loading
3. Elastic region - transient loading
4. Plastic region - transient loading

Case 1.

1. Since D and t are known from the manufacturer's specifications, and P from the gage indicating internal oil pressure, the equation $\sigma = \frac{Pd}{2t}$, was employed to determine the nominal fiber hoop stress in the specimen.
2. The strain deflection observed on the oscilloscope screen, that was caused by hoop stress, was balanced-out by turning the measuring dial on the Ellis BA - 12 until the deflection disappeared. From the calibration plot of dial reading versus simulated strain, Figure 26 Appendix D, the strain resulting from the hoop stress was obtained.

Case 2.

1. The nominal fiber hoop stress was calculated in the same manner as it was in Case 1.
2. An average diameter of the test specimen was obtained by measuring this quantity at ten points around the periphery of the specimen. The difference between the average original diameter, $\overline{D}_0$, and the average final diameter $\overline{D}_f$, divided by the original, was equal to the nominal fiber strain.

Case 3.

1. The nominal fiber hoop stress was calculated from equation 3. Again d and t were known from manufacturer's specifications. However, P was determined from Figure 20 Appendix D, theoretical incident detonation pressure versus initial gas pressure.
2. The amplitude of the initial signal on the oscillogram as described in Discussion of Results, was compared to a known amplitude. From the calibration curve, Figure 27 Appendix D, the amplitude was converted to a value of strain.

Case 4.

1. The nominal fiber hoop stress was calculated in the same manner as it was in Case 3.

2. The nominal fiber hoop strain was calculated in the same manner as it was in Case 2.

FIGURE 26

FIGURE 27

APPENDIX E

Nomenclature

A	signal amplitude, arbitrary units
c_e	velocity of propagation (plastic strain waves), feet/second
D, d	diameter, inches
$\bar{D}$	diameter (average), inches
F	gage factor, (ohms/ohm)/(inches/inch)
P	pressure, pounds/square inch
t	thickness, inches
V	impact velocity, feet/second
ϵ	fiber strain, inches/inch
e	time, seconds
ρ	density, pounds/cubic foot
σ	fiber stress, pounds/square inch

Subscripts

a	refers to active
c	refers to calibration
corr.	refers to corrected
d	refers to "dummy", or compensating
e	refers to equivalent

f refers to final
i refers to instantaneous, or incident
o refers to original, or initial
r refers to reflected
s refers to static
t refers to total

APPENDIX F

Determination of the Absolute Error in the
Transient, Elastic Strain of a Specimen

From Appendix C, Equation 7:

$$\epsilon = \frac{R_a}{F (R_a + R_c)} \quad (1)$$

If m , n , and p are the absolute errors in R_a , F and R_c respectively, Equation 1 above may be written

$$\epsilon_e = \frac{R_a + m R_a}{(F + nF) (R_a + mR_a) + (R_c + pR_c)} \quad (2)$$

where ϵ_e is the value of strain containing error.

Since $R_c \gg R_a$, $(R_c + pR_c) \gg (R_a + mR_a)$.

$$\text{Thus, } \epsilon_e = \frac{R_a + mR_a}{(F + nF) (R_c + pR_c)} \quad (3)$$

$$\text{Also, } \epsilon = \frac{R_a}{FR_c} \quad (4)$$

The absolute error in strain, therefore, is

$$(\epsilon_e - \epsilon) = \frac{R_a + mR_a}{(F + nF) (R_c + pR_c)} - \frac{R_a}{FR_c} \quad (5)$$

Now expanding the denominator of Equation 3

$$(F + nF) (R_c + pR_c) = FR_c + nFR_c + pFR_c + npFR_c$$

Considering $npFR_c$ as being much smaller than the rest of the terms,

Equation 5 is rewritten

$$(e_e - e) = \frac{R_a + mR_a}{FR_c (1 + n + p)} - \frac{R_a}{FR_c} \quad (6)$$

$$e_e - e = \frac{R_a}{FR_c} \left[\frac{(1 + m)}{(1 + n + p)} - 1 \right] \quad (7)$$

From Equation 7 it is observed that as the errors m , n and p approach zero, the right hand side approaches zero, indicating that e_e approaches e . For example, consider the following case:

$$R_a = 120 \, \Omega \quad \begin{matrix} + \\ - \end{matrix} 1\%$$

$$R_c = 10^5 \, \Omega \quad \begin{matrix} + \\ - \end{matrix} 1\%$$

$$F = 2.05 \quad \begin{matrix} + \\ - \end{matrix} 1\%$$

then,

$$e_e - e = \frac{120}{2.05 (10^5)} \left[\frac{1 + 0.01}{(1 + 0.02)} - 1 \right] =$$

$$(58.5 \times 10^{-5}) (0.990 - 1) = 58.5 \times 10^{-7}$$

The percent error in ϵ because of m, n and p would be

$$(58.5 \times 10^{-7} / 58.5 \times 10^{-5}) \times 100 = 1\%$$

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