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COLLEGE OF ENGINEERING

Department of Engineering Mechanics

Summary Technical Report

EFFECT OF STATE OF STRESS ON THE FAILURE OF METALS AT VARIOUS TEMPERATURES

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FOREWORD

This Summary Technical Report describes the research done during the period June 1, 1958, to March 31, 1960, under Contract No. AF 33(616)-6041, Project No. 7021, "Solid States Research and Properties of Matter," Task No. 73653, "Mechanisms of Flow and Fracture of Metallic and Non-Metallic Crystalline Substances." The work was administered under the direction of the Materials Laboratory, Directorate of Laboratories, Wright Air Development Division, Air Research and Development Command. Dr. A. J. Herzog acted as project engineer.

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ABSTRACT

The purpose of this research program is to evaluate the influence of state of stress and temperature on the fracture of metals. To implement the research, a series of carefully controlled experiments under combined stress conditions is planned. The work described here is concerned primarily with development of test equipment and the test program. Identification of a failure criterion in terms of stress is the ultimate objective.

An examination of the technical literature indicates that the factors involved in purely brittle fracture have been identified. For brittle fracture, plausible deformation mechanisms suggest that the principal normal stress and the ratio of principal normal stress to maximum shearing stress are important. Although some of the features of ductile fracture have been noted, a connection with the state of stress has not been proposed. Consequently, the development of a unified theory may be possible for brittle fracture. A unified theory of ductile fracture may be very complex and in particular may require consideration of more than stress alone to be valid.

A testing machine has been completed which will simultaneously apply axial load and torsion, or internal pressure and axial load to a hollow tubular specimen. Of the two specimen materials selected, AISI B1113 steel may not be entirely satisfactory but Zamak 3 zinc alloy has given good results in preliminary tests. It is planned to investigate other low-carbon steels as a replacement for the AISI B1113.

It is proposed to concentrate the experimental work in regions of behavior where the failure process is yielding followed by brittle fracture. Experimental work in ductile fracture may be aided by application of plastic instability analysis to the specimen form used.

THE APPROACH TO THE RESEARCH PROBLEM

The general objective of this research program has been to make a preliminary assessment of the influence of stress state and temperature on the failure of metals. Failure is defined to mean rupture or actual separation in the test material. Failure in the sense of yielding or onset of plastic deformation is of collateral interest.

Since a single failure or fracture phenomenon does not exist, the investigation falls into two major areas. The first is the study of conditions under which ductile fracture occurs. As will be discussed presently, the ductile fracture process itself is not a single process, since both shear and fibrous types have been identified, and it is possible that there are others. The second area is the study of conditions causing brittle fracture. It is possible that fracture may be preceded in either of the basic fracture modes by yielding or plastic deformation. Ductile fracture is necessarily accompanied by plastic deformation, although it may be highly localized.

The experimental investigation now in progress includes an assessment of only some of the variables of potential interest. The test equipment provides for variation of the state of stress in a hollow tubular specimen having a uniform stress field over an appreciable volume of the material. Loading is such that one principal stress is zero or nearly zero while the ratio of the other two principal stresses is controlled to selected fixed value. Stresses in the specimen are known to a good approximation until localized deformation begins. The temperature of the test piece can be controlled over the limited range necessary to induce both ductile and brittle behavior. Elevated temperatures at which material properties become time-dependent will be avoided. Thus the temperature variable is used primarily as a means of producing the various modes of fracture. A constant rate of loading can be maintained, although it does not follow that the strain rate is constant. However, rates of loading have been set at low values so that strain rates should not be of particular significance. At present, the test program includes two test materials chosen for their technical significance and because they undergo transition from ductile to brittle behavior in an experimentally attainable temperature range.

Experimental data, obtained in this way, may be used as a basis for formulating and evaluating criteria of failure in terms of principal stresses if such appear to be justified. Development of such criteria is the ultimate objective of the research of which the present work is an initial phase.

CONTEMPORARY THEORIES OF FAILURE

The early months of the research were devoted to a study of the various concepts which have been proposed to explain or predict failure, including both yielding and fracture. This study laid particular emphasis on the physical mechanisms that have been proposed to explain the several failure modes. It was felt that in this way some or all of the pertinent variables could be identified and a sound experimental program could be established.

It should be noted at the outset that a criterion for yielding or fracture which is stated in terms of macroscopic quantities such as stress will not predict or explain microscopic processes which occur during yielding or fracture. On the other hand, a result predicted on the basis of macroscopic considerations should not contradict a similar result predicted on the basis of microscopic considerations.

Yielding or initiation of plastic deformation furnishes an example of this apparent paradox. A yield criterion based on macroscopic stress, the von Mises criterion, has been demonstrated experimentally to be valid for several metals at or near room temperature. R. von Mises (as well as Clerk Maxwell and M. T. Huber) proposed that, for an isotropic material with no Bauschinger effect, yield would occur when the second invariant of the stress deviator tensor reached a "critical" (limiting) value. Implied here also is that yield is independent of the hydrostatic pressure component of the state of stress. This criterion in terms of the principal stresses is

$$(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2 = 2\sigma_o^2$$

$\sigma_1, \sigma_2, \sigma_3$ = principal stresses

σ_o = yield stress in simple tension

Now consider the generally accepted microscopic yield mechanism. It has been shown that slip or yielding is a process in which intense plastic strain occurs in occasional slip surfaces within a grain while the remainder of the grain is undeformed or elastically deformed. Thus, microscopically, plastic deformation or slip is an inhomogeneous phenomenon. In somewhat more detail, slip occurs on preferred planes in a metallic crystal of which one portion moves many atom diameters relative to the remainder of the crystal along the preferred slip plane. Considerable success has been attained in explaining deformation phenomena by use of the dislocation concept, defining the "boundary" of the slipped region as a slip dislocation. Pre-existing structural irregularities provide initial dislocations and dislocation sources. Generally, dislocations move or glide quite readily, and this is, in fact, the slip mechanism. Such a mechanism of localized deformation in variously oriented grains is hardly consistent with the von Mises criterion stemming from treatment of the material as an isotropic continuum. However, the von Mises criterion appears to be valid because a metallic specimen is composed of many grains so that a sort of over-all homogeneity results. Bishop and Hill have shown that the actual work done by a stress system on a polycrystalline aggregate is the same as would be done if the grains all underwent the same macroscopic strain. Thus the agreement is not surprising since both microscopic and macroscopic approaches lead to the same result. To summarize, the onset of yielding, a microscopically localized and inhomogenous phenomenon, can be successfully predicted by considering only macroscopic stresses acting in an isotropic continuum.

The situation discussed above offers some hope that a stress criterion for fracture may be derived, although other factors may also require consideration.

Let us now consider the brittle fracture phenomenon, fracture of crystalline appearance with practically no deformation. There appear to be two general mechanisms through which brittle fracture might initiate: (1) the critical normal stress (tensile) to cause rupture on a cleavage plane might be exceeded, and (2), the slip processes (moving dislocations), which have already begun, might be arrested. In regard to the first mechanism, Zener points out that for crystalline materials, such as metals, it is not possible completely to suppress plastic deformation, and that even at very low temperatures, the yield strength is far below the theoretical stress for cleavage fracture. Cottrell also suggests that yield should begin before the interatomic breaking strain (fracture across a cleavage plane) is exceeded. Thus it must be assumed that fracture is nucleated by plastic flow or that the second mechanism is the operable one. Note that in amorphous materials, such as glass, pure cleavage fractures may and do occur.

How then is plastic deformation arrested and how are cracks initiated? For crystalline materials it is assumed that a number of dislocations in a "glide" system, such as a slip band or deformation twin band, become converted to cavity dislocations at some point. A cavity dislocation is the boundary of a "hole" or separated area within a crystal. Cavity dislocations spread and multiply in the form of a growing crack. The conversion of glide dislocations (plastic deformation) to a cavity dislocation (microscopic crack) may occur when glide dislocations pile up near a grain boundary or when active slip bands coalesce along a line of intersection. The conversion may also occur if a slip band crosses a tilt boundary with the crack forming in the slip plane. Of course, it is possible that, when dislocations run together, more plastic deformation rather than a crack will result. The crack results only when the concentration of elastic energy is not dissipated in plastic flow.

In metals of hexagonal structure, such as zinc, which slip easily only on basal planes, crack formation may occur when dislocations are brought together gradually. Such metals would be brittle in most circumstances. On the other hand, metals of cubic lattice structure slip easily on several possible slip planes and a "yield drop" is necessary so that a large number of dislocations is formed suddenly. These dislocations may run together, form a crack, and the crack may be able to spread before nearby dislocation sources can be activated. The possibility of this occurrence depends sensitively on the temperature and perhaps on "localization" of the macroscopic stress. The "yield drop" phenomenon is associated with the "locking" of dislocations by solute atoms which segregate around stationary dislocations. This is the mechanism postulated for body-centered cubic metals such as iron-base alloys. Thus cubic metals may be brittle at some temperatures and not brittle at others.

Now let us evaluate the statements of the preceding paragraph quantitatively. If fracture is to initiate and propagate, the work done by the applied stress on the glide dislocations which run together must be at least sufficient to supply the surface energy of the new faces created. Symbolically,

$$pna \simeq 2\gamma$$

where:

p = significant applied stress,

γ = surface energy of crack face,

and

na = maximum displacement between crack faces.

The product "na" can be interpreted as a pile-up of "n" edge dislocations each of Burger's vector "a." Then "pna" is the work per unit area swept out by an advancing dislocation front. The quantity "na" can be related to the stresses as follows:

$$na \simeq \frac{(T_y - T_i)}{G} d$$

where:

T_y = shear yield stress,
T_i = "friction stress" that opposes motion of a dislocation,
d = length of the slip band, and
G = shear modulus.

The above would be appropriate if fracture initiates at the yield stress.

It can be shown further that:

$$na \simeq \frac{kd^{1/2}}{G}$$

The factor k is a function of rate of deformation, temperature, and the spacing

spacing of dislocation sources, while "d" is interpreted as the radius of a grain. Selection of an appropriate value of the applied stress "p" depends on which stage of the fracture process is critical. In view of the preceding discussion, three distinct stages might be identified. These are:

(a) creation of unlocked glide dislocations,
(b) conversion of glide dislocations to cavity dislocations, and
(c) growth of a crack formed by these cavity dislocations.

If (b) is more difficult than (c), fracture would initiate at the yield point and would be self-propagating with no influence of the state of stress. This disagrees with experiment. Other facets of experimental behavior also suggest that (c) rather than (b) is the critical stage. For (c) critical, the significant stress is the tensile stress normal to the crack, and the original relationship becomes

$$T_y k d^{1/2} = BG\gamma$$

where:

$$B = \frac{2T_{max}}{\sigma_{max}} .$$

$$\sigma_{max} = \text{maximum normal stress.}$$

In words, "B" relates the maximum shearing stress to the maximum normal stress at a point.

The material, then, might remain ductile when $T_y k d^{1/2} < BG\gamma$. Brittle behavior might occur when the converse is true. Note that the effects of grain size, strain rate, temperature, and stress state are included. Thus we might conclude that, for a given material, strain rate, and temperature, the significant stress-state parameter is, essentially, the ratio of maximum shearing stress to maximum normal stress. In any case, conditions for crack initiation at a point have been postulated. However, the critical conditions may not exist at nearby points so that microcracks may form but not propagate.

In contrast to the dislocation mechanism of brittle fracture the mechanisms of ductile fracture are not so straightforward. It is possible that the dislocation mechanism may be operative here and that fracture proceeds by the linking up of many short cracks. Or a so-called "delayed cleavage fracture" may occur in which microcracks form but do not propagate until plastic deformation has raised the yield stress to a sufficiently high value. However, other mechanisms have been suggested which are not associated with dislocations.

A ductile type called fibrous ductile fracture is thought to initiate at sources present in the material before loading begins. Typical sources might be interfaces, inclusions, or strain-induced porosity. Plastic strain is necessary to develop cavities at these sources and further plastic strain causes these cavities to enlarge. The result of the joining of many cavities would look like the cup in a cup-and-cone fracture in a tensile specimen. Plastic cavities are sometimes referred to as "internal necks" since they form by a receeding of material from the fracture. Such cavities are not similar to cracks since no actual rupture of the material occurs. Among the experimental evidence which justifies assumption of this mechanism is the fracturing anisotropy of wrought materials. Cottrell notes that reduction of area in a ductile material should not depend on temperature but on the distribution and properties of the fracture sources, if the assumption of this mechanism is correct. For many ductile materials, reduction in area does not depend on temperature, thus offering additional confirmation.

Another type of ductile fracture, called ductile shear fracture, has been identified. As in the cone part of the cup-and-cone fracture, fracture occurs on planes of intense, localized plastic flow. It is generally postulated that such fractures initiate at the same sites as fibrous ductile fracture and that the flow occurs on planes of maximum shearing stress, becoming unstable or uncontained. Strain rates are often rapid so that the temperature rises and adiabatic conditions are approached. Although sliding is a major characteristic of this type of failure, it is to be expected that tensile stresses could cause separation across the sliding zone. Some work has been done on identifying the important features of this type of fracture by associating it with plastic instability.

The principal factors in both types of ductile fracture are work-hardening, plastic instability, and nuclei for plastic cavities. At present no stress criterion based on these factors has been developed for fracture.

In summary, the factors involved in purely brittle fracture have been identified and have been related by considering plausible mechanisms. For brittle fracture, it appears that the principal normal stress and the ratio of principal normal stress to maximum shearing stress are pertinent. The factors involved in ductile fracture have been identified, at least in part, but as yet a connection with the state of stress has not been proposed. Of course, temperature is important in both cases and should govern which failure process will take precedence, provided that the condition of the material is held constant.

It may consequently be possible to arrive at a unified theory of fracture in terms of stress. As indicated, a theory for yielding in terms of stress has been verified for some materials at temperatures near room temperature. Further, a rational basis for predicting purely brittle fracture has been stated but needs further verification. These two states of failure may prove to be predictable and, if they are limiting states, may ultimately furnish a type of unified failure theory. On the negative side, the path-dependent nature of plastic deformation complicates the prediction of ductile fracture, and in fact may prevent its prediction by a criterion based on stress alone. For combinations of stress and temperature at which ductile fracture preceeds brittle fracture, a unified theory of failure may be very involved indeed.

THE BIAXIAL LOADING MACHINE

This machine was conceived to achieve the following objectives:

1. To provide two-dimensional (biaxial) states of stress in a tubular specimen by:

    a. Axial tension combined with internal pressure.
    b. Axial compression combined with internal pressure.
    c. Axial tension combined with torsion.
    d. Axial compression combined with torsion.

2. To increase the various loads uniformly and predictably with time.

3. To provide preset, constantly maintained ratios of the two concurrent loadings.

Obviously, certain ratios of principal stress can be obtained either by tension plus torsion-loading or by compression plus internal-pressure-loading. This feature permits a check on the isotropy of the test material as discussed in detail later.

It was less expensive to hold the ratio of the individual stresses constant than that of the strains; to measure strains and proportion them suitably would have involved the use of costly electronic apparatus with more inherent maintenance problems. A hydraulic control system was a natural choice since one of the load systems (internal pressure) was hydraulic. Tension, compression, or torsion could have been achieved by either mechanical or hydraulic means, but again a complete hydraulic system was cheaper. No precision or accuracy was lost through this choice; it did, however, represent a deviation from previous testing practice. Older machines were of the straining type as opposed to the "stressing" type because of a substantial saving as long as fixed ratios of stresses or strains were not desired. It was estimated that the cost of a strain-ratioed machine would be $10,000-$15,000 more than a stress-ratioed machine.

It was also desirable to control the temperature of the test specimen. The transition between ductile failure and brittle fracture is a function of the temperature for any one material. Since this transition takes place at relatively high temperatures for some materials and at relatively low temperatures for others, the temperature-control system is designed to operate between approximately -340°F and +200°F. The lowest temperatures are obtained by the use of liquid nitrogen, the intermediate temperatures by dry ice, and the higher by a simple electrical resistance heater. By mixing cold air from a heat exchanger cooled by liquid nitrogen or dry ice and warm air from a heat exchanger heated by the above-mentioned heater, any intermediate temperature can be established and maintained. The proportion of warm air to cold can be maintained by a simple valve controlled by a servo system which in turn is controlled by a thermocouple sensing the temperature of the specimen.

Figure 1 shows the main features of the machine. An I beam and channel frame support the main loading shaft at the center. At the bottom is a calibrated dynamometer cell to measure both the axial and torsional loads by means of SR-4 electrical resistance strain gages; above this is a simple bearing for positioning the shaft. Next is the actual test section with grips that hold the specimen and allow a path for the hydraulic fluid which furnishes the internal pressure to reach the specimen. Above this section are two other positioning bearings with the torsional loading wheel between them. A force couple is applied to the periphery of this wheel from a small hydraulic cylinder attached to a floating frame. This floating frame automatically balances the two forces at the periphery of the wheel. Next there is a set of roller thrust bearings which prevent transmission of torsional loads to the tension-compression hydraulic cylinder above. Tensions or compressions as high as 10,000 lb, torsional loads as high as 5,000 in.-lb, and internal pressures as high as 5,000 psi are possible here.

The pressure for the hydraulic cylinders and internal pressure to the specimen is supplied from specially designed control valves which provide pressures in proper proportion to the desired load ratios. These valves, shown in Fig. 2, achieve the desired pressures by admitting a higher pressure from a pump through a needle valve and bleeding it off through another needle valve to a sump at a lower pressure. The intermediate controlled pressure acts on a shaft penetrating the top of the valve body and is counterbalanced by an external force. The valve automatically adjusts the flow of hydraulic fluid into and out of the valve body so that the external force is just balanced.

The forces on the tops of the valve shafts result from a system of levers (see Fig. 3). A single force which increases linearly with time is applied to the end of lever A. This force is obtained by filling a tank with water from a controlled supply at a desired rate. The other end of lever A acts on the middle section of lever B, one end of which is attached to the shaft of the internal-pressure control valve. The other support for lever B is lever C, which in turn is supported at either end by the shafts of the control valves for tension-compression and torsion. The point of contact between levers B and C is variable, depending on the ratio of the three controlled pressures desired. As can be seen by the sketches at the top of Fig. 3, an infinite variety of positions is available.

Two separate systems are provided: the 1000-psi pressure system for the tension-compression-torsion system and the 5000-psi for the internal pressure (see Fig. 4). In the lower-pressure system, the by-pass valving around the control valves is used for gross adjustments of the motion of the hydraulic cylinders. (See by-pass control panel in Fig. 5.) The four-way valves reverse the motion of the loading cylinders. Each circuit has an electrically

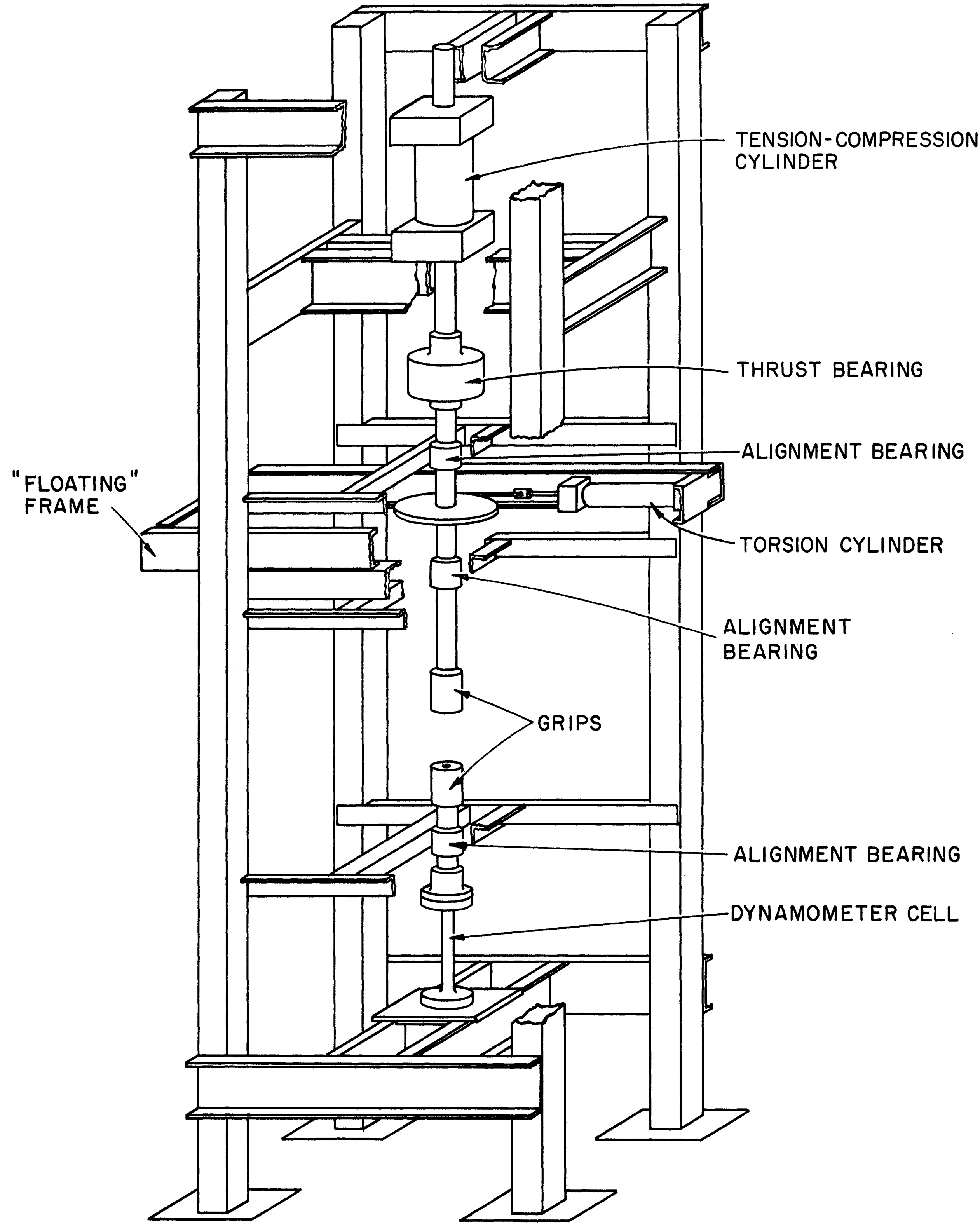

Fig. 1. Main features of the biaxial loading machine.

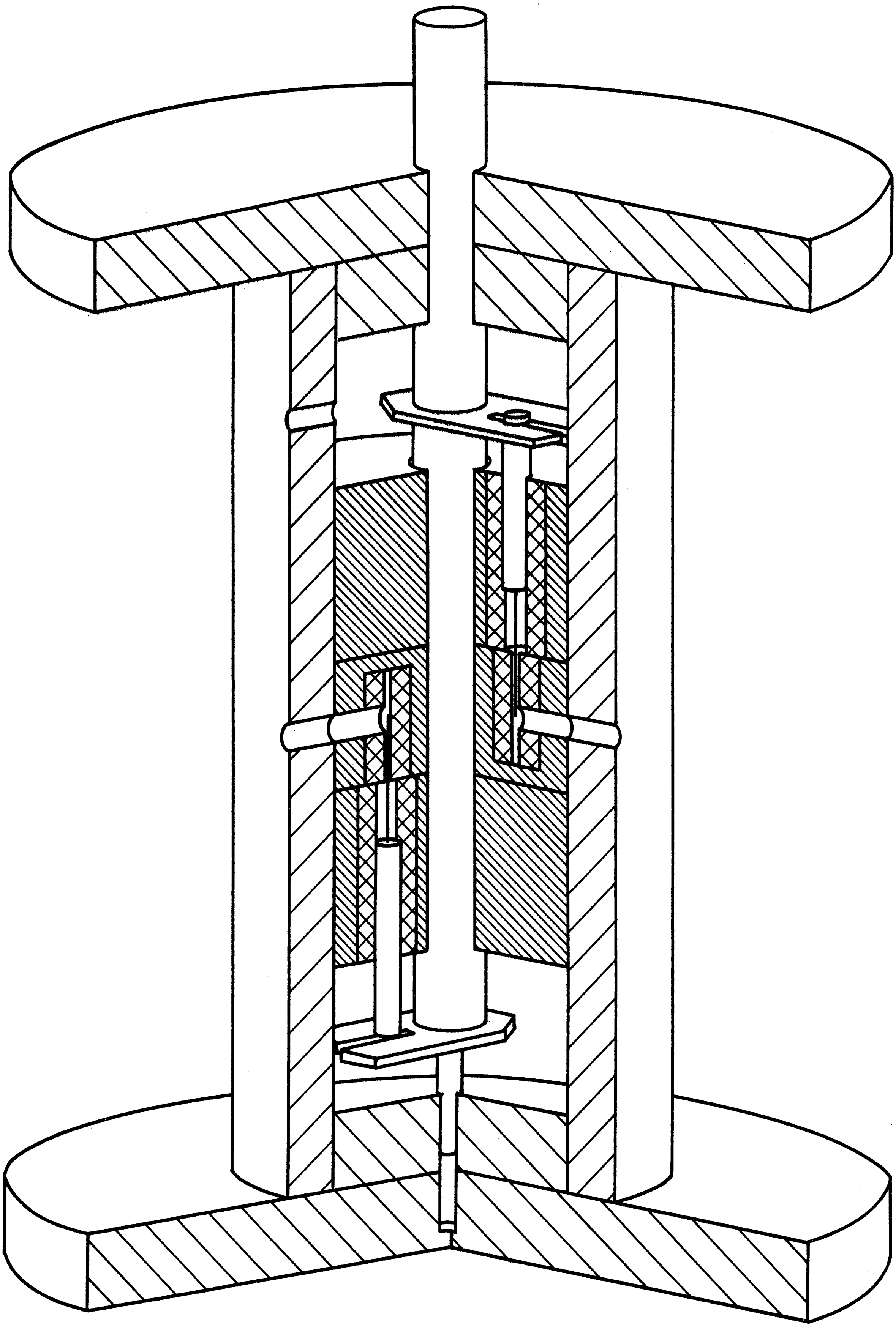

Fig. 2. Proportioning valve.

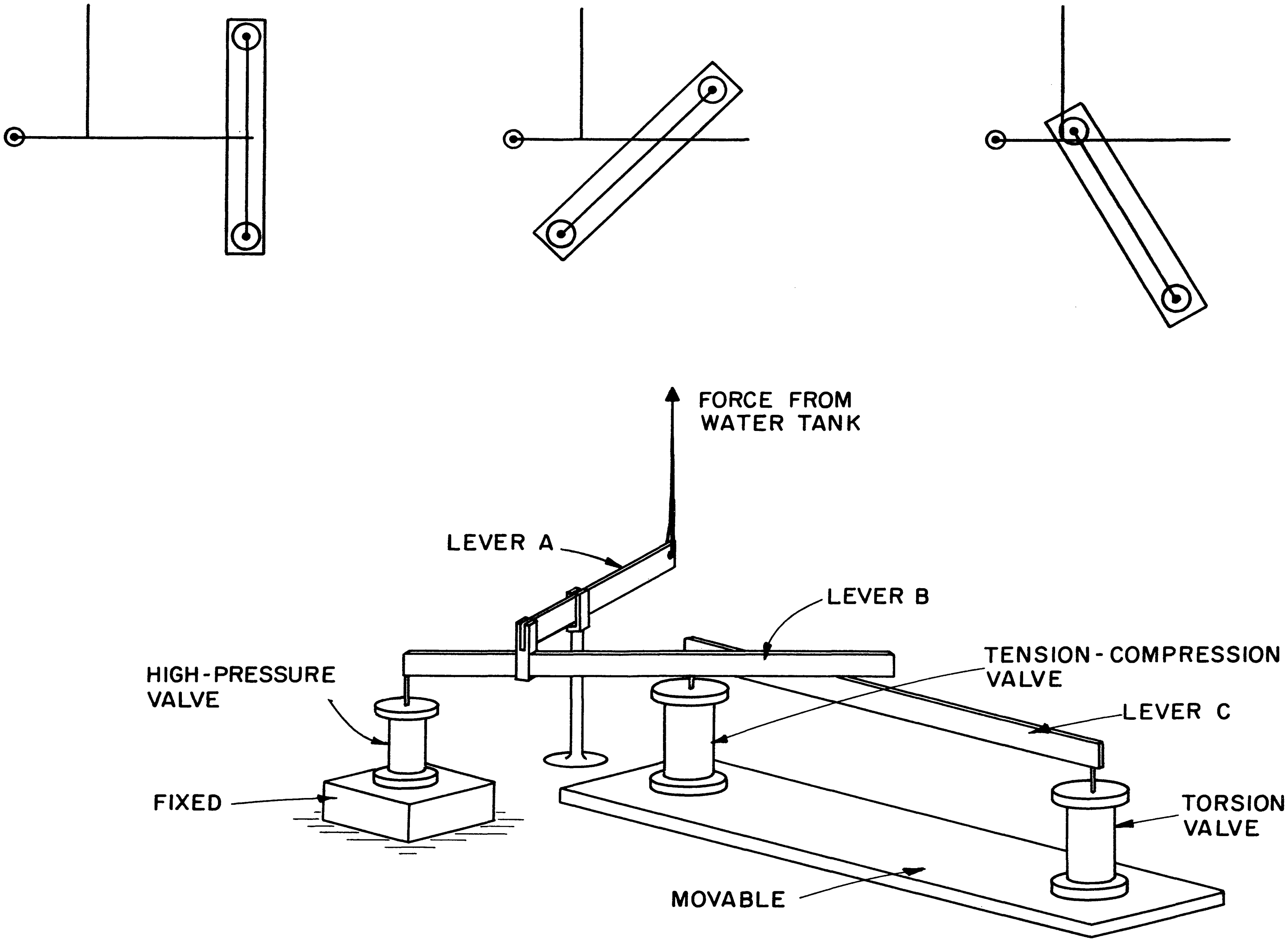

Fig. 3. Load proportioning system.

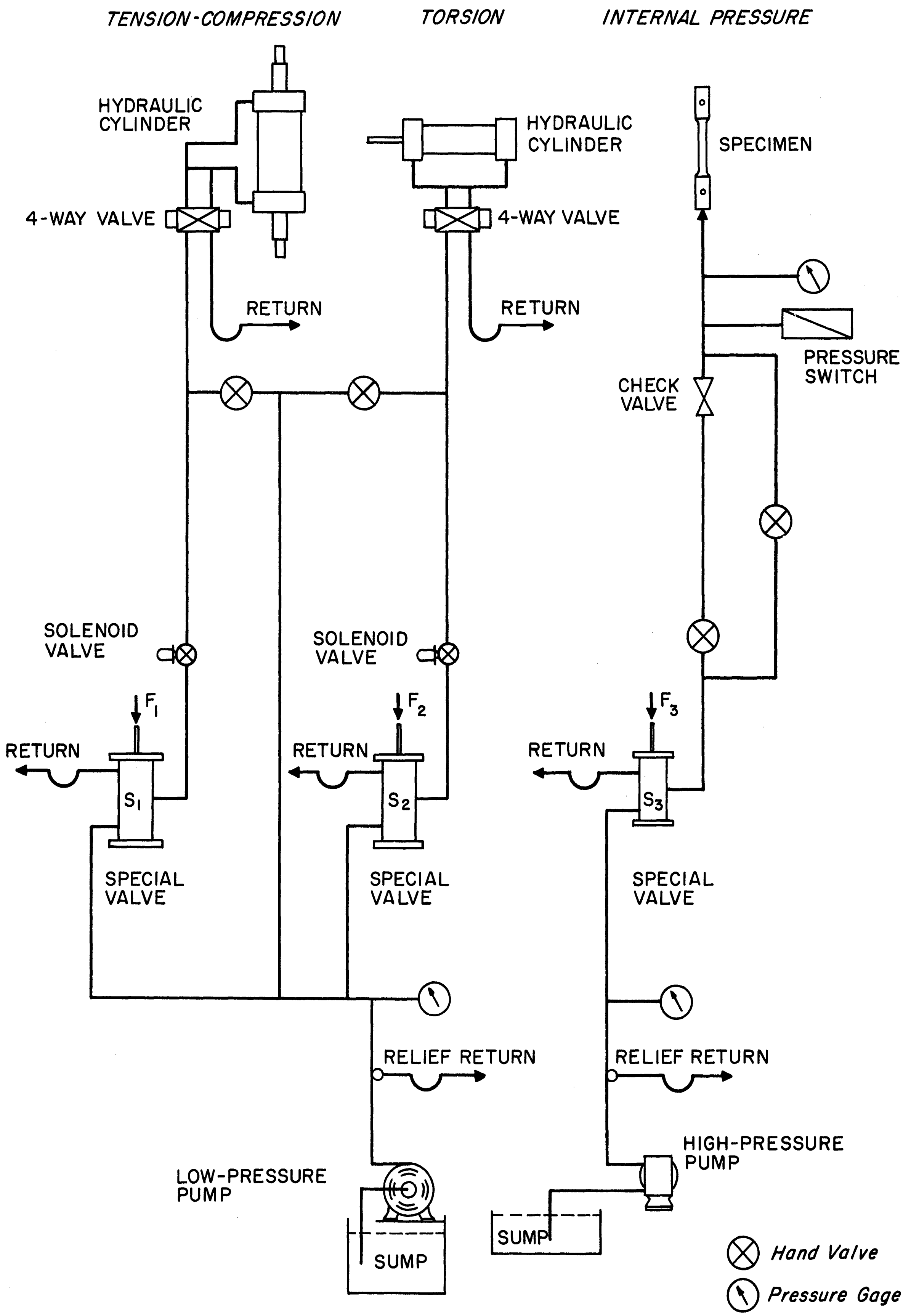

Fig. 4. Hydraulic diagram.

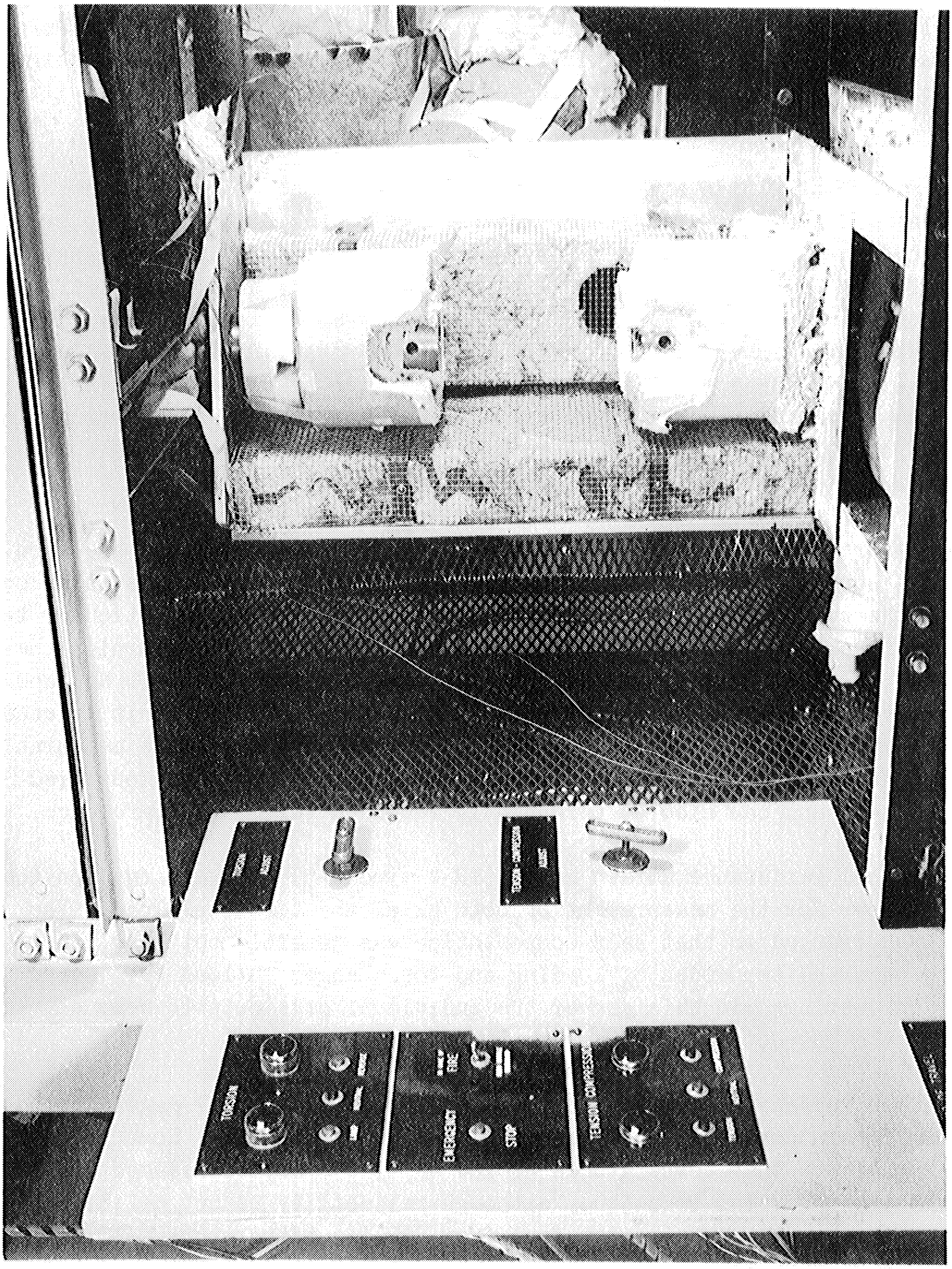

Fig. 5. Biaxial loading machine showing by-pass control panel.

operated solenoid valve which can completely restrict the fluid in its branch. The high-pressure system is similarly equipped. The by-pass is used for filling the specimen and the shut-off is a hand-operated valve instead of an electronically operated one. The high-pressure pump has a low rate of discharge since practically no flow is required during operation. The pump is designed to handle any liquid; this feature is desirable since several liquids will be used in the high-pressure system.

The different fluids are required because it is necessary to have the specimen at very low temperatures during certain phases of the testing program. Ordinary hydraulic oil is satisfactory for room-temperature applications, but it solidifies a few degrees below 0°F. Ethyl alcohol is an acceptable fluid down to approximately -150°F. For lower temperatures it is necessary to use a gas to apply the internal pressures. Gases are unsatisfactory for general use because of the danger of explosion at these high pressures, but it is possible to minimize this danger in this system by keeping the gas volume low. Still, if possible, it is advisable to orient the testing program so that use of a gas is not necessary.

To measure the load transmitted and to detect yielding of the specimen material, a continuous record of both dynamometer bar strains and strains occurring on the surface of the specimen is required. During any particular test, as many as five separate strain-gage outputs may be needed. To furnish these data versus time, a Heiland Model 712-B recording oscillograph with Heiland No. 40-1000 galvanometers and a Heiland Model 119B-1 bridge balance unit is used. This combination provides adequate sensitivity for determining the measurable quantities during the test. Strain-gage outputs can be visually monitored during the test and can also be permanently recorded for future reference.

Electrical resistance strain gages (SR-4 type A-5) were arranged on the dynamometer bar for the measurement of both axial and torsional load. The hook-up was arranged so that self-compensation was possible both for interaction between the two modes of loading and for changes in load-cell temperature during testing. In this manner the individual gage outputs were a true measure of the respective loads transmitted.

Specimen surface strains are measured using SR-4 type A-7 gages in those ranges of temperatures in which their reliability is certain. Some preliminary tests indicate that temperatures as low as -340°F may be reached with this type of strain-measuring technique, although reliability is not definite. Reliable output, however, can be obtained from dry ice temperature (-109°F) to reasonably high temperatures—300-400°F—which is the range of temperature anticipated during this program.

Specimen temperature measurements were made using copper constantan thermocouples attached to the specimen at the bottom, middle, and top of the test section. Millivolt readings were taken by use of a Leeds and Northrup Potentiometer.

RESULTS OF PROOF TESTS ON TESTING MACHINE

DYNAMOMETER-LOAD-CELL CALIBRATION

The load-measuring bar was calibrated in tension, compression, and torsion by use of a 60,000-lb Baldwin Universal testing machine and a 60,000-in.-lb Rehlie torsion machine, respectively. The dynamometer bar exhibited complete linearity in both types of loading which were in excess of the anticipated combined loading during the testing program.

CONSTANT TENSION-TORSION RATIOS

The characteristics of the load-proportioning system in tension (or compression) and torsion were determined by a series of calibration tests. A specified loading rate was established which would be realistic during the actual tests; the total test time was estimated at 10 to 15 minutes. A cold-rolled solid steel bar was used in place of the actual specimen, and the ratio of the forces applied to the tension and torsion valves was varied so that a wide range resulted in ratios of the principal stress ratio σ_2/σ_1 in the fourth quadrant of the principal stress plane. (Compression-torsion calibration was not made as it was felt to be a duplication.) Readings of the dynamometer bar strains were taken with SR-4 strain indicators at constant time intervals so that a plot of axial force versus torque applied could be plotted. (See Fig. 6 for results of the proportional loading calibration.) Note here that the calibration was made on a specimen which did not suffer gross deformation.

Three conclusions were made on the basis of these calibration tests:

1. The load-proportioning system operates in the reproducible manner.
2. The load-proportioning system for tension and torsion functions more efficiently as the operating loads become larger with respect to the mechanical friction inherent in the system.
3. Any ratio of axial load to torsional load is possible, but due to frictional effects at the beginning of an individual test, it is advisable to select ratios lying in the fan of load lines in Fig. 6.

To determine what loading path is followed in the principal stress plane for a given ratio of loads

$$\frac{P}{T} = \frac{\text{axial load, lb}}{\text{torsional load, in.-lb}} ,$$

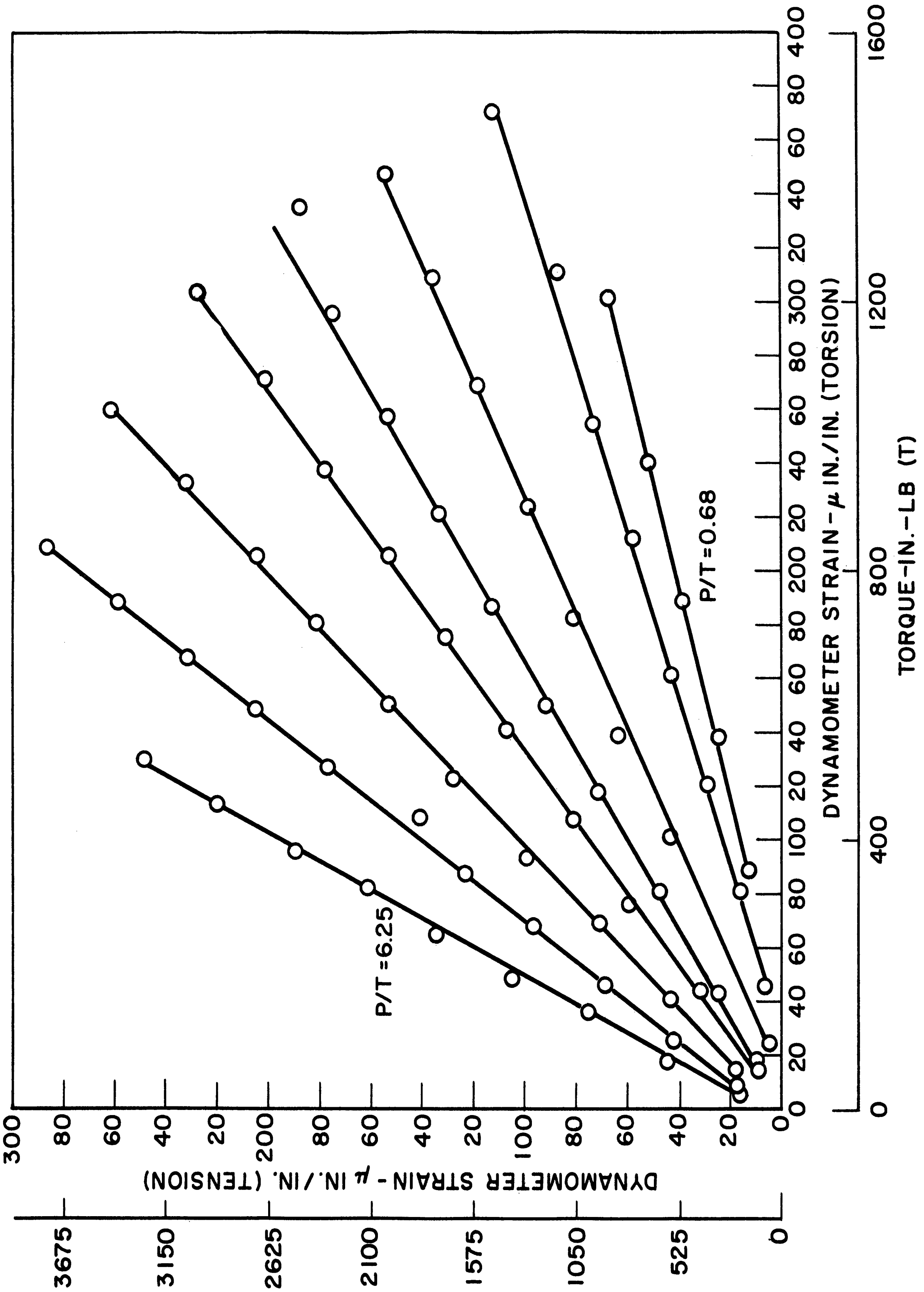

Fig. 6. Combined load calibration curves.

one needs to know the specimen geometry. By the approximations made for a thin-walled tube subjected to this system of loads, one can plot P/T versus the loading-path angle α in the principal stress plane. For the specimen geometry shown in Fig. 7, see Fig. 8 for the plot of P/T vs. α. For the extreme load lines shown in Fig. 8, one may proceed in the fourth quadrant of the principal stress plane from $\alpha = 14°$ to $\alpha = 40°$ in tension and torsion and from $\alpha = 50°$ to $\alpha = 76°$ in compression and torsion.

INTERNAL-PRESSURE SYSTEM

Because of a major redesign of the high-pressure proportioning valve, proof test results are not yet available. The redesign is complete and tests to determine the proportioning characteristics should be completed shortly.

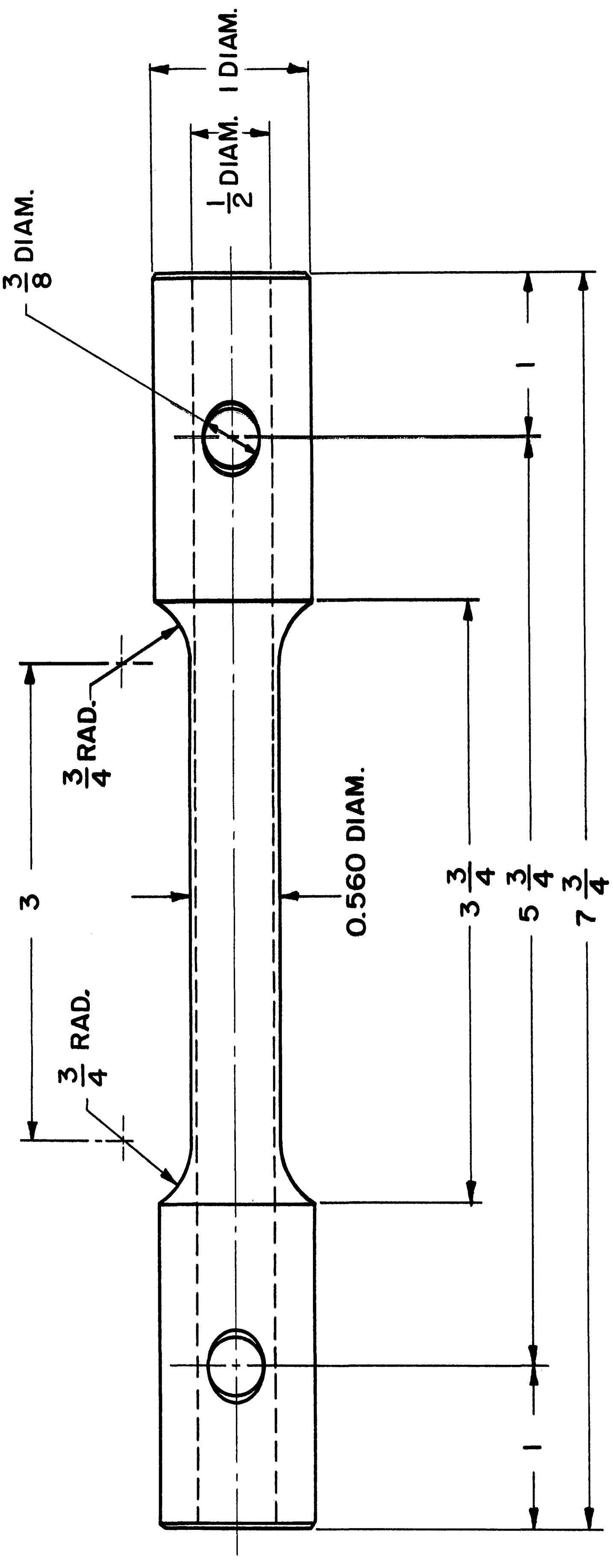

Fig. 7. Specimen.

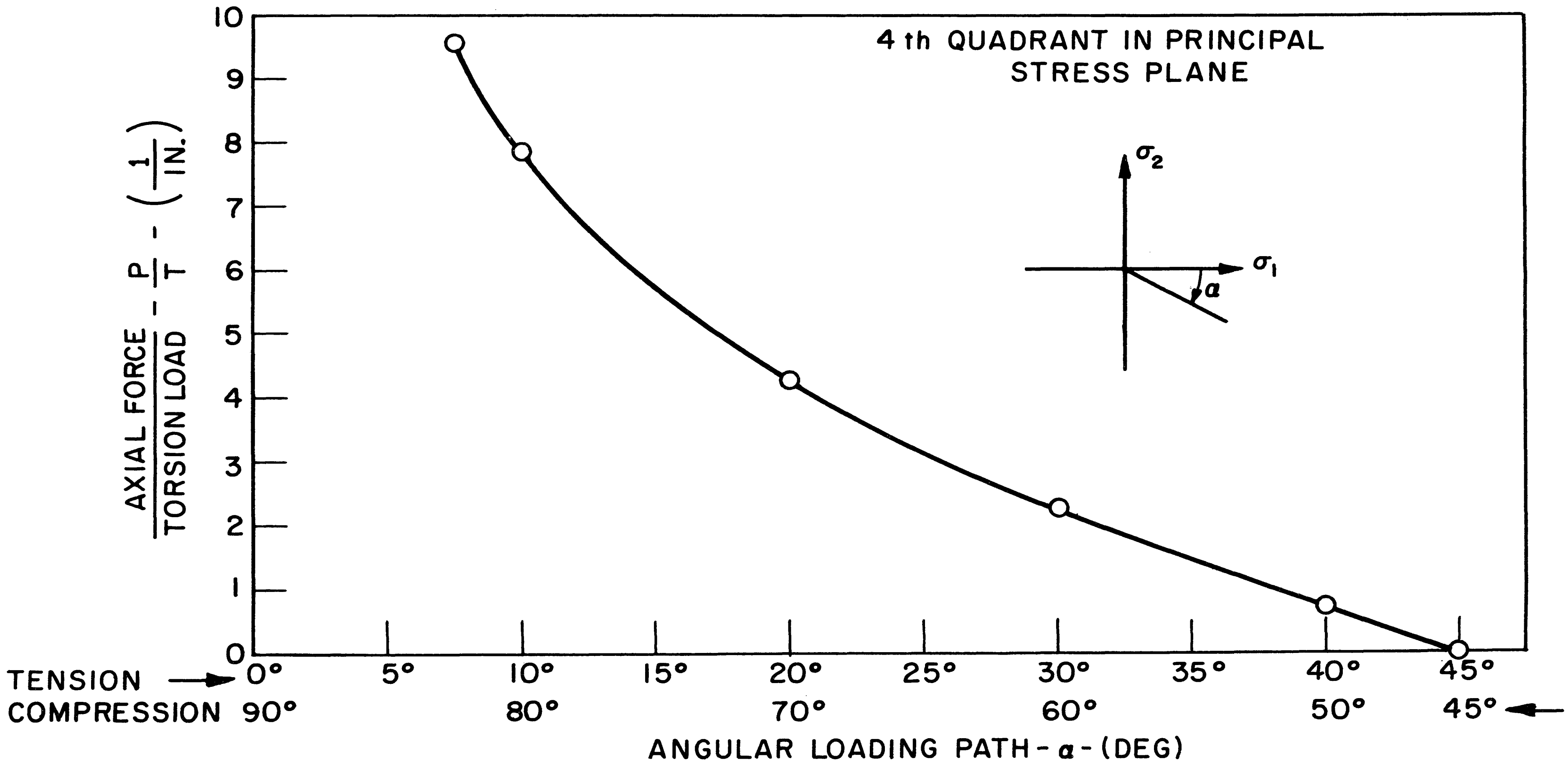

Fig. 8. Load ratio vs. angular loading path.

SPECIMEN AND FAILURE OBSERVATION

The specimen adopted for this research program consists of a thin tubular test section with enlarged end sections which fit the grips of the testing machine. Figure 7 gives the dimensions of the specimen.

A thin tube was selected since the stresses are known to a good degree of approximation for internal-pressure loading and are known exactly for torsion and tension loading. Since the wall thickness of the tube is considerably less than the tube diameter, the stresses are approximately the same at every point in the test section for any combination of loads. For all three types of loading the stresses are statically determinate or approximately so, and consequently are known whether the material is behaving elastically or plastically. This will hold until localized deformation is encountered. It was felt that the stresses must be known at every point during a test if the results were to be useful in formulating a failure theory in terms of stresses. For this reason, specimens which incorporate notches or other forms of stress concentration were not considered for the initial phases of the program discussed here.

One of the problems that may be encountered with a thin-walled specimen is its tendency to become unstable under primarily compressive stresses. For this specimen, calculations indicated that neither local buckling nor buckling as a column should occur except in the compression-compression quadrant of the principal stress space. This quadrant should be of minor interest in assessing fracture.

One principal stress will be zero or approximately so for all combinations of loading. Thus states of plane stress exist in the specimen. To facilitate discussion, a plot of one nonzero principal stress against the other nonzero principal stress is presented in Fig. 9. The load combinations which give the various combinations of principal stress are indicated in this figure. In the second and fourth quadrants a given combination of principal stresses can be produced by two different combinations of loading. However, in this instance, the direction of principal stress will differ. In this way the isotropy of the material can be checked since behavior of an isotropic material will depend primarily on the magnitudes of the principal stresses and not on their directions.

The behavior of two technically significant materials is being investigated. The choice of these materials was based on their ability to exhibit both brittle and ductile fracture in an experimentally attainable temperature range as indicated in a series of tensile tests on small specimens. It may be of interest to note that a number of materials were investigated in addition to those selected. AISI B1113 steel (Bessemer screw stock) was selected as a typical material of body-centered cubic lattice. A ferrous material is of particular interest since a large body of data on fracture of such materials

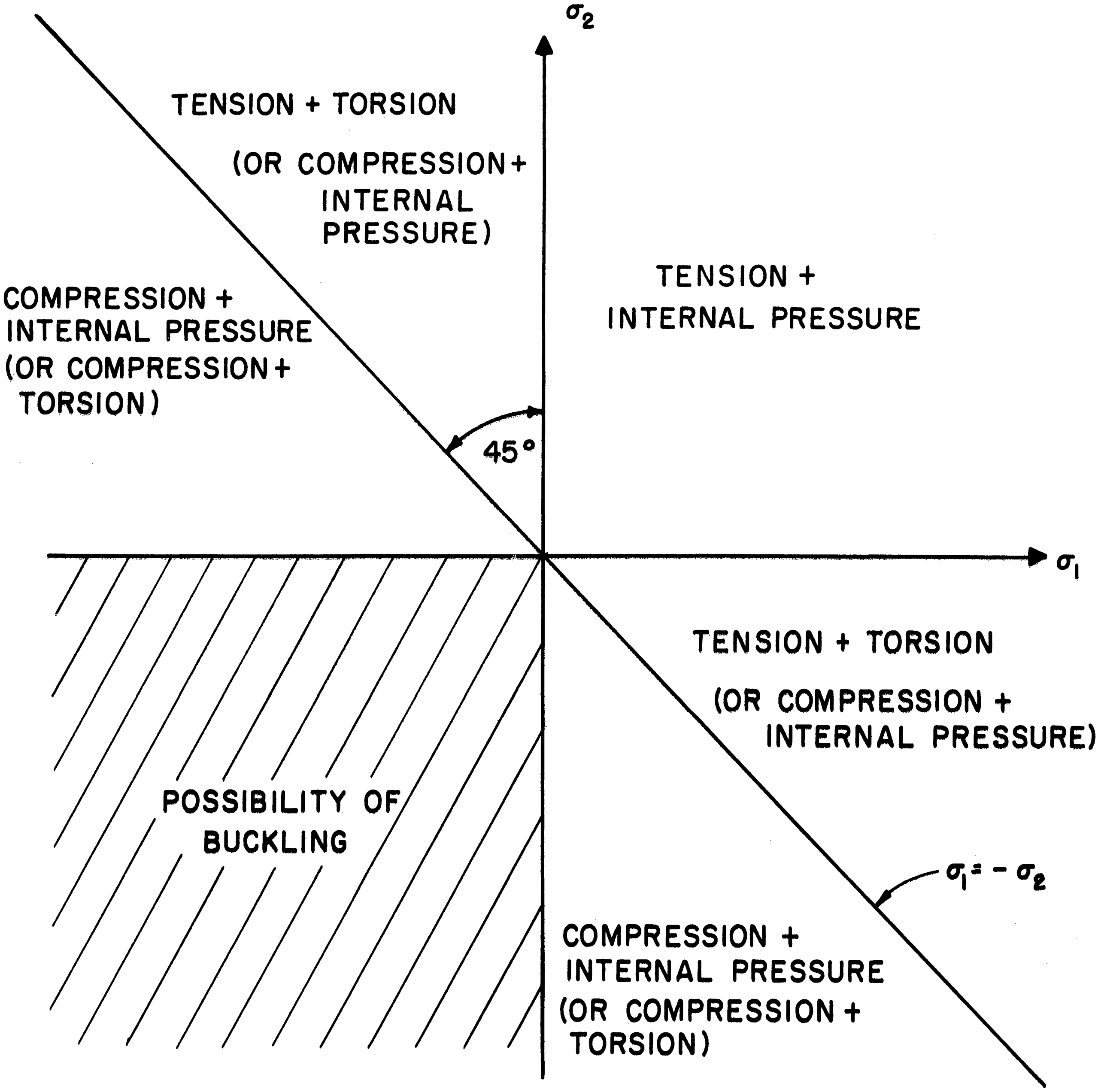

Fig. 9. Combinations of loading for various combinations of stress.

is available in the literature. As will be discussed later, some difficulties have been encountered in inducing completely brittle behavior in AISI B1113, even at the temperature of liquid nitrogen (-340°F). Two approaches have been tried to increase the brittleness of this steel. The first was to increase the grain size of the material to the range ASTM No. 3-6 by heating to a normalizing temperature of 2150°F for one hour. Very little change in ductility was induced. The second approach was to introduce hydrogen into the material by soaking specimens in a citric acid solution. This treatment did increase the brittleness, but completely brittle fractures in pure tension were not produced at liquid nitrogen temperatures. Since AISI B1113 may prove to be unsatisfactory, since brittle fractures can be produced for only a limited number of combinations of stress, the use of other steels has been given some consideration. For example, a plain carbon steel of higher carbon content, such as SAE 1040 or SAE 1050, might be used in the heat-treated condition. However, larger total loads would be required to fracture such specimens and consequently some modification in the loading or load-measuring system of the testing machine might be required.

The second test material is a zinc-base casting alloy designated commercially as Zamak 3. This material is of interest since it has a hexagonal lattice structure, thus permitting assessment of an entirely different system. Further, zinc alloys become brittle at temperatures near room temperature, making experimental observations of the behavior of the material somewhat easier than with steel. Various techniques for casting Zamak 3 specimens have been tried and reasonably good blanks have been produced by casting in a graphite mold. To improve the grain structure near the interior of a blank, porcelain rods have been inserted along the specimen axis during pouring. Although the resulting grain structure is fairly uniform, the degree of isotropy of such specimens must be investigated. A material of low strength, as zinc is, has an additional advantage: failure is more likely to occur before buckling than in a material of high strength. Thus it may be possible to investigate a wider range of stress combinations in Zamak 3.

Observation of failure is another aspect of the research problem that is intimately connected with the specimen and the material. Both the onset of yielding and the initiation of fracture must be observed. Onset of yielding requires a knowledge of both stress and strain, so that deviation from linearity can be detected. For this, wire resistance strain gages can be used since, if both strain on the specimen and some load parameter are plotted, a deviation in linearity between load parameter and strain indicates that yielding has occurred. For this program, strain gages constitute the primary means of yield detection. However, another technique has been investigated which may prove to be much more sensitive. This involves the monitoring of acoustic energy output in the megacycle frequencies. Crussard and others have noted that many materials exhibit marked changes in high-frequency acoustic energy output just prior to yielding and also just prior to fracture. Some exploratory work done on the Bessemer steel and on Zamak 3 indicates that similar phenomena occur at megacycle frequencies. This is of interest since normal machine "noises" have negligibly small components at megacycle frequencies, and consequently it is possible that acoustic detection of yield and fracture may be feasible.

INITIAL RESULTS FOR AISI B1113 STEEL

Initial tests were conducted on this material both in the as-received and hydrogen-embrittled conditions at three different temperatures: room temperature, dry ice temperature (-109°F), and liquid nitrogen temperature (-340°F). The results were as follows.

ROOM TEMPERATURE—MATERIAL AS-RECEIVED

Tests were conducted on a total of approximately six specimens in pure tension, pure torsion, and for a ratio of P/T = 6.25.

(a) The pure-tension tests revealed large amounts of plastic deformation with considerable necking taking place prior to fracture. The yield stress σ_o was calculated to be 50,000 psi. The testing machine was able to maintain a constant loading rate until just prior to fracture when large amounts of plastic deformation occurred. The machine was considered to be completely adequate for this type of loading. Only in the last 15 to 30 seconds of a total test time of 10 to 12 minutes was it not possible to maintain the loading schedule.

(b) In pure torsion, the material showed ideal plastic behavior, i.e., no increase in applied load for large changes in angles of twist. Because of this behavior, the machine was unable to maintain the loading rate. This is to be expected, as no rotation torque rate can be applied to a plastic material to increase its load-carrying capacity. The yield stress in pure torsion, τ_o, was found to be approximately 26,500 psi.

(c) Combined loading was carried out on two specimens for ratio of P/T = 6.25($\sigma/\tau \cong 1.6$). The machine was unable to maintain a constant ratio of loads because of the reason explained in (b) above. It was apparent from these tests that no meaningful fracture surface could be obtained for this material at room temperature because the loading path could not be controlled.

DRY ICE TEMPERATURE (-109°F)

Cursory tests were conducted at this temperature in tension and torsion separately to determine if the material exhibited brittle behavior. These results showed no apparent change from room temperature in ductility or load carrying capacity.

LIQUID NITROGEN TEMPERATURE (-340°F)

Approximately six total tests were made at this temperature in pure tension, torsion, and for a ratio of P/T = 6.25. The pure-tension tests revealed some reduction in ductility from room temperature, although fracture was not of an entirely brittle nature. Pure-torsion tests were essentially the same as at room temperature with an absence of brittle failure. Combined loading tests were essentially the same as room temperature.

At this point, as a method of embrittlement, hydrogen was diffused into the walls of the specimen by soaking in a solution of citric acid salts. It was hoped that in this way this material would exhibit brittle fracture at the liquid nitrogen temperature. One undesirable feature of this embrittlement scheme is inconsistency; some specimens may become more brittle than others. However, it was felt that knowledge could be gained both about the fracture phenomena and operation of the testing machine.

ROOM TEMPERATURE AFTER EMBRITTLEMENT

Four tests were conducted at this temperature. No marked change was noted in ductility as compared with the as-received material.

LIQUID NITROGEN TEMPERATURE AFTER EMBRITTLEMENT

Approximately 15 tests were made at this temperature with somewhat erratic results. The "treated" specimens showed definite brittle behavior but were not consistent for the following reasons:

(a) The method of treatment, if not closely controlled, may cause some specimens to be more brittle than others.

(b) The embrittlement process apparently raises the transition temperature to very nearly liquid nitrogen temperature. Any small temperature gradient which exists in the specimen during test (perhaps a difference in temperature of 5 to 10°F between the ends of the test section) will cause ductile behavior or a combination of ductile and brittle behavior. A few very brittle fractures were observed in both tension and torsion. In pure tension, elongation and reduction of area did not occur. In torsion, several brittle failures were observed, one of which is shown in Fig. 10.

In these cases of brittle fractures the fracture strengths were:

$$\sigma_f = 98{,}000 \text{ psi and } \tau_f = 45{,}500 \text{ psi.}$$

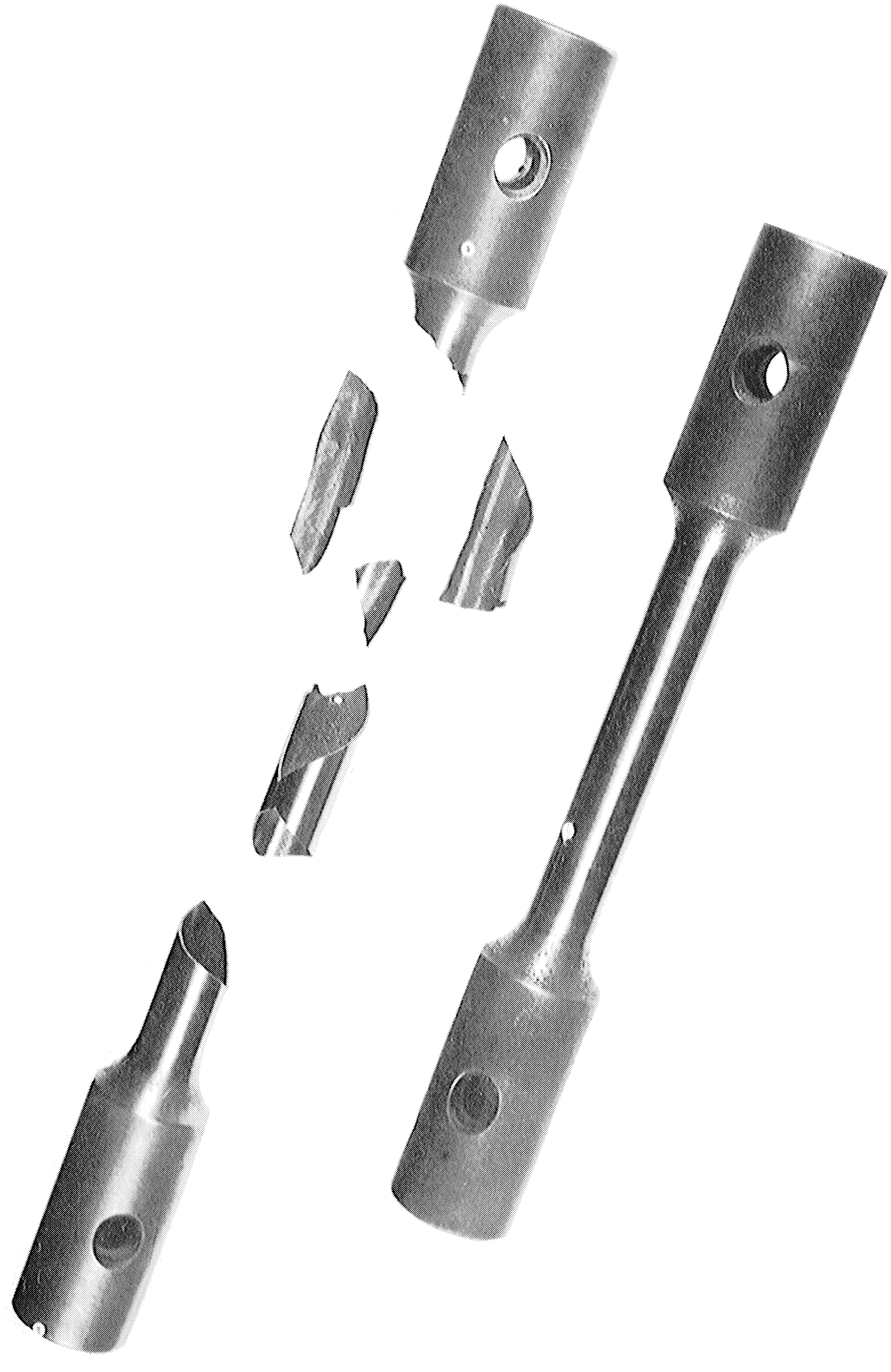

Fig. 10. Typical brittle fracture in torsion.

It is interesting to note the ratios of τ_o/σ_o for the ductile case and τ_f/σ_f for the brittle case:

$$\frac{\tau_o}{\sigma_o} = 0.53 \quad \text{and} \quad \frac{\tau_f}{\sigma_f} = 0.47 \quad .$$

Although two or three combined loading tests were made, the results were scattered due to a nonuniform temperature during the loading program.

CONCLUSIONS

As a result of the research performed during the initial phase of the program, the following conclusions are drawn.

1. The biaxial loading machine is complete and has been thoroughly calibrated for tension-plus-torsion and compression-plus-torsion loading.

2. Of the two specimen materials selected, one, AISI B1113 steel, may not be entirely satisfactory since purely brittle behavior cannot be reliably produced at conveniently attainable temperatures. However, a change to similar material, such as SAE 1040 steel in the heat-treated condition, may overcome this difficulty. Techniques for producing acceptable specimens of the second specimen material, Zamak 3 zinc alloy, have been developed.

3. A theory for yielding or elastic failure in terms of stress is well-known and is physically accurate for behavior of metals near room temperature. Further, there appears to be a good prospect of developing a theory for completely brittle fracture in terms of stress. Thus it appears justified to concentrate our future experimental work on these two areas of behavior first, following later with an investigation of ductile fractures.

4. Some of the appropriate directions of theoretical investigation in the area of ductile fracture have been indicated; the use of plastic instability analysis seems to be particularly promising.

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