THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
Department of Engineering Mechanics

BENCH-SIZE EQUIPMENT FOR AN UNDERGRADUATE STRENGTH OF MATERIALS LABORATORY

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ABSTRACT

Two different bench-size loading machines are considered for a materials testing laboratory which may be operated on an individual basis by engineering students. The needed auxiliary laboratory equipment is discussed, and it is shown that total costs of such a system are low enough so that it would be no more costly to furnish a new laboratory on this basis than it would be to purchase a conventional testing machine.

Experiments are laid out which are satisfactory for use on such bench-size equipment and which illustrate some of the important principles of the science of strength of materials. Each of these experiments is described in some detail, with drawings and photographs of the appropriate parts.

ACKNOWLEDGMENTS

The author wishes to acknowledge the valuable assistance of various graduate students at The University of Michigan who have been employed on this work, in particular, Mr. David A. Sonstegard, Mr. Thomas B. Hoekstra, Mr. Geoffrey Huggins, and Mr. Lauren Bowler.

The writer also wishes to acknowledge the benefit of conversations with Dr. Robert D. Chipman of the W. T. Bean organization in Detroit, Michigan, and with Professor F. R. Shanley of the College of Engineering, the University of California at Los Angeles.

INTRODUCTION

It has been customary for many years to construct materials testing and strength of materials laboratory courses around available mechanical loading equipment. For the most part this equipment has not evolved very rapidly in terms of reduction in size; it is much the same as equipment in laboratories 30 years ago. But it still remains the kind of thing one would wish to have for a research laboratory in which relatively large forces might be needed, say of the order of up to 100,000 pounds. Every materials laboratory probably contains at least one piece of such equipment.

While little change has taken place in the general size of testing machines, considerable changes have taken place in their efficiency, performance, and cost. For the most part, the battle between hydraulic and screw-operated machines still continues, with both types exhibiting certain desirable features. In the last twenty years, however, considerable progress has been made in controlling head velocity and strain rate in testing machines, as well as in providing relatively sophisticated programming devices for preselecting a complex sequence of loads to be applied to a given specimen. All of these developments have been desirable and have allowed significant advances to be made in the science of mechanical testing of materials. Unfortunately, these refinements have also significantly increased the cost of a typical testing machine. Educational institutions are now faced with even larger capital expenditures to provide such equipment in quantity sufficient for testing purposes. In some places, modern testing machines of the research variety are simply too expensive and hence too scarce to assign to general undergraduate use, but must be reserved for graduate work and for other research-oriented activities.

The problem of cost and the subsequent scarcity of modern testing machines is compounded by today's increasing undergraduate enrollments. Often the enrollment in undergraduate materials laboratories or in undergraduate strength of materials laboratories is so large that most students are unable to participate actively in a given experiment. One or two students actually conduct the work while the rest observe; or in some situations the instructor may run the experiment while the students observe. Under these conditions a laboratory becomes nearly synonymous with demonstration. The basic purpose of this research project is to devise techniques which will permit every student to participate actively despite increasing enrollments and costs.

Specifically, we are concerned with devising materials laboratory testing equipment, experiments, and teaching techniques which will permit the individual student, or a pair of students, to perform the experiment. In the training of engineers, a laboratory in which the student actively participates is superior to one in which the student is an observer.

In constructing such equipment and a course around such equipment, we had in mind three specific aims: One, the cost of the entire project could not greatly exceed the cost of a large research-type testing machine. This goal has been accomplished.

Second, such equipment and associated experiments as were developed should accommodate the same number of students as the large, conventional equipment, and should occupy approximately the same space. While we have been unable to maintain this ratio exactly, this goal has been substantially achieved.

Third, the student should become familiar with as many of the basic loading and failure mechanisms in solid mechanics as possible. Specifically, each student should have an opportunity, perhaps with a partner, to set up and perform experiments involving tension, torsion, compression, bending, buckling, stress concentration effects, and the idea of the measurement of elastic properties. These topics are minimal in the sense that they should be included in any laboratory course demonstrating material properties or strength of materials effects. Naturally, other topics would be included in most well-designed courses.

A sequence of experiments which meets these requirements has been constructed as a part of this research grant, and will be described subsequently in this report.

BASIC TESTING EQUIPMENT

As indicated in the introduction, we established certain standards of performance and cost for a simplified bench-style loading system which would allow an individual student or pair of students to conduct experiments of the type usually found in materials laboratories or in strength of materials laboratories.

A typical large-scale strength of materials laboratory might require eight bench-style loading units, permitting 16 students to work simultaneously. This number should be sufficient for all but the largest engineering schools in this country. Allowing for a total of eight such machines, an economically reasonable plan would allocate $1500 to each station, or a total cost of $12,000 for the entire laboratory, exclusive of space. This sum would be less than the average cost of $15,000 to $20,000 for a single large-scale research-type testing machine. Approximately $500 was allocated for necessary auxiliary equipment at each station, with the remaining $1000 to be used for the actual loading machine.

Because the testing machine is the key piece of apparatus in the whole program, much time and effort was spent examining different possible machines. We had planned to purchase and modify a small, commerical, loading machine, until we discovered that two American manufacturers had developed equipment of this general size-class. This equipment appeared to satisfy our tentative requirements, so the general scheme of mechanical development was abandoned in favor of purchasing and carefully assessing existing equipment.

Before describing the equipment, certain additional technical requirements should be mentioned. First, a large number of different loading schemes should be available to the student. A testing machine should be able to exert tension, compression, and torsion in general, and should be able to handle specimens in bending, tension, compression and buckling in particular. Second, it should be able to perform simple experiments through the yield point and in the post-yield range of many normal materials. Third, the equipment should cost approximately $1000 or less, and should be small enough to fit on a laboratory bench.

We first obtained a small, screw type, tension-compression-torsion machine manufactured by the Detroit Testing Machine Company, 9485 Grinnell Avenue, Detroit, Michigan. This particular testing machine is hand-operated by a crank operating through a worm gear onto a pair of lead screws. The first lead screw controls the tension or compression loading, and the moving end of this screw is equipped with a bolt-down grip system. The fixed end of this particular tension loading system is attached to a piston encased in a hydraulic load-weighing mechanism which indicates hydraulic pressure on a pressure gauge. This in turn may be interpreted in terms of total force at once by means of a simple conversion factor.

The hand crank and worm system also rotate a single lead screw upon whose end is attached a large three-jaw Jacobs chuck. The other end of this system carries a similar chuck, which is attached to a rigid shaft operating through a lever arm onto the same hydraulic load-weighing system as used in the tension scheme. Specimens twisted in this small torsion machine cause a force to be generated in the torque arm which acts on the piston, and this in turn is reflected in increased hydraulic pressure in the enclosed load-weighing system. Figure 1 is a photograph of this machine.

Considerable time was spent conducting individual experiments with this particular equipment. In general, this type of loading apparatus meets all of our technical requirements, and at a cost almost compatible with our budget.

This particular piece of equipment presented several minor mechanical problems, most of which involved the torsion grip system, which is admittedly not good for large torque. In particular, the three-jaw Jacobs chucks were just marginally sufficient for the torque levels involved. An exhaustive critique of such shortcomings is unnecessary, since they can easily be remedied by the machine owner or may be corrected upon manufacture.

This machine was constructed to the specifications of this project and, so far as we know, is unique. It could easily be duplicated however. Its characteristics are:

(1) Maximum compression load, 4000 lb
(2) Maximum tension load, 4000 lb
(3) Maximum torque available, 500 in-lb

Figure 4 shows two hydraulic pressure gauges for measuring the internal pressure in the hydraulic load-weighing cell. The gauge on the left is a full scale one which can measure the total forces as well as the total torques. This scale can accommodate the full range of force and torque of this machine. The hydraulic pressure gauge on the right is a low-range pressure gauge designed primarily for work with the torsion system. It may also be used to measure much smaller forces than those measured with the coarser gauge. This small gauge can measure forces up to 500 lb or torque up to 600 in-lb. One must insert a needle valve between the smaller second pressure gauge and the main one in order for this gauge to be completely shut down when forces greater than 500 lb are applied. Torques greater than 600 in-lb cannot be applied because they exceed the torque limit of the machine.

This piece of equipment has been used extensively and appears sufficiently rugged to withstand intensive student use. One advantage of the screw-type loading machine is that forces greater than the yield point of materials may be applied without producing uncontrolled deformation of the specimen. Figures 2 and 3 are closeup views of the tensile and torsion grip systems.

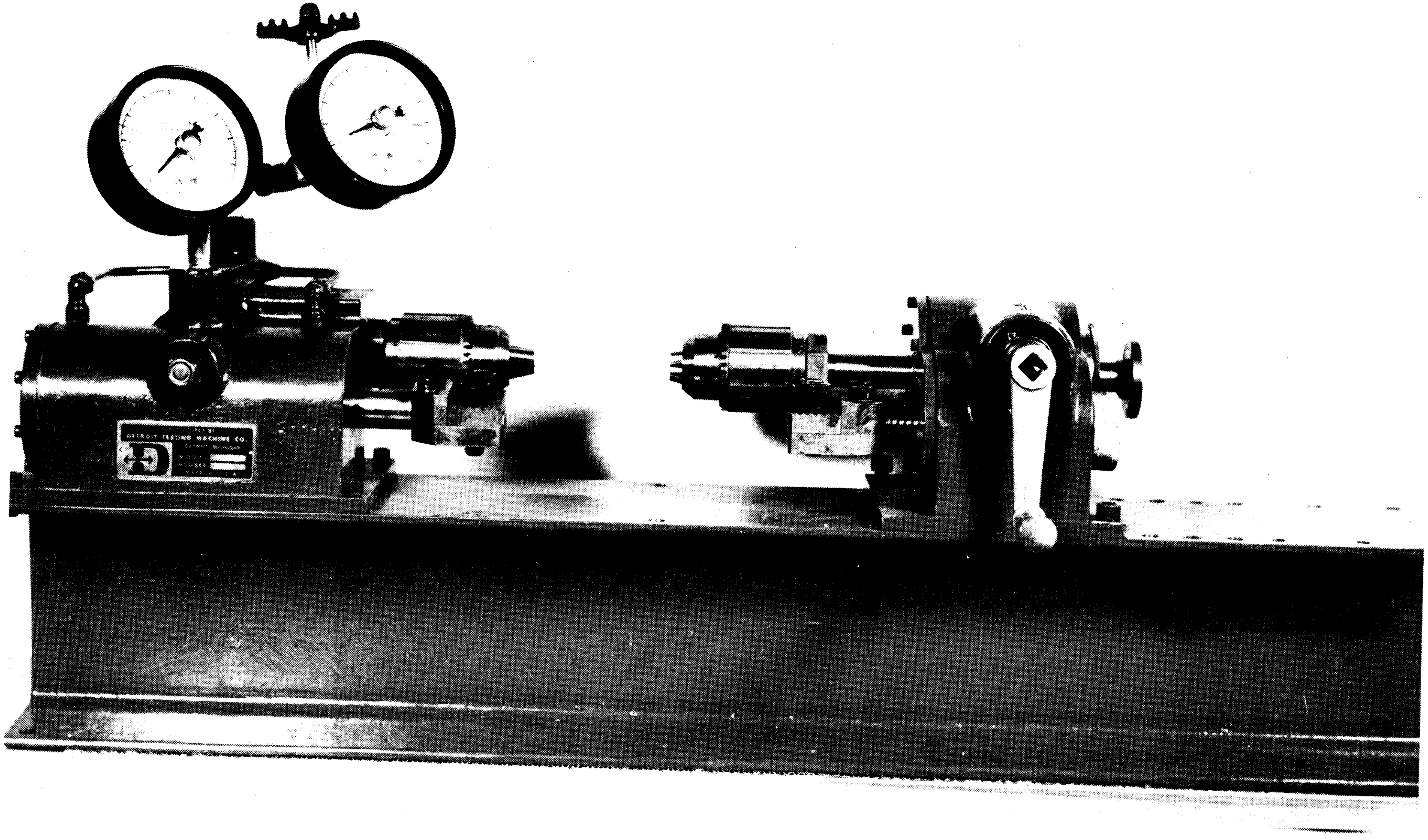

Figure 1. DTM testing machine.

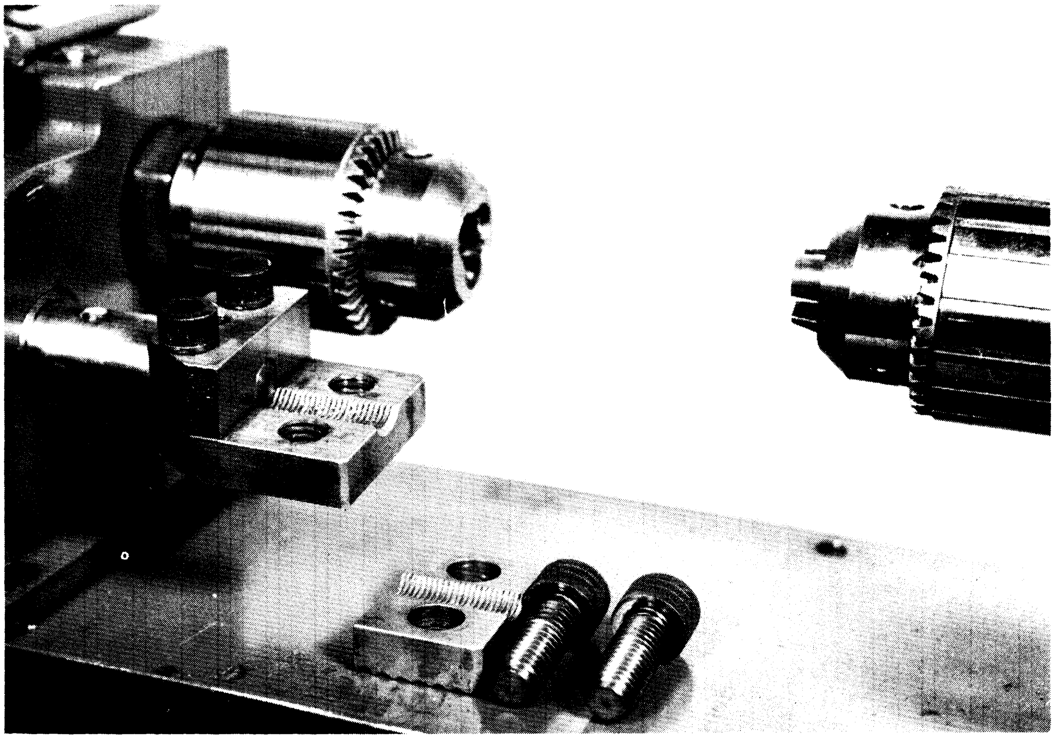

Figure 2. Tension grips on DTM machine.

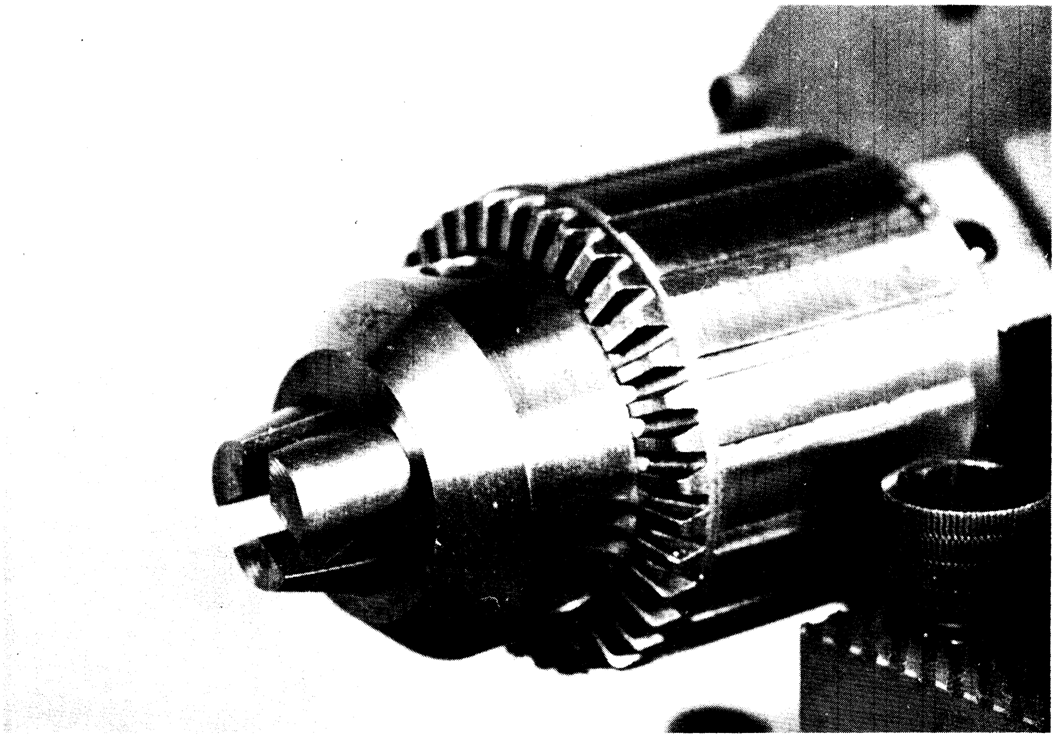

Figure 3. Torsion grip on DTM machine.

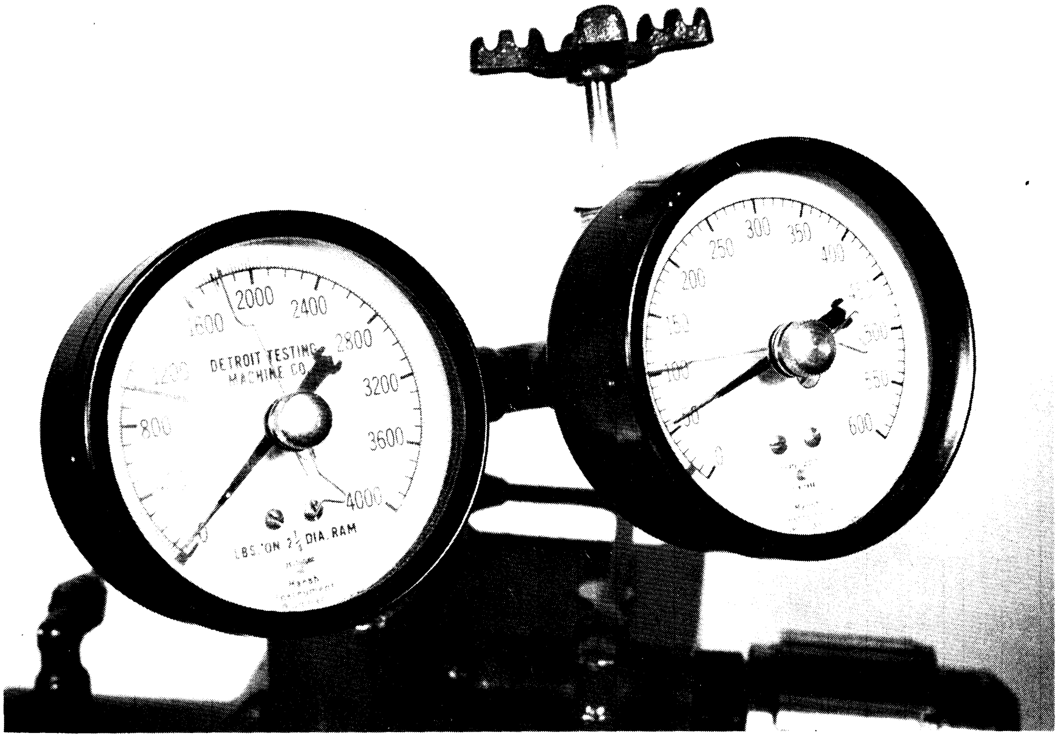

Figure 4. Pressure gauges used to monitor load.

The basic machine consists of a fixed weighing head, a moveable loading head, and a base manufactured from a length of standard I-beam. Since the loading head is moveable, it may be placed in some new position by using relocating pins and again bolted down on the I-beam base. Several bolt locations for this moveable head enable it to handle specimens in tension or compression 3 to 18 in. long, or in torsion 16 in. or less.

One difficulty with the arrangement of components in this screw-type testing machine is that bending tests are not particularly easy to perform. Such tests require a special fitting, illustrated in Figure 2.

A second machine which meets our requirements is a hydraulic bench-style testing machine manufactured by the Scott Aviation Corporation, Boca Raton, Florida. This piece of equipment is quite different in concept from the screw-type machine. It is a vertical machine using four posts as supports. Loading is accomplished by means of a small hydraulic cylinder at the bottom of the loading frame, and acting vertically. This cylinder is actuated by a small hand-pump and check-valve system, with a pressure gauge in the line whose reading may be interpreted in terms of total force. The tension and compression capabilities of this machine are 1000 lb each.

Several comments about this general type of machine are in order. First, because it has much less working space than the screw-type machine, smaller specimens must be used, and instrumentation is more difficult. Second, for student work this general class of hydraulic loading machine has certain inherent disadvantages: Leakage in the hydraulic equipment often causes the load to drop off while the strain reading is taken, so that one must either read strain very quickly or else make some correction for this. In addition, and even more serious, when dealing with specimens near the yield point it becomes very difficult on hydraulic equipment to control the strain rate and, as a matter of fact, even to control accurately the load-deformation region past the yield point. This is particularly true where relatively large amounts of elastic energy are stored in the loading frame compared to the energy storage capabilities of the specimen. In a large, conventional testing machine the metal hydraulic line and large cross-sectional area of frame members usually result in this being a minor factor. In the machine in question, however, it appears to be a larger factor; we had difficulty conducting load deflection curves past the yield point. The hydraulic equipment satisfies the basic cost requirements, but does not, of course, provide the desired torsion capability. Scott Aviation Company representatives recently informed us that a torsion attachment is to be made, but it was not available at the time of this writing. The compression load characteristics are somewhat proscribed by the mechanical instability of the hydraulic piston moving upward in the cylinder. Under large compressive loads, the system may cock over and become unstable. Figure 5 is a photograph of the hydraulic testing machine. Figure 6 is a close-up of the loading and grip region of the specimen.

In comparing these two basically different types of equipment, one finds that the screw-type machine has a wider range of loading capabilities and hence more fully satisfies the original requirements. The Scott hydraulic machine has special fittings for conducting bending tests, making it much more convenient than the horizontally acting screw machine.

Because both machines accept relatively small specimens, from the beginning we felt obliged to provide the students with some kind of strain gauge instrumentation. Two possible schemes are available for doing this.

The first method for providing strain gauge instrumentation is to equip each work station with one strain gauge bridge to accompany the testing machine. However, most American strain gauge bridges are high-quality precision instruments designed primarily for research. At a cost of $600 or more apiece, they exceed our limit of $500 for each work station. Should the budget allow, conventional American bridges are excellent research tools and are well worth the cost. These units are well known in the instrumentation industry, and we shall not review them in detail. The Appendix lists the names and addresses of several American strain gauge manufacturers; anyone interested may contact them directly.

Strain gauge bridges of sufficient quality for educational purposes may be obtained at considerably reduced cost. Although we have been unable to make a detailed study of each instrument, we have discovered three Japanese-made strain gauge bridges for sale in this country. Because these instruments are considerably less well known than their American counterparts, they are shown in Figures

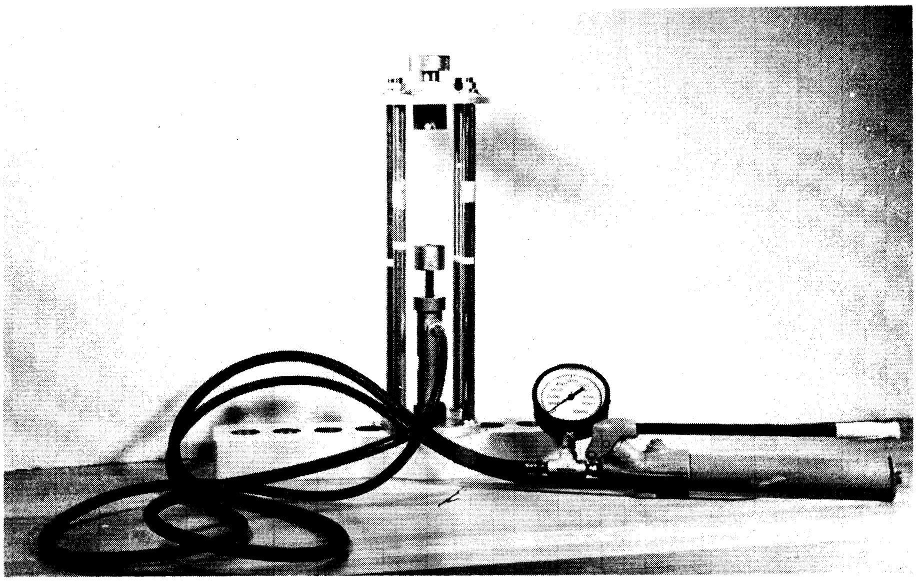

Figure 5. Scott Hydraulic testing machine.

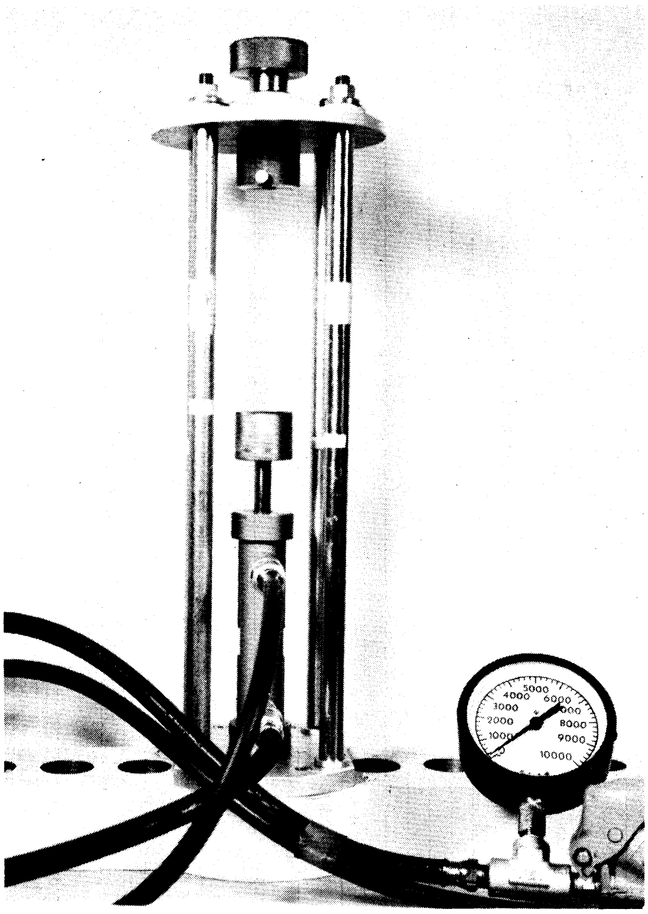

Figure 6. Loading and grip region of Scott testing machine.

7,8, and 9. Note especially that the Kyowa bridge (Figure 8) has provision for three separate measuring circuits built into the bridge circuit itself. The manufacturers of these bridges are also listed in the Appendix.

At the time of writing, each of these bridges had been purchased at a price sufficiently low to permit the purchase of most of the additional accessories. However, the maintenance and repair of imported instruments may become a serious problem for those institutions unable to do a complete diagnosis and component substitution job themselves. Such institutions might find yet another way of providing strain gauge instrumentation to be more satisfactory.

During the course of this project, we talked with several engineers who felt that some sort of educational-type strain gauge bridge could be designed and built for a sum well within the proposed budget, probably using some type of meter readout system. Two serious efforts were made to obtain such a unit: the first effort involved the design and construction of such a device, while the second effort sought to modify an existing instrument. In both cases difficulties arose which caused the resulting strain gauge bridge to be unsatisfactory for our purposes, and this goal must therefore be left for others to accomplish.

Dr. Robert Chipman, of the W. T. Bean organization in Detroit, Michigan, has suggested a somewhat different approach to this problem. He proposes using a good-quality digital strain gauge bridge at some central station in the laboratory, and with it a ten-channel switch and balance unit along with the necessary switching apparatus. This would allow each work station to balance a particular bridge circuit of its own and to use the digital strain indicator as a meter on a shared time basis. This would probably work out satisfactorily, since an individual strain reading takes only a few seconds, while considerable time must be spent in setting up the experiment and loading the specimen. With six or eight groups working simultaneously,the shared time system on a digital meter would cause little inconvenience to the individual student or pair of students.

The cost of this system is about the same as that of providing indivdual bridges of moderate cost to six or eight work stations. The digital strain indicator has the advantage of considerably increased accuracy, while its disadvantage lies in the shared time usage. Although we have not had time to investigate this system in detail, we mention it as a possible alternative. It does provide a scheme whereby an instrument of extremely high quality can be used for general laboratory service while later the same instrument can easily be used for research.

LABORATORY LAYOUT

In general, the equipment developed here is suitable for a multiple-station laboratory for materials testing or strength of materials, similar to a chemistry laboratory. A certain number of such work stations would have to be constructed so that individuals or pairs of students could work on projects using their own

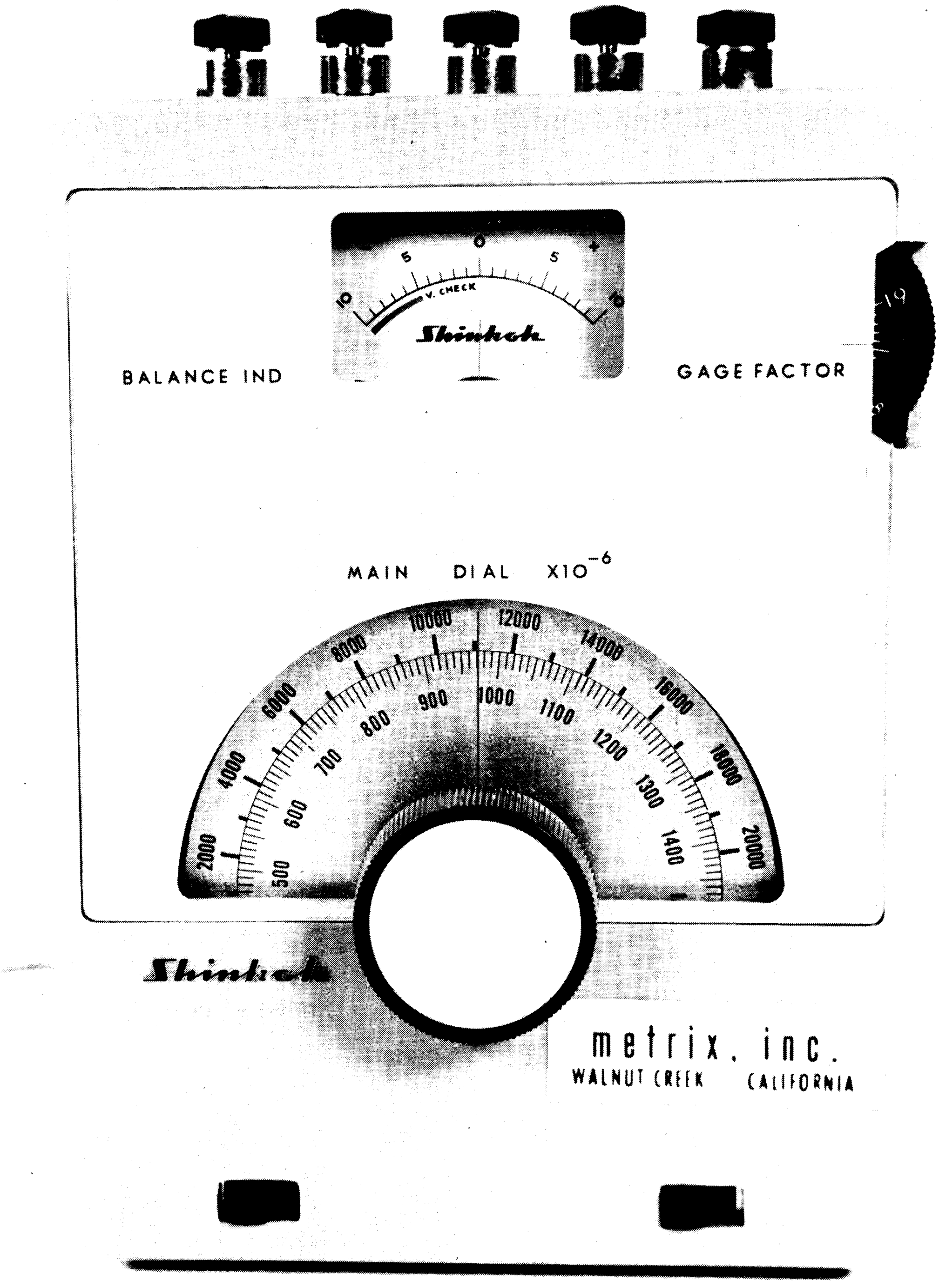

Figure 7. Shinkoh strain gauge bridge.

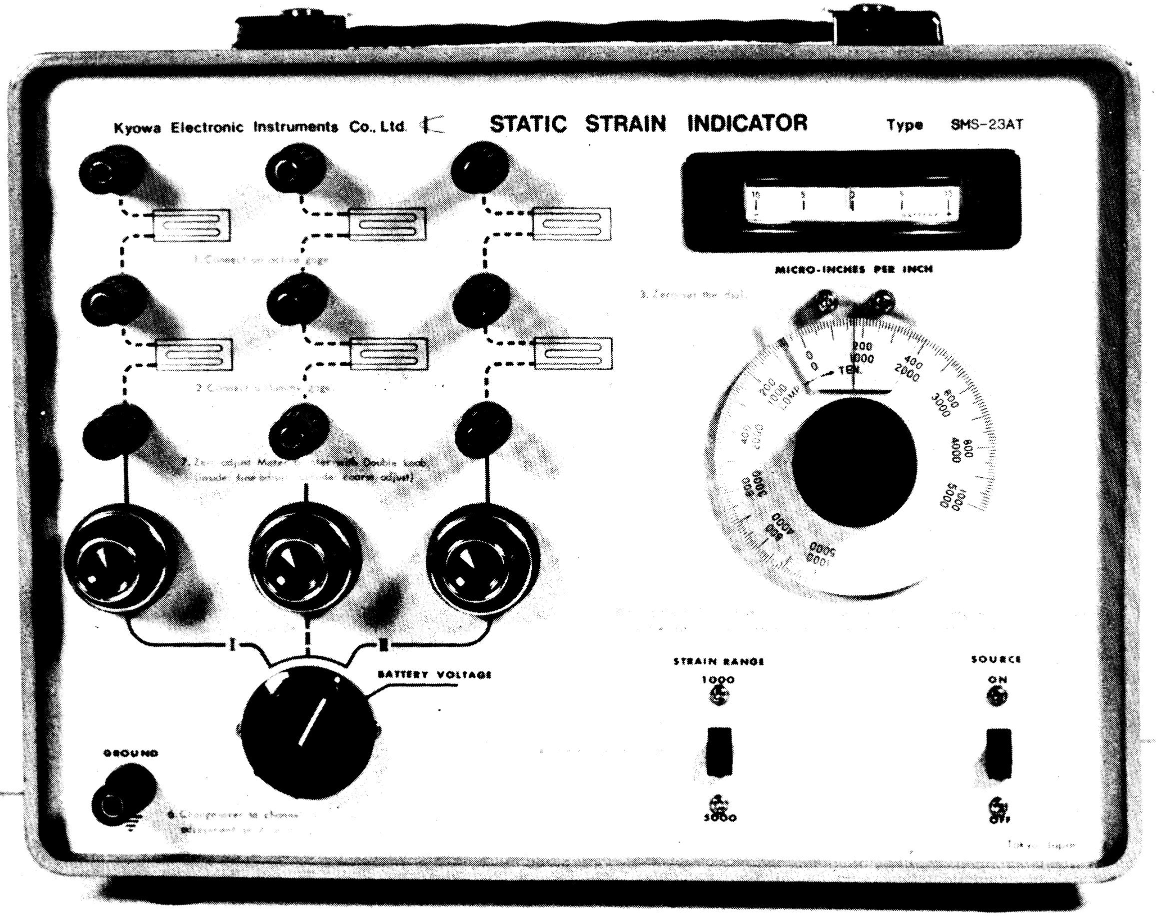

Figure 8. Kyowa strain gauge bridge.

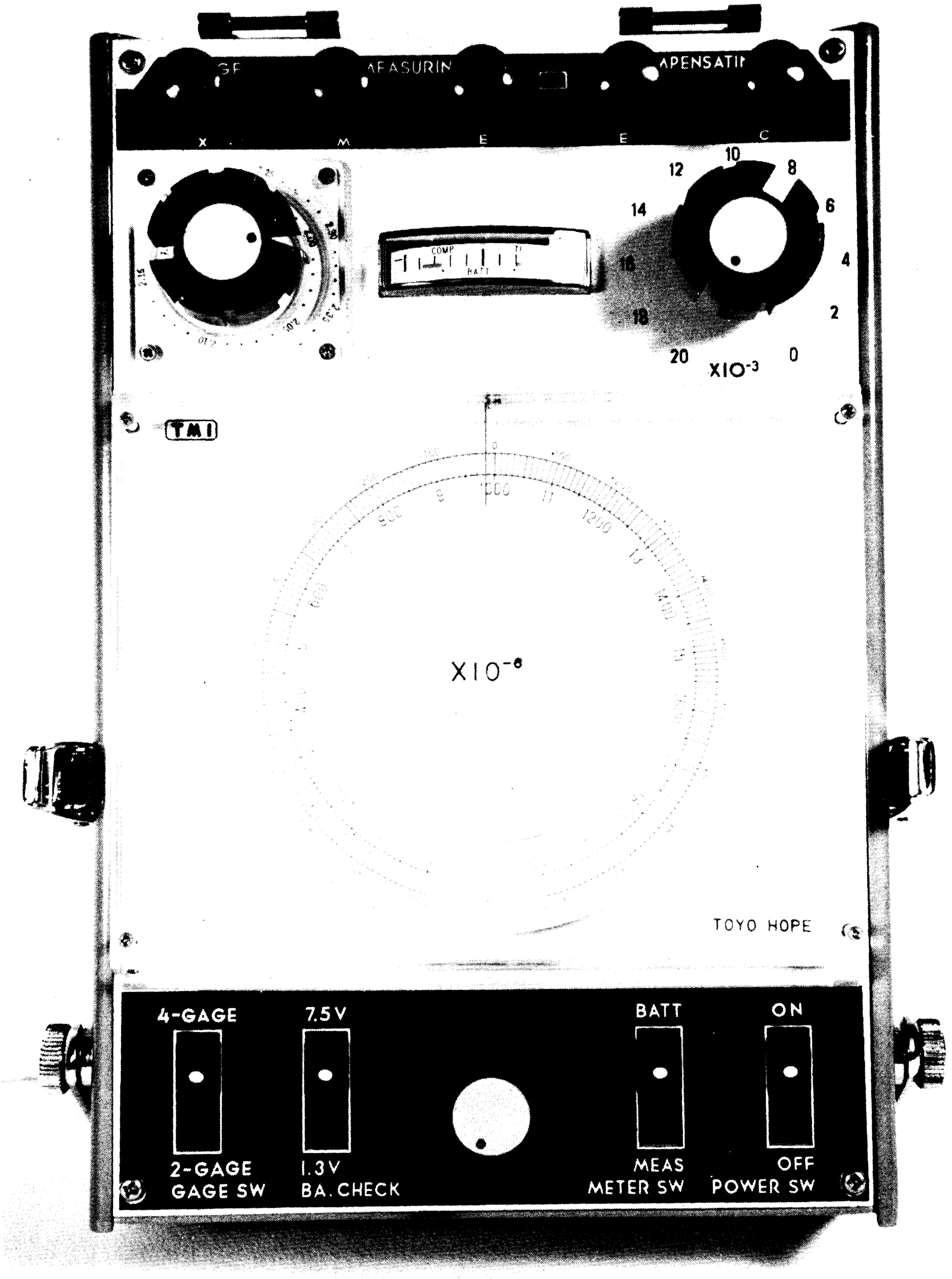

Figure 9. Toyo strain gauge bridge.

laboratory techniques and developing laboratory skills in the process. The exact number of such work stations is of course a function of the enrollment at any institution. Based upon current enrollment at The University of Michigan, we have assumed throughout this equipment development work that eight work stations would be required. Figure 10 shows a typical flow plan for eight work stations.

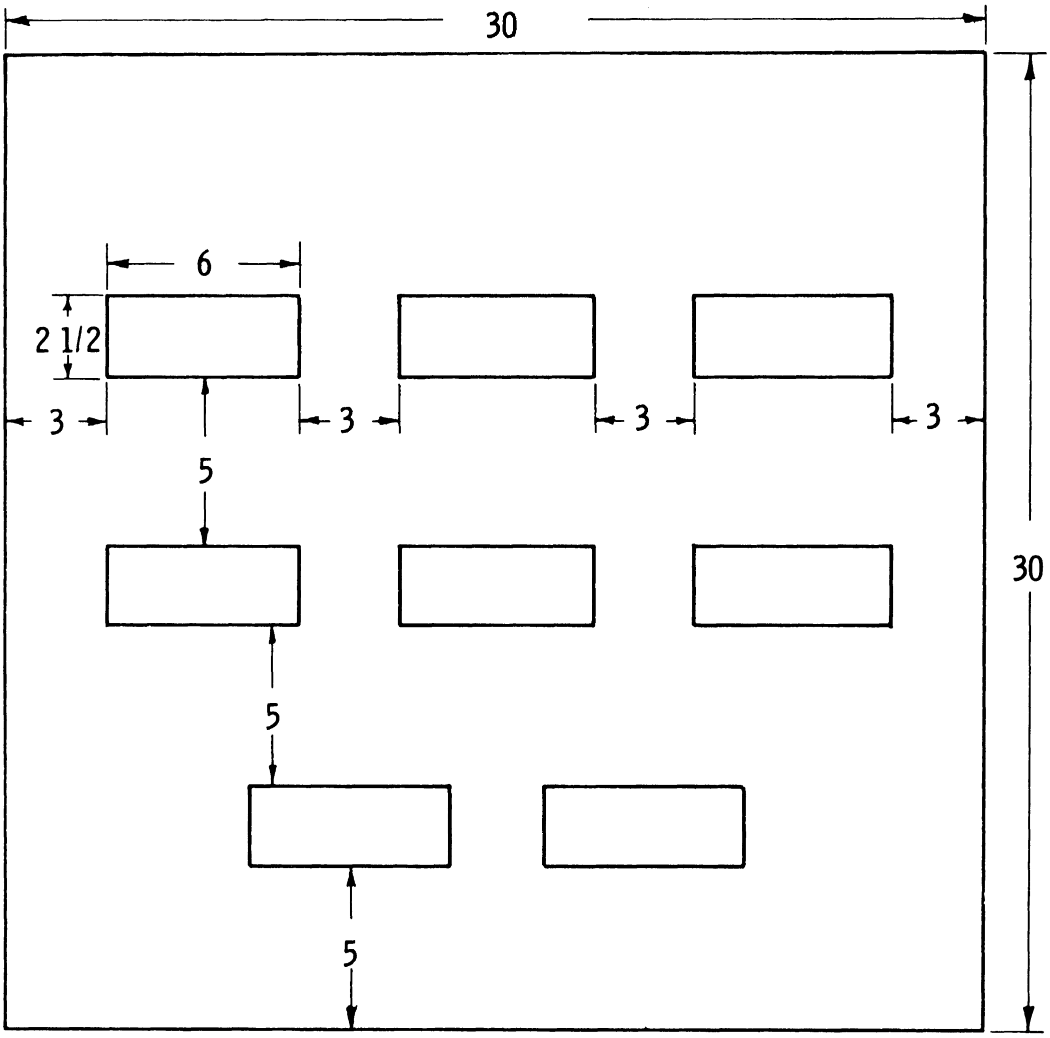

Figure 10. Floor plan of typical eight-station laboratory.

The student experiments can probably best be performed with two students rather than one. In many situations loads must be applied and readings taken simultaneously; this is more easily done with two students, and each will still have ample opportunity to develop individual laboratory techniques.

Thus, sixteen students could be accommodated in an eight-station laboratory, or, for three- or four-hour laboratory sessions, 150 students in a five-day week.

This is a fairly intensive use of such laboratory facilities and probably represents a maximum that could be accommodated. Larger numbers could obviously be handled by scheduling Saturday or evening sessions, or by having two-hour laboratory sessions. The University of Michigan has two-hour laboratory sessions, and we anticipate that such a laboratory will be able to handle our projected enrollment in a strength-of-materials course now and for some years to come.

Figure 11 is a photograph of a bench-top testing machine along with an appropriate work table.

ACCESSORIES

In addition to the basic loading machine and strain gauge bridge, each work station in this proposed laboratory should be equipped with certain accessories for conducting experiments in strength of materials:

(a) 3 dial gauges
(b) 3 dial gauge stands
(c) soldering pencil
(d) solder
(e) strain gauge lead wire
(f) strain gauges
(g) small crescent wrench
(h) small set of Allen wrenches
(i) C-clamp
(j) mallet or hammer

Of these accessories, only the resistance strain gauges are not permanent parts of the station. The gauges must be considered expendable. In some experiments strain gauges will not be needed, such as in beam deflection and column work. In others, resistance strain gauges are needed, but by careful planning their use may be thoroughly taught to the student within an acceptable operating budget. Conceivably, special ways of doing this might be developed on an individual basis. For example, Bakelite-base strain gauges could be used with deKhotinsky cement, so that the gauges could be removed and reused. This would considerably reduce the cost of providing strain gauges.

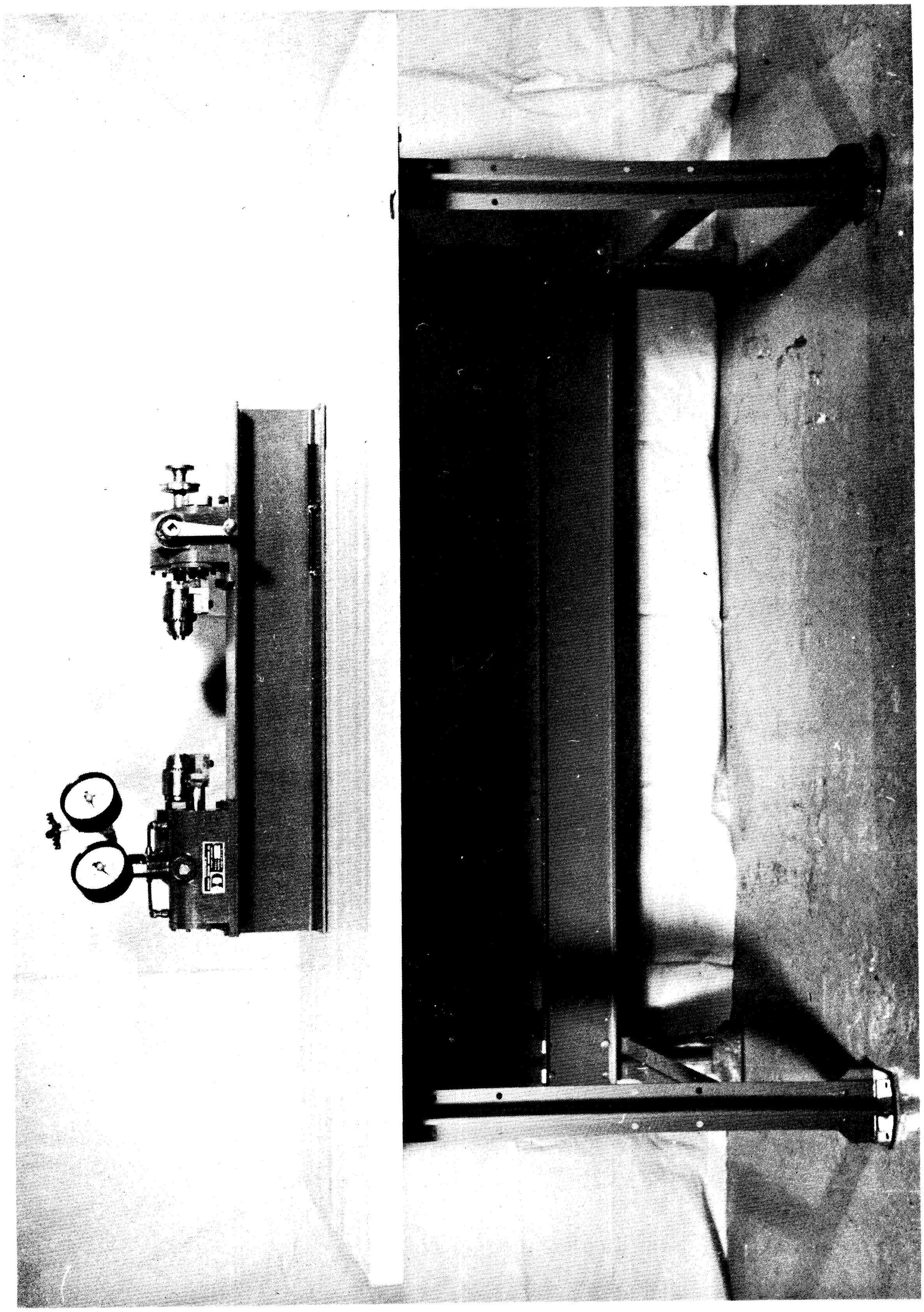

Figure 11. DTM bench-top testing machine and work table.

SUITABLE EXPERIMENTS

The experiments described in this section have been designed to be performed easily on the equipment described earlier. These experiments have proved satisfactory for our materials laboratory course and could presumably be adapted wholly or in part by other institutions. Before presenting this sequence of experiments, a brief statement of the role of this particular course is perhaps in order.

For many years sophomore engineering students at the University of Michigan were required to elect a materials course taught by staff from the Chemical Engineering and Metallurgy Departments. This course emphasized ferrous metallurgy but also touched on various other materials. Accompanying it was a separate two-hour weekly laboratory course which covered aspects of materials properties. This often included such experiments as heat treating, hardness, welding, and considerable mechanical testing of such brittle materials as cast iron or brick, and such ductile materials as low carbon steel or aluminum. These tests were almost exclusively confined to tensile tests of the standard ASTM specimens. As a consequence of this requirement, the Department of Engineering Mechanics in subsequent courses dealt with students who already had been exposed to certain elements of mechanical testing and who had some understanding of the phenomena of yield point and ultimate strength.

As juniors, such students in the Engineering College were for the most part required to elect a course in strength of materials which was accompanied by a one-credit-hour laboratory session, taught and graded separately, which met for two hours each week. Since these students had already observed most of the conventional tests, and since the subject matter which the laboratory supplemented was actually strength of materials, a course was designed with a slightly different flavor than is commonly found in first undergraduate materials laboratory courses. Here the emphasis was on two things:

(a) Demonstration of some of the fundamental phenomena arising in strength of materials, along with some of the effects upon which the science of strength of materials is based.

(b) Demonstration of reasonably good laboratory techniques in materials testing, along with modern strain measuring instrumentation.

Accordingly, the experiments presented in this section are geared much more closely to a strength of materials course than to many conventional materials laboratories. We feel this is no disadvantage, however, since more interest has been generated by some of these experiments than by the usual materials laboratory experiments.

EXPERIMENT NO. 1. STRAIN GAUGE INSTRUMENTATION

Small testing machines require small specimens, which are generally more difficult to instrument mechanically than are large ones, so that resistance strain gauges are almost mandatory in certain phases of the proposed syllabus. Accordingly, the first experiment involves student participation in the process of strain gauge application and hookup, so that the basic ideas of this kind of instrumentation can be learned at the beginning. Strain gauge bridge theory is also touched on briefly.

This experiment can be organized in a number of ways. One procedure uses foil practice gauges, obtainable from manufacturers at very low prices, and requires each student to apply a foil practice gauge to some specimen and then have his application checked by the instructor. These practice gauges are regular commercial gauges which for some reason are slightly defective in resistance and hence are sold cheaply for student work. Occasionally the instructor may require the use of Eastman 910 cement to apply foil gauges. This cement demands more technique from the student than do other adhesives, but it requires no drying time, and the gauge is ready for use instantly.

A slightly different experiment is to apply a good wire-resistance paper-base gauge to some simple specimen, such as a hacksaw blade or other flexible member, and to solder on the lead wires and hook up the gauge to the bridge system. Simple bending may then indicate the magnitude of strain involved, which often can be correlated with radius-of-curvature information by forming the hacksaw blade on a circular arc of known radius of curvature cut from plywood, as shown in Figure 12. The student who has measured the thickness of the hacksaw blade with his micrometer can immediately correlate strain reading with bending theory.

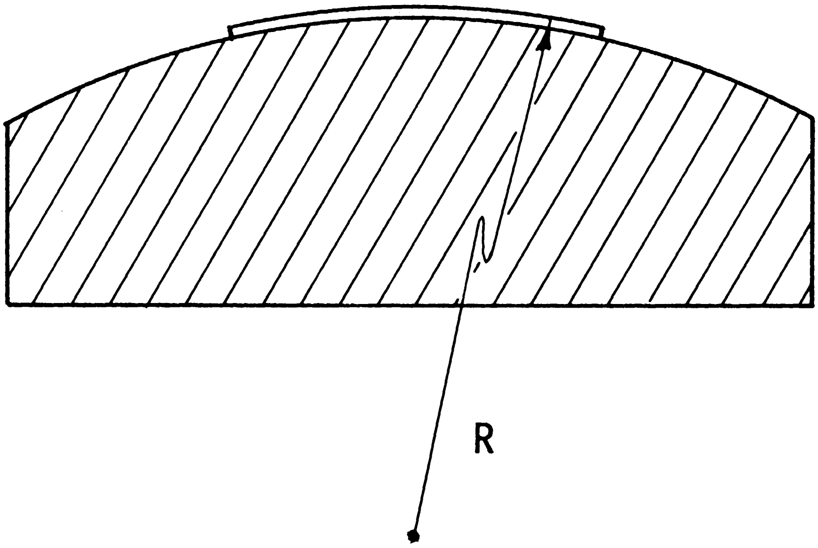

Figure 12. Cam for producing known radius of curvature.

As a third alternative, the instructor may occasionally demonstrate the proper application of the strain gauges and the proper techniques for hooking them up into a particular bridge system. Sometimes this is desirable as a beginning step, followed by active participation of the individual students in their own strain gauge setup.

EXPERIMENT NO. 2. WHEATSTONE BRIDGE

This experiment is designed to acquaint the student with the use of resistance strain gauges in quantitative measurement, and especially to acquaint him with the Wheatstone bridge circuit and its various possible bridge designs. The basic requirement is a specimen upon which four different strain gauges are attached. For economy, the specimen should be one which can be used later for other bending and tension tests. The specimen illustrated in Figure 13 will be used as a bending specimen in this experiment, and will later be used for other purposes; it is cut from an aluminum alloy of fairly high-yield strength characteristics. This will give fairly large strains which the student can read in a very direct way. Strain gauges are attached to the specimen as shown in the photograph of Figure 14. The construction of the screw-type loading machine necessitates a special bending fixture; the parts for it are illustrated in Figure 15, 16 and 17. Figure 18 shows the entire assembly mounted in the testing machine ready for readings to be taken. With the strain gauges mounted as shown in Figure 14, four resistances changes are available for use in various bridge circuits.

The first bridge circuit might use one active gauge from one of the primary strain gauges on the specimen with one unstrained dummy gauge for temperature compensation. This would give a strain signal which should be proportional to the strain at the outer surface of the beam while under bending. The variations on this would include two active arms, where both primary gauges would be used, or two active arms where one primary and one secondary gauge would be used. Some strain gauge bridges provide for a four-active-arm system; in such cases a three-active-arm bridge with one dummy as a compensator may be used, or even all four active arms. The student can be asked to set up any or all of these various bridges and to make the appropriate readings. A knowledge of simple beam theory should allow the student to correlate theoretical predictions with strains measured at the outer surface of the beam in the primary and secondary directions. Although the loading system is relatively crude, it gives fairly satisfactory comparisons with the theory. More sophisticated loading schemes involving a two-point loading with a uniform bending moment in the central section would probably be even better.

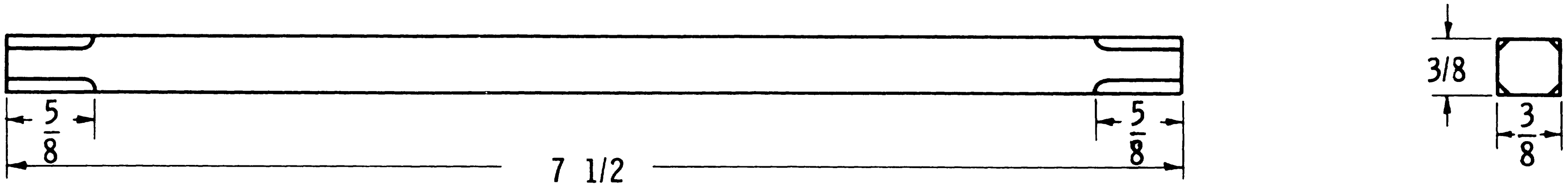

Figure 13. Aluminum bending and tensile specimen.

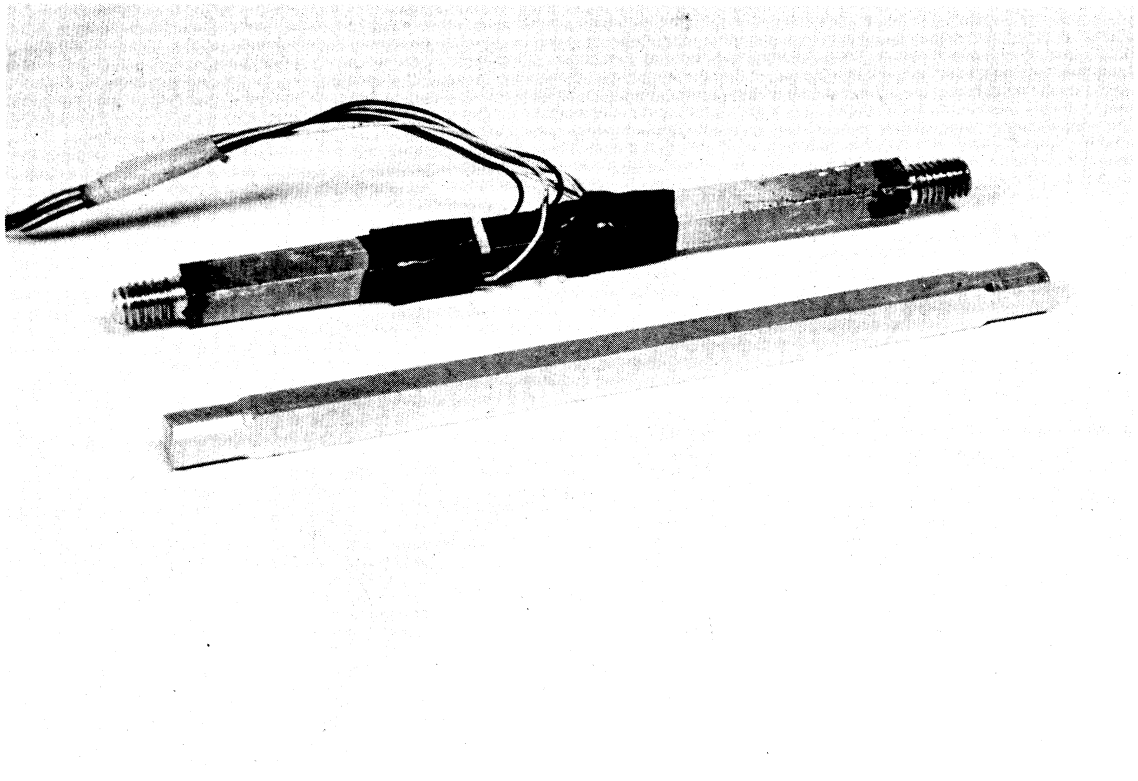

Figure 14. Aluminum bending and tensile specimen with strain gauges attached.

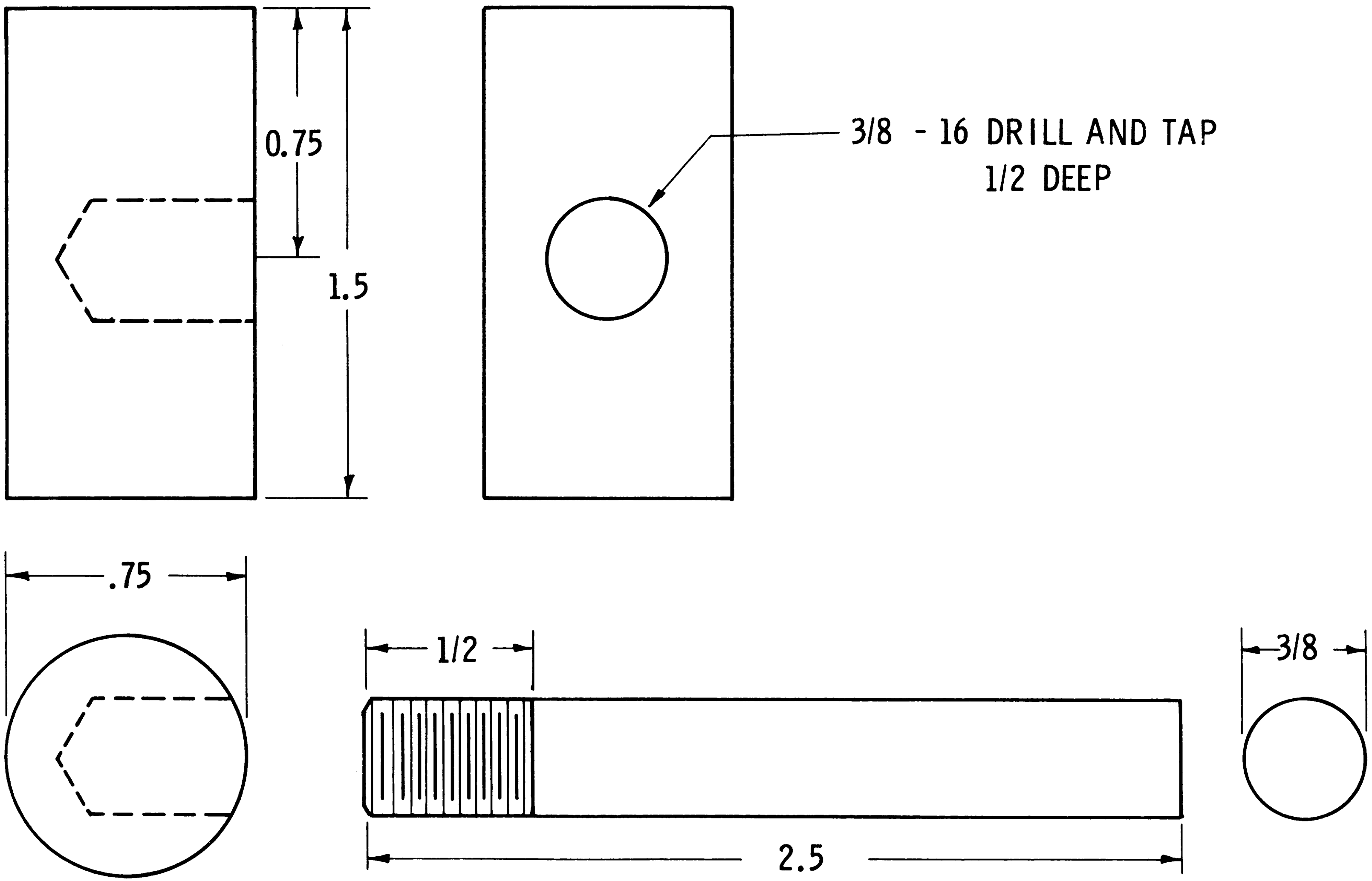

Figure 15. Loading fixture.

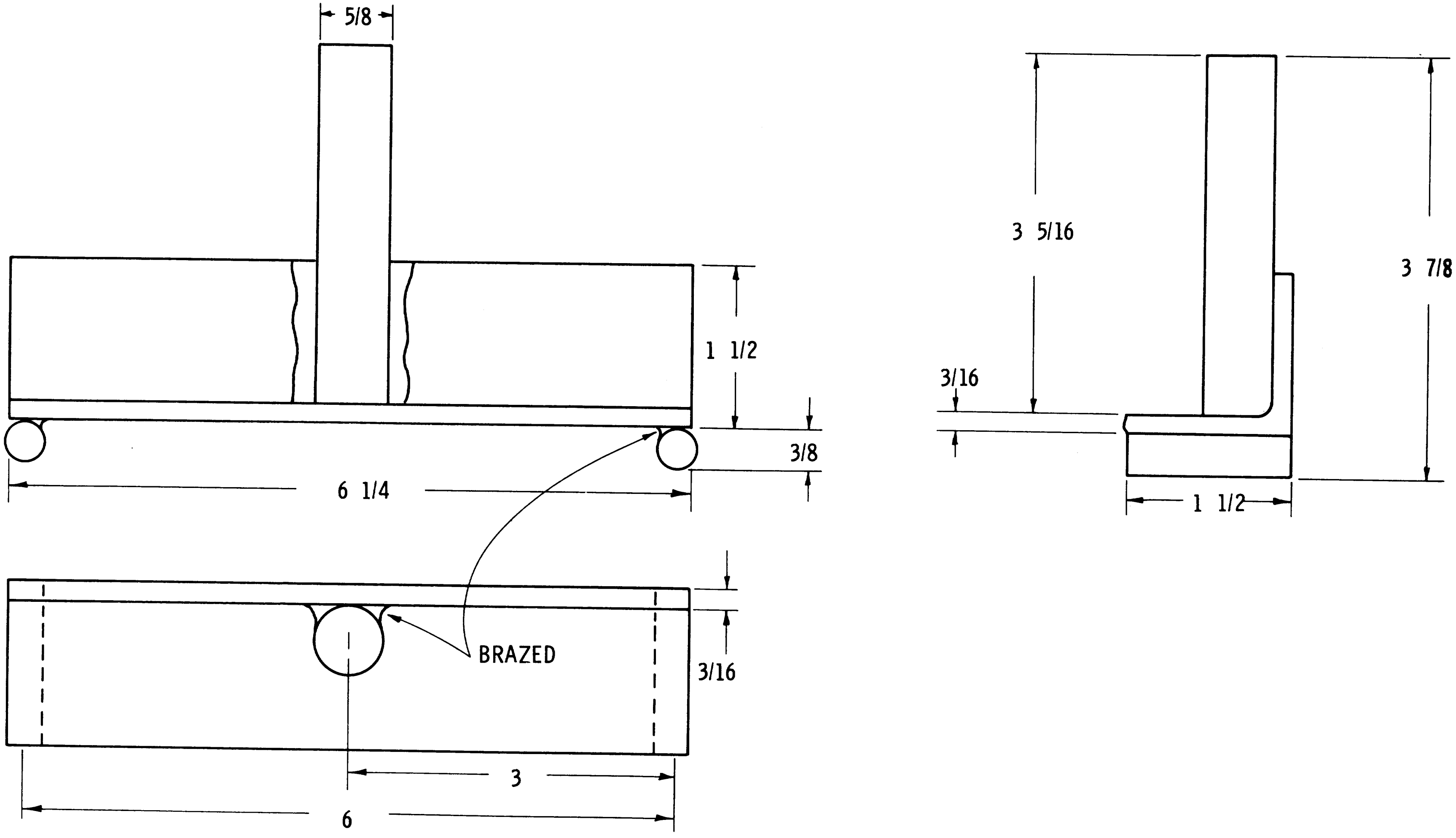

Figure 16. Holder or support for beam.

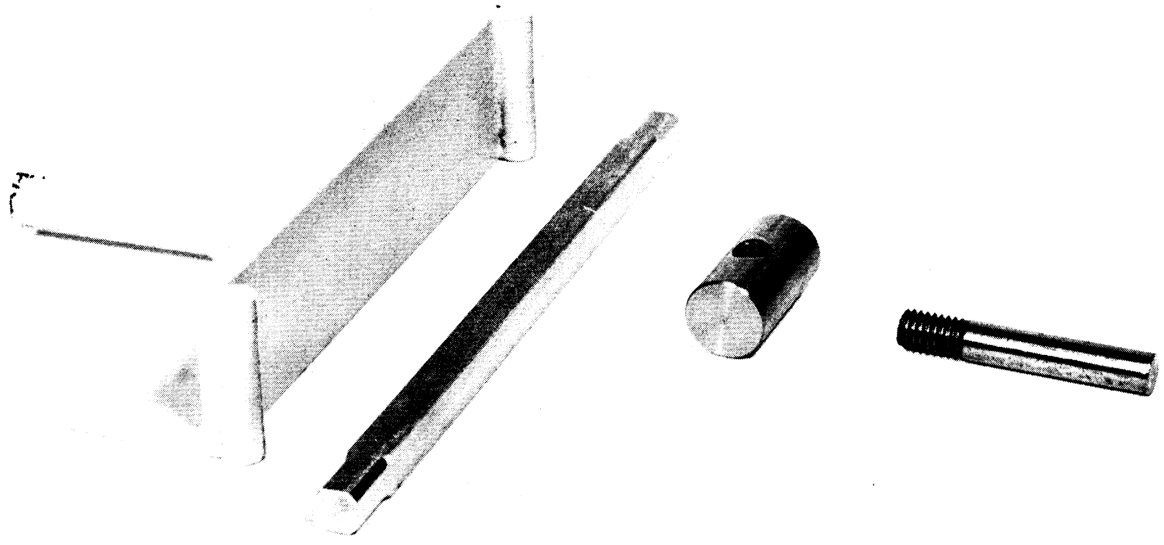

Figure 17. Beam, holder and loading fixture.

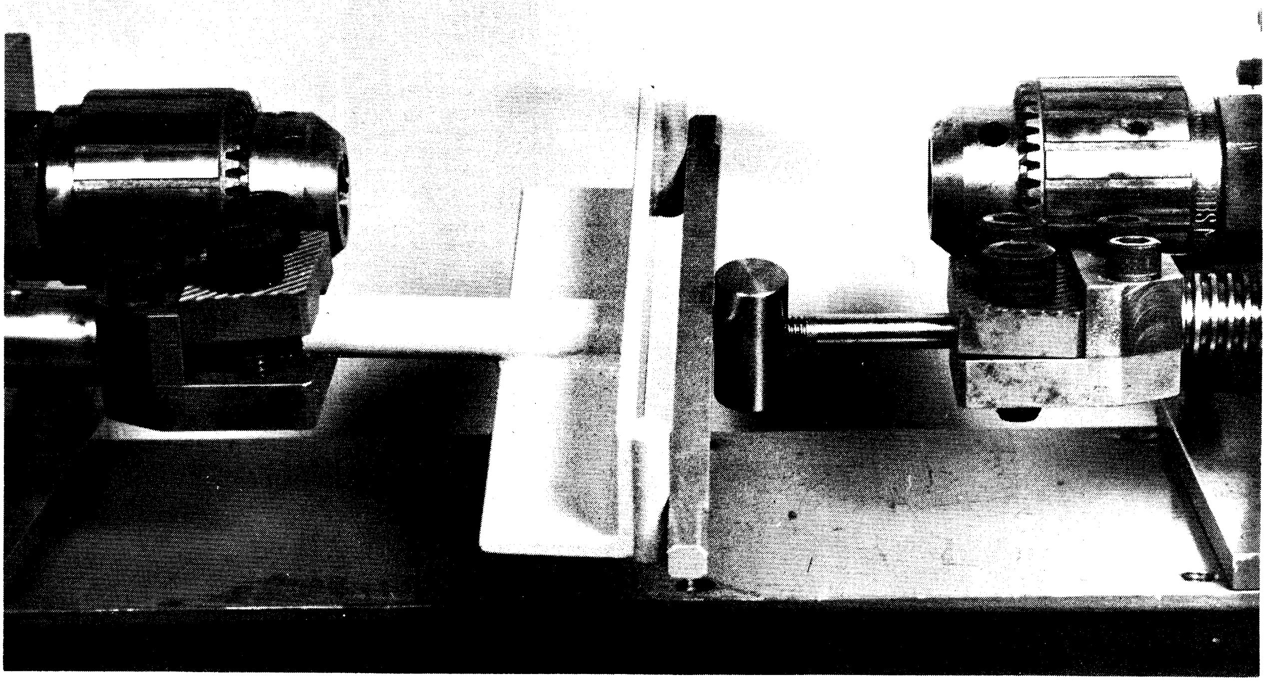

Figure 18. Beam in loading position.

EXPERIMENT NO. 3. MEASUREMENT OF YOUNG'S MODULUS AND POISSON'S RATIO

Young's modulus is probably the most fundamental single concept from the point of view of mechanical properties of materials. Accordingly, the measurement of Young's modulus is considered one of the primary experiments in this syllabus. The experiment is very straightforward: The specimen prepared for Experiment No. 2 (Figure 13) is used in the tension grips of the machine as a simple tensile specimen. Readings may be taken at various load levels. This experiment illustrates the desirability of having students work in pairs, one to operate the loading apparatus and the other to record data and read the strain indicators.

Occasionally bending effects creep into tensile data due to the design of the grip system (Figure 19), so that usually the two primary strain gauges must be averaged in order to get the tensile component of the total strain. The resulting data may be plotted on graph paper and the Young's modulus of the material determined.

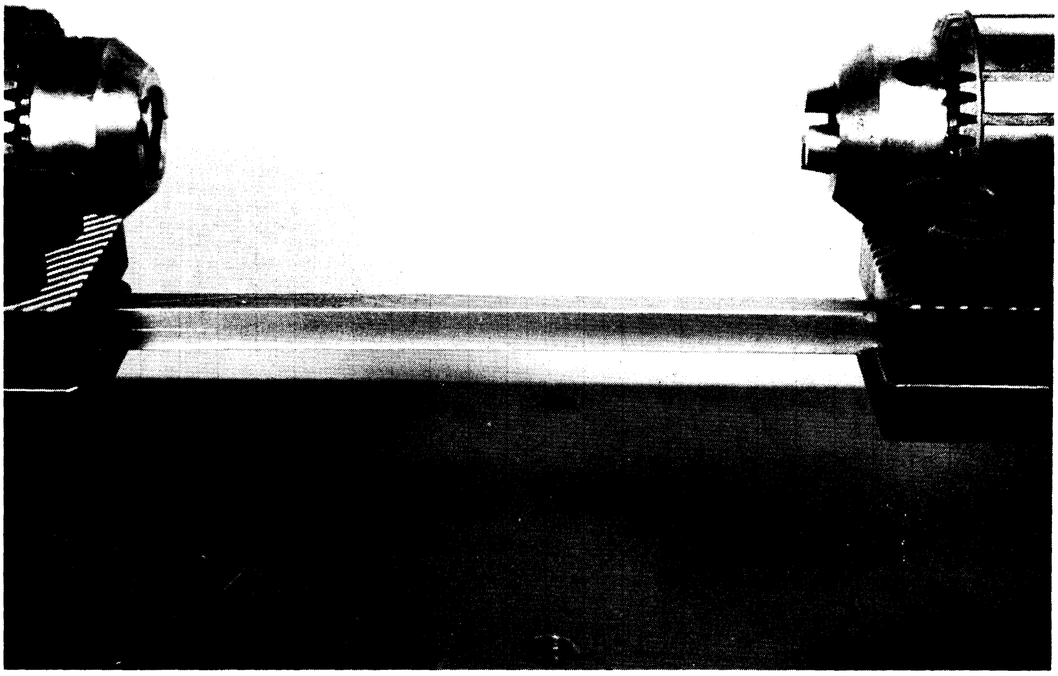

Figure 19. Tension bar.

Poisson's ratio may be determined from data given by the secondary gauges on the tensile specimen. This may be done while the other data are being taken, but if four gauges are to be read simultaneously, a switching mechanism must be provided for each work station. This mechanism is not included in our equipment list, but it is relatively inexpensive and could be furnished by an institution if desired.

Figures 20 and 21 give load-strain curves in both tension and compression for averages of the primary, or axially oriented, gauges and the secondary, or transversely oriented, gauges. These show that the values of Young's modulus and Poisson's ratio, which are determined from these curves, fall within the usual range of values for aluminum. In addition, the data points very nearly form a straight line, thereby demonstrating the linearity of the material.

EXPERIMENT NO. 4. DETERMINATION OF SHEAR MODULUS

The shear modulus is another basic quantity which should be measured in a strength of materials laboratory. This experiment measures shear modulus using a simple specimen cut from one-half inch diameter bar stock (shown with pertinent dimensions in Figure 22). Figure 23 shows the specimen in the torsion jaws of the testing machine ready for test. The strain gauges are applied in the directions shown in Figure 22: longitudinal, at 45° to the longitudinal axis; and circumferential, or at right angles to the longitudinal axis of the cylinder. The ends of the specimen are filed or ground to a roughly triangular shape to provide a better gripping surface in the three-jaw chucks of the torsion grip system.

One student applies torque to the specimen while the other reads strain directly. Observation of the transverse gauge and the longitudinal gauge demonstrates to the student the validity of the assumption that strain in the circumferential and longitudinal directions vanishes under applied torque. This assumption is illustrated by the following data taken from actual tests on a specimen.

TORQUE	STRAIN AT 0° TO CENTER LINE	STRAIN AT 90° TO CENTER LINE
0	0	0
300 in.-lb	-12 μ	+103 μ
500 in.-lb	+9.5 μ	+192 μ

The large values of strain in the 90° direction are undoubtedly due to poor orientation of the strain gauge.

Test data from this experiment, given in Figure 24, show that good linearity is obtained from this setup.

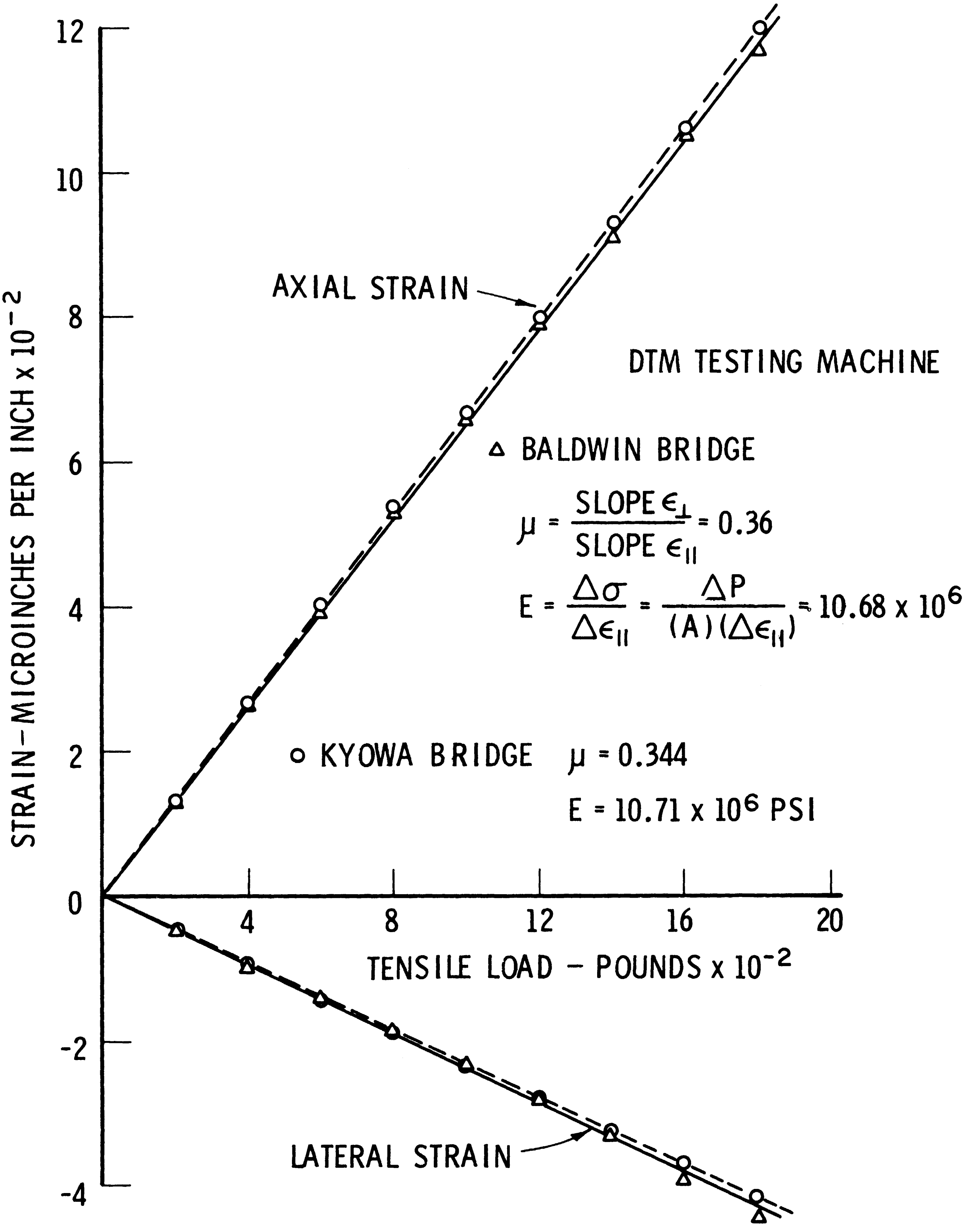

Figure 20. Tensile data used for determination of elastic constants.

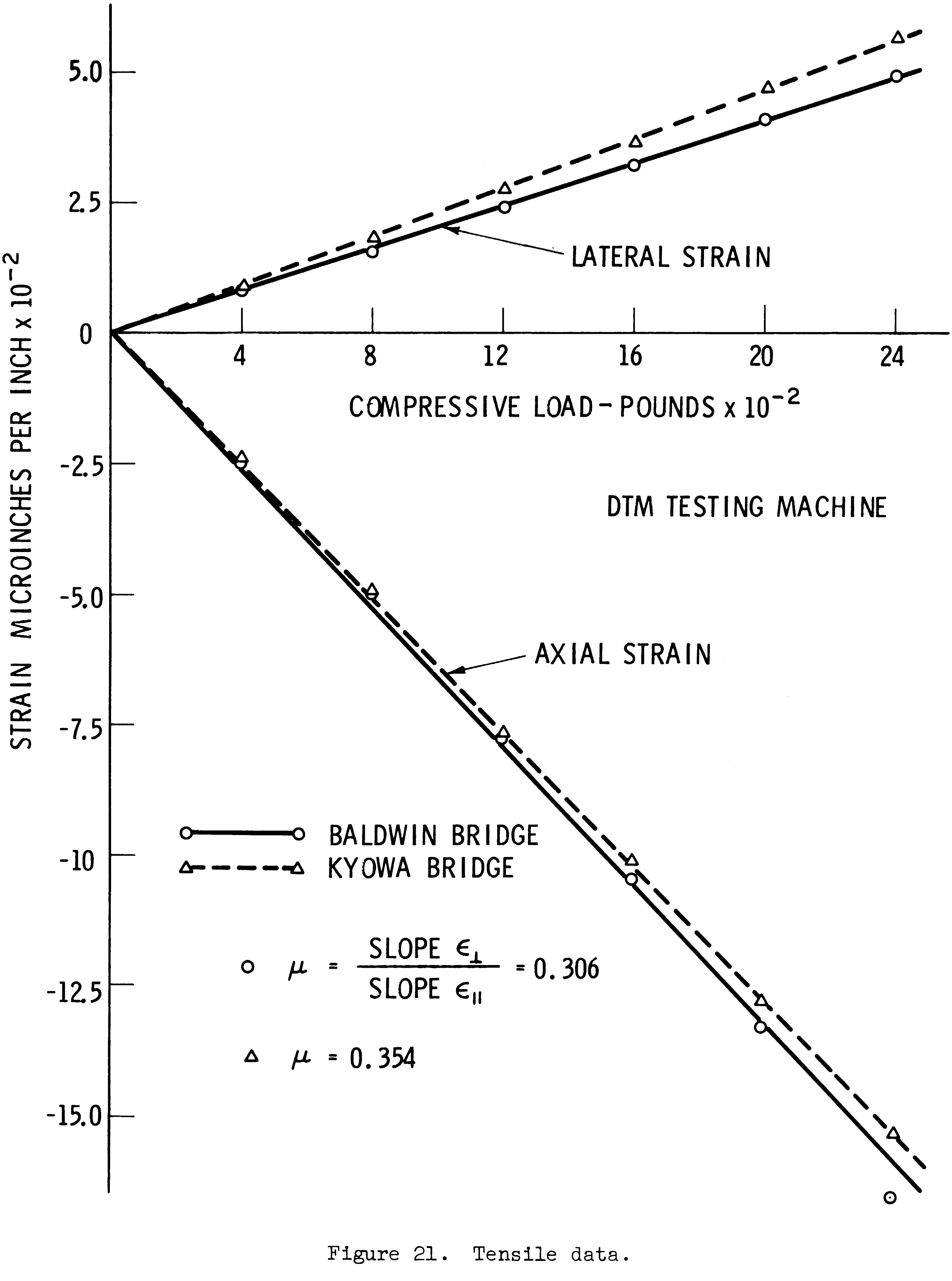

Figure 21. Tensile data.

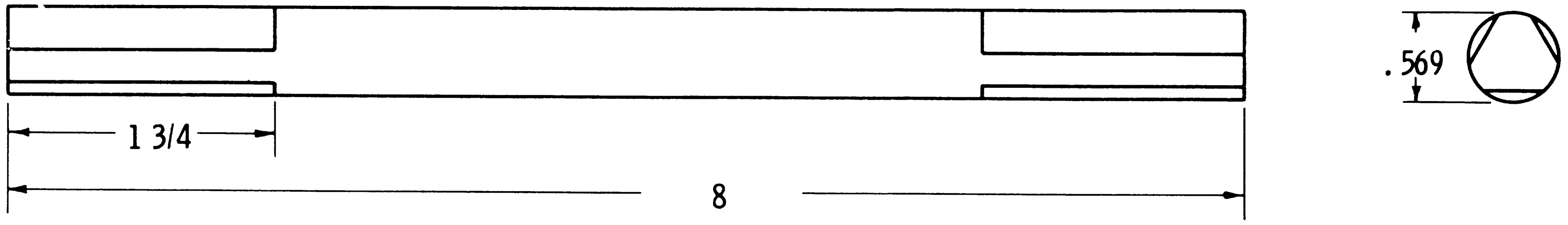

Figure 22. Torsion specimen.

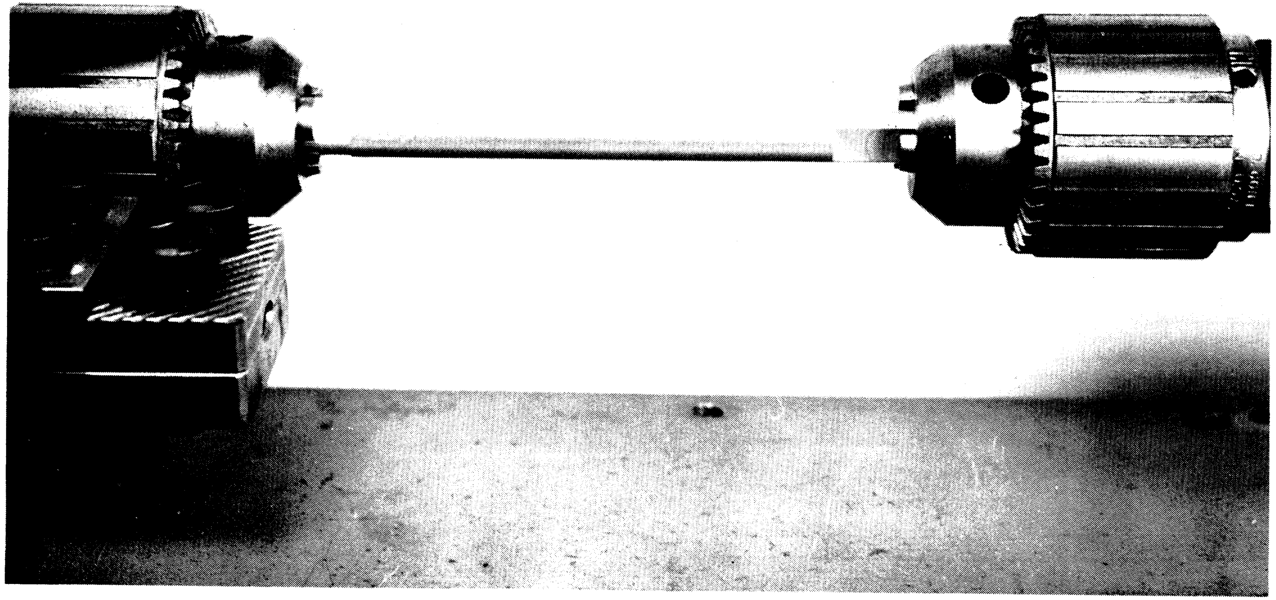

Figure 23. Torsion specimen in position for loading.

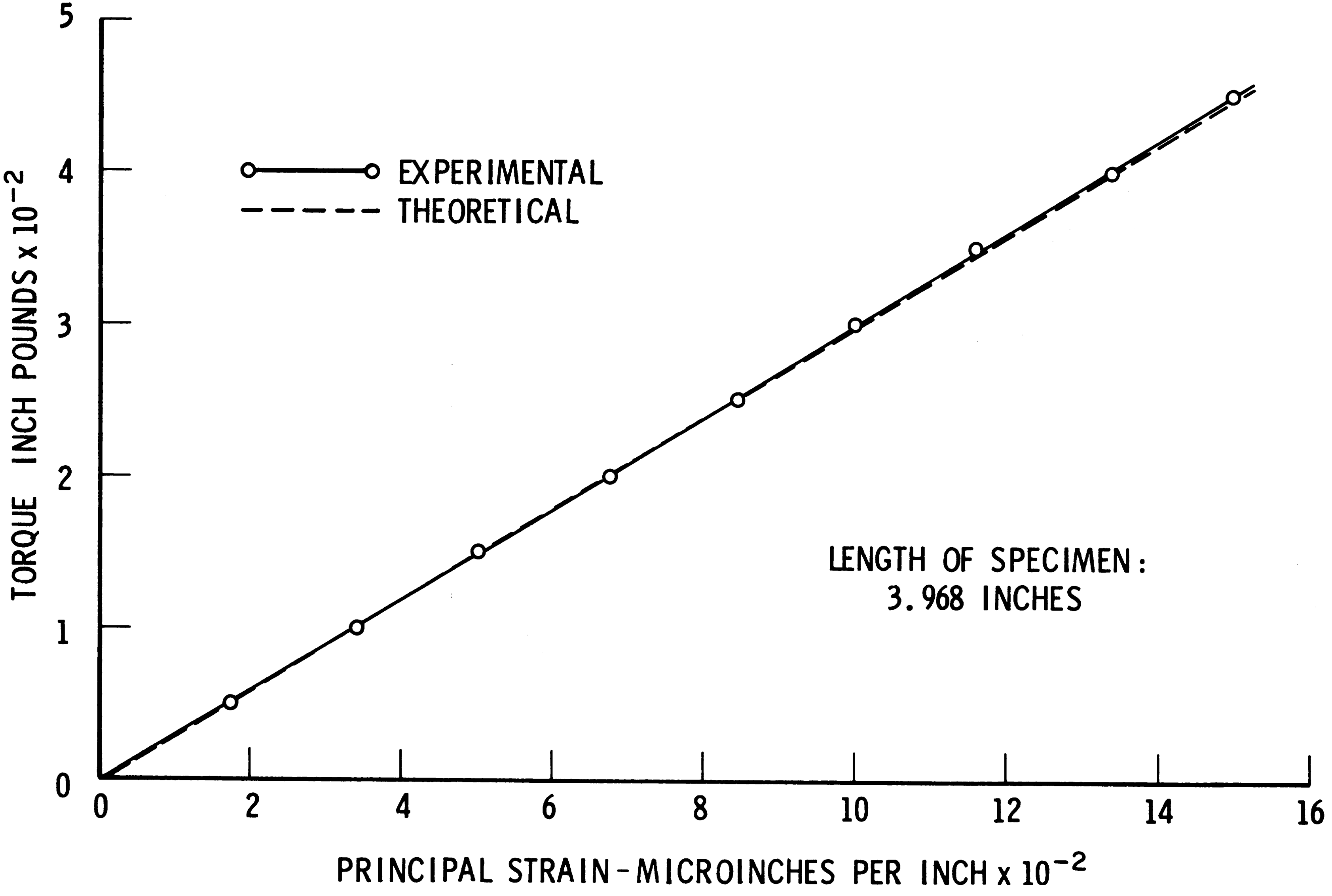

Figure 24. Torsion test data.

EXPERIMENT NO. 5. VERIFICATION OF BASIC TORQUE-TWIST RELATIONSHIPS

This experiment employs the same torsion specimen used in Experiment No. 4. Here, the specimen is subjected to various known values of torque and the resulting angles of twist are observed. A simple troptometer, manufactured from parts of a chemical ring stand clamp, is attached to each end of the specimen (described in Figures 22 and 23). Dial gauges are used to measure angles of twist. Figure 25 shows the troptometer arms, and Figure 26 shows the torsion specimen with the troptometer arms attached in the torsion machine, and the dial gauges in place. By the usual methods of measuring the distance between troptometer arms and obtaining relative angle of twist, the student may calculate the apparent shear modulus of this material as well as observe the linearity of the relative angle of twist versus torque curves. Data from this type of test are given in Table I, which compares both angle of twist and average strain data from the previous experiment.

TABLE I

Torque	Average $\theta_1 - \theta_2$	ϵ
50	3.35	177
100	8.0	342
150	12.35	501
200	17.2	675
250	22.3	845
300	26.8	1000
350	31.6	1160
400	36.95	1340
450	41.6	1500

Length between troptometer arms 3-31/32 in.

The following are calculations made from data taken on the torsion test and given in Table I.

I. Round specimen - at 400 in-lb, find σ_{max}

$$\tau_m = \sigma_m = \frac{TR}{J} = \frac{2T}{\pi R^3}$$

$$R = 0.285'' \qquad R^3 = 2.31 \times 10^{-2}$$

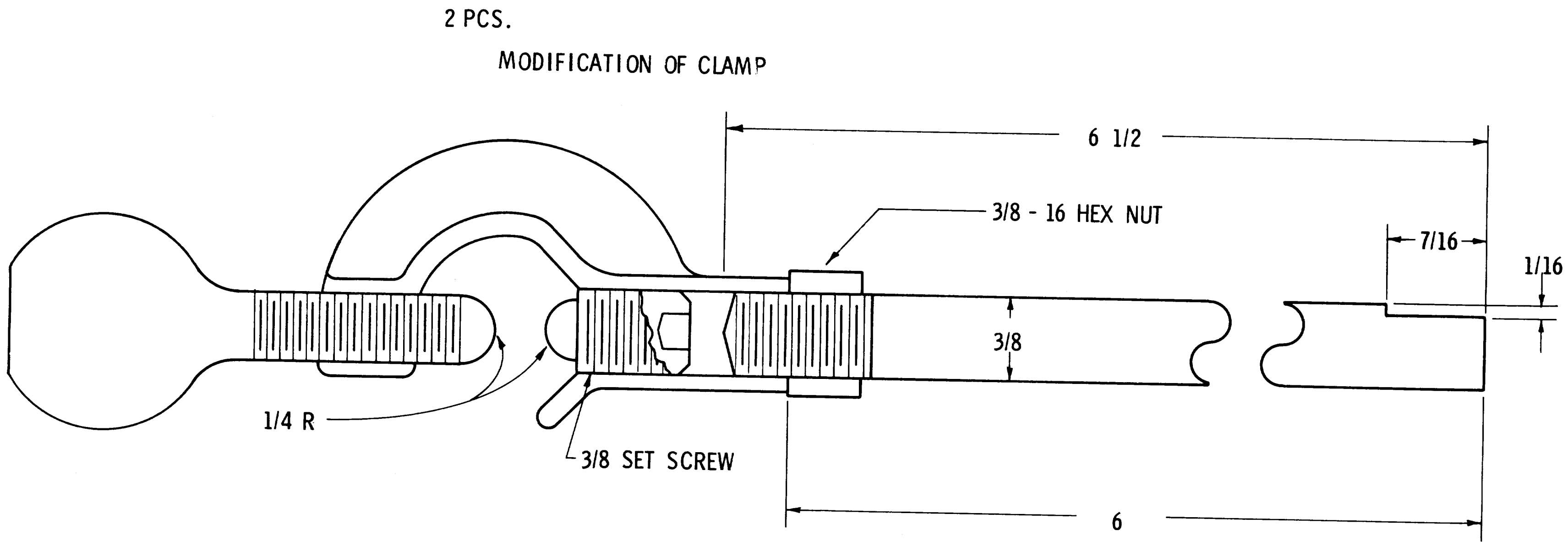

Figure 25. Troptometer arms made by modifying chemical clamps.

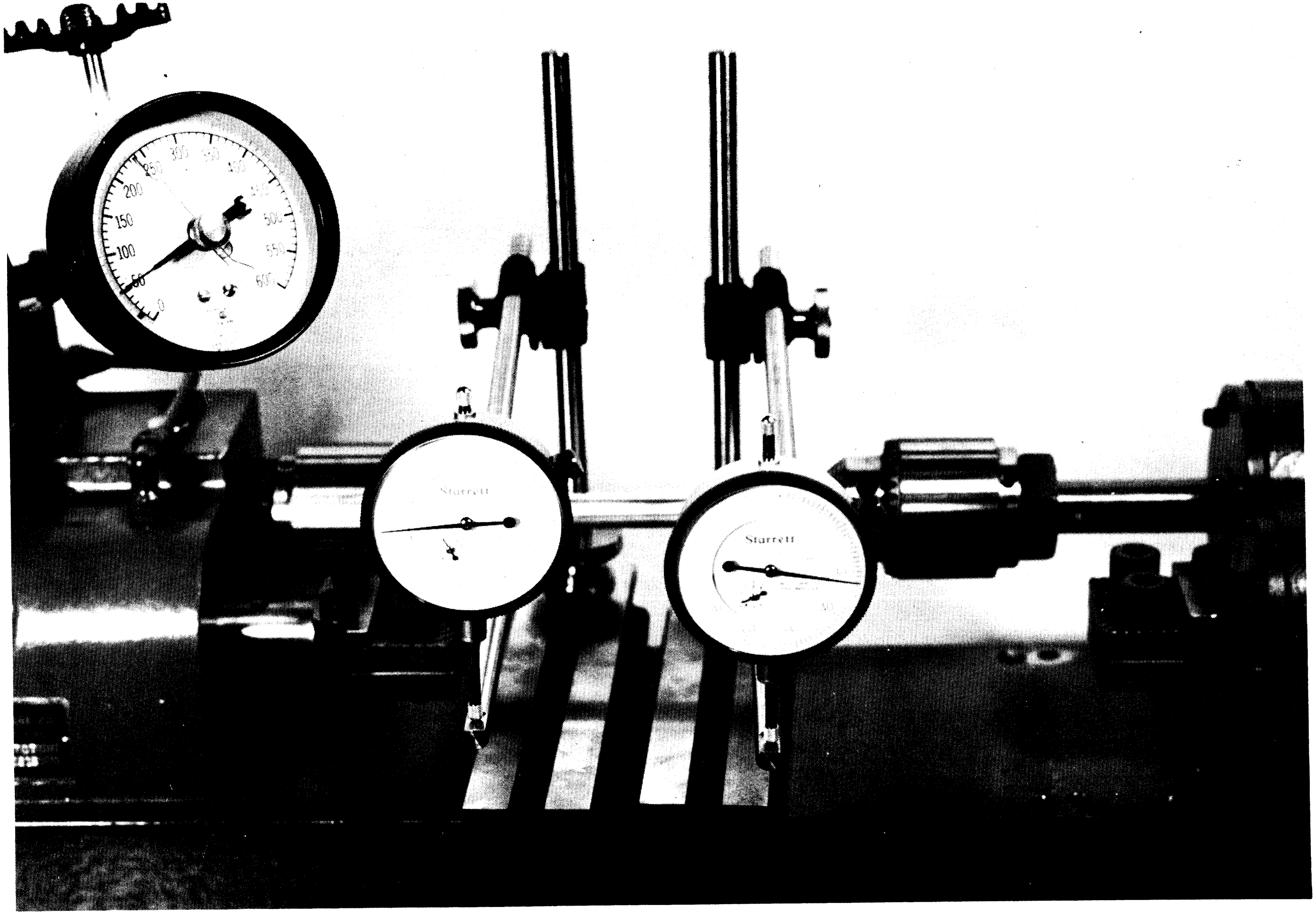

Figure 26. Torsion test setup and instrumentation.

$$\sigma_m = \frac{2(400)}{\pi(2.31 \times 10^{-2})} = 11{,}030 \text{ psi}$$

Find ϵ_m.

$$\gamma L = \theta R \quad \text{or} \quad \gamma = \frac{\theta R}{L}$$

$$\epsilon_m = \frac{\gamma}{2} = \frac{\theta R}{2L} \quad \frac{(36.95)(10^{-3})(0.285)}{2(3\ 31/32)} = 1330\ \mu \text{ in/in}$$

From the ϵ vs. T graph at 400 in-lb:

$$\epsilon = 1340\ \mu \text{ in/in}$$

II. Round specimen, find G.

From ϵ_{45} vs. T graph:

$$\tau = \frac{TR}{J} = \frac{2T}{\pi R^3} = \gamma G = 2\epsilon_{45} G$$

$$G = \frac{2T}{\pi R^3} \frac{1}{2\epsilon_{45}} = \frac{T}{\pi R^3 \epsilon_{45}} = \frac{430}{\pi R^3 (1400)(10^{-6})}$$

$$= 4.14 \times 10^6 \text{ psi}$$

From θ vs. T graph:

$$\theta = TL/GJ$$

$$G = \frac{TL}{J\theta} \quad \frac{432(3.968)}{(1.042 \times 10^{-2})(40 \times 10^{-3})} = 4.1 \times 10^6 \text{ psi}$$

These comparisons show that Experiments 4 and 5 are in relatively good agreement, and they should illustrate to the student that surface strains may also be deduced by deformation measurements.

EXPERIMENT NO. 6. COLUMN EXPERIMENTS

Column theory is an area of strength of materials in which laboratory experiments can be easily arranged to agree rather closely with theoretical predictions. A number of different methods for conducting such experiments have been used in this laboratory; we are currently using the method described here and it appears to be quite satisfactory. It is based on a Southwell plot, in which the central deflection of the column is measured as a function of load and the ratio of deflection to load is plotted against deflection. This slope of this curve may be used to define accurately the buckling load of a column. This greatly reduces the extreme dependence upon end conditions which might exist if one were to attempt to observe visually the buckling load of a column.

Various lengths of column may be chosen for this experiment. Here, the experiment is conducted with one-quarter by one-half inch cold rolled steel columns of three different lengths: 9 inches, 11 inches, and 13 inches. Pin-ended conditions must be provided for these specimens. This is accomplished by attaching to each end of the test column a roller made from 3/4 inch diameter drillrod which simply slips over the end of the column. Figure 27 is a drawing of the roller, while Figure 28 is a photograph of the roller mounted on the end of a column.

In order for the roller column ends to rotate freely, hardened loading platens must be provided. This requires a fairly simple tee member (shown in Figure 29 and 30). Figure 31 shows the T-bolts mounted in the testing machine with a column in place, as well as the dial gauge used to measure the central deflection of the column.

Figure 32 shows typical load deflection data from the 9-inch column plotted from the test results; Figure 33 is the Southwell plot for the 9-inch column, in which center deflection is the ordinate and the ratio center deflection divided by load is the abscissa. The slope of this curve then defines the critical buckling load of the column.

This set of data may be quickly compared with theoretical predicitions; the resulting deviations are briefly described in Table II.

TABLE II

COLUMN LENGTH	P_{critical} (THEORETICAL)	P_{critical} (EXPERIMENTAL)	% ERROR
12.94	1150	1140	-0.87
10.88	1630	1650	+1.23
8.97	2410	2510	+4.15

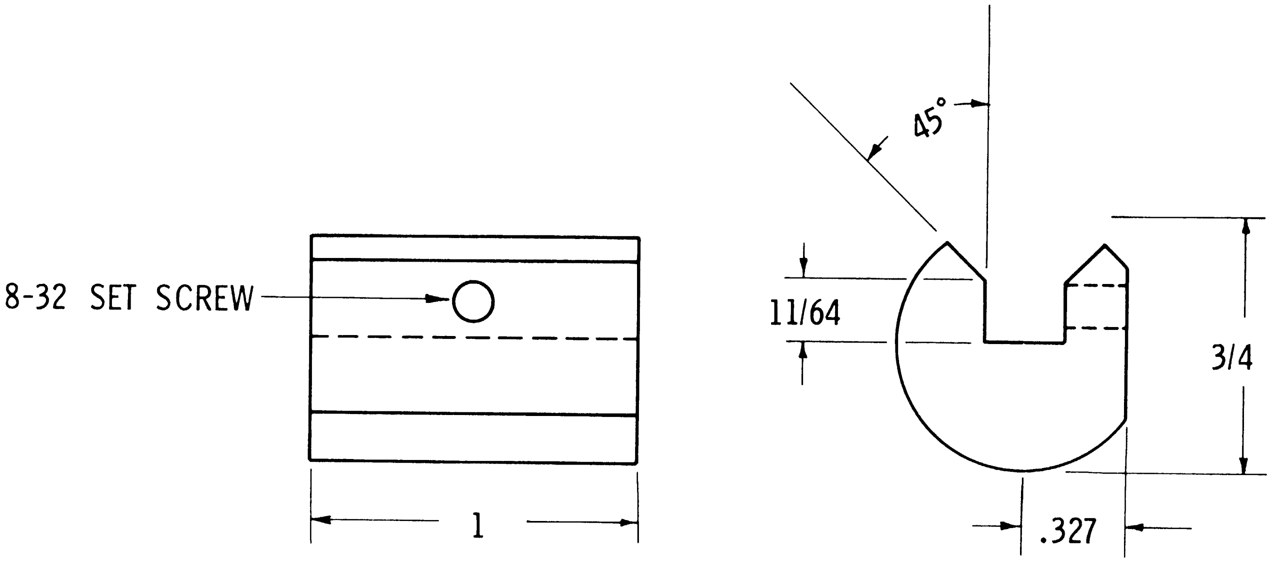

Figure 27. Column end fitting.

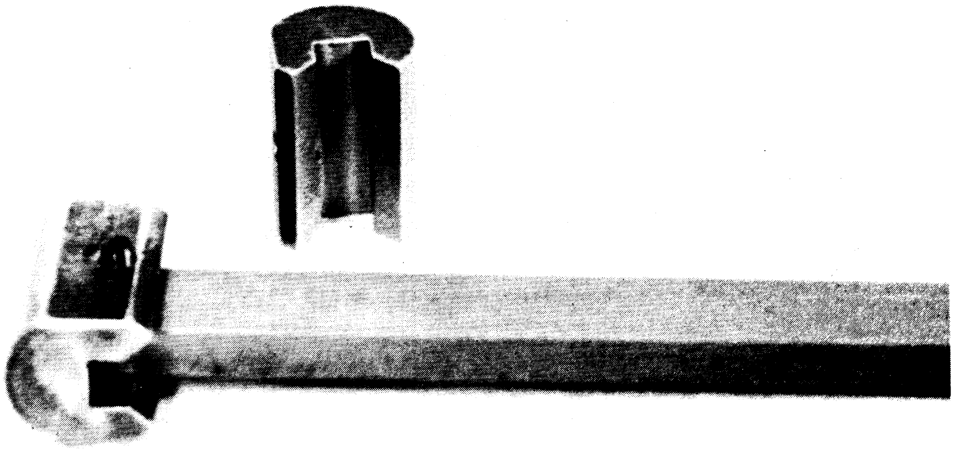

Figure 28. Column end fittings.

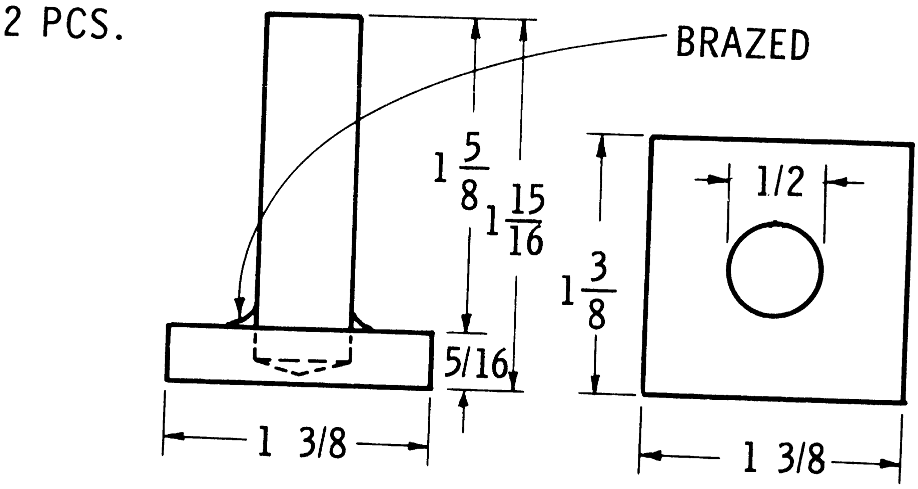

Figure 29. Column end support.

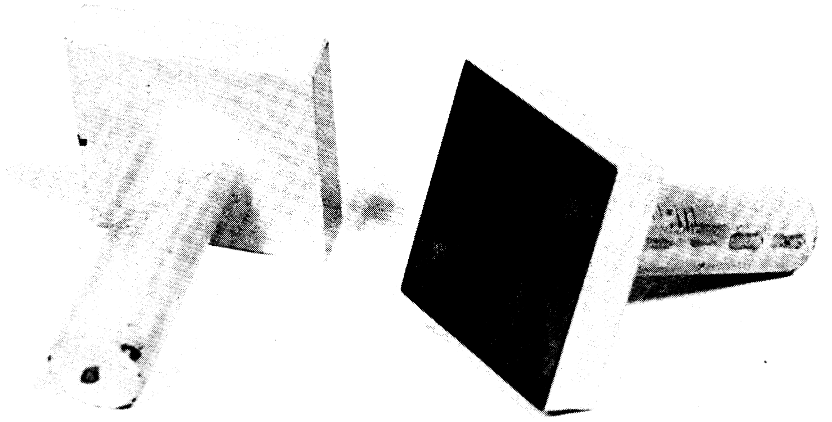

Figure 30. Column end support fittings.

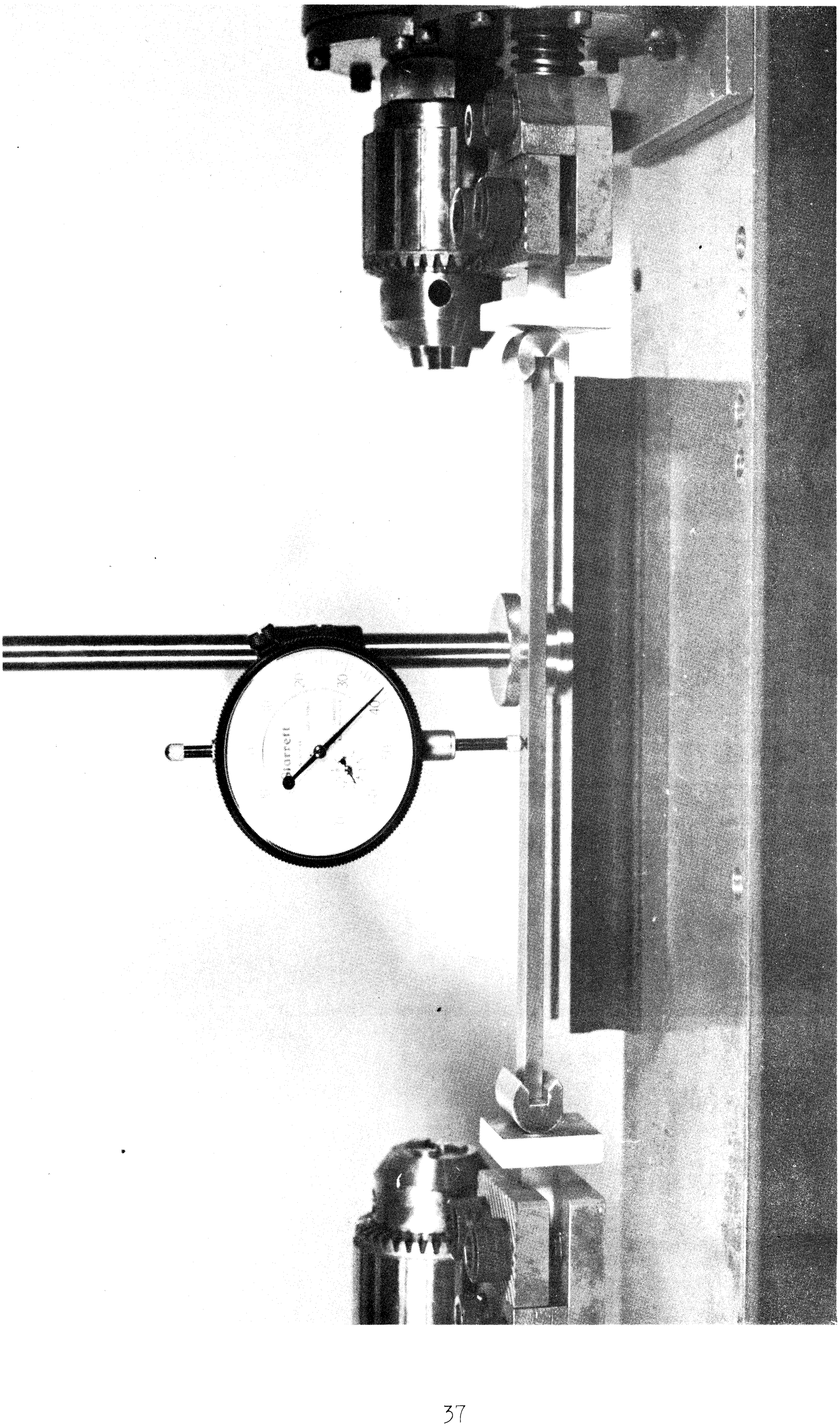

Figure 31. Column test setup.

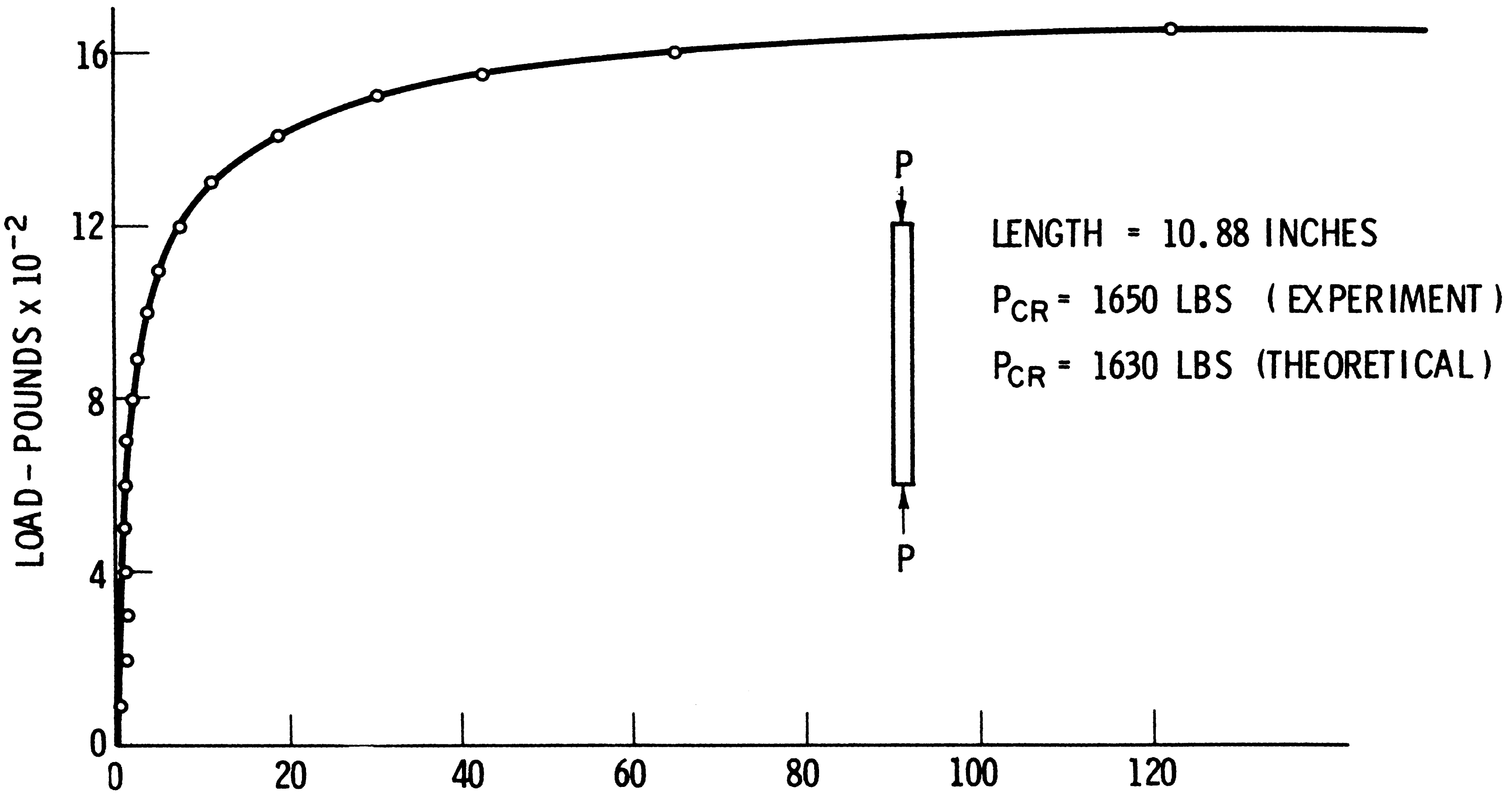

Figure 32. Column load deflection curve.

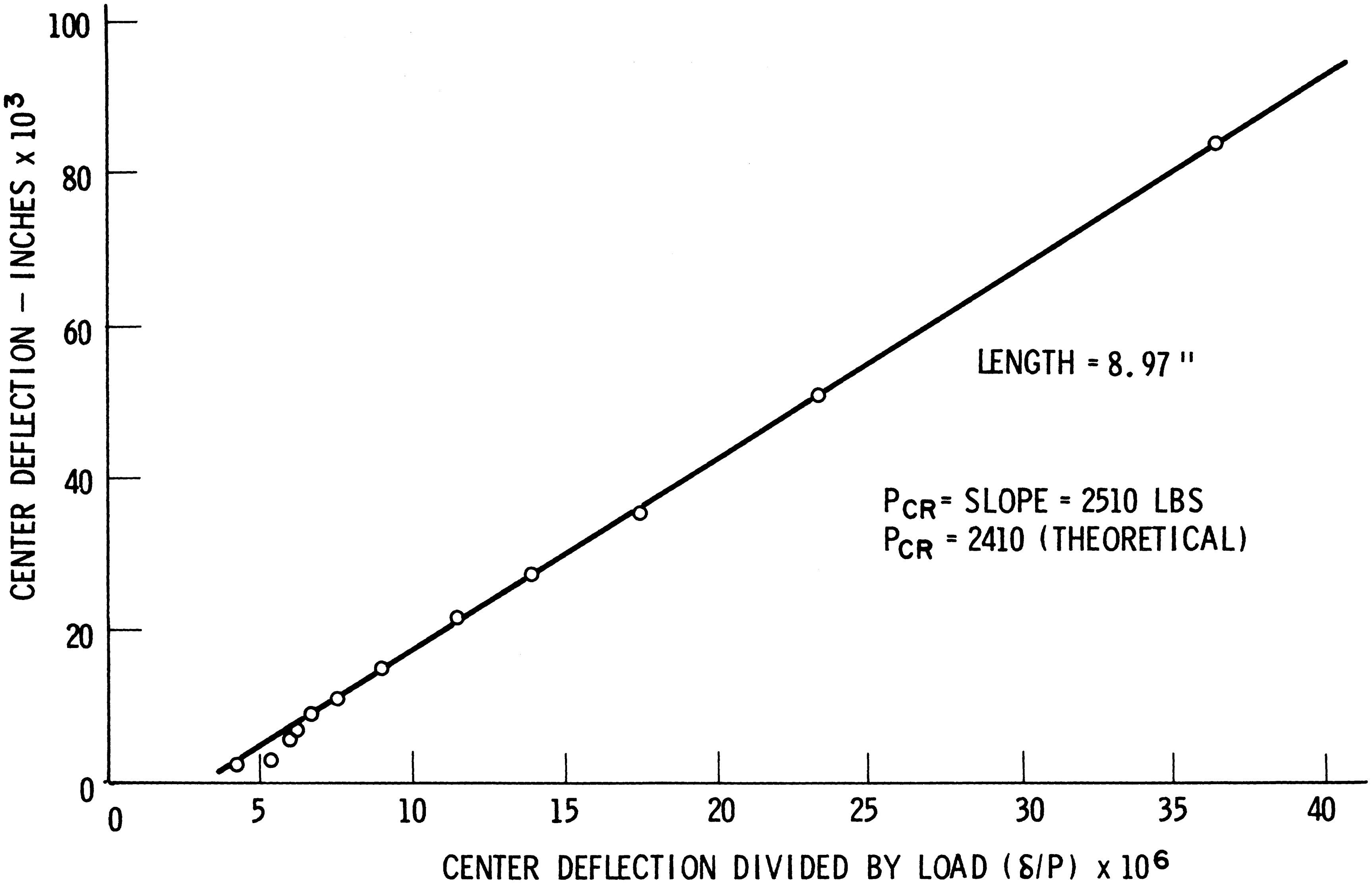

Figure 33. Southwell plot of column data.

More columns could be used if desired, but the range of sizes of specimens with the same cross-sectional area cannot be changed very much, because:

(a) Longer columns exceed the length capacity of the machine.

(b) Shorter columns require loads larger than the machine is capable of exerting.

For more extensive column experimentation several different cross-sectional areas should be used to obtain greater freedom in choice of column length.

EXPERIMENT NO. 7. PLASTIC BEAM EFFECTS

Because experiments on the plastic yielding of materials are difficult to perform on small, bench-type equipment, a number of designs are suggested, some of which have worked well in larger sizes while others have never been very successful. (It must be admitted that no really good experiment is available here.) One experiment is presented which may be modified according to the wishes of the instructor or institution.

A beam built in at one end and simply supported at the other has a concentrated load located at some percentage of the span length from the built-in end. The loading mechanism and the theoretical load deflection curves for this system are shown in Figure 34. The curves show that the two yield points eventually result in unconstrained deformation, but only after completion of the second yield; before that time the system still has load carrying integrity and still has an appreciable load deflection slope.

This experiment demonstrates two ideas: First, the idea of a plastic hinge and its development, which is fairly clearly demonstrated by the theoretical curves of Figure 34. Second, these curves demonstrate that the load-carrying ability of the structure is not lost after the development of the first yield point, but continues until such time as uncontrolled deformation occurs. Such deformation occurs only after full development of the second-yield hinge.

Figure 35 shows the fitting used to perform this experiment. The main portion of the load-carrying channel is simply cut from a section of Unistrut P1000 construction material, obtainable from the Unistrut Corporation, Wayne, Michigan; but many other types of construction are possible. Figure 35 also shows the specimen mounted at one end to a rather rigid block while simply supported at the other end. The specimen could be either 1/4- or a 3/8-inch hot rolled, of low-carbon steel. In terms of rigidity of the so-called built-in end, the 1/4-inch material would probably be more satisfactory. Figure 36 shows the entire assembly mounted in the testing machine with the loading point shown in Figure 34 acting as a load. Figure 37 is a plot of actual test data of load versus deflection for such a system. The data were obtained for a load located 20 percent of the free span from the built-in end.

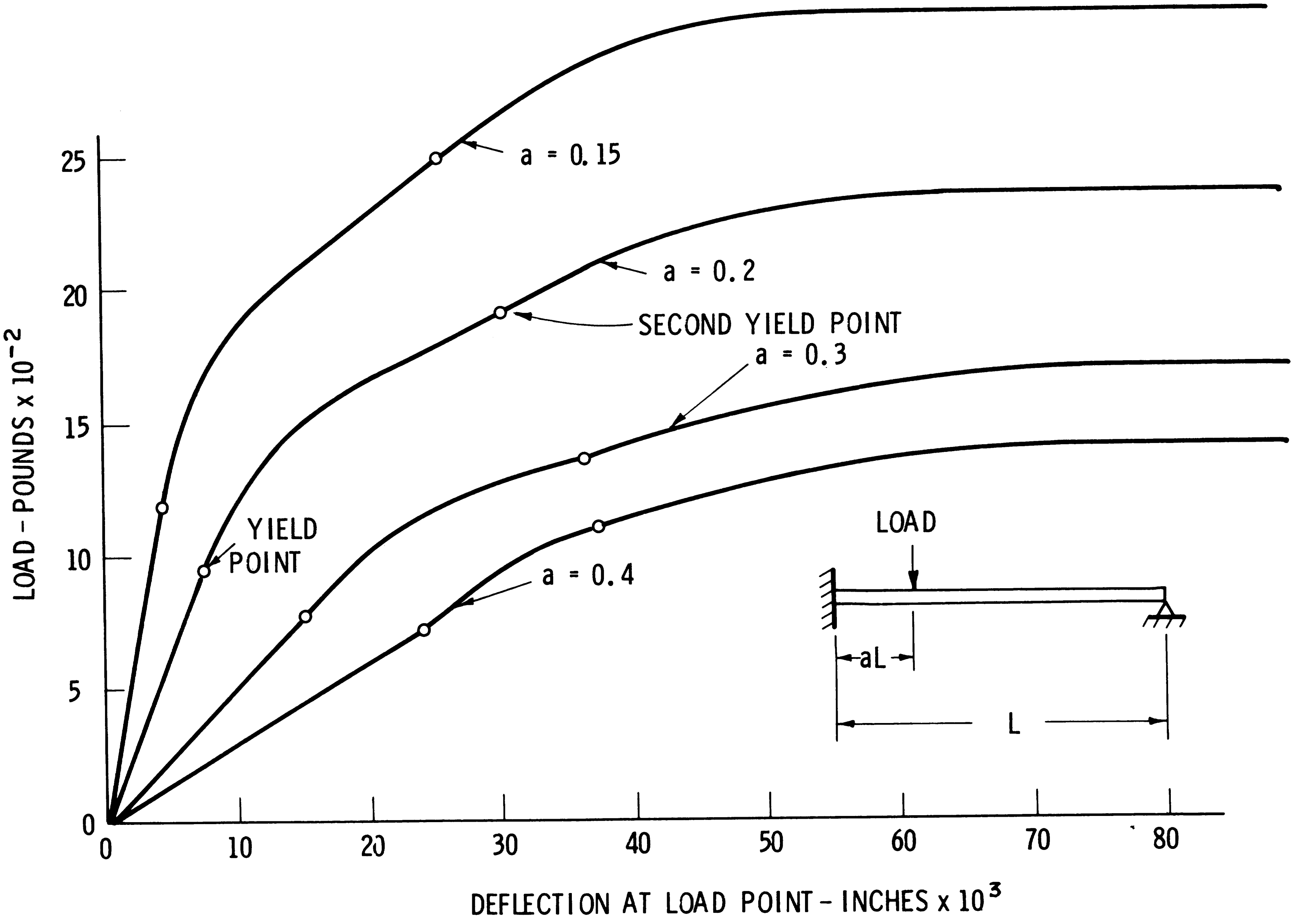

Figure 34. Theoretical load-deflection curves showing the post-yield range.

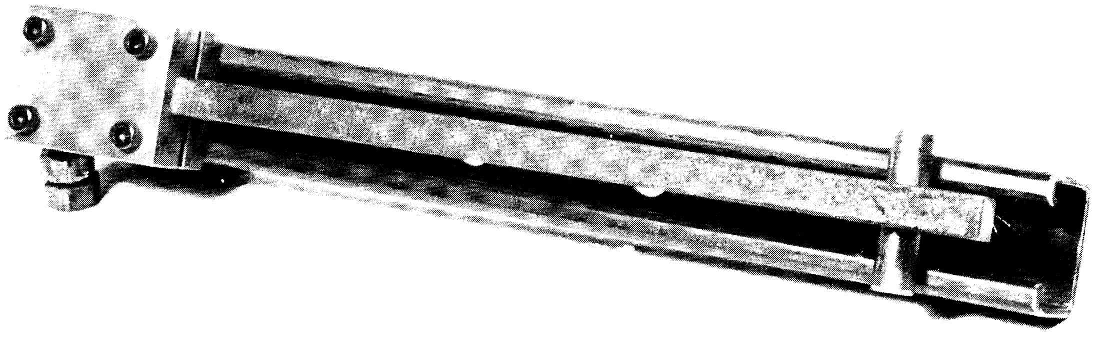

Figure 35. Beam loading fixture and low-carbon beam.

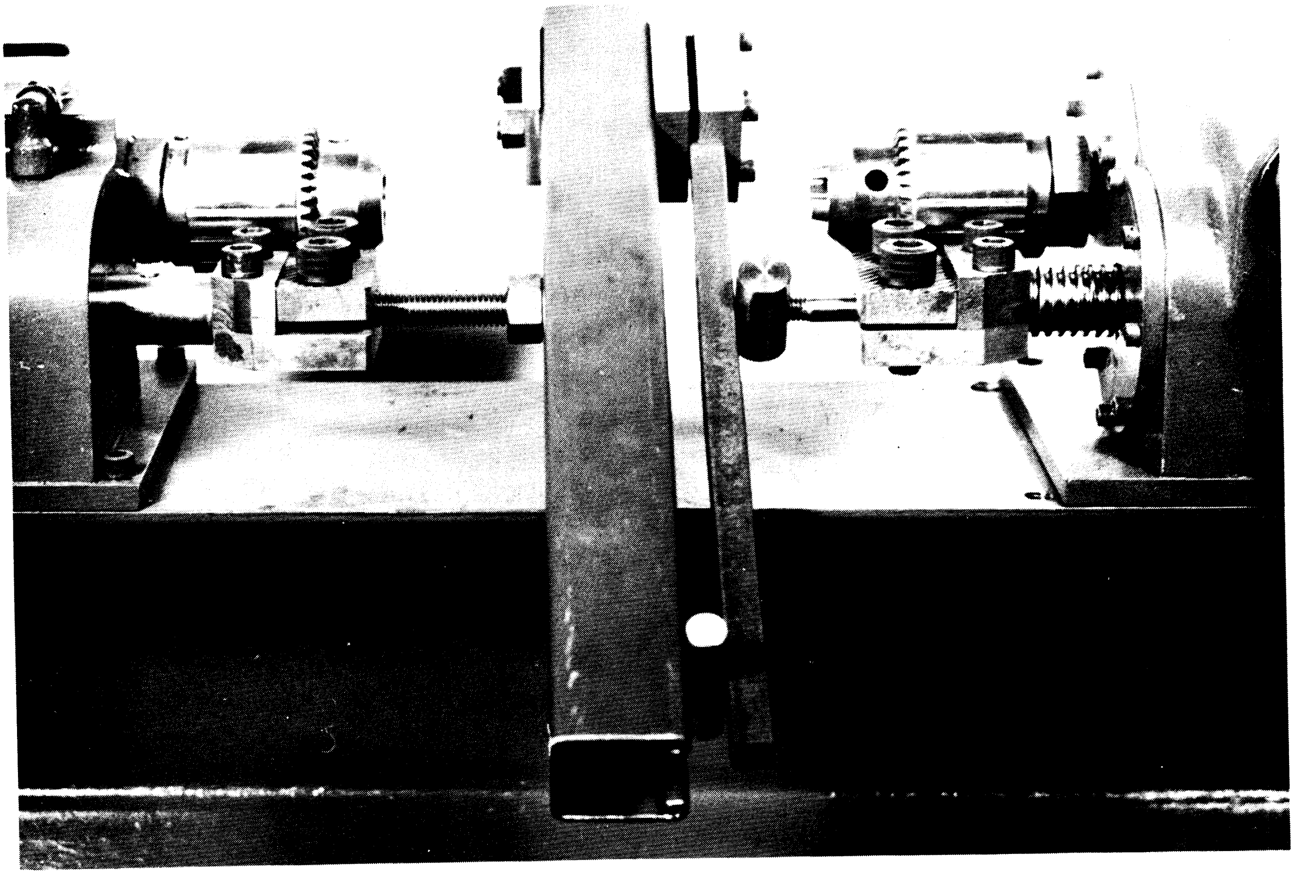

Figure 36. Yielding beam setup in testing machine.

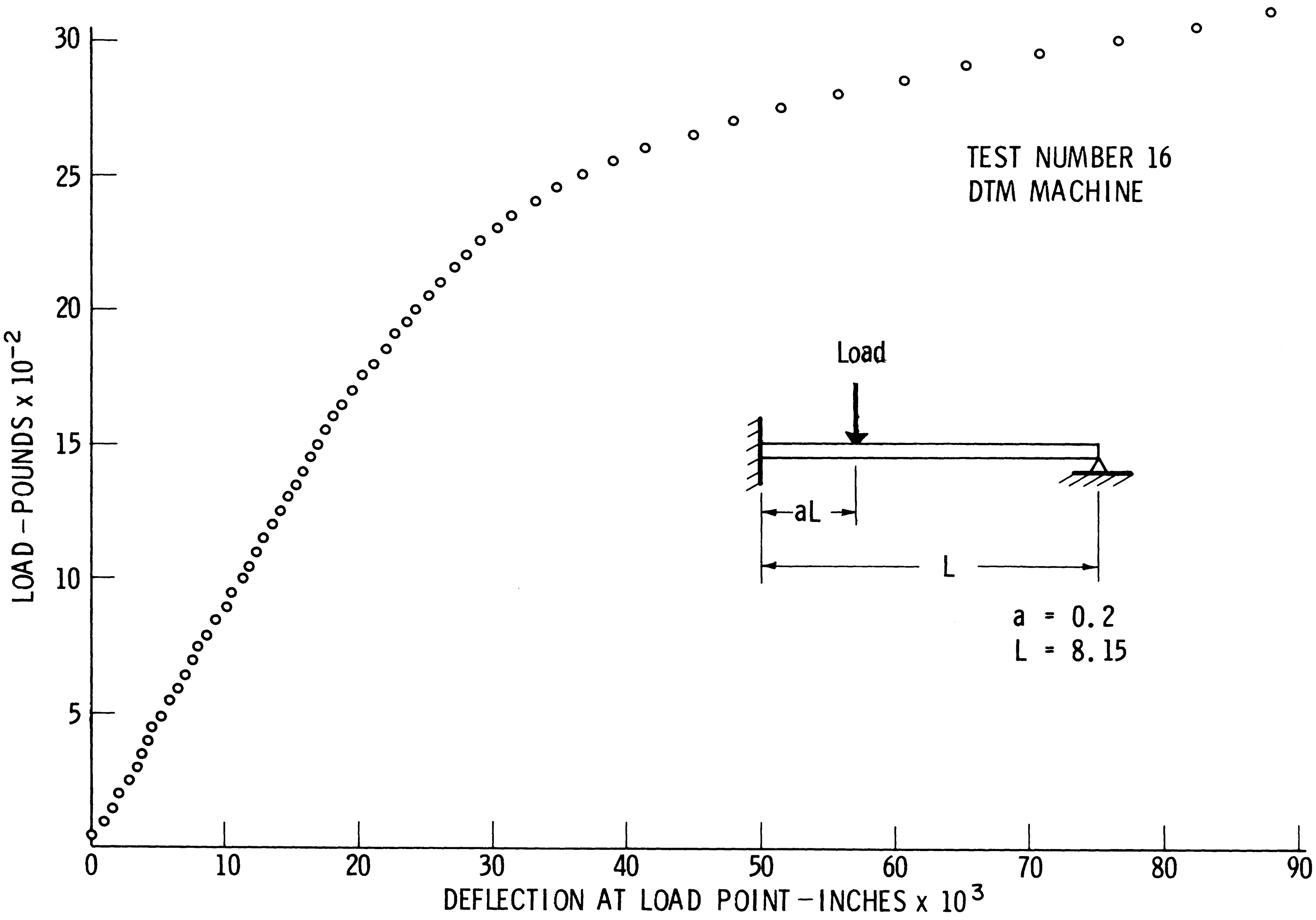

Figure 37. Test data from yielding beam.

One shortcoming of the experiment is the fact that the built-in end is, of course, not truly built-in. This is not easy to remedy because the effective fixity of the built-in end is difficult to calculate. It might be easier to measure this end rotation and to use that measure as a means of correcting the experiment; such an approach will be left to the individual to pursue.

EXPERIMENT NO. 8. ALUMINUM TENSILE BAR

This experiment uses an aluminum tensile bar to demonstrate some of the primary characteristics of a stress-strain curve in tension. The small size of the loading machine necessitates the use of a specimen whose geometry differs from the standard ASTM test bar. Figure 38 shows such a specimen and its dimensions; Figure 39 shows the specimen in the testing machine.

The bar may be provided with either a resistance strain gauge or with a mechanical dial gauge or extensometer. The exact details of the instrumentation may vary with the individual institution or instructor. We used mechanical dial gauges to read head motion as a function of applied load so that the average overall strain could be estimated directly. Obvious errors are associated with this approach because factors other than the working-section elongation enter into the total relative motion of the loading grips. These factors include grip slippage and some small motion in the enlarged area of the test specimen. One objective in designing the specimen was to reduce these extraneous effects to a minimum; Figure 38 would seem to indicate that this objective has been reasonably well accomplished.

Experience has shown that such a tensile test is best used to illustrate some of the "second loading" properties of the stress-strain curve of a typical ductile material. The process forces the student to think about the elastic properties under repeated loading and to evaluate the influence of work-hardening upon the yield point of the material. The specimen is loaded in tension well past the yield point; it is then unloaded and the elastic form of the unloading curve is observed. At this point the instrumentation is reset to zero and the system is again loaded along an elastic response line parallel to and almost coincident with the unloading curve; yield occurs near the original unloading point and the test continues until either some large deformation or perhaps fracture occurs. Figures 40 and 41, which show typical load elongation curves, illustrate the type of thing the student should obtain from an experiment such as this. As these figures show, the original modulus of unloading, the subsequent unloading modulus, and finally the subsequent loading modulus are all essentially equal. The coincidence of the yield point upon reloading and the unloading portion of the curves is very striking in Figure 41. It is felt that experimental information such as this forms a valuable part in building up a background in the mind of the student concerning the behavior of materials outside of the region conventionally dealt with in strength of materials.

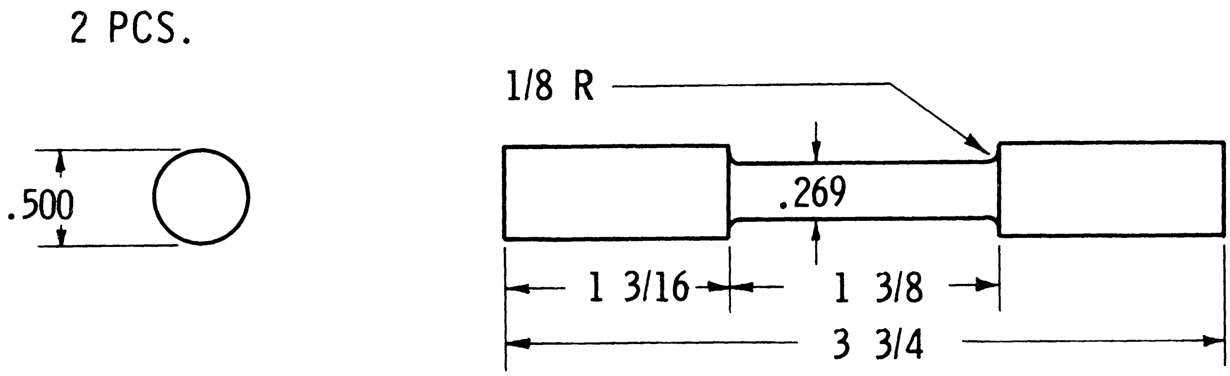

Figure 38. Small tensile test bar.

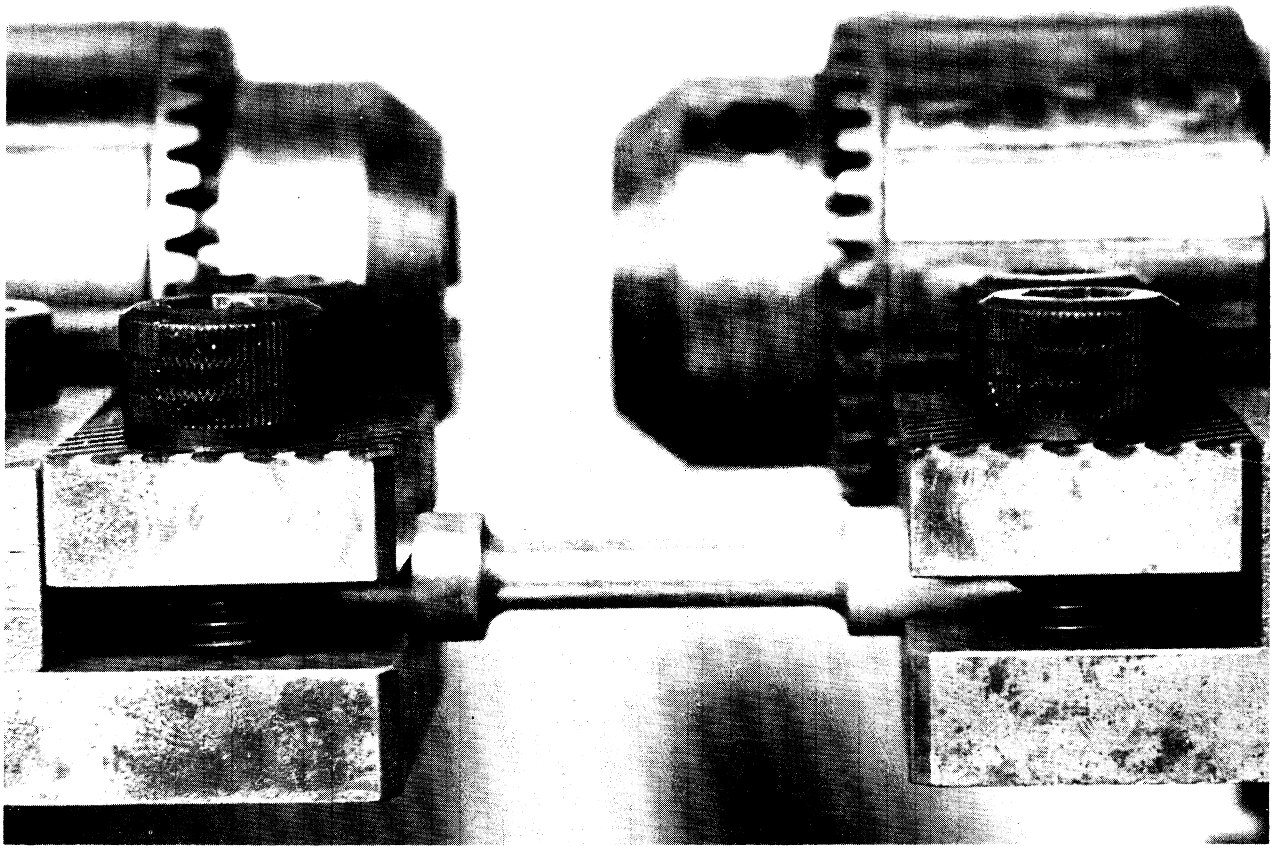

Figure 39. Tensile bar in testing machine.

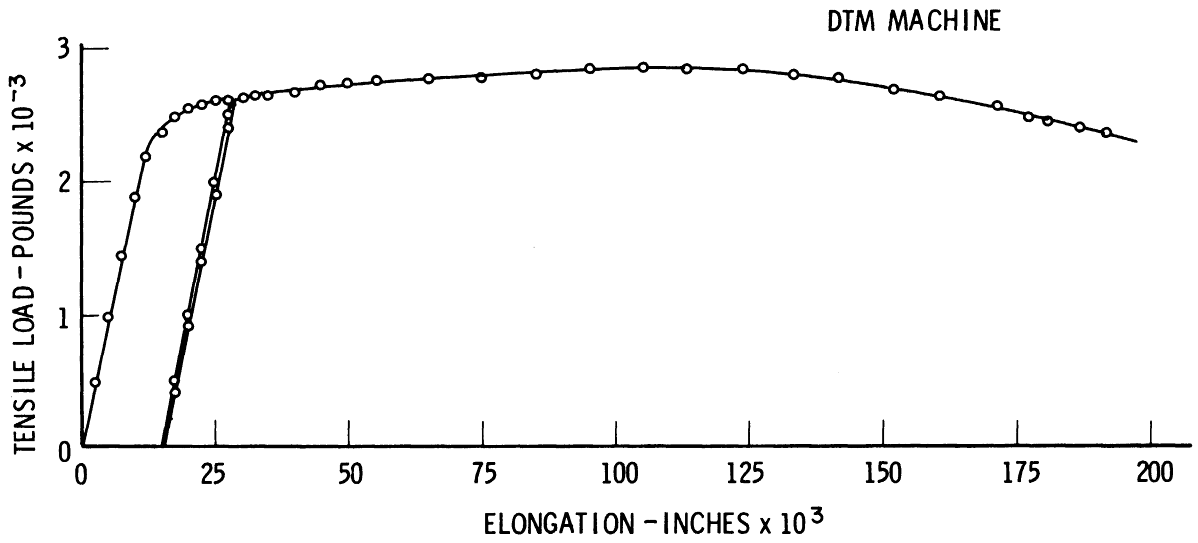

Figure 40. Stress-elongation curves in tension.

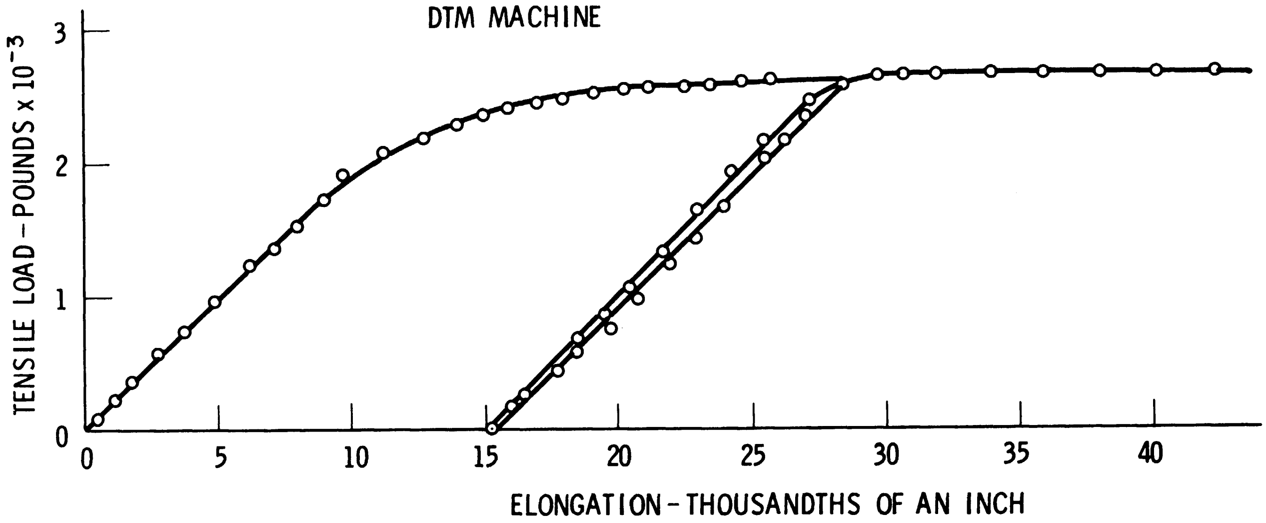

Figure 41. Stress-elongation curves in tension.

EXPERIMENT NO. 9. BAUSCHINGER EFFECT AND HYSTERESIS LOSS PHENOMENA

The aluminum tensile bar used in Experiment No. 8 (Figure 38 and 39) is designed to withstand a certain amount of compression without buckling. This allows the demonstration of Bauschinger effect and various hysteresis phenomena, provided the grips of the testing machine can accept both tensile and compressive loads. The Detroit Testing Machine Company manufactures a machine with such grips (see Basic Testing Equipment, p. 3 ff); therefore, both compression and tension tests can be performed without removing the specimen, a convenient and important advantage.

One phenomenon of considerable interest in a laboratory course on strength of materials is the Bauschinger effect. It may be demonstrated rather simply by first loading a specimen in tension beyond the nominal yield point, and then reversing the loading direction first to reduce the tension to zero and to then force the specimen into compression. The effect observed is well known, namely the yield point on the compression cycle is somewhat lower than the yield point on the original tension cycle. The various explanations of this phenomenon will not be pursued here; the point is that the Bauschinger effect can be demonstrated rather easily on this bench-top equipment. It is not so easily demonstrated on most conventional large-scale testing machines, whose grips are so arranged that different grip systems and even different specimen locations must be chosen in order to produce tension as well as compression.

The data shown in Figure 42 were obtained using a pair of dial gauges mounted on the tension loading grips of the small testing machine. Figure 43 shows a similar set of data. These data illustrate the kind of information which can be obtained from this relatively simple machine using an inexpensive specimen turned from half-inch aluminum bar stock.

In this experiment the student can easily observe a second phenomenon: that completing the cycle of loading from the zero load position back to the zero load position (shown most clearly in Figure 43) results in a closed curve conceptually similar to a pressure indicator diagram on a steam or internal combustion engine. The difference here is that work is done on the specimen, and the area under the load deflection curve represents the magnitude of this work. Thus, internal strain energy is stored in the specimen and a certain amount of heat is dissipated to the atmosphere. The atmosphere generally receives the work done, and the quantitative measure is given by the area under the curve (shown in Figure 43).

Detailed quantitative calculations using the data points such as are plotted in Figures 42 and 43 are not essential, but the general concepts demonstrated by this experiment are important to the student.

EXPERIMENT NO. 10. HORIZONTAL SHEAR IN BEAMS

This experiment is designed to compare beam deflection theory with experiment and to observe the effect of varying the horizontal shear stress capacity of a particular beam system.

The beam (shown in Figure 44) consists of four leaves which may be pinned together with dowels at different locations along the length. Figure 45 shows the beam set up on the knife edges (shown in Figure 46).

Considerable care must be taken in constructing the apparatus for this experiment. Using any one of the four leaves as an individual beam is fairly easy: experiment and theory seem to agree quite well, and no particular difficulty is encountered as the beam is loaded with dead weights and its deflection measured by the dial gauges. Comparing the deflection of the beam when the

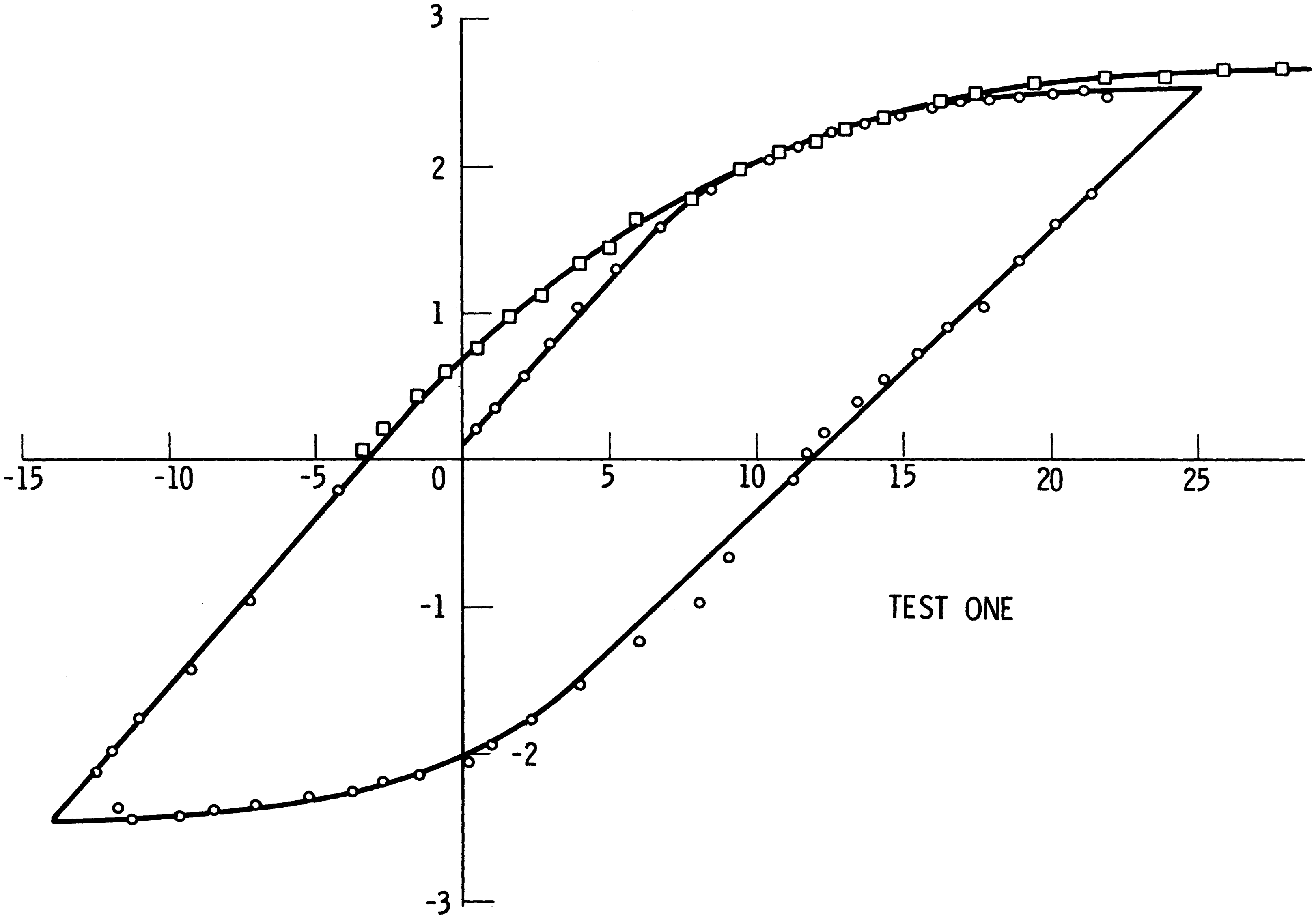

Figure 42. Hysteresis loop curve from aluminum tensile specimen.

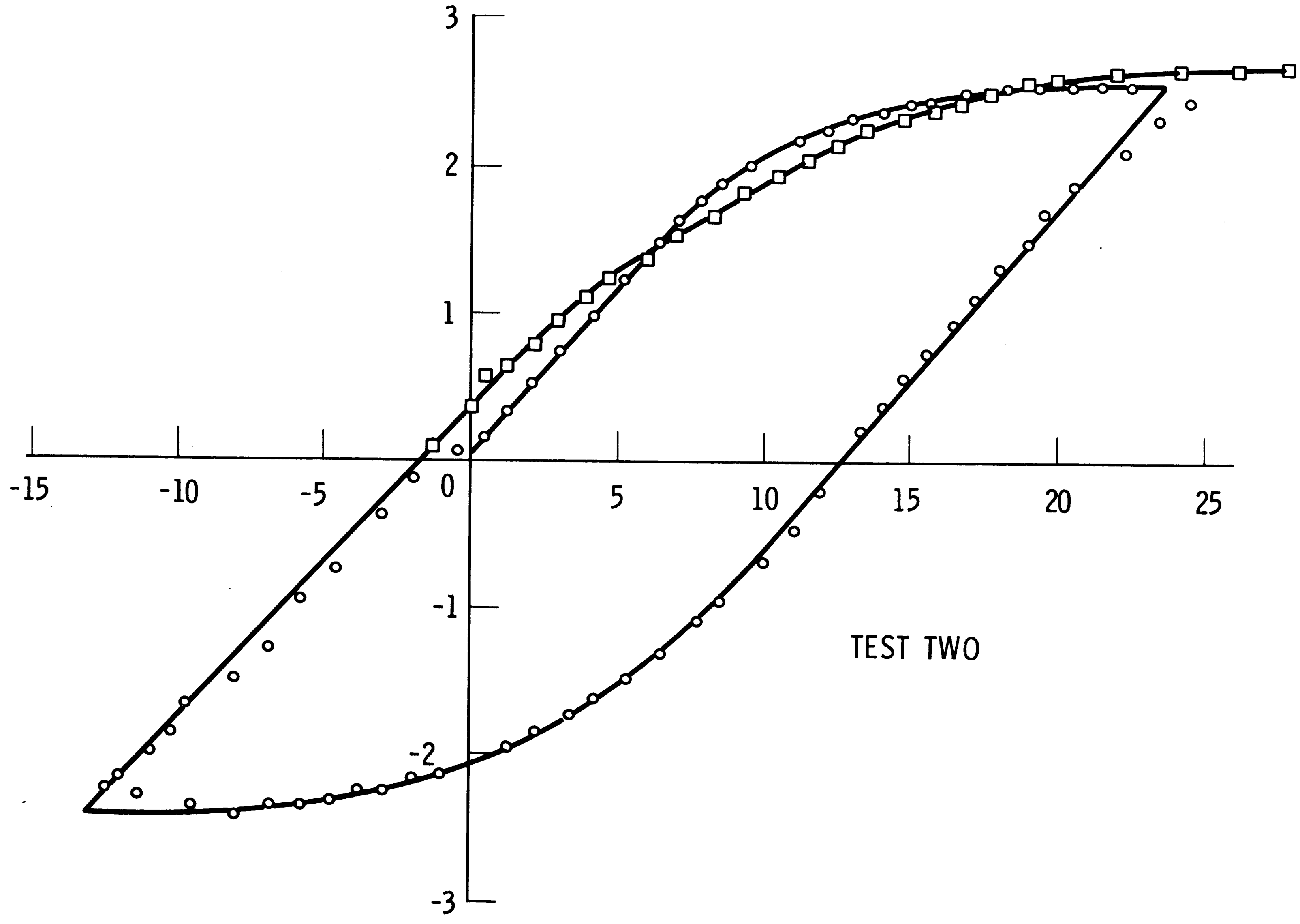

Figure 43. Hysteresis loop curve from aluminum tensile specimen.

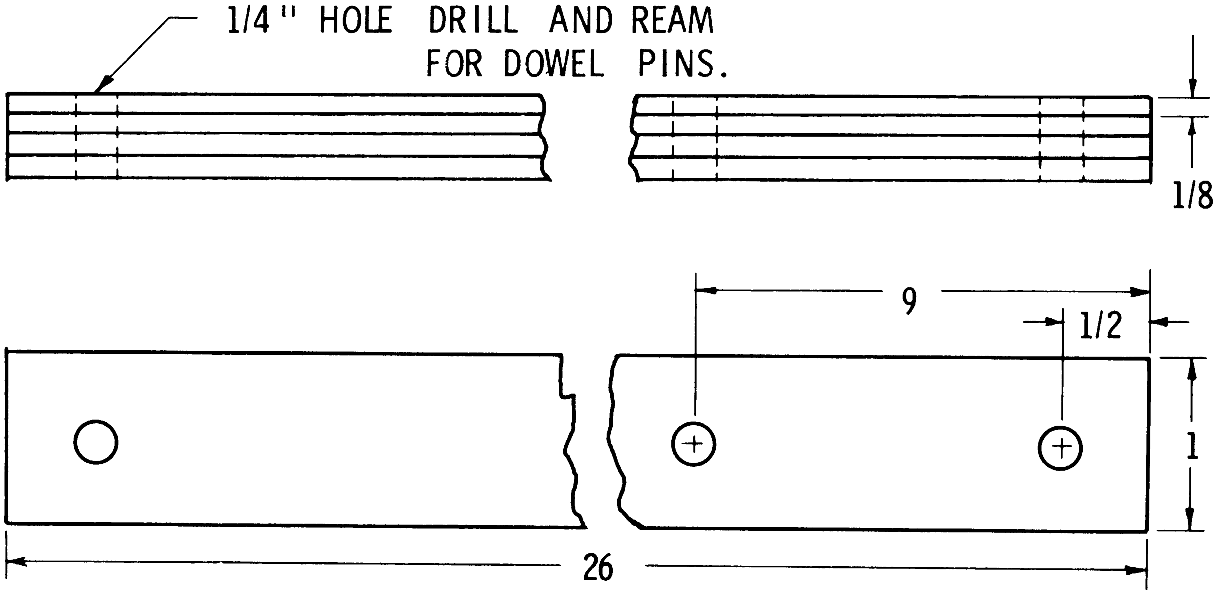

Figure 44. Laminated beam.

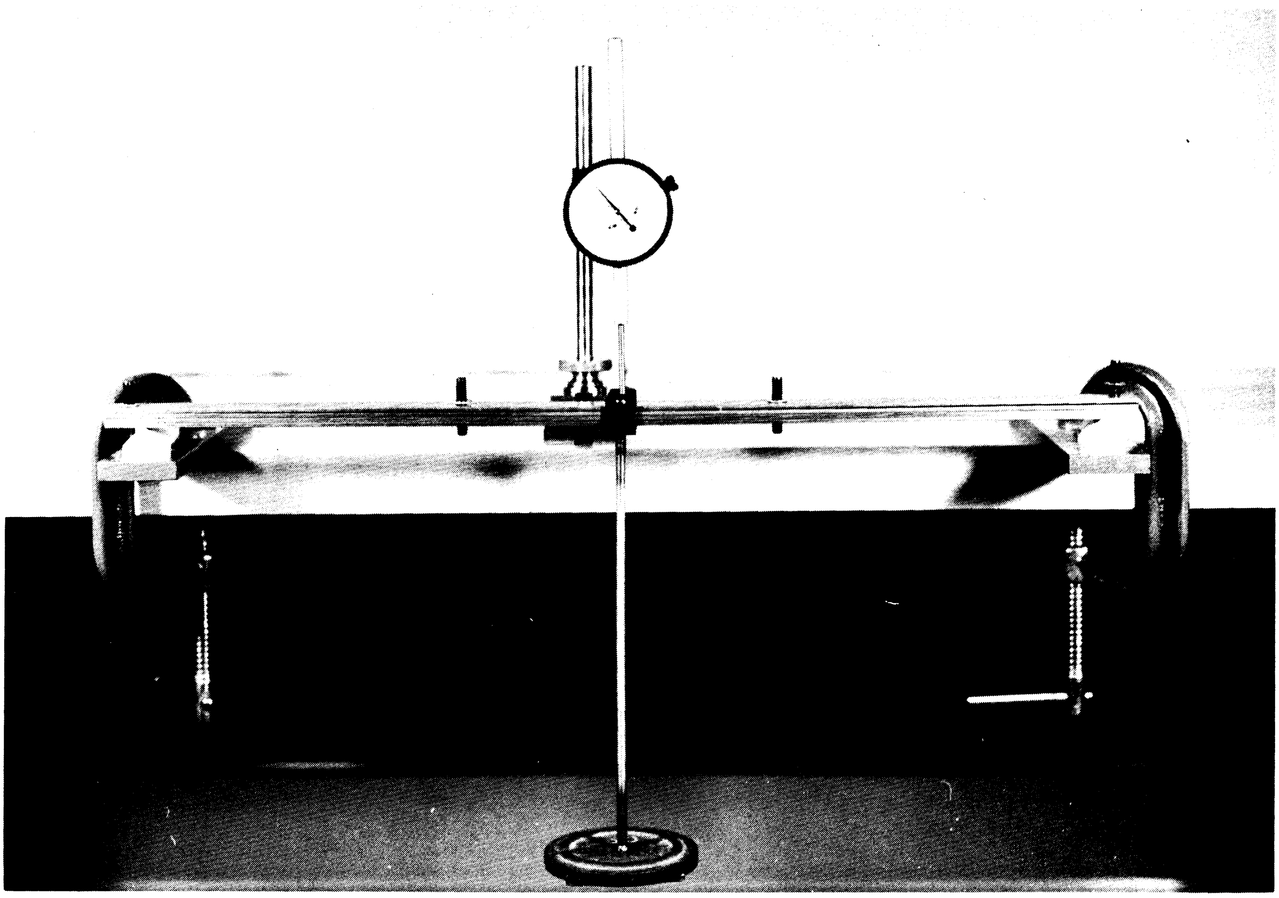

Figure 45. Laminated beam under load.

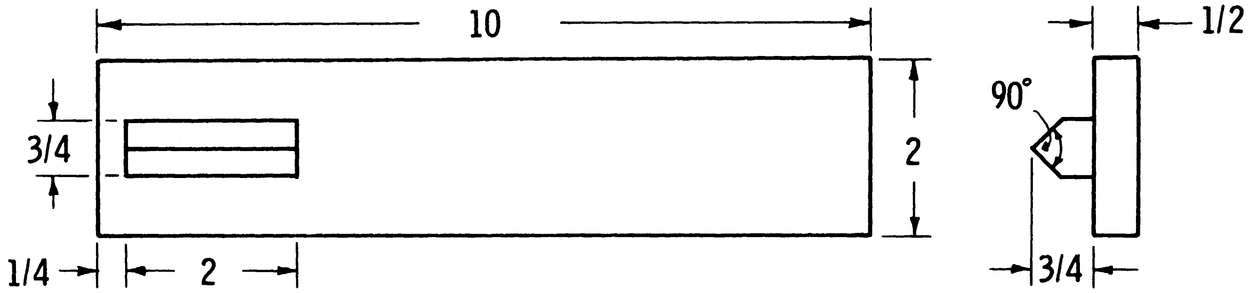

Figure 46. Beam knife edges.

four leaves are unpinned with deflection of the beam when all the pins are inserted is much more difficult, and at this point considerable care must enter into the construction of this experiment. First, during the unpinned phase, the leaves should probably be lubricated in some way so that dry friction does not play an important part in the load deflection curve. However, when the pins are inserted the system probably should not be lubricated and the pins should fit tightly. A tight fit is rather difficult to achieve, and it will probably be impossible to get a completely rigid system by pinning the four beams together as described.

Figure 47 shows typical data obtained from such tests. Note that for a single leaf the load deflection curve is almost a straight line, as one would expect; for four leaves without pins linearity is still quite good, but the system is considerable stiffer; for four leaves pinned there is some nonlinearity, undoubtedly because of looseness between the pins and the holes bored in the leaves. Probably the pins become effective only after some slack has been taken up; this is borne out by the general shape of the curve.

Various numbers of leaves and locations and numbers of pins may be tested. Generally they will give load deflection curves lying somewhere between those for a single free leaf and those for four leaves pinned together (shown in Figure 47). Any of these combinations may be compared with calculations based on simple beam theory.

For the beam designs given in Figure 44, the maximum beam deflection should not be allowed to exceed 0.75 inches, to insure that the stresses remain below the yield point.

EXPERIMENT NO. 11. STRESS CONCENTRATION

Stress concentration effects represent important classes of problems. They are too difficult for a first course in strength of materials, but are well suited to laboratory investigation. This sequence of experiments will examine stress concentration using a fairly simple aluminum-plate tensile specimen with a central hole (shown in Figure 48). Figure 49 shows the specimen mounted in the tensile grips of the testing machine by means of the two holes at either end; a new specimen without strain gauges is also shown in this figure.

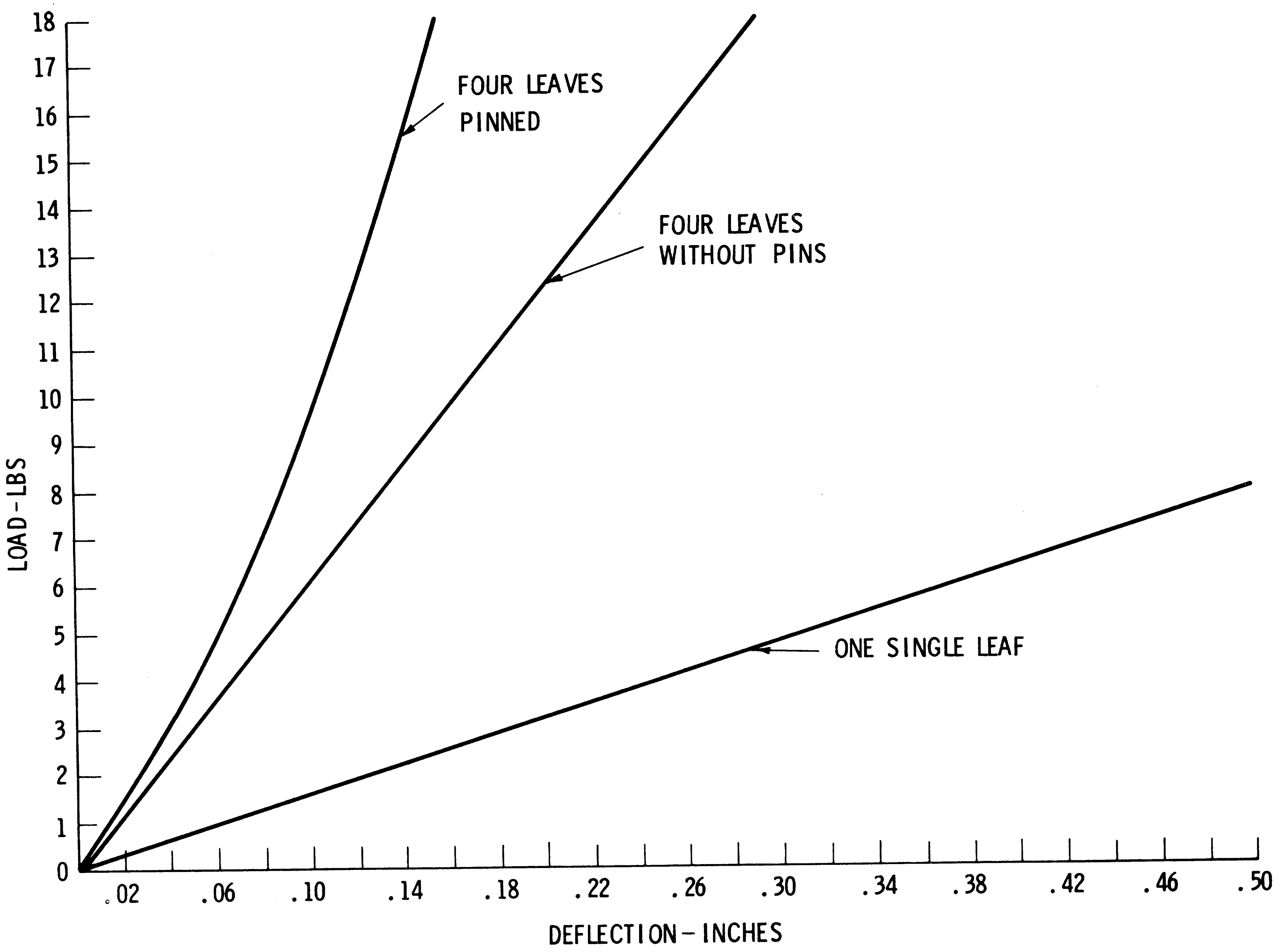

Figure 47. Beam load-deflection data.

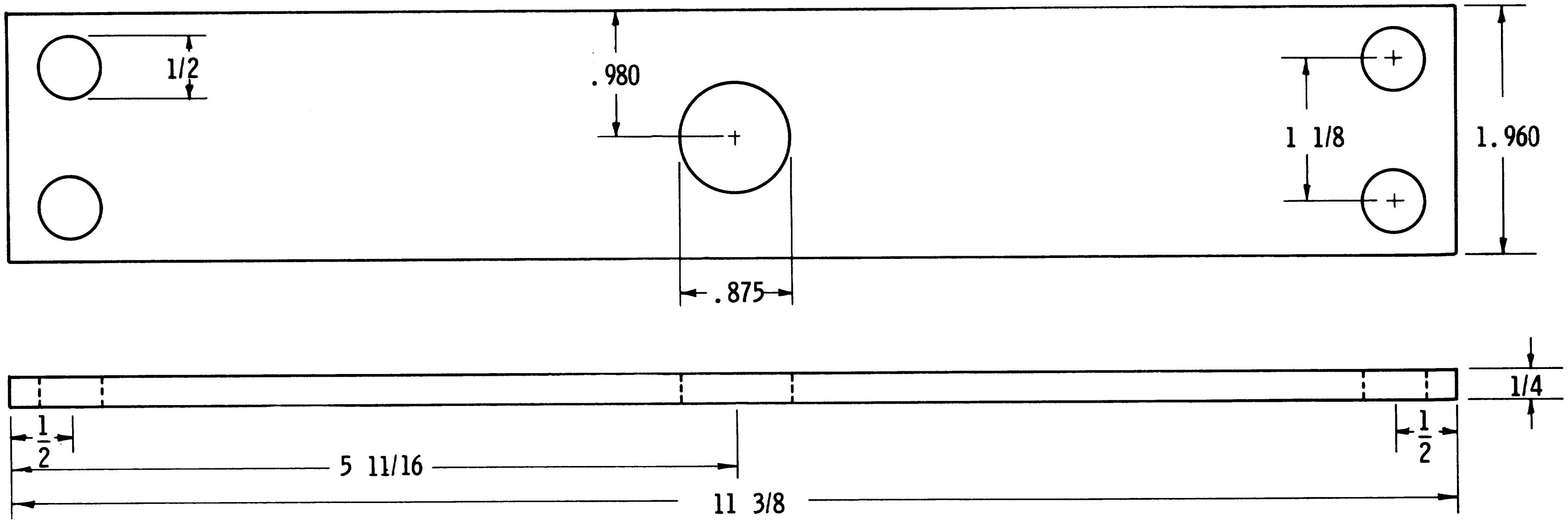

Figure 48. Stress concentration specimen.

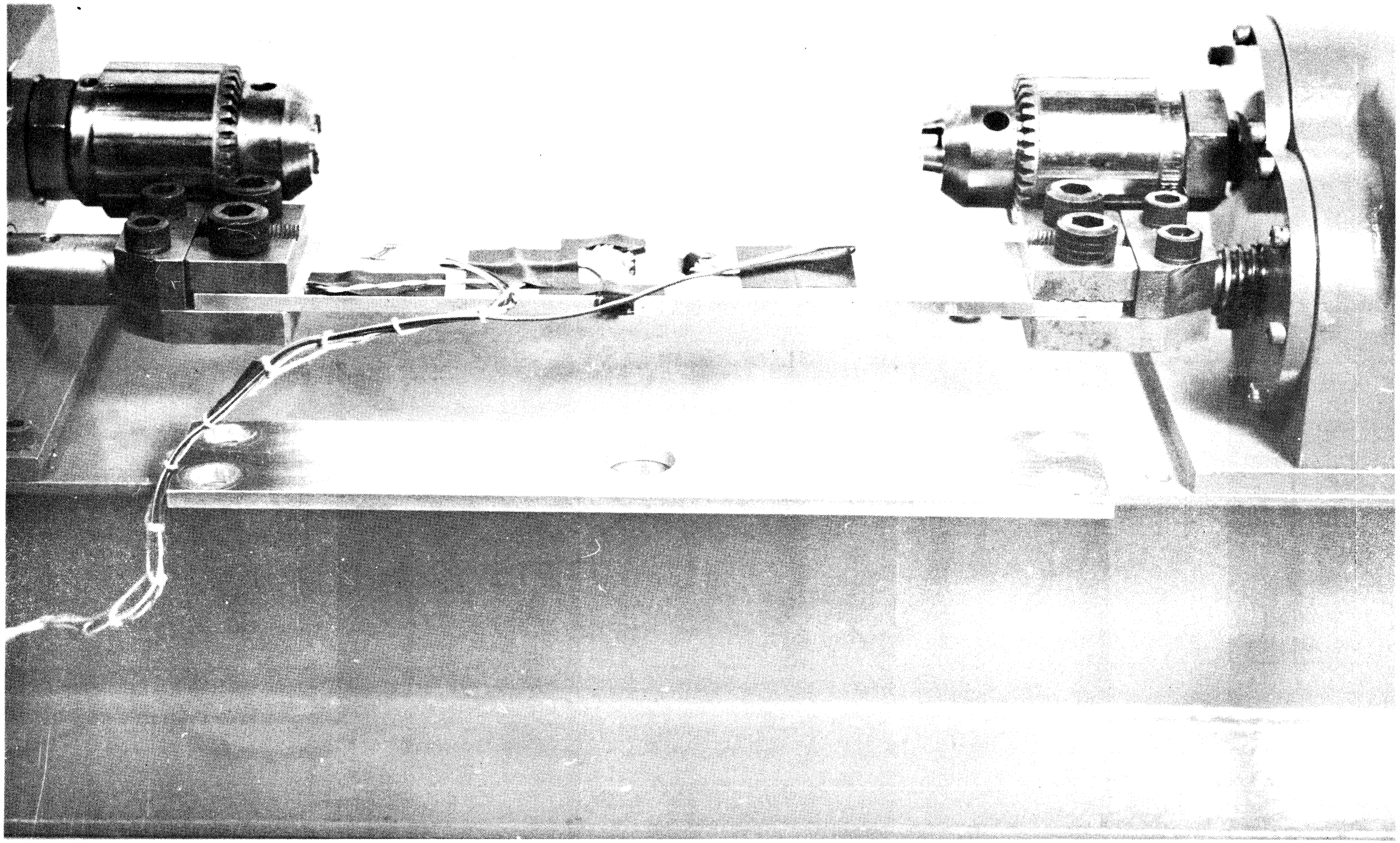

Figure 49. Stress concentration test setup.

The strain gauges are mounted lengthwise on the inside surface of the hole in the center of the specimen, across a horizontal diameter (shown in Figure 48). Other strain gauges are cemented to the outer surface of the specimen, parallel to the first (also shown in Figure 48).

This experiment requires almost the full tension capacity of the machine.

Data from this experiment are shown in Figure 50. The results are approximately what one would expect: The gauges on the outer surface of the specimen show a smaller than average reading in strain, while the gauges at the inside of the hole show larger than average strains. The data in Figure 50 also indicate a stress concentration factor of about 2.2, which is about the right order of magnitude.

Students should be cautioned not to load the specimens excessively since it is quite easy to cause points of high stress to yield.

EXPERIMENT NO. 12. DYNAMIC MATERIAL PROPERTIES

The purpose of this experiment is the simple determination of the dynamic elastic properties of materials. The dynamic shear modulus of a material is determined by means of a torsion pendulum. Such a pendulum is easily constructed from a sheet of light-gauge steel and a length of 1/16-inch diameter welding rod; the dimensions and assembly are shown in Figure 51.

The upper end of the torsion pendulum is clamped to some suitable fitting on the testing table, such as one of the overhanging knife edges used for the beam experiment, and various weights added to the flat pan to reduce the frequency of oscillation. To do this effectively, of course, the weights must be of such a form that their moment of inertia may be easily determined analytically. For example, the additional weight shown in Figure 51 may be bolted to the bottom of the six inch diameter weight pan. The torsional oscillation of the pendulum allows the student to determine fairly accurately the shear modulus of the 1/16-inch diameter rod by timing the period of oscillation and by calculating from this the resulting shear modulus of the material. Other weights may be added to obtain different periods.

Young's modulus may be determined by using a cantilever beam with a concentrated load at the end as a system which oscillates in bending (Figure 52). The beam is clamped to the bench top with 24 inches of it extending over the edge. A four-pound weight is attached to the end of the beam with a small C-clamp. By giving the system an initial deflection and measuring its period, the Young's modulus of the beam material may be determined by conventional methods. Figure 53 is a photograph of the beam and weight system.

At this stage of their studies, many students are not familiar with simple oscillation phenomena, in which case they may be provided with expressions for

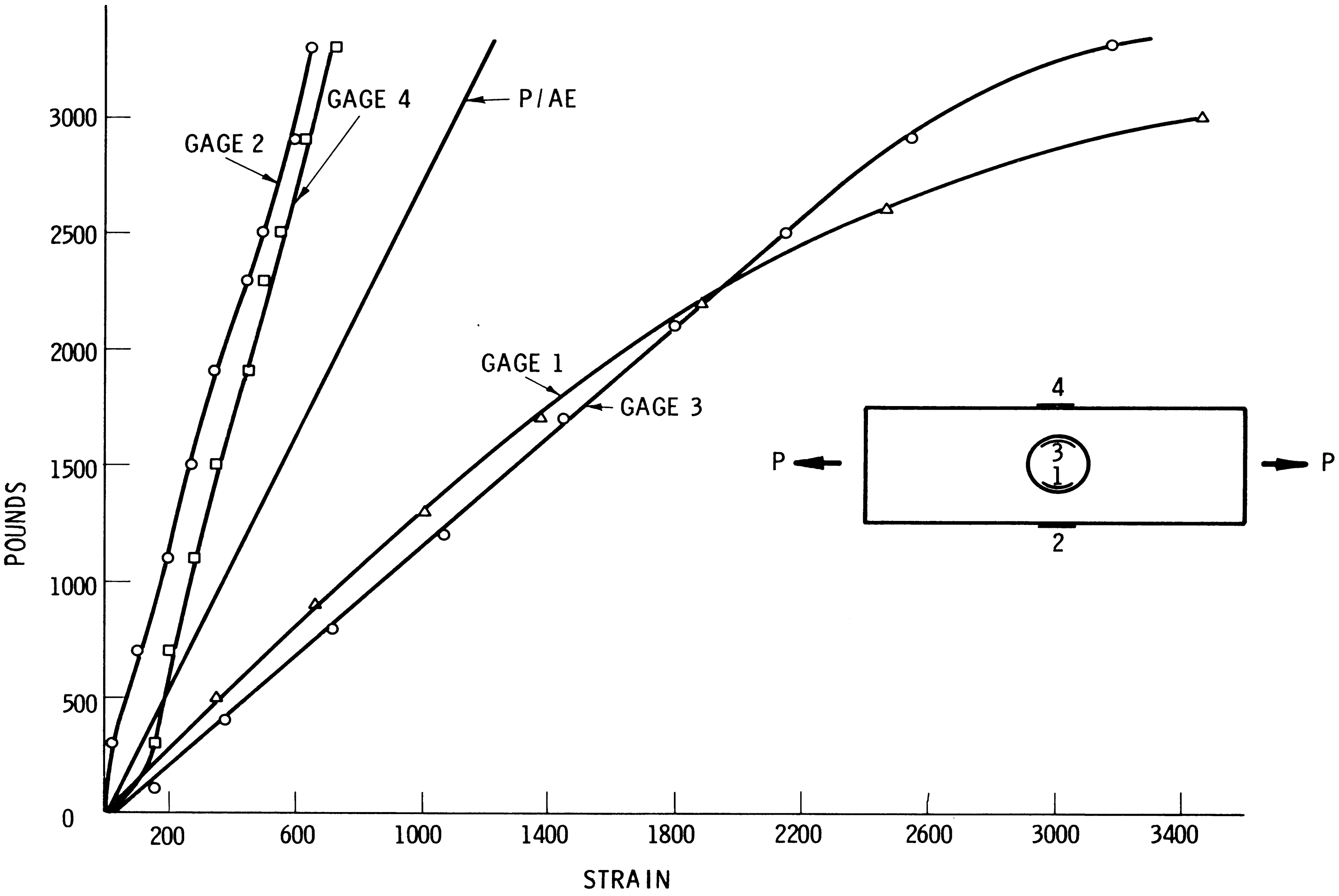

Figure 50. Stress concentration data.

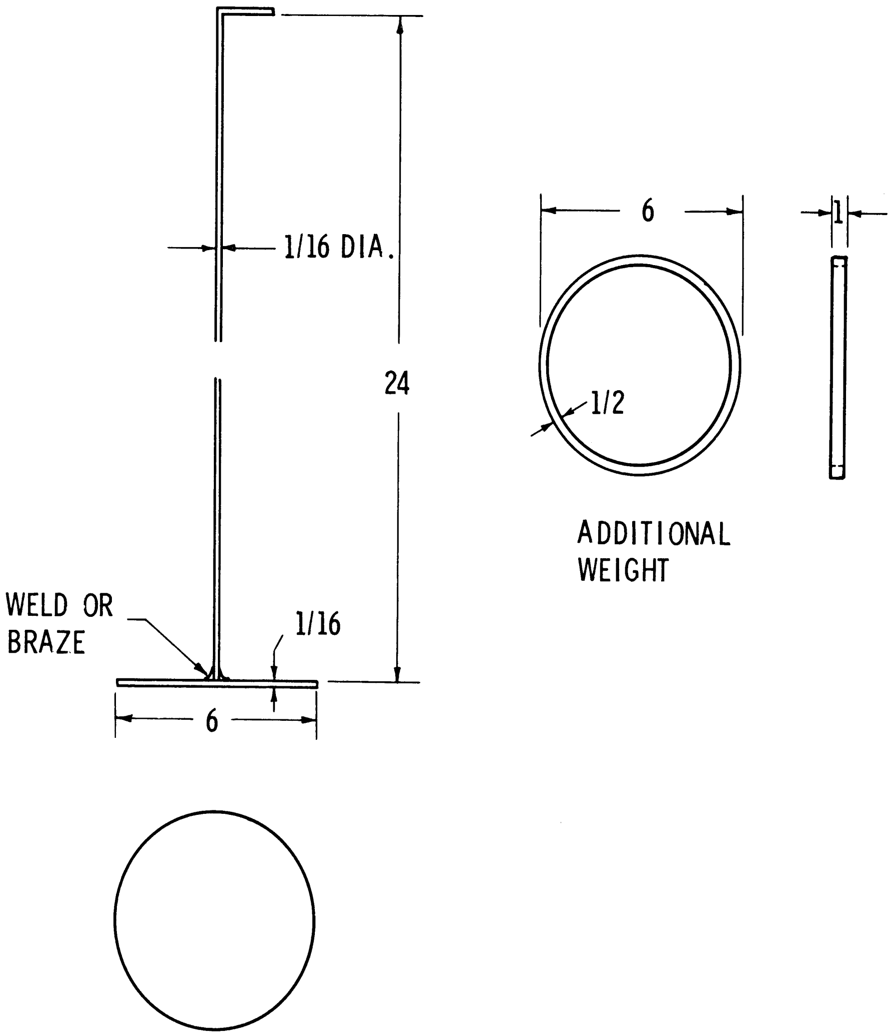

Figure 51. Torsion pendulum.

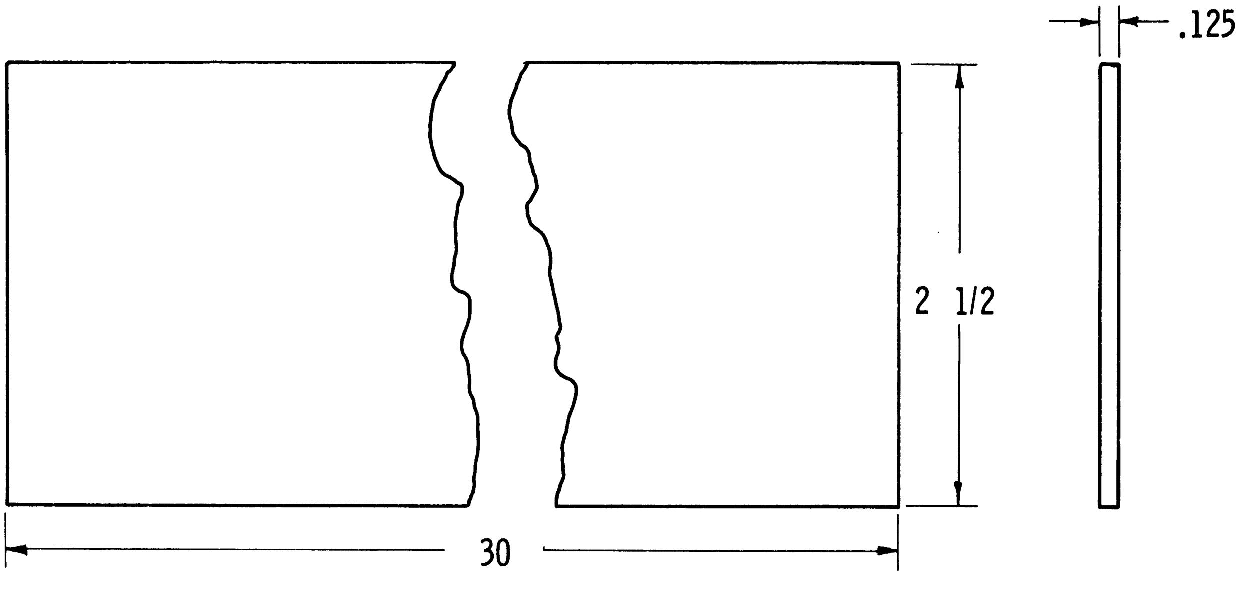

Figure 52. Oscillating beam.

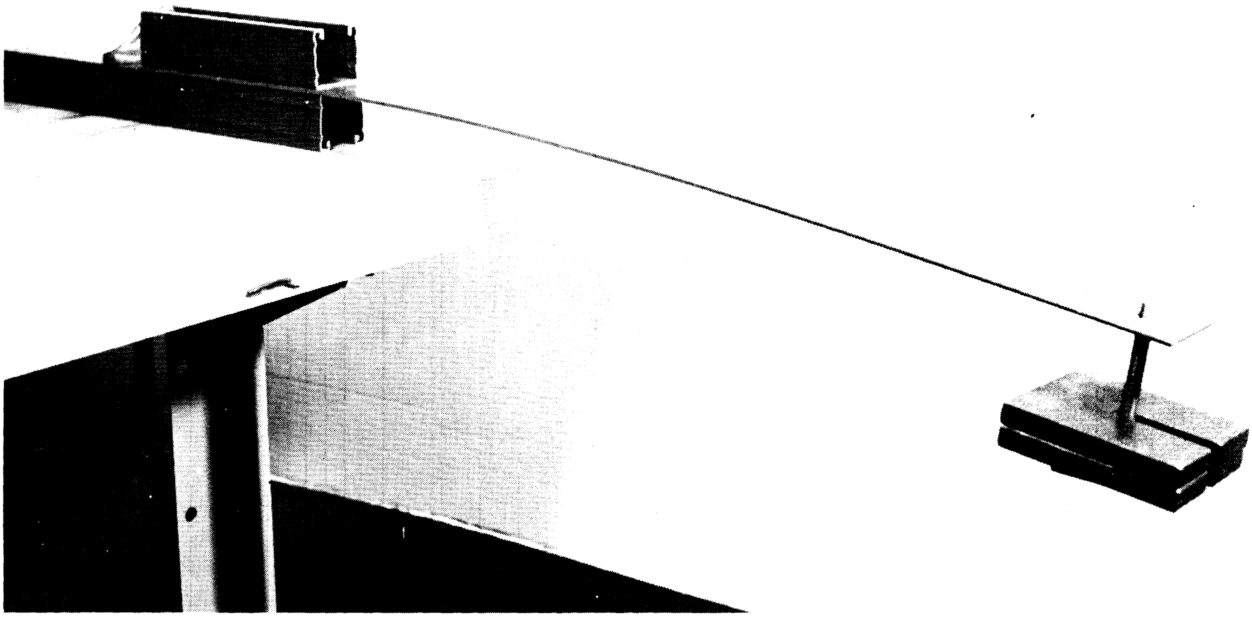

Figure 53. Oscillating beam test arrangement.

the frequency or period of motion. This somewhat reduces the effectiveness of the experiment, which nevertheless remains quite important in demonstrating the dynamic elastic properties of materials.

EXPERIMENT NO. 13. CREEP OF PLASTICS

This experiment uses a Plexiglas beam approximately 3/8 inch by 1 inch by 20 inches to demonstrate the time-dependent strain behavior of common plastic materials. The beam is extended approximately 12 inches over the edge of the work table and a standard weight pan is attached to the end of the beam and loaded with various dead weights (Figure 54). Resistance strain gauges are attached to the Plexiglas beam immediately adjacent to the point at which it contacts the table.

Figure 55 shows plots of strain versus time obtained from such tests, from which it may be seen that axial strain is definitely time dependent for a range of load values. Figure 56 shows similar readings for a 3/4-lb fixed load. In this case the load was removed after 20 minutes, and the time-dependent behavior of the material is clearly seen. Figure 57 illustrates time-dependent behavior for the same 3/4-lb load using the strain immediately upon load application as a base point. The general nature of the time-dependent strain phenomenon is also clearly seen here.

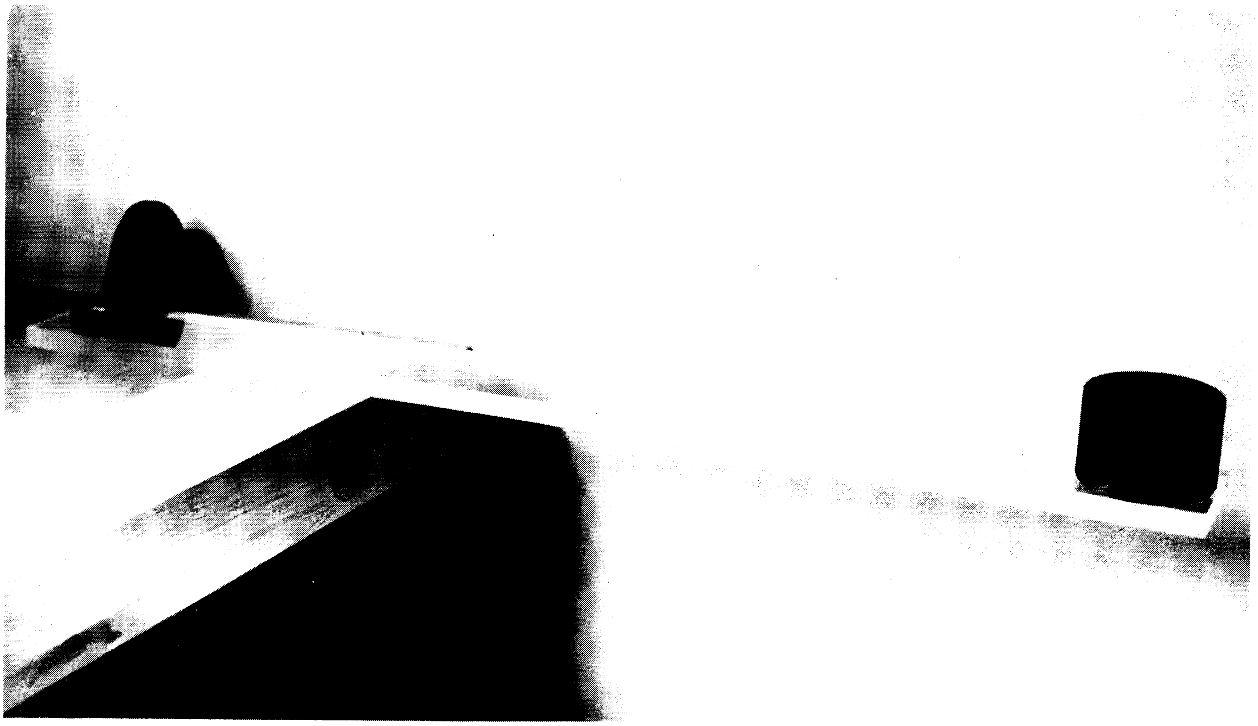

Figure 54. Plexiglas beam.

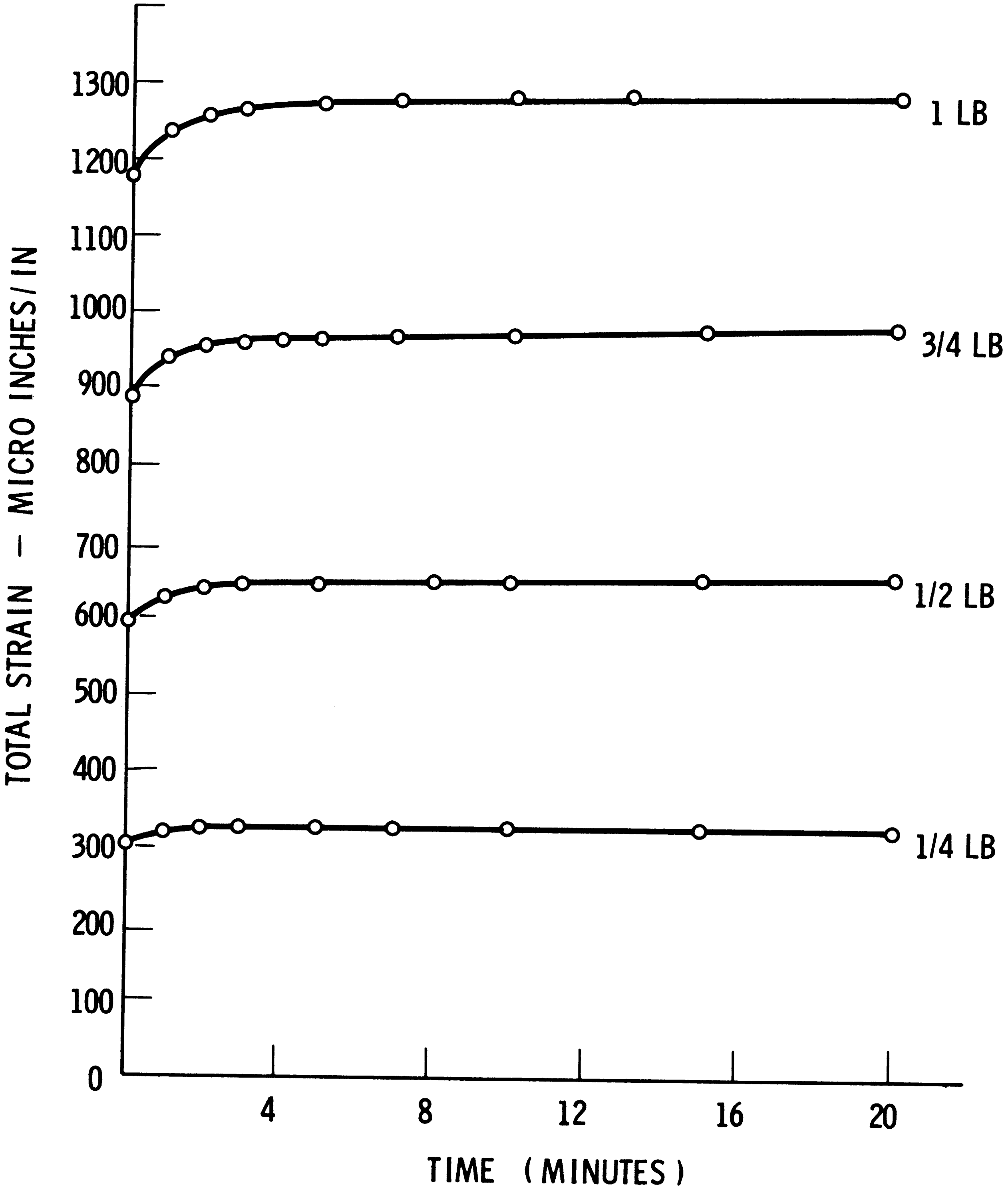

Figure 55. Strain-time data for Plexiglas beam.

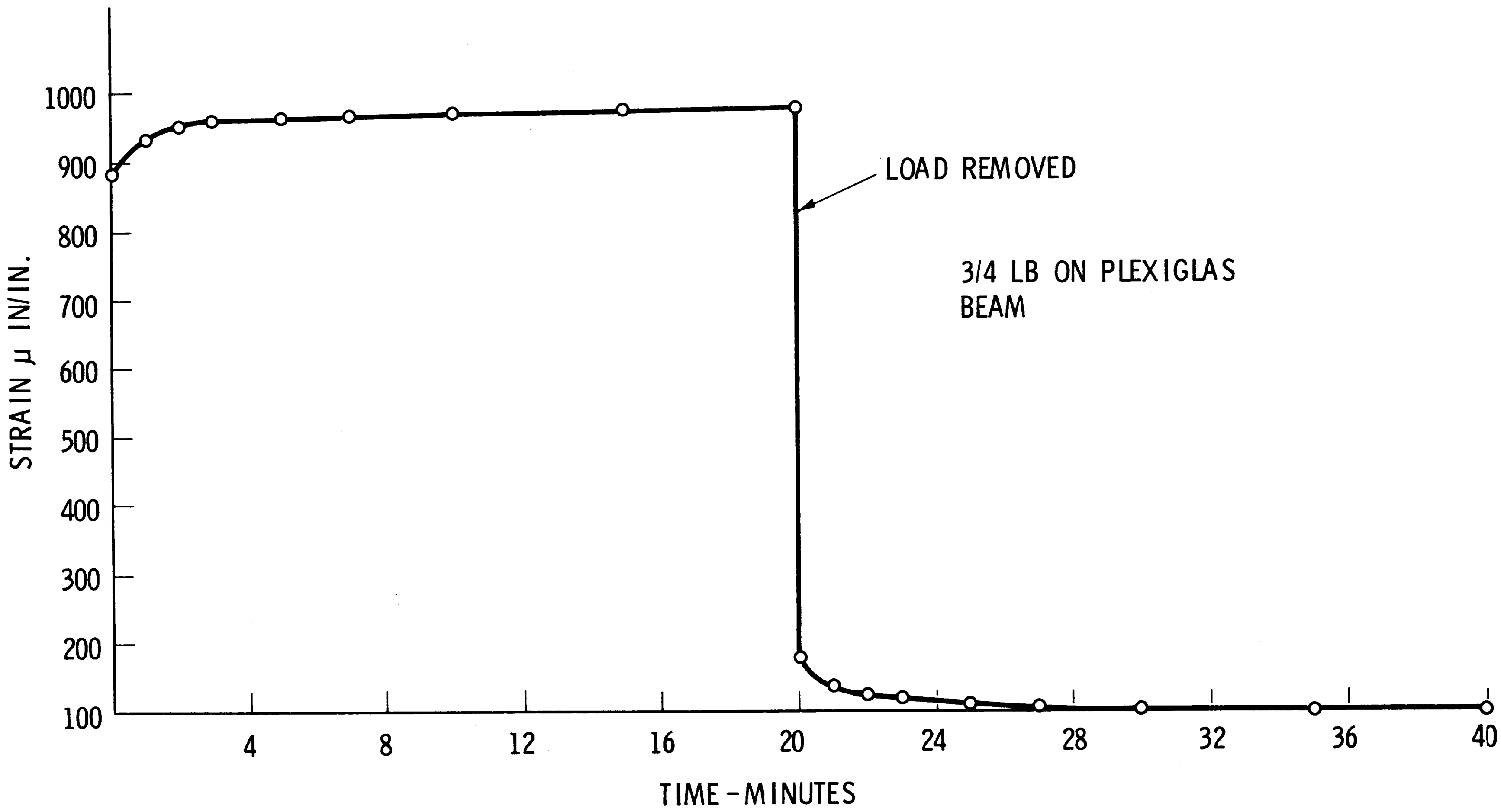

Figure 56. Relaxation curves for Plexiglas beam.

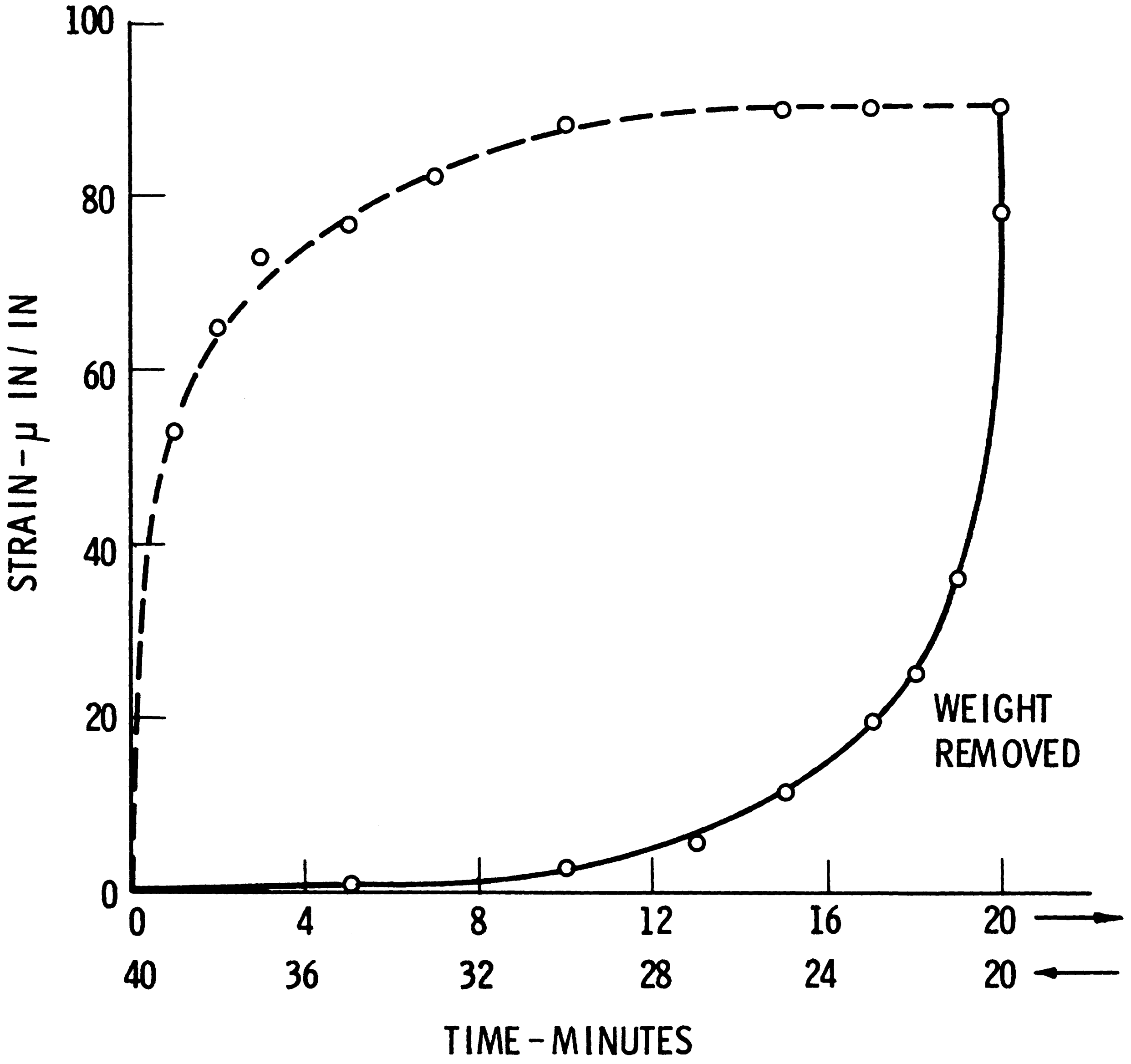

Figure 57. Relaxation curves for Plexiglas beam.

APPENDIX

Manufacturers of Strain Gauge Equipment

Baldwin-Lima-Hamilton Corporation
Instrumentation Division
Waltham 54, Massachusetts

Budd Instruments Division
Box 245
Phoenixville, Pennsylvania

Metrix, Inc.
P. O. Box 683
Walnut Creek, California

Gulton Industries, Inc.
Metuchen, New Jersey
(Distributors of Kyowa products)

Toyo Measuring Instruments Co., Ltd.
104 1-Chome Minemachi
Ota-Ku, Tokyo
Japan