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TECHNICAL NOTE

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MECHANICAL PROPERTIES OF FIVE LAMINATED PLASTICS

By William N. Findley and Will J. Worley

University of Illinois

Washington

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TECHNICAL NOTE NO. 1560

MECHANICAL PROPERTIES OF FIVE LAMINATED PLASTICS

By William N. Findley and Will J. Worley

SUMMARY

Results of mechanical tests of the following laminated plastics are reported: canvas laminate molded at low pressure, grade-C canvas laminate, rayon laminate, paper laminate, and glass-fabric laminate. The following tests were performed on these materials: static tension, compression, and torsion tests; long-time creep tests at different stresses on specimens loaded in tension; fatigue tests of unnotched specimens in bending; fatigue tests of notched specimens in bending; fatigue tests in bending at temperatures of -75°, 77°, and 160° F; and fatigue tests in torsion.

Of the five laminates studied, the glass-fabric laminate had the most desirable mechanical properties for nearly all the properties measured. The properties of the paper laminate were next in order of desirability. It was observed that the creep rate of the glass-fabric laminate increased only slightly (compared with the other laminates) with increase in stress and that temperature made much less difference in the fatigue strength of the glass-fabric laminate than of the other laminates. The mechanical properties of the canvas laminate molded at a pressure of 180 psi were about 30 percent lower than those for the canvas laminate molded at 1800 psi for most of the properties tested. The most pronounced effect of the lower molding pressure was a decrease of 61 percent for the fatigue strength in torsion.

INTRODUCTION

The program of tests reported herein is a part of a coordinated research program initiated to investigate the mechanical properties of a group of plastic laminates which were of interest in aircraft construction. A knowledge of the mechanical properties of the laminates described in this report was needed for selection of the proper material for given applications and for design of parts to be made of such materials, so that they would be capable of withstanding the projected service conditions.

A number of reports and papers which describe the mechanical properties of different plastics have recently become available. A bibliography of some of these papers is given at the end of this report.

This work was conducted at the Engineering Experiment Station of the University of Illinois under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

Credit is due to the laminators and material manufacturers who prepared the laminates and supplied the information regarding the composition and manufacturing conditions of these laminates; namely, Synthane Corporation; Formica Insulation Company; Consolidated Water Power and Paper Company; the Air Materiel Command, Army Air Forces, Wright Field; Bakelite Corporation; Ironside Company; and Plaskon Company, Inc.

The authors are indebted to Professor F. B. Seely for suggestions and criticisms during the conduct of these tests and the preparation of this paper. Credit is also due A. J. Ruthenberg and C. D. Kacalieff for their assistance in the performance of some of the tests and in preparation of this report and to G. H. Steward for preparation of specimens and equipment.

TYPE OF TESTS

The following tests were performed on the five laminated plastics under conditions of constant temperature and constant relative humidity: short-time "static" tests in tension, compression, and torsion (with the exception of the low-pressure-molded canvas laminate for which no torsion tests were performed) to determine the ultimate strength, yield strength, and modulus of elasticity under the three conditions of loading; Rockwell hardness tests; tension creep tests at several different values of stress; rotating-cantilever-beam fatigue tests of both notched and unnotched specimens; and fatigue tests in torsion at constant amplitude of deflection under completely reversed stress cycles. In addition, rotating-cantilever-beam fatigue tests of unnotched specimens of all five materials were performed at temperatures of approximately 160° F and -75° F. These tests were performed in the same type of machine and at about the same testing speed used in the rotating-beam fatigue tests conducted at 77° F.

MATERIAL AND SPECIMENS

Material

The five laminated plastics tested in this program were: a canvas laminate molded under the relatively low pressure of 180 psi with a phenol-formaldehyde resin; a grade-C canvas laminate of construction similar to the other canvas laminate but molded at a high pressure of 1800 psi with a resin formed from formaldehyde and a mixture of meta- and para-cresol; a rayon laminate of the saponified acetate type molded at a pressure of 1100 psi with a phenolic resin; a Mitscherlich-paper laminate molded at a low pressure of 250 psi with a phenolic resin; and a glass-fabric laminate

molded at the low pressure of 40 psi with an unsaturated polyester resin. The preparation and the composition of the laminates tested are described in table I. The laminators and sources of resin and reinforcing material are also indicated in table I.

At this point it may be well to note that visual inspection of the glass-fabric laminate as received indicated that there were certain defects which may have affected the test results. There were two important defects: (1) the glass fabric had been pulled and distorted during the laminating process to such an extent that the thread directions were at some points as much as 30° out of line with the general direction of the fabric and (2) the layers in the laminate were not well bonded in some portions of the sheet. In preparing specimens from this laminate, care was taken to avoid such defects as far as possible.

Specimens

Dimensions of static tension, compression, and torsion specimens, as well as the creep specimens used for these tests are shown in figure 1, and the three types of fatigue test specimen used in this investigation are shown in figure 2. All specimens were cut from the sheet with their longitudinal axes parallel to one another. Four of the five laminates were cross-laminated. For these four laminates the direction of the longitudinal axes of specimens was chosen arbitrarily. The glass-fabric laminate, however, was parallel-laminated and the longitudinal axes of specimens from this laminate were made parallel to the direction of greatest strength in the sheet, as determined by preliminary tension tests.

The tension specimens were machined on a shaper to the dimensions shown. In the case of two of the materials, namely, the grade-C canvas laminate and the paper laminate, a few of the tension specimens were altered by filing the gage sections so as to produce a gradual taper from a $\frac{1}{2}$-inch width at each end of the gage section to a 0.01-inch undersize at the middle. This reduction was necessary in order to cause fracture to occur within the gage section of the specimen in these two cases. Straight specimens failed at the shoulder as a result of stress concentration at the fillet.

The compression specimens were turned on a lathe to the two lengths shown in figure 1. The 2-inch specimen was used to obtain stress-strain relationships, and the 1-inch specimen was used to obtain ultimate strength values only. The torsion specimens were also machined by turning on a lathe.

The creep specimens were cut from the original sheet with a milling cutter in such a manner that the flat side of the specimen was perpendicular to the plane of the sheet. The reduced section and radii at the end were formed on a shaper. All the specimens shown in figure 1 were finished by sanding with No. 0 emery cloth.

The dimensions of the fatigue specimens used in this investigation are shown in figure 2. All fatigue specimens were cut from the laminated sheet in such a way that the long axis of the specimen was parallel to the corresponding axis of the static specimens. The test sections were prepared by turning on a lathe, and the 2-inch radius used on specimens of the types shown in figures 2(a) and 2(c) was produced by swinging the compound of the lathe by means of a tangent screw so that the lathe tool traveled in a 2-inch arc. All fatigue specimens were finished by sanding with No. 000 emery paper. The final strokes in the sanding operation were made by hand and were longitudinal with the specimen's axis.

Some difficulty was experienced in machining all the laminates because of the tendency to chip the laminate, especially in lathe work. The tendency to chip and also the tendency to overheat was minimized by using tools of high-speed steel, the cutting edges of which were maintained sharp by frequent honing. High-speed-steel tools were used on all laminates, except the glass-fabric laminate. The abrasive nature of the latter material, however, made it necessary to employ tool bits and milling cutters having tips made of tungsten carbide.

Preconditioning of Specimens

All specimens were allowed to remain in the air-conditioned laboratory for at least 2 weeks after machining before the tests were started. All tests except the fatigue tests at high and low temperatures were carried out in a laboratory which was maintained at a constant temperature of 77° ± 1° F and a relative humidity of 50 ± 2 percent continuously throughout the duration of the tests. This procedure was necessary because of the sensitivity of some of the laminates to small changes in temperature and relative humidity.

APPARATUS AND TEST PROCEDURE

Static Tension Tests

Short-time tension tests were performed on specimens shown in figure 1(a). These specimens were tested in tension on a 10,000-pound, three-screw machine. This was a beam-weighing machine equipped with a separate variable-speed drive. The specimens were held in Templin wedge grips A and the strain in the specimen was measured by means of an extensometer B of 2-inch gage length. (See fig. 3.) This instrument provided a multiplication such that one division on the dial indicated 0.0001 inch per inch of strain in the specimen. In order to make it unnecessary for the specimen to support the weight of the extensometer and in order to prevent damage to the instrument if the specimen should fracture while the extensometer was attached, the extensometer was suspended by means of the light coil spring C shown in figure 3.

Two sets of tension tests were run when necessary – one set in which the stress–strain characteristics were determined and the other set in which only the tensile strength was obtained. In the former group the gage section of the specimen was straight, and readings of load, deformation, and time were read simultaneously at frequent intervals throughout the test. In the latter only the load at fracture was recorded. For this latter purpose specimens with the width reduced at the middle were used.

A preliminary test was made for each laminate to determine the rate of testing speed required to produce a rate of tensile strain of about 0.0016 inch per inch per minute. All succeeding tests were run at or near this rate of strain. This rate was selected in order to permit correlation between the results of these tests and tests performed on other materials (references 1, 2, and 3). This rate of strain corresponds roughly to the rate of strain produced by testing machines operated at a head speed of 0.05 inch per minute. However, it should be noted that different machines and even different materials tested in the same machine at the same rate of cross–head motion will not in general produce the same rate of strain in the specimen. This is due to different relative stiffnesses of the machine, the specimen, and the auxiliary gripping apparatus. During the test, readings of load, deformation, and time were recorded up to a point within a few percent of the load at which failure was expected. The extensometer was removed before failure.

From these data the stress and strain were computed. Then diagrams of stress against strain and time against strain were plotted. The modulus of elasticity was determined in each case from the slope of the initial part of the stress–strain curve. The yield strengths at 0.05– and 0.2–percent offset were determined by employing lines parallel to the initial part of the stress–strain curve and offset 0.05 and 0.2 percent. The rate of strain was determined from a time–strain curve by measuring the reciprocal of the slope of this curve in the region just below the value of strain above which the stress was no longer proportional to strain. The terms "yield strength" and "rate of strain" are defined in an appendix to this report.

Static Compression Tests

Compression specimens were tested in the same machine as the tension specimens and under the same temperature and humidity conditions. In order to minimize the effect of possible eccentric loading, the specimens were tested by using a compression tool A (fig. 4). A compressometer B of 5–to–1 lever ratio having a 0.001–inch dial and a 1–inch gage length was used to determine the strain. As in the case of the tension tests, the instrument was supported on a light coil spring.

Two different shapes of specimen were required, one to determine stress–strain relations (fig. 1(b)) and another to determine the compressive strengths (fig. 1(c)). The 2–inch specimen $\left(\frac{l}{r} = 16\right)$, where

$\frac{l}{r}$ is the ratio of the length of the specimen to the radius of gyration of the cross section of the specimen, was used with the compressometer having a 1-inch gage length to determine the stress-strain relations. The 1-inch specimen ($\frac{l}{r}$ = 8) was used in determining the compressive strength of the material to eliminate as far as possible the tendency for specimens to buckle. The rate of strain for the tests of 1-inch-length specimens was substantially the same as the rate of strain in the 2-inch specimens. This was accomplished by adjusting the speed of the testing machine so that the rate of increase in load during a test was substantially the same as the rate of increase in load observed in the tests of the 2-inch specimens, for which the strain rates were known.

During the compression tests of the 2-inch specimens, readings of load, deformation, and time were recorded. From these data the stress and strain were computed, and stress-strain and time-strain curves were plotted. The modulus of elasticity, yield strengths at 0.05- and 0.2-percent offset, and the rate of strain were determined from these curves in the same manner as that described for the tension tests.

Static Torsion Tests

The special torsion testing machine used for these tests is shown in figure 5. The machine was constructed as an attachment for a low-capacity tension testing machine. The pendulum weighing system of the tension testing machine was used as the torque measuring device for the torsion machine. This was accomplished by attaching to the tension machine a twisting head A (fig. 5) driven by a double worm-drive. A special chuck B was attached to the shaft of this twisting head and another chuck C to the axis of the pendulum D. These chucks were designed to apply a torque to the specimen with little danger of bending the specimen at the same time. This was accomplished by mounting the specimen on centers and applying the torque as a couple by means of adjustable screws.

The gage used for measuring the shearing strain is shown in figure 6. The instrument consisted of two rings A (fig. 6) which were slipped over the specimen and fastened to it by three pointed screws in each ring. A gage length of 2 inches was obtained by use of a removable spacer B. To one of the rings was fastened a circular scale C for measuring large angles of twist. Two 10-inch arms D, fastened to the same ring, carried scales on the ends which were used to measure small angles of twist. Adjustable pointers E were attached to the other ring in such a way as to indicate the readings on their respective scales.

The torsion tests were performed on specimens (fig. 1(d)) under conditions as nearly comparable with the tension and compression tests as possible. In order to accomplish this, the rate of tensile strain was kept the same as nearly as possible in all three types of test. For torsion tests the required shearing rate of strain was computed from the

tensile rate of strain by the relation $\frac{d\gamma}{dt} = \frac{E}{G}\frac{d\epsilon}{dt}$, where $\frac{d\gamma}{dt}$ is the shearing rate of strain, $\frac{d\epsilon}{dt}$ is the tensile rate of strain, and $\frac{E}{G}$ is the ratio of tensile modulus of elasticity to shearing modulus. This equation was derived from the fact that the maximum tensile stress in a circular torsion member is equal to the maximum shearing stress. The equation, however, is not exact owing to the anisotropic character of the material.

The required rate of strain was determined from the value of G obtained from a preliminary test. The resulting shearing rate of strain required was different for each material and was rather high owing to the low value of G. Thus it was possible to obtain only relatively few test points in the elastic range at this rate of testing.

During the torsion tests simultaneous readings of torque, angle of twist, and time were recorded. The equations of stress and strain for torsion used herein are applicable only for isotropic materials and cannot be expected to indicate accurately the stress or strain in laminated materials, since their properties are not the same in all directions. Nevertheless, the equations developed for isotropic materials were used herein to give nominal values of shearing stress and strain as a basis for comparison. The nominal shearing stress τ at the surface of the cylindrical specimen and the nominal shearing strain γ were computed from the equations $\tau = \frac{Tc}{J}$ and $\gamma = \frac{c\theta}{l}$, where T is the applied torque, c is the radius of the circular section, J is the polar moment of inertia, θ is the angle of twist, and l is the length of the test section of the specimen.

Curves of shearing stress against shearing strain and of time against shearing strain were then plotted. The shearing modulus of elasticity G and rate of shearing strain were determined as in the case of the tension tests.

Hardness Tests

The equipment used for the hardness tests was a standard Rockwell hardness testing machine equipped with a $\frac{1}{4}$-inch-diameter ball penetrator. The testing procedure used was that recommended in A.S.T.M. Method D785-44T of reference 4, page 1651.

Hardness tests were performed on both faces of each laminated sheet. Tests were also performed edgewise of the sheet, that is, with the direction of loading parallel to the laminations. In the case of the glass-fabric laminate, tests were performed edgewise of the sheet in two directions, one in the direction of the greatest tensile strength of the laminate and the other at right angles to the direction of the greatest tensile strength.

Tension Creep Tests

The equipment used for conducting the creep tests consisted of 2 steel racks from which 38 specimens could be suspended, calibrated weights and levers used for loading the specimens in tension, calibrated extensometers, a traveling microscope for measuring the strain indicated by the extensometer, and a clock equipped with a counter to record the elapsed time in hours. Figure 7 shows a creep rack with loading levers, specimens, extensometers, and auxiliary equipment. Figure 8 shows a specimen with strain-measuring equipment in place. In this figure specimen A was subjected to an axial tensile load through rod B. The specimen was held by grips C which contained a hook-and-eye type of swivel joint. This joint was provided in order to minimize the possibility of eccentric loading.

The extensometer used for measuring the creep consisted of a lever-type instrument with a traveling microscope D (fig. 8) for measuring the displacement between reference marks on the end of the lever E and a stationary arm F. The lever ratio was 10 to 1. One end of the lever was forked and fastened by pivots to the lower clamp attached to the specimen. The axis of this pivot passed through the centroid of the cross section of the specimen (the pin itself did not go through the specimen). Thus the strain measured by this instrument was the average strain in the specimen. The fulcrum of the lever was pivoted to a rod, the other end of which was fastened to the upper clamp on the specimen. A spring clip G (fig. 8) was used to attach this rod to the upper clamp so that the extensometer could be left on the specimen, during fracture if necessary, without damage to the instrument.

The dials on the traveling microscope and on each extensometer were calibrated against a micrometer screw before use, so that readings were accurate to ± 0.000001 inch per inch and were reproducible within ± 0.000002 inch per inch. Flat clamps instead of pointed screws were used to attach the extensometer to the specimen because creep of the material might cause screws to sink into the specimen, thus causing early fracture. The distance between the centers of the flat clamps was considered to be the gage length of the extensometer. As used in these tests, this gage length was 10 inches. A track was provided for the microscope so that it could be moved from specimen to specimen quickly.

Creep specimens for each laminate (fig. 1(e)) were tested simultaneously under a constant tension load at values of stress ranging from 0 to 24,000 psi. The values of stress chosen were evenly spaced from zero to a maximum value, which was chosen as follows. A preliminary creep test was made on each material, starting at a load which would produce a stress of about 60 percent of the tensile strength of the material. If the specimen did not fracture in 24 hours the load was increased about 6 percent for the next 24 hours. This process was repeated until the specimen failed. The maximum stress to be used in the creep tests was then made equal to 80 percent of the highest stress which the specimen sustained for at least 24 hours without fracturing. The reason for the foregoing procedure was to

select as high a maximum stress as possible without having a specimen fracture within 1000 hours. However, the highest stressed specimen did fail in less than 1000 hours for four of the five materials tested.

All creep tests were conducted in the room maintained at a constant temperature of 77° ± 1° F and a constant relative humidity of 50 ± 2 percent for the entire time of the test, which was 17,000 hours or about 19 months for one of the laminates. One specimen of each laminate was tested at a stress of zero in order to determine the magnitude of the shrinkage which might occur because of gradual changes in moisture content or other aging phenomena. All tests for a given laminate were started at approximately the same time, and all were started by applying loads quickly but very gently to the specimens. Before applying the load, the initial extensometer readings were obtained with the traveling microscope. Then the loads were applied, the time was recorded, and the extensometer was immediately read again. Readings of strain and time were thereafter taken at the following intervals: 0.1, 0.2, 0.3, 0.5, 0.7, 1, 2, 3, 5, 7, 10, 20 hours; then every 24 hours to 500 hours; then every 48 hours to about 1000 hours; then twice per week to 1500 hours; and then once a week for the remainder of the test.

Fatigue Tests

Rotating-cantilever-beam fatigue tests. - The rotating-cantilever-beam fatigue tests were performed on machines such as shown in figure 9. These machines consisted of a motor-driven spindle B, to which the specimen A was attached coaxially by means of a split collet. A shaft extension C was fastened to the outer end of the specimen by means of a split collet machined integrally with the shaft. The entire assembly (spindle, specimen, and extension shaft) was rotated by a motor driving through a V-belt.

The specimen was bent downward by a load applied to the end of the extension shaft C. This load was produced by a beam-and-poise mechanism D. The stress σ at the minimum section of the specimen was computed from the equation $\sigma = \frac{Mc}{I}$, in which the bending moment M was obtained from the load applied by the poise, with suitable correction for the moment produced by the extension shaft.

In order to determine the number of cycles to cause failure, a counter E was attached to record the number of cycles, and an electric contact at F was used to stop the machine when a crack had started in the specimen. (The microswitch shown was not used.) The electric contact was adjusted to shut off the machine when the fatigue crack had become severe enough to cause the deflection of the specimen to increase 0.1 inch at the point of loading, which was 5 inches from the center of the specimen.

Specimens were tested at various amplitudes of alternating stress, and the number of cycles to failure was determined. These data were plotted with the amplitude of the alternating stress as ordinate and

the number of cycles for fatigue failure as abscissa, and semilogarithmic plotting was used.

Rotating-cantilever-beam fatigue tests at different temperatures. - For fatigue tests conducted at temperatures above and below the temperature available in the air-conditioned testing room, an insulated box was constructed to house one of the rotating-cantilever-beam fatigue testing machines. The equipment used is shown in figure 10. The loading lever and poise A, an electric contact at B, motor C, and counter D, were mounted outside the insulated cabinet. (The microswitch shown was not used.) For the high-temperature tests the box was heated by electric strip heaters, which were controlled by a thermostat adjustable from the outside of the cabinet. The air temperature in the cabinet and the temperatures of the specimens were measured by means of a thermocouple and potentiometer E. The temperatures of the specimens were obtained by means of a thermocouple mounted on a lever which was moveable from the outside of the cabinet and so positioned as to cause the thermocouple to touch the central portion of the specimen when the lever was deflected. Temperature readings were taken by stopping the machine, applying the thermocouple to the surface of the specimen immediately, and recording the indicated temperature. The temperatures thus obtained were somewhat below the actual operating temperatures of the specimens because the specimen began to cool as soon as the machine was stopped.

When tests were to be run at temperatures below the testing-room temperature, a separate insulated cabinet F was used to house dry ice for use as a cooling medium. Air was circulated through the dry ice and the test cabinet and back again to maintain the desired temperature. Thermostatic control was provided to manipulate the damper which controlled the flow of air through the dry ice. With this equipment it was found possible to conduct continuous fatigue tests over periods of several days, since the equipment required servicing only every 8 to 12 hours. In order to prevent ice from fouling the loading rod, which projected through the cabinet, a kerosene seal was used to prevent escape of cold air around the loading rod.

Torsion fatigue tests. - One of the machines arranged for torsion fatigue tests at constant amplitude of deflection is shown in figure 11. For torsion fatigue tests, an arm A was attached to the machine so as to support the fixed end of the torsion specimen B and the dynamometer C with its dial D. The specimen B was fastened at an angle to the torque arm E, which was attached to the connecting rod F through a universal joint. The angle between the axis of the specimen and the torque arm was so chosen that the static bending moment at the minimum section of the specimen was zero, and the only significant stresses at the minimum section were shearing stresses due to torsion. There was, however, a horizontal shearing stress, the magnitude of which was negligible compared with the stresses resulting from torsion. No account was taken of possible dynamic effects except to place the wrist pin of connecting rod F near the center of percussion of torque arm E.

The testing procedure for fatigue tests in bending described in the A. S. T. M. Method D671-42T (reference 4, p. 1638) was used for the tests reported in this section, with the modifications noted. The specimens used for the torsion fatigue tests were turned to the dimensions shown in figure 2(c). The amplitude of the alternating shearing stress was computed from the equation $\tau = \frac{Tc}{J}$ in which the torque T was obtained from readings of the calibrated dynamometer C (fig. 11). The number of cycles to which the specimen was subjected was indicated by a counter I.

The stress values to which each specimen was subjected at the beginning of the test were calculated from the torque measured by means of the dynamometer while the machine was at rest, and the number of cycles for fatigue failure was determined in the manner described in the appendix. These data were then plotted as S-N diagrams, with the amplitude of the alternating shearing stress as ordinate and the number of cycles for failure as abscissa. The range of stress, that is, the relationship between the maximum stress and the minimum stress in a stress cycle, was adjusted by means of a mechanism, one form of which, consisting of screws H for tilting the bracket to which the specimen and dynamometer were attached, is shown in figure 11.

TEST RESULTS

Static Tension Tests

Sample stress-strain curves and time-strain curves for tension tests of the five laminates are shown in figures 12 to 16. From these curves the following quantities, which are defined in the appendix, were measured: modulus of elasticity, yield strength at 0.05- and 0.2-percent offset, and rate of strain. The ultimate strength (see appendix) was computed in each case from the load at which fracture of the specimen occurred. The values of these quantities obtained from each of the specimens tested for all the five laminates are shown in table II, together with the average values of each of the quantities except the rate of strain. In the case of the high-strength paper laminate and the grade-C canvas laminate, additional tests were run on especially prepared specimens in order to obtain the ultimate strength values. The technique used is described in the section entitled "Static Tension Tests" under APPARATUS AND TEST PROCEDURE. The values obtained for these tests are also shown in table II. The grade-C canvas laminate showed no significant difference between the special test in which the failure was confined to the center of the specimen and the first set of tests in which failure occurred at the shoulder. However, in the case of the paper laminate the ultimate strength obtained from specimens, the failure of which was confined to the center section, was about 15 percent higher than the ultimate strength obtained from the specimens in which failure occurred at the shoulder of the specimens.

Static Compression Tests

Representative stress–strain curves and time–strain curves for static compression tests of the five laminated materials are shown in figures 17 to 21 for specimens 2 inches long. From these curves the following quantities were measured: the modulus of elasticity in compression, yield strength at 0.05– and 0.2–percent offset, and the rate of strain. The ultimate strength was calculated from the maximum load sustained by these 2–inch specimens. The values obtained for these quantities are shown together with the ultimate strength obtained from tests of specimens 1 inch long in table III for compression tests of all five laminates.

The ultimate strength observed from tests of the 1–inch specimens in every case differed less than 5 percent from the ultimate strength obtained from the 2–inch specimens. In all cases except one, the average ultimate strength obtained from the 1–inch specimens was higher than the average ultimate strength obtained from the 2–inch specimens. However, in the case of the canvas laminate molded at low pressure, the average ultimate strength obtained from the 1–inch specimens was about 1 percent less than the average ultimate strength obtained from the 2–inch specimen.

Static Torsion Tests

Representative stress–strain curves and time–strain curves for torsion tests of rayon laminate, paper laminate, and glass–fabric laminate are shown in figures 22 to 24. From these curves the following quantities were measured: shearing modulus of elasticity, yield strength at 0.05– and 0.2–percent offset, and rate of strain. The modulus of rupture in torsion was calculated from the maximum torque which the specimens sustained before fracture. The values of these quantities obtained for the three different laminates are shown in table IV. In the case of three out of the five specimens of paper laminate for which test results are reported in table IV, the specimens fractured before 0.2–percent offset was reached.

Rockwell Hardness Tests

The Rockwell hardness values obtained from tests of the five laminates are shown in table V together with the average of each set of tests. The hardness values ranged from M89 to M119 for tests perpendicular to the laminations and from M82 to M121 for tests parallel to the laminations.

Tension Creep Tests

The creep (in percent) obtained from the specimens under several different values of tension stress was plotted against the elapsed time in hours for each of the five materials tested. These data are shown

plotted for the first 1,000 hours in figures 25 to 29, and the data from the same tests, but for longer time intervals, are shown plotted in figures 30 to 34. The time intervals covered by the latter curves vary from 3,000 to 17,000 hours. The scales used in all the plots for 1000 hours are the same, so that direct comparison between the materials can be made by inspection. In the case of the creep curves showing data for longer time intervals, however, the scales chosen were those which would best present the data.

It was observed that the rate of creep was rapid at the beginning of the test and decreased as time progressed. The lowest curve plotted in each case was taken from the data obtained with a specimen which carried no load, that is, zero stress. In all cases except the glass-fabric laminate the specimen carrying no load was observed to shrink slightly during the first part of the test. In the case of the glass-fabric laminate a slight increase in length was observed. These dimensional changes may possibly be the result of a continuous change in the moisture content of the specimen. The effect of short interruptions of humidity control is evident in all data shown. A decrease in relative humidity was observed to cause a decrease in strain, the amount of which was approximately the same for all specimens of a given laminate.

The "elastic" strain as determined for the creep test specimens in this report was defined as the total strain measured in the specimen at the time at which the load had been applied to the specimen for 20 seconds. This strain was determined by plotting the readings obtained during the first hour of tests on logarithmic paper and reading the strain corresponding to a time of 20 seconds from the straight line which resulted from this plot. The values of 20-second elastic strain are shown in the third column of table VI and in figure 35.

The total creep (including the elastic strain) was measured for all specimens at 1000 hours and also at 3000 hours. These data were then corrected for the change in length of the specimens having zero load by subtracting the algebraic value of the change in length of this specimen. The adjusted values are shown in table VI.

The rate of creep did not remain constant throughout the time of testing but decreased rapidly at first and then more gradually. In order to evaluate the effect of stress on the different rates of creep, it was therefore necessary to determine the rate of creep at some definite time. The rate of creep was determined for a time of 1000 hours by measuring the slope of the creep-time curve at 1000 hours for each of the specimens tested. The rate of creep was determined by measuring the slope of the curve represented by the test data between a time of 700 hours and 1300 hours. The measurements were made on a plot having an expanded creep scale to increase the accuracy of the slope measurements. The rate of creep thus obtained for each specimen is shown in table VI and plotted in figure 36.

The increase in strain at 1000 hours compared with the elastic strain at 20 seconds was computed for all specimens. The values obtained

are shown in table VI together with the average value of the percent increase in strain at 1,000 hours for each of the five laminates. The percent increase in strain from the elastic value of 20 seconds to the value at 3,000 hours is also shown in table VI together with the average of these values for each laminate. The percent increase in strain from 1,000 hours to 3,000 hours is also shown in table VI, together with the average of these values for each of the laminates.

Fatigue Tests

S–N diagrams were prepared from the results of all fatigue tests, by using semilogarithmic coordinates. The S–N diagrams for all fatigue tests conducted in a room maintained at a temperature of 77° ± 1° F and at a relative humidity of 50 ± 2 percent are shown for each of the five laminates in figures 37 to 41. Each of these figures shows three S–N diagrams for one material. The diagrams shown were obtained from rotating–cantilever–beam fatigue tests of notched specimens and unnotched specimens and from torsion fatigue tests of unnotched specimens. All the S–N diagrams were carried beyond 10,000,000 cycles; some of them extend beyond 100,000,000 cycles. The fatigue strengths measured from these S–N diagrams at 10,000,000 cycles are shown in table VII. The speeds of testing used are also shown in table VII.

The S–N diagrams for rotating–cantilever–beam fatigue tests at temperatures of −75° F, 77° F, and 160° F are shown in figures 42 to 46 for each of the five laminates. The tests at −75° F were carried as far as 10,000,000 cycles, whereas the tests at 77° and 160° F were carried to nearly 100,000,000 cycles. It was observed that the temperature of the specimens was always somewhat higher than the temperature of the surrounding air, because of heat developed within the specimens as a result of internal friction and because of heat developed in the bearings of the fatigue machine. The temperature of a specimen which ran for 10,000,000 cycles or more at temperatures of −75° F and 160° F was measured. These temperatures are indicated adjacent to the specimens on which the temperature was measured in each of the five figures. The fatigue strength at 10,000,000 cycles for tests at a testing speed of approximately 6600 rpm and at the three different temperatures is shown in table VII. The effect of temperature on the fatigue strength at 10,000,000 cycles is shown in figures 47 and 48 for the five laminates.

Mode of Failure

Photographs of representative fractured specimens are shown in figures 49 to 52. Figure 49 shows fractured tension specimens of all five laminates. Figure 50 shows fractured compression specimens 2 inches long and 1 inch long of all five laminates, together with a fractured torsion specimen of the paper laminate. All the torsion specimens tested showed longitudinal cracks, but most of the specimens were not twisted to complete rupture so that fractures would not be visible in a photograph.

A fractured creep specimen is shown in figure 51 for each of the five laminates tested. The specimen shown for the low-pressure-molded canvas laminate was the specimen used in the preliminary creep test of this material, since none of the specimens fractured in the final series of creep tests of this laminate.

Representative fractures of fatigue specimens are shown in figure 52. Unnotched specimens fractured in rotating-beam fatigue tests are shown for each of the five laminates. However, most of the rotating-beam fatigue specimens did not fracture completely before the tests were stopped. None of the fatigue specimens of the rayon laminate completely fractured, but all the notched specimens of paper laminate fractured. None of the torsion fatigue specimens fractured completely before the tests were stopped. In the paper laminate, longitudinal cracks were observed in the torsion fatigue specimens. However, in the torsion fatigue tests of the fabric laminates, fatigue cracks were usually not observed before fatigue failure (as defined in this report) took place. This probably was the result of the fact that the fabric tended to obscure such cracks as may have occurred.

ANALYSIS AND DISCUSSION OF RESULTS

Static Tension Tests

A summary of all the mechanical properties determined in this investigation is presented in table VIII for the five laminates. The tensile properties are given in items 3 to 6.

Item 3 shows that the glass-fabric laminate had the highest modulus of elasticity in tension (3,280,000 psi) of the five laminates, the highest yield strength at 0.2-percent offset (23,800 psi), and the highest ultimate strength (39,900 psi). The paper laminate had nearly as high yield strength at 0.2-percent offset (22,500 psi) but had the highest yield strength at 0.05-percent offset (15,300 psi) of any of the laminates. The yield strength at 0.05 percent was higher for the paper laminate than for the glass-fabric laminate because there was a small change in slope of the stress-strain curve of the glass-fabric laminate at about 6000 psi followed by a straight line extending nearly to fracture. This change in slope has not been noted in any previous reports on tensile tests of glass-fabric laminates.

The low-pressure-molded canvas laminate had the lowest values for all the quantities measured in the tension tests. Compared with the grade-C canvas laminate the low-pressure-molded canvas laminate was 29 percent lower in modulus of elasticity, 27 and 30 percent lower in yield strength at 0.05 and 0.2 percent, respectively, and 25 percent lower in ultimate strength.

The ultimate strengths of the laminates tested are in fair agreement with the values obtained by Marin (reference 5) for the same materials. The variations noted were from 2 to 19 percent. The large variation found in the case of the paper laminate may have been due to differences in the shape of specimens used in determining the ultimate strength.

The ultimate strengths obtained by Marin were 7 percent lower than the results obtained herein for straight test sections. Such specimens (straight test sections) of paper laminate tested in the present tests failed near the shoulder of the specimen at a stress 13 percent lower than that of specimens having a test section reduced at the center. The moduli of elasticity reported by Marin are from 9 to 23 percent lower than those obtained herein. A comparison of the moduli reported by Lamb, Albrecht, and Axilrod (reference 6) for the same laminates tested in flexure with a span-depth ratio of 8 to 1 indicates exact agreement with the average of the tension and compression moduli reported in the present report for the paper laminate, 6 percent lower than reported herein for the low-pressure-molded canvas laminate, and 17 percent lower for the grade-C canvas laminate. These differences may be due in part to differences in amount of data obtained in different investigations at the foot of the stress-strain curve; to differences in the manner in which the curves were drawn through the test points; to differences in the testing machines, rate of strain, and specimen temperature; and to differences between the sheets of laminate tested.

The values obtained herein for the strength and stiffness of the glass-fabric laminate in tension appear consistent with other reports (references 7, 8, 9, and 10), although considerably large variation occurs for different fabrics and resins, and no other data are available on either the fabric or resin used in the present investigation.

The ultimate strength obtained from specimens having straight test sections and the yield strength at 0.2-percent offset reported in the present paper are within 3 percent of the values reported for a comparable paper laminate by Erickson and Mackin (reference 11). The modulus of elasticity reported by Erickson and Mackin was 12 percent higher than that found in the present investigation.

The ultimate strength in tension of the strongest paper laminate tested by Field (reference 12) was about the same as the value obtained in the present investigation from specimens having straight test sections and the ultimate strength reported in reference 10 for the strongest paper laminate is about 11 percent less than that reported in the present paper for specimens having straight test sections. The yield strength at 0.2-percent offset reported in reference 10 was about 17 percent less, and the modulus of elasticity was about 8 percent less than that given in the present report for the paper laminate.

The tensile properties reported herein for the paper laminate are considerably better than the properties previously reported by the authors (reference 2) from tests of one of the first paper laminates molded from

Mitscherlich paper. The paper laminate of the present tests has 44 percent higher modulus, 62 percent higher yield strength at 0.2-percent offset, and 99 percent higher tensile strength. These comparisons are based on an average of the properties parallel and perpendicular to the grain of the paper, as reported in reference 2.

The ultimate strength, yield strength at 0.2-percent offset, and modulus of elasticity reported in the present paper are in substantial agreement with the average of the with- and cross-grain values reported by Oberg, Schwartz, and Shinn (references 10 and 13) for grade-C canvas laminate. No data are available on rayon or low-pressure-molded canvas laminates for comparison with the present tests.

Static Compression Tests

The static compression properties of the five laminates are summarized in table VIII, items 7 to 10. Item 7 shows that the modulus of elasticity in compression is highest for the glass-fabric laminate (3,230,000 psi) and lowest for the low-pressure-molded canvas laminate (940,000 psi). A comparison of item 7 with item 3 shows that the modulus of elasticity in compression is very nearly the same as that in tension for all laminates, although the tension modulus of the low-pressure-molded canvas laminate was about 15 percent lower and the tension modulus of the rayon laminate was about 6 percent higher than the compression modulus.

The ultimate strength in compression was highest for the glass-fabric laminate (45,300 psi) and lowest for the low-pressure-molded canvas laminate (18,300 psi). It is significant that in compression the ultimate strength of the grade-C canvas laminate was about 25 percent higher than either the rayon or paper laminate, while in tension the grade-C canvas laminate was from one-half to one-third as strong as the rayon or paper laminates. It is also of interest to note that the glass-fabric laminate had about 12 percent lower ultimate strength in tension than in compression and that the ultimate strength of both canvas laminates was less than one-half as great in tension as in compression.

The yield-strength values show a somewhat different relationship. The yield strengths in tension are within 20 percent of the value for compression for both of the canvas laminates and the rayon laminate. However, for the paper laminate the yield strengths in compression are about one-half those in tension, and for the glass-fabric laminate the stress-strain curve in compression was so straight that an offset as small as 0.05 percent was not reached before fracture.

For the canvas laminates and the paper laminate the compression moduli obtained were about twice those reported by Marin (reference 5) for the same laminates. For all but the low-pressure-molded canvas laminate the ultimate strength is higher than that reported by Marin. The only comparison it is possible to make with the flexure tests reported by

Lamb, Albrecht, and Axilrod (reference 6) for the same laminates was described under tension tests. The possible reasons for the differences are the same as those described for the tension tests.

The values obtained herein for the strength and stiffness of the glass-fabric laminate in compression appear consistent with the data reported by C. D. Jones (reference 8). However, the compression strength obtained herein is about twice that reported by Armstrong (reference 9) and in reference 10.

The modulus of elasticity reported by Erickson and Mackin (reference 11) for a comparable paper laminate is 7 percent lower than that obtained herein. The ultimate strength was 4 percent higher and the yield strength at 0.2-percent offset was 0.1 percent lower.

The ultimate strength in compression of the strongest paper laminate tested by Field (reference 12) is about 9 percent higher than the value obtained herein, and the ultimate strength reported in reference 10 for the strongest paper laminate is about 13 percent higher than that obtained herein. The compression strength of paper laminates reported in references 10 and 12 was higher than the value reported in the present paper and also in reference 11, whereas the reverse was true of the tension strength.

The compression properties reported herein for the paper laminate have higher values than the properties reported in reference 2 from tests of one of the earlier Mitscherlich-paper laminates. The paper laminate of the present tests has 36 percent higher modulus, 45 percent higher yield strength at 0.2-percent offset, and 25 percent higher compression strength. These comparisons are based on an average of the properties reported in reference 2, parallel and perpendicular to the grain of the paper.

The modulus of elasticity reported for a grade-C canvas laminate by Oberg, Schwartz, and Shinn (reference 13) and in reference 10 is 20 percent higher than the values obtained in the present paper; the ultimate strength reported is 11 percent higher, but the yield strength at 0.2-percent offset was 20 percent lower than that obtained herein. No other data are avilable on rayon or low-pressure-molded canvas laminates for comparison with the present data.

Static Torsion Tests

The static torsion properties of three of the laminates are summarized in table VIII, items 11 to 14. Item 11 shows that the shearing modulus of elasticity as determined from a torsion test is highest for the glass-fabric laminate (598,000 psi). On comparing the shearing modulus with the tension modulus for the three laminates shown in item 11, it is found that the shearing modulus is a larger percentage of either the tension or compression modulus for the glass-fabric laminate than for the rayon or paper laminates. However, in all cases the shearing modulus was lower than would be expected of isotropic materials. If the laminates

were isotropic the shearing modulus could not be less than one-third the tension or compression modulus (reference 14).

The modulus of rupture in torsion was highest - of the three laminates tested - for the glass-fabric laminate (7900 psi). The modulus of rupture in torsion for the glass-fabric laminate was about one-sixth the compression strength and about one-fifth the tensile strength. A similar relationship exists for the rayon and paper laminates, although the differences are less marked.

The shearing yield strength at both 0.05- and 0.2-percent offset was the greatest for the paper laminate. The reason for the low yield strength in the case of the glass-fabric laminate may have been the poor bond between laminations, which was described under MATERIALS AND SPECIMENS in the section entitled "Material."

The shearing moduli of elasticity reported by Marin (reference 5) were 10 and 8 percent lower than the results obtained herein for the rayon and glass-fabric laminates, respectively, and the modulus of rupture was lower for all three laminates - 11, 19, and 23 percent lower for the rayon, paper, and glass-fabric laminates, respectively. The possible explanations for these differences are the same as those given for the tension tests.

The only previous data on torsion tests of laminates are those of one of the first Mitscherlich-paper laminates (reference 2). The testing technique used in tests of that laminate was the same as that used in the present tests but the results were quite different. The shearing modulus of elasticity for the paper laminate of the present tests is 24 percent higher than that obtained for the older paper laminate, and the modulus of rupture is 105 percent higher.

The shape of the stress-strain curve for the present torsion tests of the paper laminate is quite similar to that for the tension and compression tests. However, the stress-strain curve for the older paper laminate (reference 2) was different. Instead of a smooth curve, an abrupt change occurred - like a yield point in mild steel. This was accompanied by a splitting crack along the laminations and was probably due to the poor bond between laminations noted in the older material.

Rockwell Hardness Tests

The results of the Rockwell hardness (resistance to indentation) tests are shown in table V. These data show that the glass-fabric laminate is the hardest (M119 to M118) and the low-pressure-molded canvas laminate is the softest (M95 to M87) for tests perpendicular to the laminations. Some difference was observed between the hardness of the two faces of the canvas laminates. A difference of 6 points in Rockwell M numbers was observed for the low-pressure-molded canvas laminate and 3 points for the

grade-C canvas laminate. Such differences may have been due to differences in temperature of the top and bottom platen of the press used to mold the laminate.

It is also of interest to note that the hardness parallel to the laminations is 6 to 8 points less than the hardness perpendicular to the laminations in all the laminates having cellulosic fillers. Since the glass-fabric laminate was parallel-laminated, hardness tests were made both parallel and perpendicular to the direction of the greatest tensile strength. The hardness parallel to the greatest tensile strength was 7 points higher than that in the perpendicular direction. The average of these hardness values was, however, about the same as the hardness perpendicular to the laminations.

Tension Creep Tests

The elastic strain at 20 seconds and the total strain at 1000 hours are plotted in figure 35 for all five of the laminates. It is observed that the data form smooth curves similar in appearance to the stress-strain curves in tension except that the coordinates have been reversed. In fact the moduli of elasticity obtained by measuring the reciprocals of the slopes of the curves of elastic strain at 20 seconds in figure 35 agree fairly well (considering the few test points available) with the moduli obtained from the static tension tests at the same temperature.

The values of moduli of elasticity of the laminates obtained from the curves of elastic strain at 20 seconds are 3 percent lower for the low-pressure-molded canvas, 15 percent lower for the grade-C canvas, 10 percent higher for the rayon, 0.4 percent higher for the paper, and 23 percent lower for the glass-fabric laminates. The large difference in modulus of elasticity of the glass-fabric laminate was caused by the fact that the stress-strain curve in static tension changes slope at about 5000 psi so that the initial slope of the stress-strain curve was not detected in the creep tests. Figure 35 shows that the increase in strain due to creep after 1000 hours of creep is a larger percentage of the elastic strain at 20 seconds for the canvas laminates and rayon laminates than for the paper and glass-fabric laminates.

The percent increase in strain from 20 seconds to 1000 hours is shown for each specimen in table VI; the percent increase in strain from 20 seconds to 3000 hours is also shown in table VI. An examination of these data discloses that there is no systematic variation with stress. In fact the percent increase in strain at 1000 hours and at 3000 hours is substantially independent of stress (except for scatter).

This observation is consistent with one of the equations proposed in reference 15 to describe creep behavior. The equation used is

$$\epsilon = \epsilon_0 + mt^n \qquad (1)$$

where ϵ is the total strain, ϵ_0 and m are functions of stress (ϵ_0 is not necessarily the elastic strain), t is time, and n is a constant independent of stress. The constants ϵ_0, m, and n are functions of the material.

If $\epsilon_0 = m$ (a condition which was shown to be a possibility in reference 15), then

$$\epsilon = \epsilon_0 (1 + t^n) \tag{2}$$

The percent increase in strain ϕ_1 from $t = 0$ to t_1 is then

$$\phi_1 = \frac{\epsilon_0 (1 + t_1^n) - \epsilon_0}{\epsilon_0} \times 100 = 100\ t_1^n \tag{3}$$

which is a constant independent of stress and dependent on the material and the chosen time t_1.

It can also be shown that the percent increase in strain computed from equation (2) (where $\epsilon_0 = m$) between any two times t_1 and t_2 is also a constant independent of stress. When $\epsilon_0 = 0$ in equation (1) it can also be shown that the percent increase in strain between any two times t_1 and t_2 is a constant independent of stress. Further evidence that the foregoing discussion may have merit is found in table VI, in which is recorded the percent increase in strain from 1000 to 3000 hours. These data are also nearly independent of stress, although there is a large amount of scatter.

If further studies should show that the percent increase in strain from the start of creep to a specified time under constant load is a constant dependent only upon material and temperature, then this constant (termed "creepocity" in the present paper) would serve as a convenient measure of the serviceability of a material under conditions of creep. High values of creepocity would denote poor resistance to creep.

Of course the creepocity alone does not define the complete creep behavior of a material even at a given temperature, but it does define one of the terms in equation (1), namely, the constant n. This constant may be computed from equation (3) by taking logarithms of both sides of the equation, with the following result:

$$n = \frac{\log \phi_1 - 2}{\log t_1} \tag{4}$$

where ϕ_1 is the creepocity in percent and t_1 is the time for which ϕ_1 was determined.

The rate of creep at 1000 hours was determined as described under TEST RESULTS in the section entitled "Tension Creep Tests" and is tabulated in table VI for each specimen. The effect of stress on the rate of creep for all five laminates is shown in figure 36. The rate of creep for a given stress, such as 4000 psi, is greatest for the low-pressure-molded canvas laminate and least for the glass-fabric laminate. It was observed that the curves in figure 36 were all concave downward. This suggests that all the curves might be made linear by adding a certain constant C to the rate of creep before plotting the data or by using logarithmic plotting of stress as well as rate of creep.

If the first technique caused the data to form straight lines, then the relations between stress σ and rate of creep v at a given number of hours would be as follows:

$$v = C\, e^{k\sigma} - C = C(e^{k\sigma} - 1) \tag{5}$$

where C is a constant depending on material, temperature, and time and k is a constant depending on material and temperature. This equation corresponds to the relationship obtained for another laminate in reference 2 and is nearly in agreement with the activation energy theory for creep in the form discussed in reference 15.

If the second technique (logarithmic plotting) caused the data to form straight lines, then the relation between stress σ and rate of creep v at a given number of hours would be as follows:

$$v = C_3\sigma^N \tag{6}$$

where C_3 is a constant depending on material, temperature, and time and N is a constant depending on material and temperature. Equation (6), however, is not in agreement with the activation energy theory and is therefore of doubtful validity.

The measurement of the rate of creep from the slope of the creep-time curves is subject to considerable error, which accounts in part for the scatter shown in figure 36. Thus a careful analysis of these data in the manner discussed would probably be unprofitable. It is felt that the data should be studied along the lines indicated in reference 15.

The equation used in reference 15 to represent the creep behavior is:

$$\epsilon = C_2(e^{k\sigma} - 1)\,(1 + t^n) \tag{7}$$

where σ is the stress, t is time, ϵ is total creep, and C_2, k, and n are constants depending on material and temperature. Such an equation might be useful to a designer since it would permit computation of a design stress σ_1 based on an allowable total creep ϵ_1 at a time t_1, by

substituting in the following equation obtained by solving for σ in equation (7) and substituting σ_1, ϵ_1, and t_1 for σ, ϵ, and t:

$$\sigma_1 = \frac{1}{k} \log_e \left[\frac{\epsilon_1}{C_2(1 + t_1^n)} + 1 \right] \tag{8}$$

Or if it were desired to base design stress σ_1 on a given allowable creep rate v_1 at a time t_1, this could also be done, although there seems to be no reason to prefer to use creep rate rather than total creep.

The creep rate can be obtained from equation (7) by taking the derivative with respect to time. The result as given in reference 15 is

$$v = C_2(e^{k\sigma} - 1)nt^{n-1} \tag{9}$$

A design value of creep rate v_1 is then found by substituting v_1, σ_1, and t_1 for v, σ, and t as follows:

$$v_1 = C_2(e^{k\sigma_1} - 1)nt_1^{n-1} \tag{10}$$

Some of the creep characteristics of the five laminates included in the present series of tests are summarized in table VIII, items 16 to 18. The total creep (including elastic deformation) at 1000 hours for a stress of 4000 psi (item 16) is the least for the glass-fabric laminate (0.15 percent) and the greatest for the low-pressure-molded canvas laminate (1.03 percent). The average of the percent increase in strain of specimens at several values of stress and for 1000 hours of creep is the least for the glass-fabric laminate (16.4) and the greatest for the grade-C laminate (88.5). The rate of creep at 1000 hours for a stress of 4000 psi is the lowest for the glass-fabric laminate (2.8×10^{-8} in./in./hr) and the greatest for the low-pressure-molded canvas laminate (69×10^{-8} in./in./hr).

It is of interest to note that these three quantities do not place the laminates in the same order. The total creep and rate of creep give the following order of increasing resistance to creep: low-pressure-molded canvas, grade-C canvas, rayon, paper, and glass-fabric laminates. The average percent increase in strain after 1000 hours indicates the grade-C and rayon laminates to be about equal and the low-pressure-molded canvas laminate to be better than either grade-C or rayon laminates.

The creep rates reported by Marin (reference 5) for different sheets of the same laminate are from two to five times the creep rates reported herein. This discrepancy may be due in part to differences in the samples tested, differences in strain measuring technique, or differences in method of measuring the creep rate. Marin measured the slope of a straight line passed through the test points between 100 to 300 hours and 1000 to 1400 hours, whereas in the present investigation the slope of the creep-time

curves was measured at 1000 hours by using the data between 700 hours and 1300 hours in measuring the slope.

It is also of interest to note that the total creep at 1400 hours obtained by Marin was lower for all laminates than the total creep at 1000 hours reported in the present paper for corresponding stress values. The differences noted vary from almost zero to 44 percent. Most of the comparable specimens tested by Marin had a total creep about 20 percent less than the values reported in the present paper. Another difference observed is that the creep specimens tested by Marin were able to withstand much higher stresses without fracture than specimens tested herein. This may be partly the result of the difference in shape and size of specimens used in the two series of tests.

The only previous creep tests of laminates which have come to the attention of the authors are those by Chasman (reference 16), Perkuhn (reference 17), and in reference 10. The shape of the creep curves obtained in these investigations is similar to those reported herein. Since the laminates tested in these investigations were quite different from those tested in the present investigation no comparisons are made.

Fatigue Tests

The fatigue strengths obtained from all series of fatigue tests of the five laminates are summarized in table VIII in items 19 to 23. The fatigue strengths at 10,000,000 cycles for specimens tested in rotating-beam fatigue machines at 77° F are shown in item 20 for tests of unnotched specimens and in item 22 for notched specimens. For unnotched specimens it was found that the glass-fabric laminate had the highest fatigue strength (14,600 psi) and the low-pressure-molded canvas laminate, the lowest (2700 psi). The fatigue strength of the notched specimens was the highest for the glass-fabric laminate (12,200 psi) and the lowest for the low-pressure-molded canvas laminate (2500 psi). The fatigue strength of unnotched specimens of the five laminates was in the same order as their tensile strengths, whereas this was not true of the notched specimens.

An examination of the data given in table VII for the fatigue strengths at 10,000,000 cycles indicates that the fatigue strength of the notched specimens is nearly as large or larger than that of the unnotched specimens for all laminates except the paper laminate. This is quite a different result from that predicted by Neuber (reference 18). His calculations were, of course, based on elastic behavior of homogeneous, isotropic materials. The stress-concentration factor given by Neuber for a notch of the shape used was about 2.8. The values of the effective stress-concentration factors obtained by dividing the fatigue strength of the unnotched specimens at 10,000,000 cycles by the fatigue strength of the notched specimens at 10,000,000 cycles was about 1.0 for the grade-C and rayon laminates, 1.1 for the low-pressure-molded canvas laminate, 1.2 for the glass-fabric laminate, and 1.5 for the paper laminate. However, it does

not seem reasonable to designate these ratios as the actual stress-concentration factors when several other factors may have affected the fatigue strengths obtained.

A comparison of the S–N diagrams of the notched and unnotched specimens (figs. 37 to 41) shows a quite different effect of the notch on the fatigue strength from that given by reference to the fatigue strengths at 10,000,000 cycles only. The slope of the S–N diagrams for the notched specimens is greater than the slope of the corresponding part of the S–N diagrams of the unnotched specimens for all materials tested and for the entire range of stress value used. For all five laminates the S–N diagrams for the notched and unnotched specimens cross, so that the notched specimens are stronger in fatigue than the unnotched specimens for tests which fail before the number of cycles at which the two S–N diagrams cross and weaker in fatigue for tests which last a larger number of cycles than that at which the two S–N diagrams cross. It is interesting to note that the number of cycles at which the S–N diagrams cross varies from about 50,000,000 cycles for the rayon laminate to 50,000 cycles for the paper laminate.

The crossing of the two S–N diagrams may have been due to some of the following factors: In the notched specimens there was a large volume of low-stress material immediately adjacent to the high-stress material in the notched specimens so that the heat developed by hysteresis damping in the material of the notch may have been more readily dissipated than heat developed by an equal stress in the unnotched specimen. Thus, the temperature developed in the notched specimens may have been nearer room temperature than that developed in the unnotched specimens. The lower temperature would tend to produce higher fatigue strengths, as observed. Also the higher stresses would probably produce greater temperature differences which would tend to cause the difference in slope of the curves, as noted. However, the differences in specimen temperature which seem possible are not large enough to account entirely for the effect observed.

Another factor, which may have contributed to the difference between the notched and unnotched fatigue tests, is the difference in the state of stress of the two specimens. In the unnotched specimens the state of stress was a uniaxial tensile stress (only one principal stress different from zero) at the surface of the specimens; whereas, in the deep-notch specimens, the state of stress in a region slightly below the surface of the notch approached a state of triaxial tensile stress (three equal principal stresses in tension).

The fact that the laminates consist of layers of fabric or paper bonded by resin may also cause the stresses in the notched specimens to be markedly different from the values expected for isotropic materials. When general cracking or more than one fatigue crack develop (as was true of these laminates) the criterion of fatigue failure used for the rotating-beam fatigue tests might operate differently for the notched as compared with the unnotched specimens. This may explain some of the difference

in behavior of notched and unnotched specimens, especially if the rate of crack growth is affected both by the intensity of stress and the presence of a notch.

The S–N diagrams for torsion fatigue tests obtained from fatigue machines of constant amplitude of deflection are shown in figures 37 to 41. These figures show that the curves for the torsion tests are similar in shape to the curves for flexure obtained from tests on rotating-cantilever–beam fatigue machines. The fatigue strengths at 10,000,000 cycles are given in table VII. The order of torsional fatigue strength for the laminates is as follows: glass–fabric (highest 3300 psi), grade–C canvas, paper, rayon, and low–pressure–molded canvas (lowest 900 psi). Except for the highest and the lowest values, this order is different from that in flexure fatigue.

S–N diagrams for rotating–cantilever–beam fatigue tests at three different temperatures (–75°, 77°, and 160° F) are shown in figures 42 to 46. For all but one of the laminates tested the three S-N diagrams at different temperatures form a family of similar curves. The shapes of the curves for the glass–fabric laminate (fig. 46), however, are dissimilar for some unexplained reason. In all cases, the fatigue strength increased as the temperature decreased.

The fatigue strengths at 10,000,000 cycles are given in table VII. In order to show the effect of temperature more clearly, the fatigue strengths were plotted against temperature, as shown in figure 47. The shape of these curves suggested that they might be hyperbolas so the data were replotted with logarithmic coordinates. The results are shown in figure 48. Although only three test points are available for each material, the fact that the straight lines were obtained for all five laminates lends support to the possibility that the relationship between fatigue strength and temperature may be hyperbolic, that is,

$$\sigma_a = pT^{-q} \tag{11}$$

where σ_a is the fatigue strength, T is the absolute temperature, and p and q are positive constants.

It is of interest to note that the straight lines representing the relation between fatigue strength and temperature are nearly parallel (that is, the constant q is nearly the same) for all the laminates having fillers of cellulosic materials. The slope of the curve for the glass–fabric laminate is smaller numerically than the slope of the other laminates. Thus, if the trend shown continues to still lower temperatures, the fatigue strength of the paper laminate and even the other cellulose–filled laminates would be greater than the fatigue strength of the glass–fabric laminate at a sufficiently low temperature. Also the fatigue strength of all the materials would increase indefinitely as the temperature approached absolute zero, if the relation given in equation (11) should hold over the temperature range of 0° to about 600° Rankine.

The effect of aging on the fatigue strength of the grade-C canvas laminate is shown in figure 43 by the two S-N diagrams for tests at 77° F. The specimens from which the lower of these two curves was obtained were machined and tested 1 year earlier than the specimens for the upper curve. The specimens for the curves at −75° F and 160° F were machined and tested at about the same time as the upper of the two curves at 77° F. This shows that the fatigue strength of this laminate at 10,000,000 cycles increased with age about 16 percent during the second year.

The results obtained for the paper laminate of the present tests were similar to those obtained for an older paper laminate (reference 19), except that the fatigue strength was higher (36 percent higher for flexure of unnotched specimens, 74 percent higher for flexure of notched specimens, and 166 percent higher for torsion fatigue tests). This difference is due to the improvement in the Mitscherlich-paper laminate. The difference in slope of S-N diagrams of notched and unnotched specimens was noted in reference 19 also, but the two curves did not cross as in the present series of tests. The effect of temperature was also similar but the slope of the curve formed by a logarithmic plot of fatigue strength against absolute temperature was slightly less numerically for the paper laminate of the present tests; that is, the present laminate was less sensitive to changes in temperature.

Fatigue tests in flexure at constant amplitude of deflection reported by Erickson and Mackin (reference 11) for a Mitscherlich-paper laminate indicate a fatigue strength at 10,000,000 cycles nearly identical to that obtained in the present paper. However, the S-N diagram reported by Erickson and Mackin had a steeper slope than that in the present paper so that the fatigue strength at 10,000,000 cycles was about 21 percent higher than that shown by the present tests. This difference is no doubt partly caused by temperature effects arising from the difference in type of machine used.

Rotating-beam fatigue tests (constant-bending-moment type) reported by Oberg, Schwartz, and Shinn (reference 13) indicate a fatigue strength at 10,000,000 cycles for grade-C canvas laminate about 16 percent higher than reported herein. (The comparison was made by averaging the fatigue strength parallel and crosswise of the sheet as reported in reference 13.) All the laminates tested by Oberg, Schwartz, and Shinn also indicated a crossing of the S-N diagrams for notched and unnotched specimens.

Rotating-beam fatigue tests of a high-strength paper laminate (cross-laminated) were reported by Field (reference 12) and in reference 10. The fatigue strength at 10,000,000 cycles was about 18 percent lower for unnotched specimens than the fatigue strength of the paper laminate of the present tests. The behavior of the tests of notched specimens reported by Field differed from that of the present tests in that the S-N diagram for notched specimens did not cross the S-N diagram for unnotched specimens. The fatigue strength at 10,000,000 cycles for notched specimens was about the same for the present tests and for those reported by Field.

Fatigue tests in tension of glass-fabric laminates reported by Foster (reference 7) show a similarity to those reported herein. No direct comparison is possible owing to the difference in range of stress between the two tests and to the fact that the fabric and resins used were not the same.

General Comparison of Properties of the Five Laminates

A summary of all the mechanical properties determined in this series of tests for the five laminates tested is given in table VIII. An inspection of this table discloses that the glass-fabric laminate had the most desirable mechanical properties in 18 of items 3 to 23; the low-pressure-molded canvas laminate had the least desirable mechanical properties in 16 of the 17 items for which test data were available. The glass-fabric laminate was next to the strongest in three yield strengths: tension at 0.05-percent offset, shearing at 0.05-percent offset, and shearing at 0.2-percent offset. Both the grade-C and rayon laminates were less desirable than the low-pressure-molded canvas laminate with respect to percent increase in strain after 1000 hours of creep.

The paper laminate was the strongest in the yield strengths for which the glass-fabric laminate was next to the strongest and was next to the strongest in all but four of the remaining items. The rayon laminate was next to the strongest in only one item - the fatigue strength of notched specimens at 10,000,000 cycles. The grade-C canvas laminate had next to the most desirable properties in three items: ultimate strength in compression, Rockwell hardness, and fatigue strength in torsion

When the weight of a structure is a significant factor in its design, the greater strength and stiffness values of the glass-fabric laminate tend to be nullified by its greater specific gravity. In applications in which the size of a given structure is fixed and its weight is to be held to a minimum, the strength and stiffness of the glass-fabric laminate have only a slight advantage over the paper laminate, or none at all; the advantage depends upon the type of loading the structure carries and the service conditions to which it is to be subjected. An exact comparison cannot be made without a knowledge of the structure involved because the significance of the specific gravity depends on the type of loading to which the component parts of the structure are subjected. (See discussion at end of reference 3.)

Of the two canvas laminates, one molded at a molding pressure of 180 psi and the other at 1800 psi, the grade-C (molding pressure of 1800 psi) had the most desirable properties in all but one item, the average percent increase in strain after 1000 hours of creep. In general the mechanical properties were about 30 percent lower for the low-pressure-molded canvas laminate than for the grade-C canvas laminate. Exceptions were as follows: 19 percent lower in compression modulus; 44 and 41 percent lower in compression yield strength at 0.05- and 0.2-percent offset, respectively; 12 percent lower in Rockwell hardness; 43 percent higher (less desirable)

in total creep at 1000 hours for a stress at 4000 psi; 30 percent lower (more desirable) in percent increase in strain after 1000 hours of creep; 39 percent higher (less desirable) in rate of creep at 1000 hours and a stress of 4000 psi; and 61 percent lower in fatigue strength in torsion. These differences between the two canvas laminates are attributed largely to the difference in molding pressure, although some other differences of less consequence did exist between the two laminates. (See table I.)

CONCLUSIONS

Results of tests to investigate the mechanical properties of five laminated plastics – canvas laminate molded at low pressure, grade-C canvas laminate, rayon laminate, paper laminate, and glass-fabric laminate – have led to the following conclusions:

1. The glass-fabric laminate had the most desirable mechanical properties of the five laminates in all but the following properties measured: the yield strength at 0.05-percent offset in tension and the yield strengths at 0.05- and 0.2-percent offset in torsion. However, the greater specific gravity of the glass-fabric laminate may nullify its greater strength for certain applications.

2. The paper laminate had the next most desirable mechanical properties in all but seven items and had the highest values for the yield strengths at 0.05-percent offset in tension and at 0.05- and 0.2-percent offset in torsion. The grade-C canvas laminate had next to the most desirable properties in compression strength, hardness, and torsion fatigue strength, while the rayon laminate had next to the highest fatigue strength of notched specimens.

3. The mechanical properties of the canvas laminate molded at a molding pressure of 180 psi were about 30 percent lower than those for the canvas laminate molded at a molding pressure of 1800 psi for most of the properties tested. The most pronounced effect of the lower molding pressure was a decrease of 61 percent for the fatigue strength in torsion.

4. Some of the creep test data present some evidence to support the proposition that the percent increase in strain caused by creep for a given time interval is the same for any stress, in which case the percent increase in strain or "creepocity" may be a useful quantity for use in comparing the creep resistance of materials. The evidence, however, is not conclusive.

5. The data on fatigue strength of the five laminates indicate that there is a possibility that the relationship between the fatigue strength of laminates and the absolute temperature may be expressed by an equation

expressed by an equation of the following form:

$$\sigma_a = pT^{-q}$$

where σ_a is the fatigue strength, T is the absolute temperature, and p and q are positive constants. The data available for the range of temperature from -75° to 160° F agree with this expression.

University of Illinois
Urbana, Ill., May 22, 1946

APPENDIX

DEFINITION OF TERMS

Modulus of elasticity. – In this report modulus of elasticity is understood to refer to the tangent modulus at the initial portion of the stress–strain curve; that is, the modulus was obtained by measuring the slope of a line drawn tangent to the curve through the lower portion of the curve. It is important to note that friction lag or backlash in the strain measuring instrument may result in some irregularity in position of the first two or three readings, and because of this lag the stress–strain curve does not necessarily pass through the origin of coordinates.

Yield strength. – Yield strength is designated as the stress corresponding to an arbitrarily selected percent deviation from the straight-line portion of the curve (or "modulus line"). It is obtained from a plotted stress–strain curve by drawing a line parallel to the modulus line and at a distance from this line equal to the specified offset measured along the strain axis. The yield strength is the stress corresponding to the point of intersection of the stress–strain curve and the auxiliary line.

Rate of strain. – The rate of strain as used in this report refers to the time rate of straining of the specimen in the elastic (or straight-line) portion of the stress–strain curve. The value of the rate of strain was obtained from the slope of a strain–time diagram plotted from data taken during the tests. The rate of strain as interpreted for these diagrams was the slope of the curve at the portion just below the value of strain corresponding to the maximum strain for which stress was directly proportional to strain.

Modulus of rupture. – The modulus of rupture is a fictitious stress obtained, in the case of the torsion test, by substituting the maximum value of twisting moment into the equation $\tau = \frac{Tc}{J}$. The value of stress obtained does not represent the actual maximum stress in the material at fracture, because the equation used is correct only when stress is directly proportional to the strain; this is usually not the case at rupture. Modulus of rupture in flexure is a fictitious stress obtained by substituting the maximum bending moment obtained in the flexure test into the equation $\sigma = \frac{Mc}{I}$. This does not represent the actual maximum stress at fracture because this equation also is correct only when stress is directly proportional to strain – a condition which is usually not true at rupture of a flexural member.

Creep. – Creep is designated as the total extension in a tension member which has occurred up to a given time as a result of a constant load; it is expressed in percent. It should be noticed that creep

includes both the elastic stretch and the stretch which occurs progressively during the time of loading.

Rate of creep. – The rate of creep represents a time rate of extension of the tension member under a constant load. It is determined by measuring the slope of the creep–time curve at a specified time. Note that the rate of creep multiplied by the time does not give the total creep.

Creepocity. – In this report the term "creepocity" is used to denote a constant, depending only on the temperature and material, which is equal to the percent increase in strain in a tension member during a specified period of time under constant load.

Fatigue strength. – In this paper a cycle of repeated stress is resolved into two components – a steady or mean stress upon which is superimposed an alternating stress. The maximum amplitude of an alternating stress cycle, expressed in pounds per square inch, which will not cause fracture of the material for a given number of cycles of alternating stress is called the fatigue strength. The number of cycles used in this report was 10,000,000. If the stress cycle does not produce complete reversal of stress, the mean stress of the cycle must be stated when specifying the fatigue strength because in general the fatigue strength changes with different values of mean stress.

Mean stress. – The mean stress is the algebraic mean between the maximum and minimum stress produced in a material during an alternating cycle of stress. When used in conjunction with the fatigue strength, the term "mean stress" denotes the mean stress for which the stated fatigue strength was determined.

Fatigue failure. – In this report fatigue failure is arbitrarily defined as having occurred when fatigue cracks of a given severity had developed in a specimen. For torsion fatigue specimens of the size used in this report the severity of cracks which was defined as constituting fatigue failure was that which produced a decrease in stiffness of the specimens to three–fourths of the initial stiffness. The change in the stiffness was measured by observing the change in the maximum deflection of the dynamometer while the amplitude of motion remained the same. In order to determine the number of cycles at which fatigue failure occurred for the completely reversed fatigue tests used in this report, the changes in the maximum values of the dynamometer readings were recorded at intervals throughout the life of the test until the required changes in the dynamometer readings were observed. The criterion of fatigue failure used for rotating–beam fatigue tests was an increase in the specimen deflection of 0.1 inch while under load.

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TABLE I. – PREPARATION AND COMPOSITION OF LAMINATES

Type of laminate	Resin									
	Manufacturer	Number	Type	Process	Reaction rate	Catalyst used	Solvent	Acetone solubility (1)	Solids	Viscosity at 77° F
Low-pressure-molded canvas (2)	Bakelite Corporation	BV-16887	Phenol-formaldehyde	Single stage	Fast	--------	Ethyl alcohol	30 percent	-------	----------
Grade-C canvas (3)	Bakelite Corporation	BV-1112	Formaldehyde with meta- and para-cresol	Single stage	Slow	Yes	Ethyl alcohol	----------	-------	----------
Rayon (4)	Ironside Company	91-L	Phenolic	------	----	---------	Ethyl alcohol	----------	65 percent	90 to 130 centipoises
Paper (5)	Bakelite Corporation	BV-16526	Phenolic	Single stage	Fast	No	Ethyl alcohol	----------	-------	----------
Glass-fabric (6)	Plaskon Company, Inc.	900	Unsaturated polyester	------	----	Lucidol, 2 percent	None	----------	-------	----------

Type of laminate	Mitscherlich paper								
	Pulp	Process	Ream weight (lb) (7)	Thickness (in.) (8)	Mullen test (psi)	Densometer (sec)	Tensile strength (lb/in.)		Character of surface
							With grain	Across grain	
Paper (5)	Spruce and hemlock wood from Canada	Sulphite	32.5	0.0031 to 0.0034	24 to 30	30 to 54	22 to 25	6 to 7	Densified

Type of laminate	Fabric									
	Kind	Yarn		Weave	Thickness (in.)	Weight raw (oz/sq yd)	Thread count	Tensile strength		Elongation at break
		Warp	Woof					Warp	Woof	
Low-pressure-molded canvas (2)	Army Duck	Cotton	Cotton	Square	-----	10.38	38 by 52	160	120	----------
Grade-C canvas (3)	Army Duck	Cotton	Cotton	Square (plain)	-----	10	40 by 50	160	130	----------
Rayon (4)	Celanese WE-3975	Special high-tenacity Fortisan (saponified acetate) 1100 denier[10] 1440 filament[10] 2.5 turns per in. (Z)[10]	Cotton	3/1 twill	0.022	12.5	12 by 75	1100	---------	10 percent[9]
Glass-fabric (6)	Owen-Corning Fiberglas ECC-11-112, heat treated	Glass fiber[11] 450 1/2 408 filaments[10] 5 turns per in.[10] (Z)[10] in first twisting and 4.4 turns per in. (S)[10] in plying operation	Same as warp	Plain	.003	2.19	39 by 40	100 (minimum)	70 (minimum)	----------

Type of laminate	Molding conditions											
	Preparation					Molding						
	Number of plies	Percent resin by weight in –		Lay of laminations	Machine used	Heating		Temperature (°F)	Pressure (psi)	Time of heating cycle	Time of cooling cycle	Temperature at which removed from press (°F)	Final volatile content (percent)
		Body of laminate	Surface layer			Type	Uniformity						
Low-pressure-molded canvas (2)	32	51	51	Cross-laminated	Press	------	----------	320	180	50 min	-------	---	---
Grade-C canvas (3)	27	48	48	Cross-laminated	Press	Hot water	Within 20° F	340	1800	50 min	20 min	100	---
Rayon (4)	23	37 to 40	37 to 40	Cross-laminated	Press	Steam	Negligible variation	320	1100	20 min	20 min	104	2.7
Paper (5)	225	30	30	Cross-laminated	Press	Steam	Within 5° F	310 ± 10	250	30 min	Cooled in still air at 70° F	315	3
Glass-fabric (6)	42	45	Cellophane sheet used on surface	Parallel-laminated	Press	Hot water	Not known	180 to 220	50	2 hr at 180° F 2 hr at 220° F	Cooled in still air	250	---

[1] 4 minutes in acetone; dry 2 minutes at 160° C.
[2] Laminator, Synthane Corporation.
[3] Laminator, Synthane Corporation; laminator's designation, Grade C.
[4] Laminator, Formica Insulation Company; laminator's designation, FRV 91-B.
[5] Laminator, Consolidated Water Power and Paper Company; laminator's designation, CPS-MP23 Type I.
[6] Laminator, Air Materiel Command, Army Air Forces, Wright Field.
[7] 48 sheets 24 by 36 inches.
[8] Prior to impregnation.
[9] At relative humidity of 63 percent and temperature of 74° F.
[10] For definition see ASTM Standards, part III-A, 1946, pp. 513 and 1117.
[11] Fiberglas. ECC-11-112 was heat-treated by baking 4 hours at 450° F.

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TABLE II. - TENSION TESTS

Material	Specimen number	Modulus of elasticity (psi)	Yield strength		Ultimate strength (psi)	Rate of strain (in./in./min)
			0.05-percent offset (psi)	0.2-percent offset (psi)		
Low-pressure-molded canvas laminate	2	0.77×10^6	4,100	5,200	8,400	0.0016
	3	.81	3,800	5,000	8,200	.0016
	4	.82	3,600	5,000	8,300	.0016
	5	.82	3,700	5,000	8,300	.0015
	Average	.81	3,800	5,100	8,300	
Grade-C canvas laminate	12	1.13	5,300	7,400	10,700	.0016
	13	1.15	5,100	7,300	11,000	.0016
	14	1.13	5,300	7,300	11,400	.0016
	Average	1.14	5,200	7,300	11,000	
	15				10,900	
	16				11,200	
	Average				[a]11,100	
Rayon laminate	3	1.77	7,600	10,800	26,000	.0016
	4	1.78	7,800	10,700	25,500	.0016
	6	1.80	7,700	10,900	25,400	.0015
	Average	1.78	7,700	10,800	25,600	
Paper laminate	4	2.32	13,600	(b)	26,400	.0015
	5	2.54	15,200	21,400	28,100	.0013
	6	2.34	17,100	23,600	27,200	.0017
	Average	2.40	15,300	22,500	27,200	
	7				31,800	
	8				28,400	
	13				32,500	
	14				32,300	
	15				30,900	
	Average				[a]31,200	
Glass-fabric laminate	3	3.27	9,500	23,300	40,300	.0013
	4	3.37	9,400	21,600	39,600	.0015
	5	3.13	11,300	25,100	39,200	.0016
	6	3.33	11,200	25,300	40,500	.0013
	Average	3.28	10,400	23,800	39,900	

[a]Cross section of specimens reduced at center.
[b]Yield strength at 0.2-percent offset was not obtained because of slippage in the grips.

TABLE III. – COMPRESSION TESTS

Material	Specimen number	Modulus of elasticity (psi)	Yield strength		Ultimate strength (psi)	Rate of strain (in./in./min)
			0.05-percent offset (psi)	0.2-percent offset (psi)		
Low-pressure-molded canvas laminate	2-inch length					
	3	0.96×10^6	3100	5000	18,300	0.0016
	4	.92	3200	5200	18,900	.0017
	5	.93	3200	5100	18,300	.0016
	Average	.94	3200	5100	18,500	
	1-inch length					
	1				17,900	
	2				17,800	
	3				18,800	
	4				18,500	
	5				18,600	
	Average				18,300	
Grade-C canvas laminate	2-inch length					
	7	1.14	5900	8800	24,900	.0016
	10	1.19	5300	8300	23,300	.0015
	11	1.16	5700	8500	23,800	.0016
	12	1.15	5800	8600	23,700	.0016
	Average	1.16	5700	8600	23,900	

TABLE III. – COMPRESSION TESTS – Continued

Material	Specimen number	Modulus of elasticity (psi)	Yield strength		Ultimate strength (psi)	Rate of strain (in./in./min)
			0.05–percent offset (psi)	0.2–percent offset (psi)		
Grade–C canvas laminate	1–inch length					
	6				25,200	
	7				25,100	
	8				24,800	
	9				25,000	
	Average				25,000	
Rayon laminate	2–inch length					
	1	1.72×10^6	7200	9,600	20,000	0.0016
	2	1.65	7300	9,600	19,700	.0016
	3	1.68	7100	9,400	19,900	.0016
	4	1.68	7200	9,600	19,900	.0016
	Average	1.68	7200	9,600	19,900	
	1–inch length					
	8				20,000	
	9				20,000	
	10				20,200	
	12				20,000	
	Average				20,100	
Paper laminate	2–inch length					
	6	2.40	8600	11,200	19,700	.0016
	7	2.48	8900	11,300	19,800	.0017
	9	2.45	8600	11,300	19,900	.0017
	Average	2.44	8700	11,300	19,800	

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TABLE III. – COMPRESSION TESTS – Concluded

Material	Specimen number	Modulus of elasticity (psi)	Yield strength		Ultimate strength (psi)	Rate of strain (in./in./min)
			0.05–percent offset (psi)	0.2–percent offset (psi)		
Paper laminate	1–inch length					
	2				20,400	
	3				20,000	
	4				19,900	
	Average				20,100	
Glass–fabric laminate	2–inch length					
	4	3.24×10^6	(a)	(a)	46,200	0.0016
	5	3.18	---	---	42,600	.0016
	6	3.26	---	---	41,200	.0016
	Average	3.23			43,300	
	1–inch length					
	4				48,900	
	5				45,900	
	6				45,000	
	7				41,500	
	Average				45,300	

[a]Specimens failed before 0.05–percent offset was reached.

TABLE IV. – TORSION TESTS

Material	Specimen number	Shearing modulus of elasticity (psi)	Yield strength		Modulus of rupture (psi)	Rate of strain (in./in./min)
			0.05-percent offset (psi)	0.2-percent offset (psi)		
Rayon laminate	1	0.220×10^6	2700	3400	4500	0.013
	2	.210	2800	3500	4500	.015
	3	.202	2900	3500	4400	.014
	4	.220	2500	3300	4400	.013
	5	.211	2700	3400	4400	.013
	Average	.213	2700	3400	4400	
Paper laminate	9	.376	4900	6100	6100	.011
	10	.352	5100	(a)	5300	.011
	11	.361	4500	5700	5900	.011
	12	.352	4800	(a)	5700	.011
	13	.347	5000	(a)	5900	.011
	Average	.358	4900	5900	5800	
Glass-fabric laminate	1	.616	3700	5300	7800	.010
	2	.580	3500	5200	7900	.009
	3	.598	3600	4800	8100	.009
	4	.578	3500	5300	7900	.008
	5	.616	3000	4900	7800	.009
	Average	.598	3500	5100	7900	

[a]Specimen failed before 0.2-percent offset was reached.

TABLE V. – HARDNESS TESTS

Material		Rockwell hardness, M scale			
		Perpendicular to laminations		Parallel to laminations and parallel to direction of greatest tensile strength	Parallel to laminations and perpendicular to direction of greatest tensile strength
		Front face	Back face		
Low-pressure-molded canvas laminate		94	89	81	
		96	89	80	
		95	89	85	
	Average	95	89	82	
Grade-C canvas laminate		107	111	102	
		109	110	102	
		105	110	103	
	Average	107	110	102	
Rayon laminate		98	96	92	
		97	98	91	
		99	98	90	
	Average	98	97	91	
Paper laminate		110	110	82	
		111	113	84	
		112	110	82	
	Average	111	111	83	
Glass-fabric laminate		117	117	121	112
		120	118	121	114
		119	119	120	116
	Average	119	118	121	114

TABLE VI. - CREEP TEST

Material	Stress (psi)	20-second elastic strain (percent)	[a]Total creep (percent)		Rate of creep at 1000 hours (in./in.hr)	Increase in strain (percent)			
			At 1000 hours	At 3000 hours			At 1000 hours	At 3000 hours	From 1000 to 3000 hours
Low-pressure-molded canvas laminate	600	0.065	0.0954	0.1070	8.6×10^{-8}		46.8	64.6	12.16
	1200	.142	.2075	.2273	14		46.2	60.1	9.54
	1800	.218	.3281	.3614	27		50.5	65.6	10.15
	2400	.307	.4961	.5462	46		61.6	77.8	10.10
	3000	.394	.6484	.7096	53		64.6	80.0	9.44
	3600	.481	.8674	.9487	66		80.4	97.4	9.37
	4200	.610	1.1178	1.2312	69		83.2	101.8	10.14
						Average	61.9	78.2	10.13
Grade-C canvas laminate	930	.073	.1440	.1604	11		97.2	120	11.39
	1900	.171	.3017	.3343	22		76.4	95.5	10.8
	2850	.240	.4606	.5040	32		92	110	9.42
	3800	.369	.6704	.7335	47		81.6	98.5	9.41
	4750	.478	.9036	.9930	60		89.1	107.5	9.89
	5700	.630	1.2260	1.3747	95		94.7	118	12.13
	6650	.706	------	------	----------		-----	-----	-----
						Average	88.5	108.3	10.51
Rayon laminate	1900	.120	.1767	.1946	13.6		47.2	62	10.13
	3900	.222	.4084	.4353	33		84.0	96	6.59
	5800	.351	.6994	.7427	43		99.4	111	6.19
	7800	.520	1.0570	1.1072	46		103.2	113	4.75

[a]Values corrected for change in length of specimen carrying zero load.

TABLE VI. – CREEP TEST – Concluded

Material	Stress (psi)	20-second elastic strain (percent)	[a]Total creep (percent)		Rate of creep at 1000 hours (in./in./hr)	Increase in strain (percent)			
			At 1000 hours	At 3000 hours			At 1000 hours	At 3000 hours	From 1000 to 3000 hours
Rayon laminate	9,700	0.720	1.4211	1.4850	58×10^{-8}		97.5	106	4.50
	11,600	.965	1.8274	1.8957	72		89.4	96.5	3.74
	13,600	1.320	------	------	---------		----	-----	----
						Average	86.7	97.4	5.98
Paper laminate	2,000	.082	.1033	[b].1067	4.3		26.0	30.	3.29
	4,000	.159	[b].2159	[b].2218	6.4		35.8	39.5	2.73
	6,000	.249	.3391	.3505	12.9		36.2	40.7	3.36
	8,000	.326	.4667	.4816	21		43.1	47.5	3.19
	10,000	.407	.6002	.6222	19		47.5	48	3.67
	12,000	.548	------	------	---------		----	-----	----
						Average	37.7	41.1	3.25
Glass-fabric laminate	4,020	.125	.1550	.1574	2.9		24.0	26	1.55
	8,000	.291	.3359	.3424	3.1		15.4	17.7	1.94
	12,000	.441	.5148	.5210	4.2		16.7	18.	1.20
	16,000	.606	.6700	.6749	4.3		10.6	11.4	.73
	20,000	.763	.8680	.8712	4.2		13.8	14.2	.37
	24,000	.965	------	------	---------		----	-----	----
						Average	16.4	17.5	1.16

[b]Corrected for shock. See figure 33.

TABLE VII. – FATIGUE TESTS

Machine	Rotating–cantilever–beam fatigue machine				Torsion fatigue machine
Specimens	Unnotched			Notched	Unnotched
Air temperature (°F)	−75	77	160	77	77
Speed (rpm)	6500 to 6700	6400 to 6700	6500 to 6700	6400 to 6700	1750
Material	Fatigue strength[a]				
	Tensile stress				Shearing stress
Low–pressure–molded canvas laminate	4,000	2,700	2,100	2,500	900
Grade–C canvas laminate	5,900	3,700 and [b]3,200	2,900	3,600	2300
Rayon laminate	8,900	5,800	4,400	6,000	1700
Paper laminate	12,700	7,900	6,300	5,400	2100
Glass–fabric laminate	17,200	14,600	13,600	12,200	3300

[a]All fatigue strength values are for 10,000,000 completely reversed stress cycles, in psi.

[b]Machined and tested 1 year earlier than tests for which first value is given.

TABLE VIII. – SUMMARY OF MECHANICAL PROPERTIES DETERMINED

Item number	Material / Item	Low-pressure-molded canvas laminate	Grade-C canvas laminate	Rayon laminate	Paper laminate	Glass-fabric laminate
1	Molding pressure (psi)	180	1800	1100	250	40
2	Specific gravity	[a]1.29	1.34	[a]1.37	[a]1.42	[a]1.87
3	Tension modulus (psi)	0.81×10^6	1.14	1.78	2.40	3.28
4	Ultimate strength in tension (psi)	8,300	11,100	25,600	31,200	39,900
5	Tension yield strength at 0.05-percent offset (psi)	3,800	5,200	7,700	15,300	10,400
6	Tension yield strength at 0.2-percent offset (psi)	5,100	7,300	10,800	22,500	23,800
7	Compression modulus (psi)	0.94×10^6	1.16	1.68	2.44	3.23
8	Ultimate strength in compression (psi)	18,300	25,000	20,100	20,100	45,300
9	Compression yield strength at 0.05-percent offset (psi)	3200	5700	7200	8700	(b)
10	Compression yield strength at 0.2-percent offset (psi)	5,100	8,600	9,600	11,300	(b)
11	Torsion (shearing) modulus (psi)			0.213×10^6	0.358	0.598
12	Modulus of rupture (torsion) (psi)			4400	5800	7900

[a]Data taken from tests made at the National Bureau of Standards.

[b]For the glass-fabric laminate the stress-strain curve in compression was so straight that an offset as small as 0.05 percent was not reached before fracture.

TABLE VIII. – SUMMARY OF MECHANICAL PROPERTIES DETERMINED – Concluded

Item number	Material / Item	Low-pressure-molded canvas laminate	Grade-C canvas laminate	Rayon laminate	Paper laminate	Glass-fabric laminate
13	Shearing (torsion) yield strength at 0.05-percent offset (psi)			2700	4900	3500
14	Shearing (torsion) yield strength at 0.2-percent offset (psi)			3400	5900	5100
15	Rockwell hardness perpendicular to laminate	M95	M107	M98	M111	M119
	Rockwell hardness parallel to laminations	M82	M102	M91	M83	M121
16	[c]Total creep at 1000 hr for a stress of 4000 psi (percent)	1.03	0.72	0.42	0.22	0.15
17	Average for tests at several stresses of the percent increase in strain after 1000 hours of creep	61.9	88.5	86.7	37.7	16.4
18	[d]Rate of creep at 1000 hr for stress of 4000 psi (in./in./hr)	69×10^{-8}	49	31	6.9	2.8
19	[e]Fatigue strength at -75° F (psi)	4,000	5,900	8,900	12,700	17,200
20	[e]Fatigue strength at 77° F (psi)	2,700	3,700	5,800	7,900	14,600
21	[e]Fatigue strength at 160° F (psi)	2,100	2,900	4,400	6,300	13,600
22	[f]Fatigue strength of notched specimens at 77° F (psi)	2,500	3,600	6,000	5,400	12,200
23	[g]Fatigue strength in torsion at 77° F (psi)	900	2300	1700	2100	3300

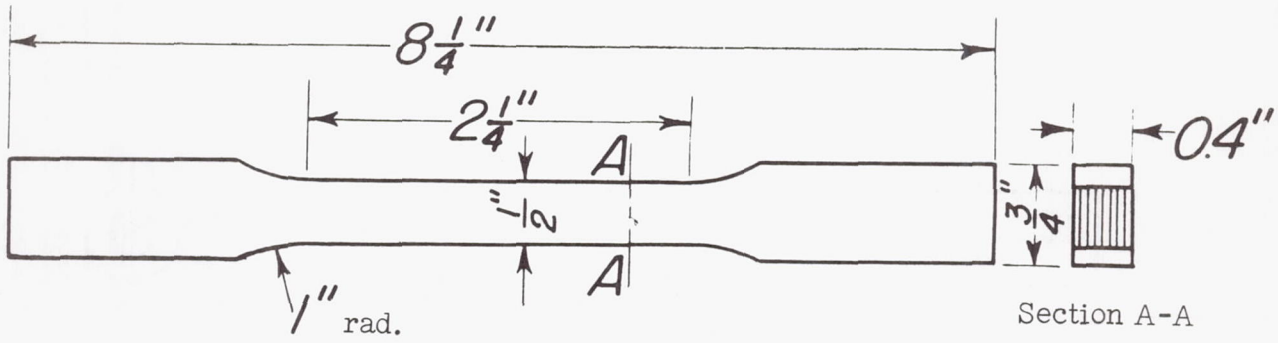
[c]Values interpolated from curves in figure 35.

[d]Values interpolated from curves in figure 36.

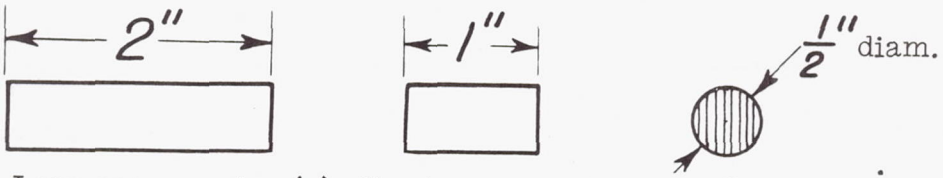
[e]Fatigue strength at 10,000,000 cycles for unnotched specimens tested in a rotating-cantilever-beam fatigue machine.

[f]Fatigue strength at 10,000,000 cycles. Rotating-cantilever-beam fatigue machine.

[g]Fatigue strength at 10,000,000 cycles in terms of shearing stress for unnotched specimens.



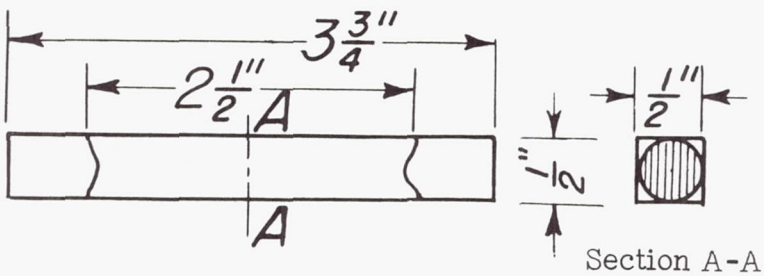
(a) Tension specimen.



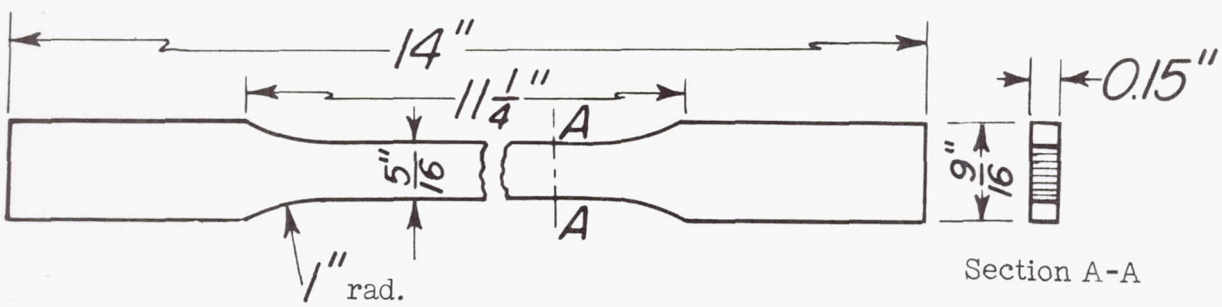
(b) Long compression specimen.

(c) Short compression specimen.

Cross section

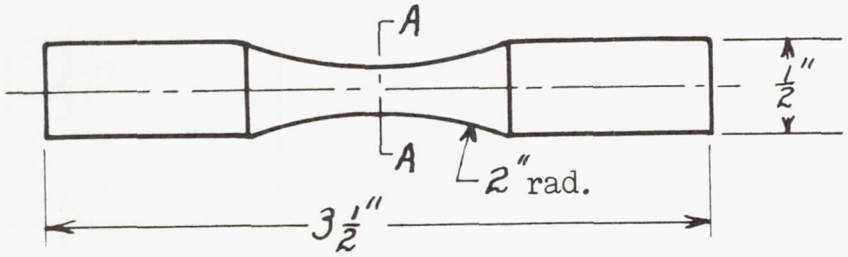


(d) Torsion specimen.

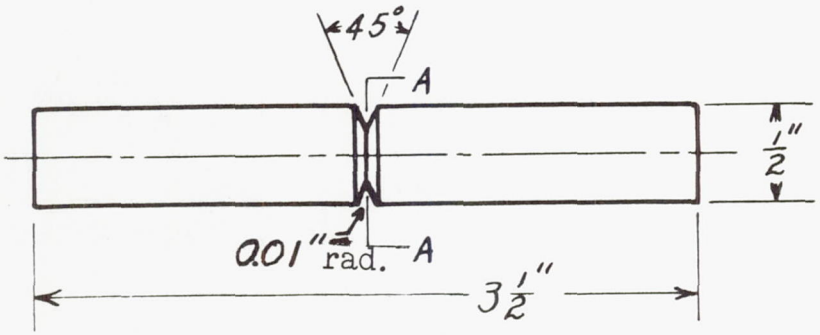


(e) Creep specimen.

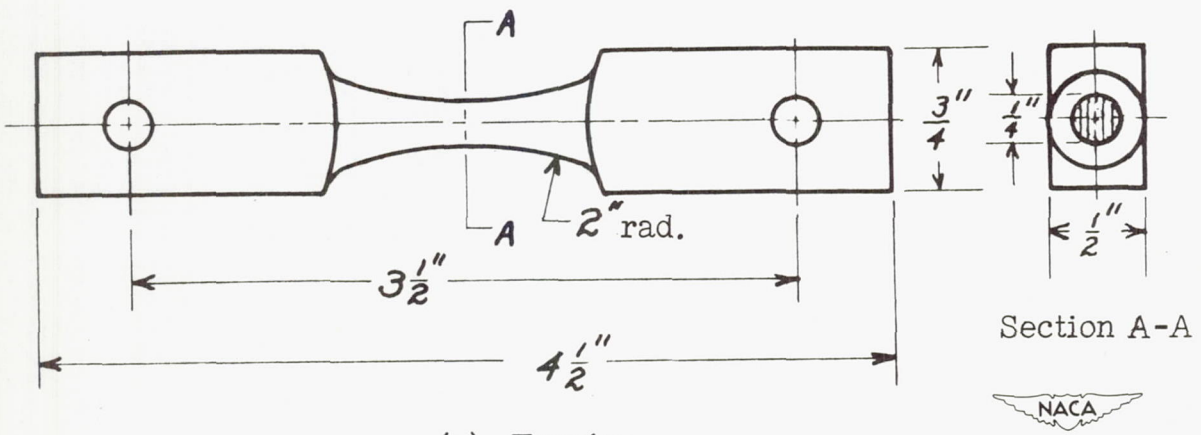
Figure 1.- Static and creep specimens. Cross-hatched lines indicate plane of laminations. Scales differ in parts of figure.



(a) Unnotched rotating beam.



(b) Notched rotating beam.



(c) Torsion.

Figure 2.- Fatigue specimens. Cross-hatched lines indicate plane of laminations.

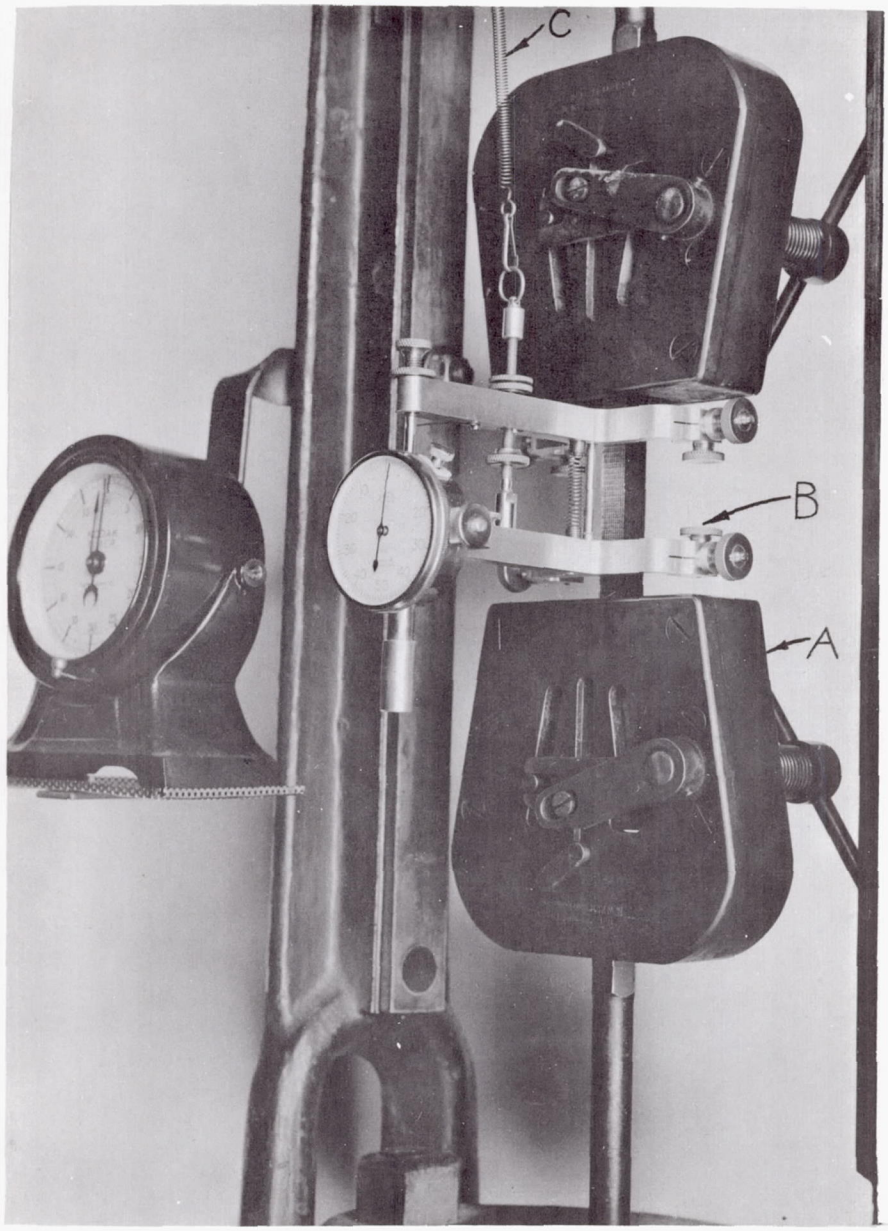


Figure 3.- Apparatus used for static tension tests.

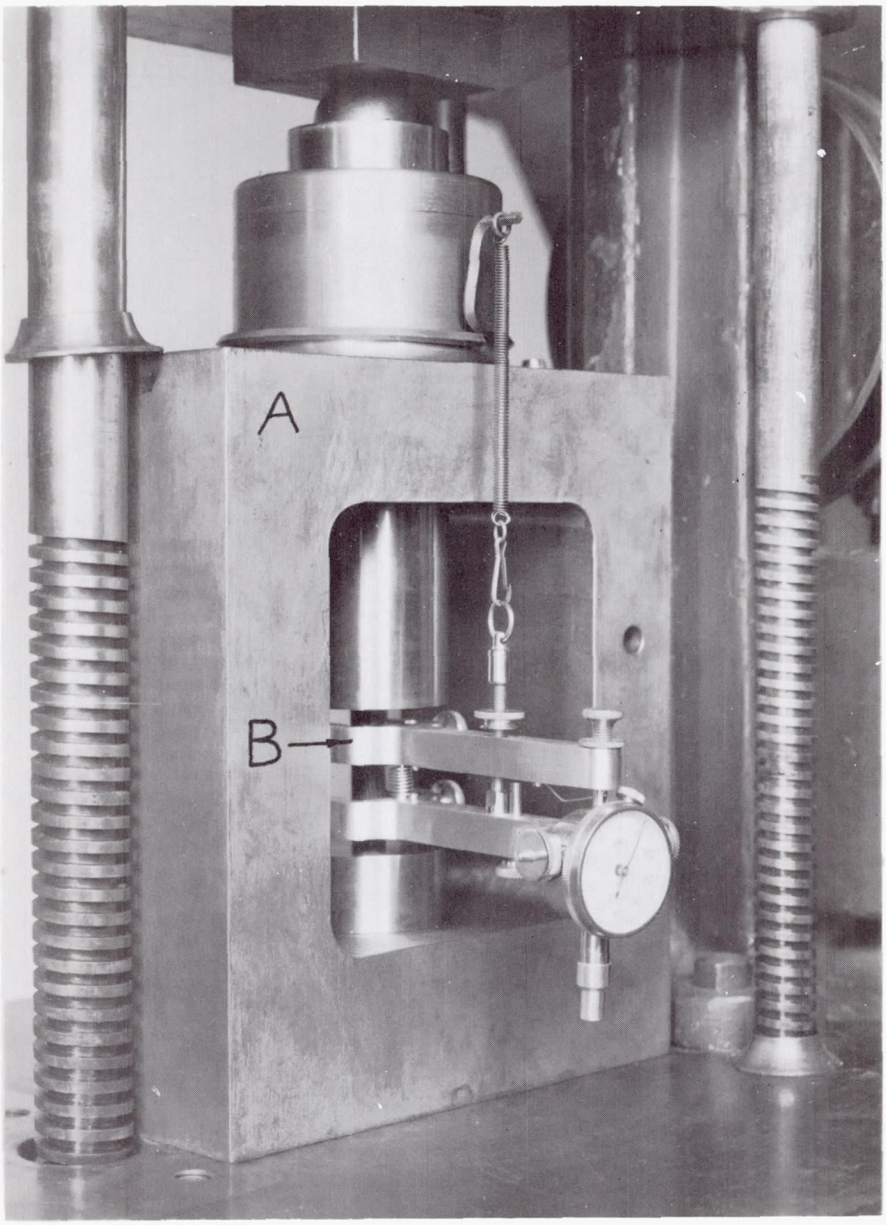


Figure 4.- Apparatus used for static compression tests.

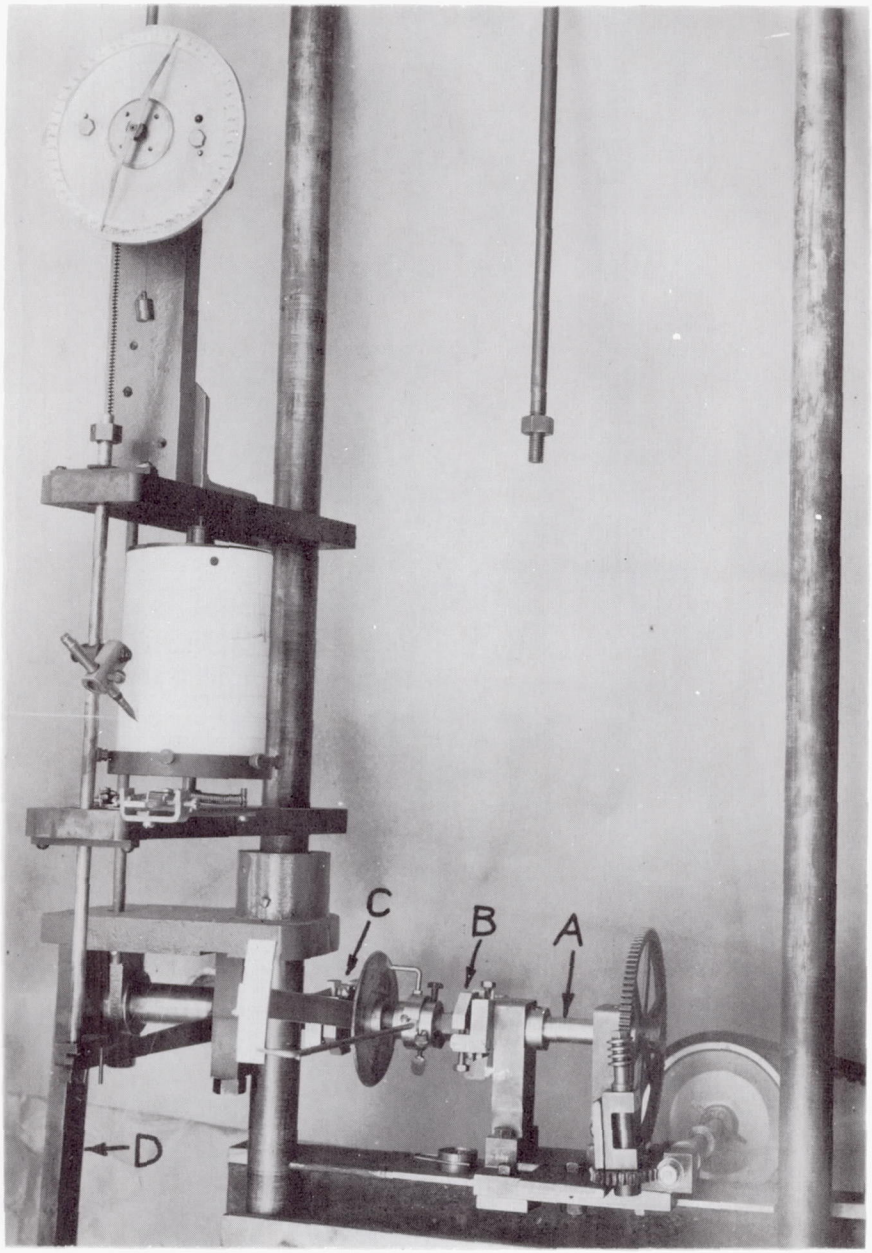


Figure 5.- Apparatus used for static torsion testing.

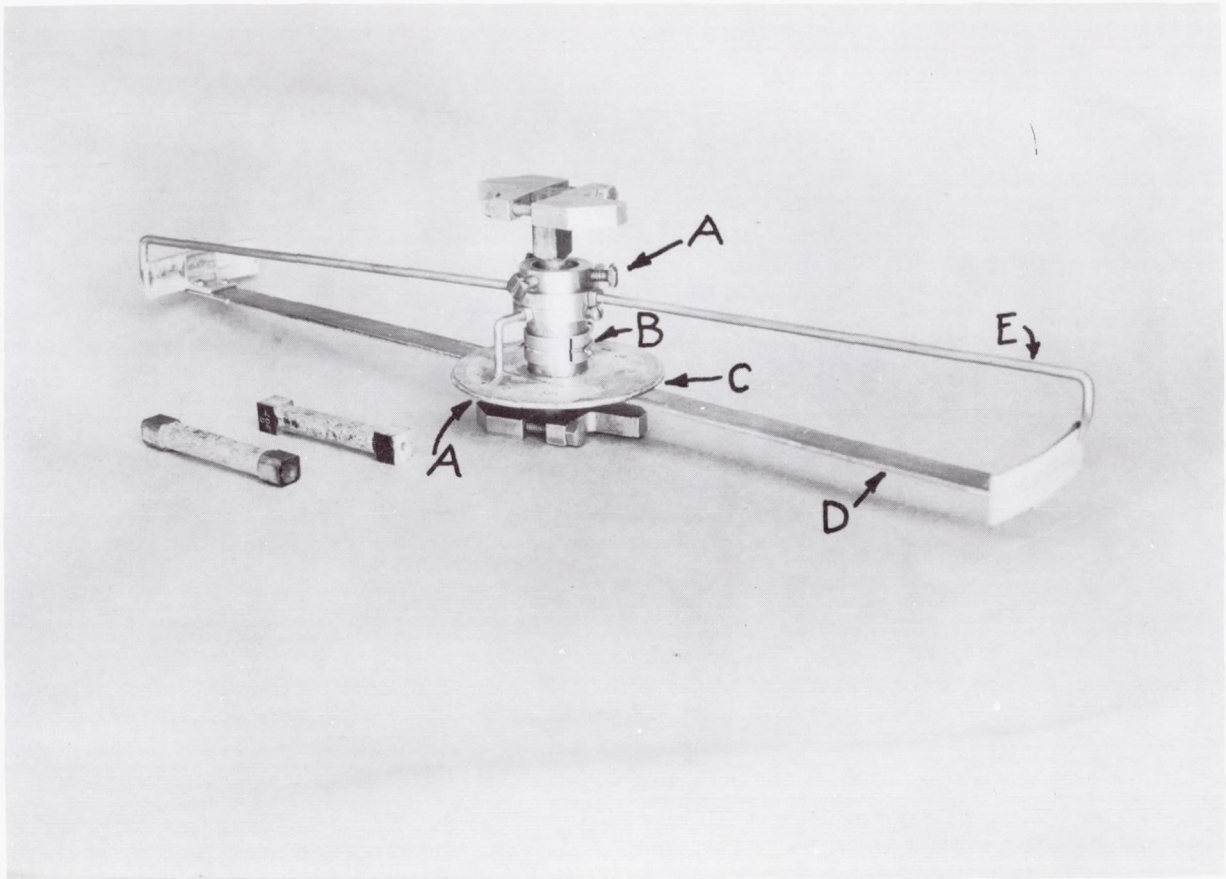


Figure 6.- Detrusion gage used for measuring the angle of twist in torsion.



Figure 7.- Creep rack.

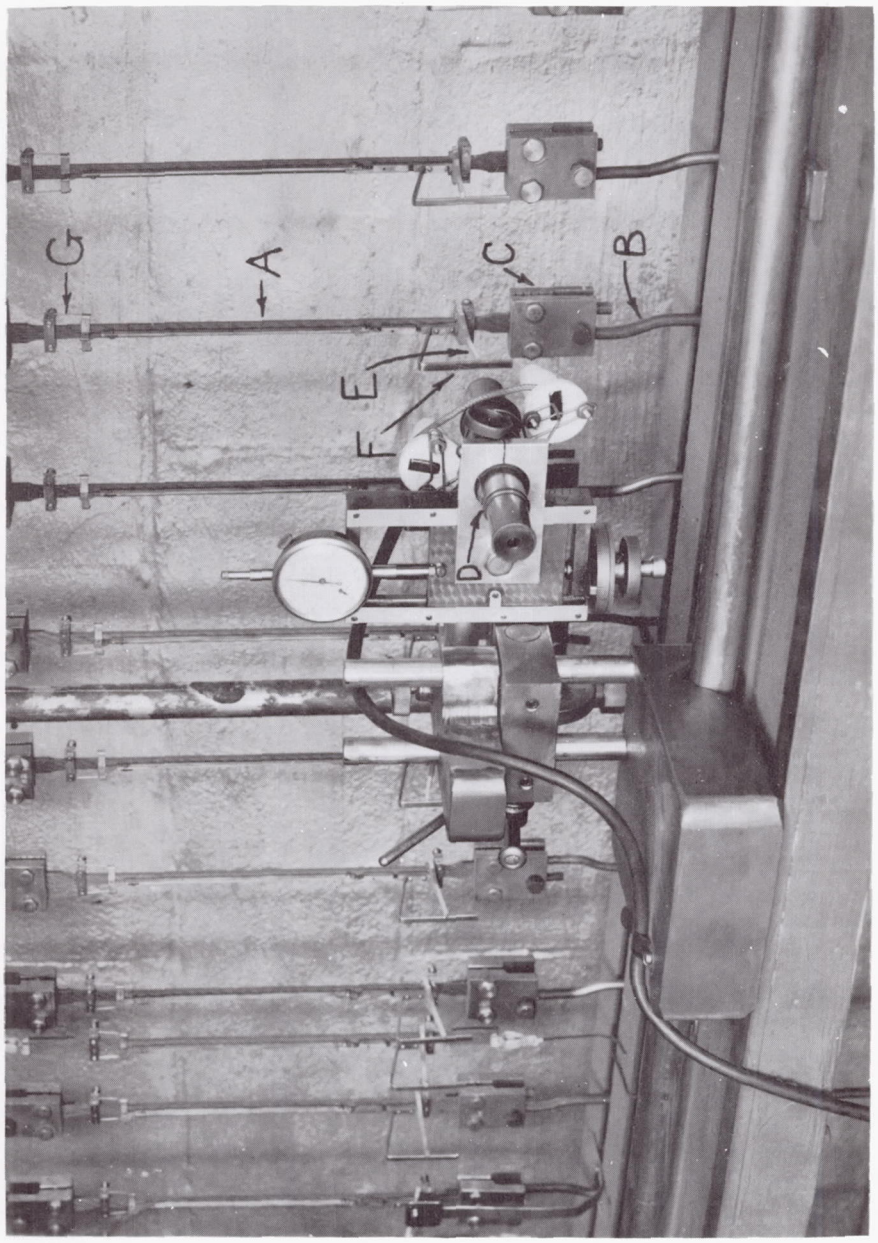


Figure 8.- Creep measuring apparatus.

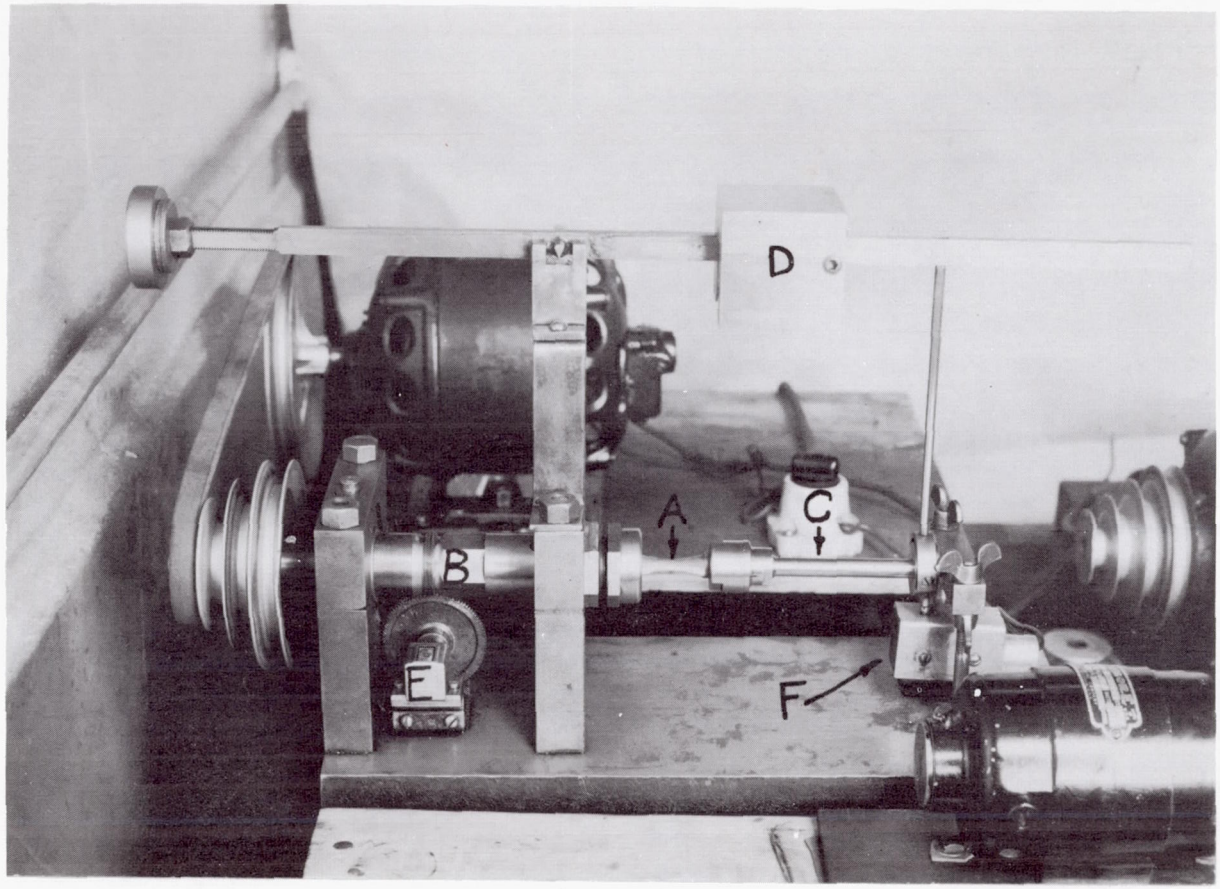


Figure 9.- Rotating-cantilever-beam fatigue testing machine.

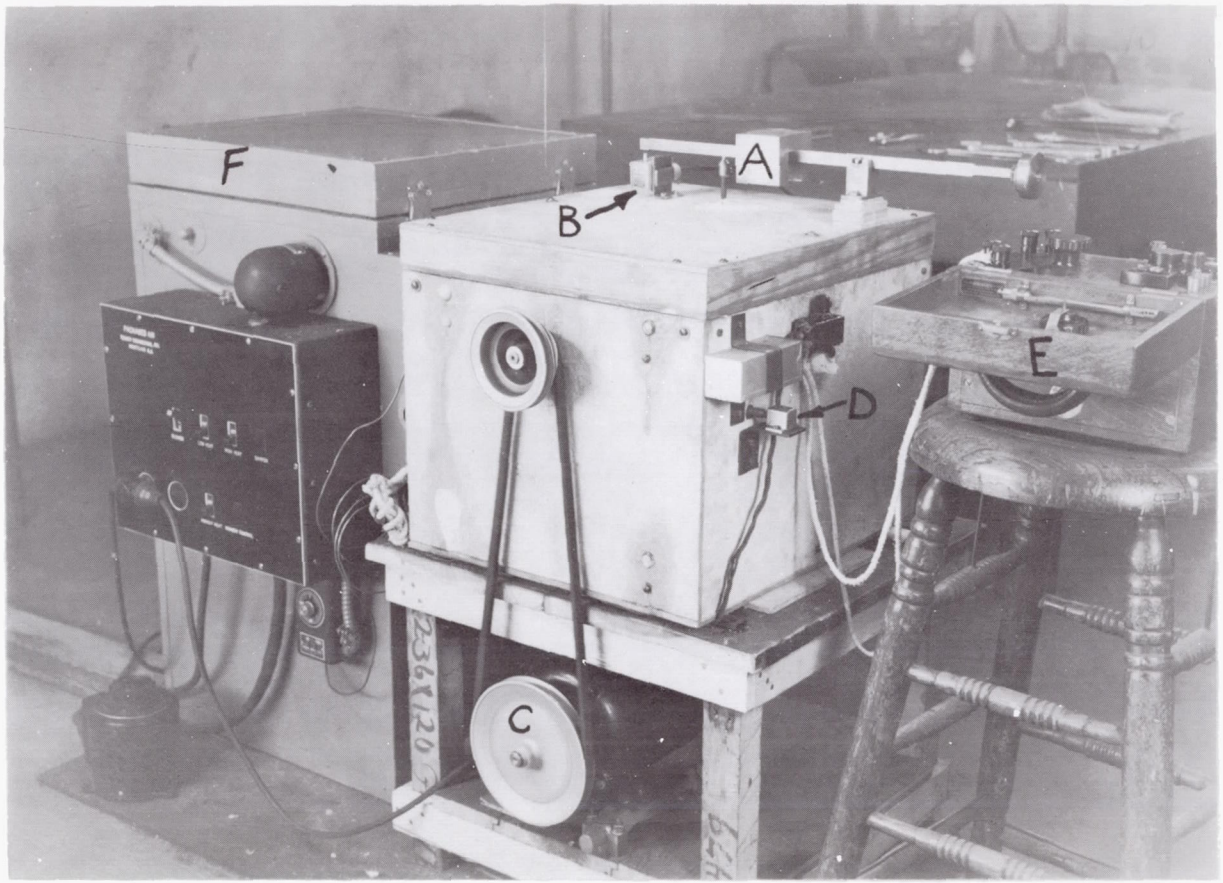


Figure 10.- Rotating-cantilever-beam fatigue testing machine equipped with apparatus for controlling temperature over a range from -75° F to 400° F.

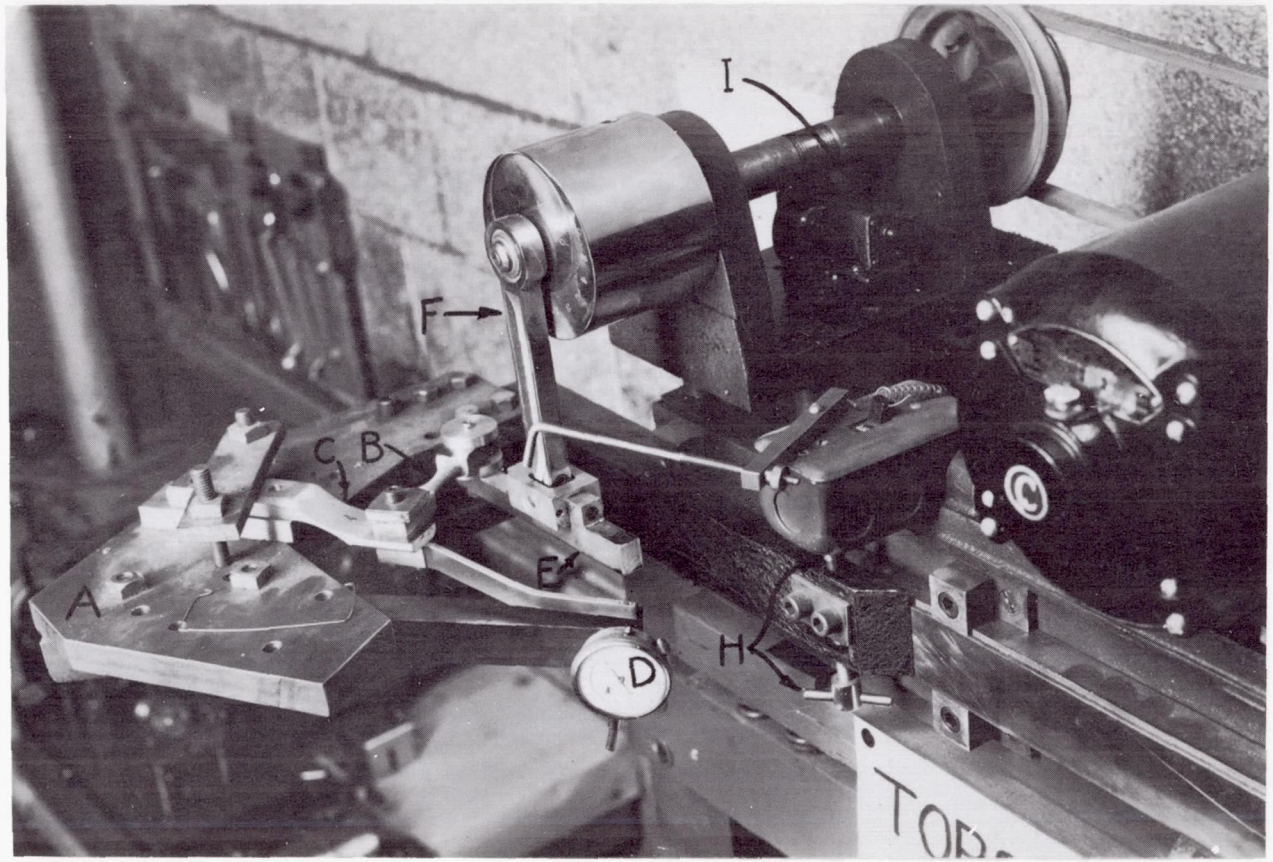


Figure 11.- Fatigue machine of constant amplitude of deflection arranged for tests in torsion.

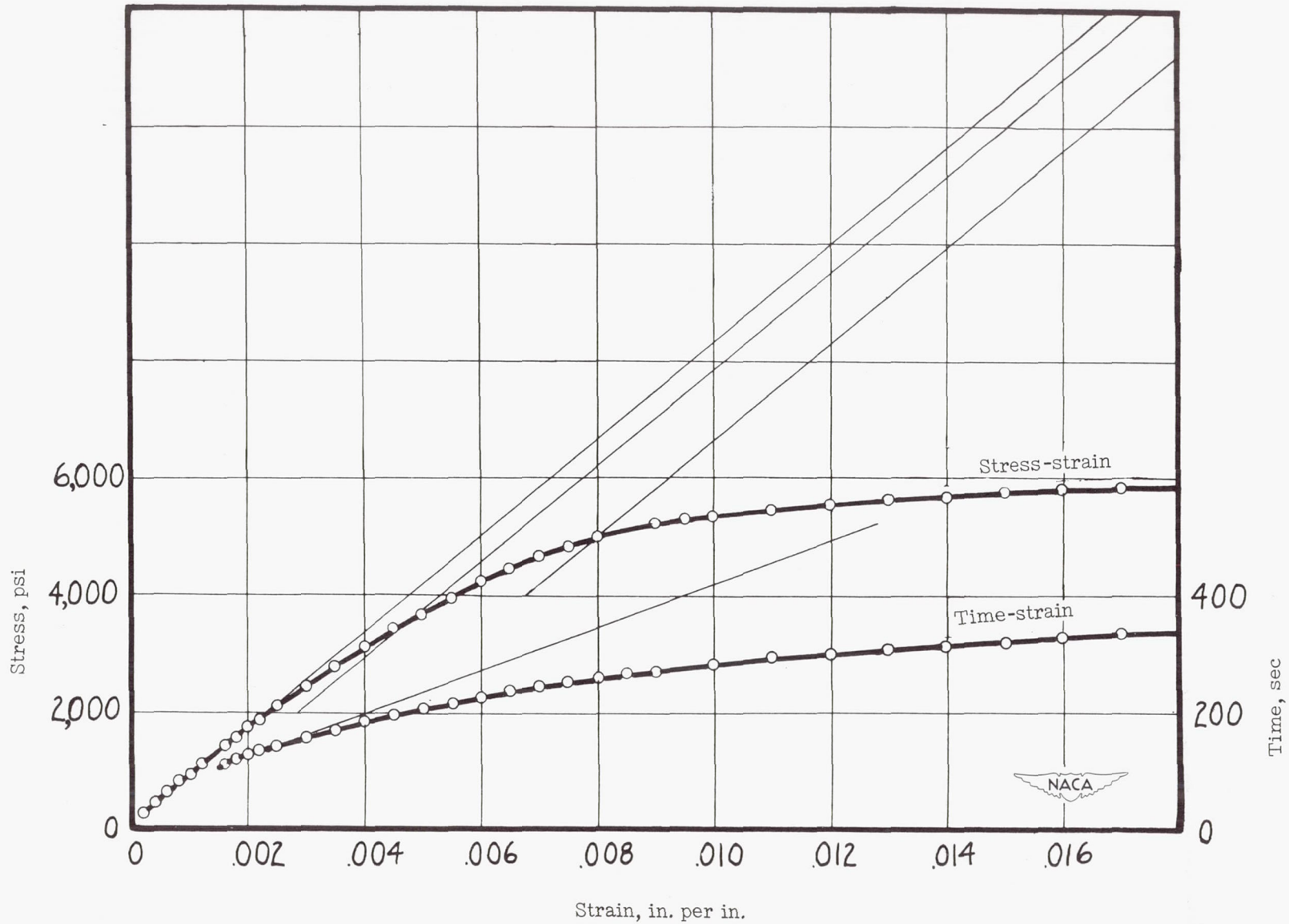


Figure 12.- Static tension test of low-pressure-molded canvas laminate. Elastic modulus E, 820,000 psi; yield strength at 0.05-percent offset, 3600 psi; yield strength at 0.2-percent offset, 5000 psi; rate of strain, 0.0016 inch per inch per minute; specimen B-4.

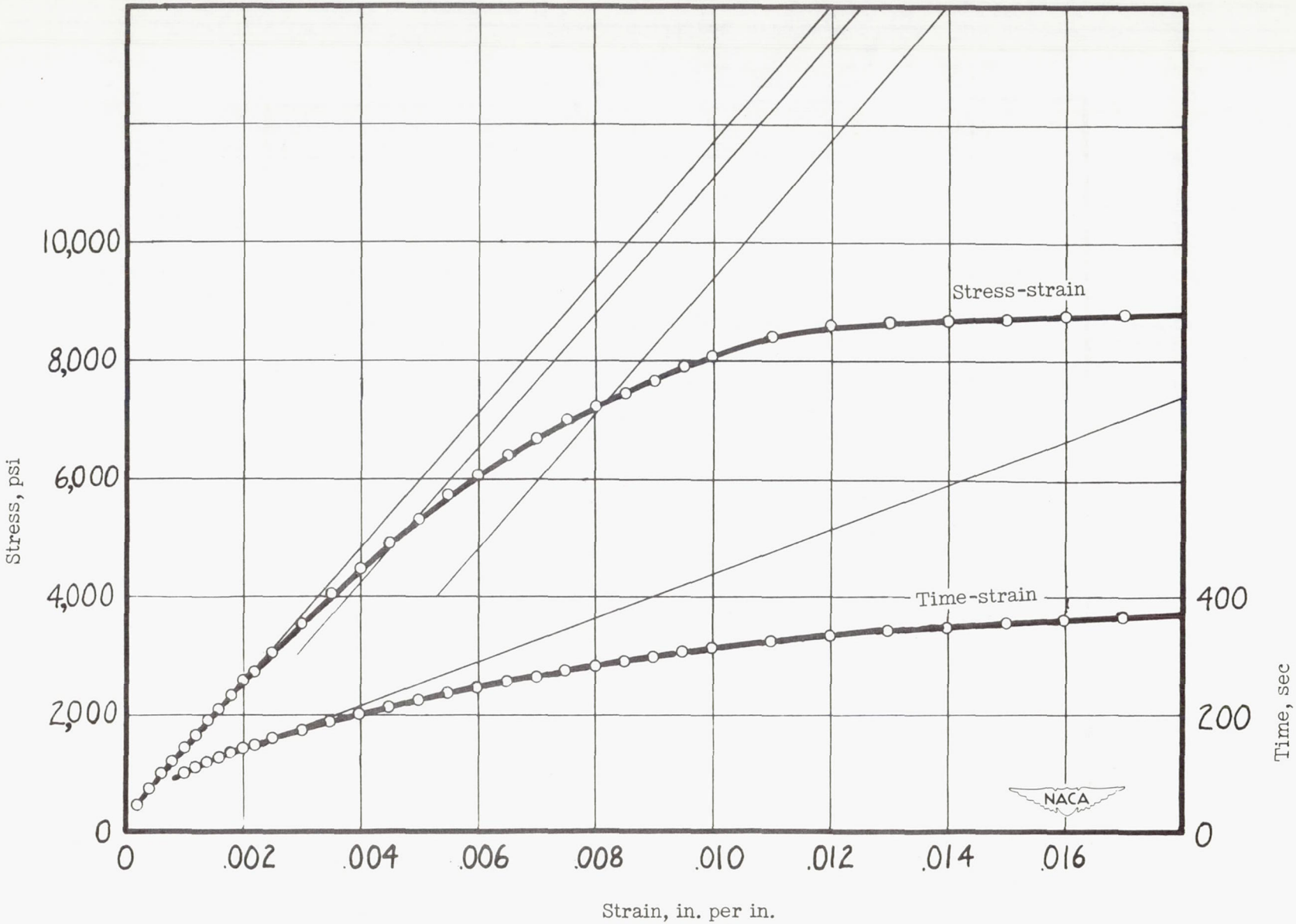


Figure 13.- Static tension test of grade-C canvas laminate. Elastic modulus E, 1,150,000 psi; yield strength at 0.05-percent offset, 5100 psi; yield strength at 0.2-percent offset, 7300 psi; rate of strain, 0.0016 inch per inch per minute; specimen B-13.

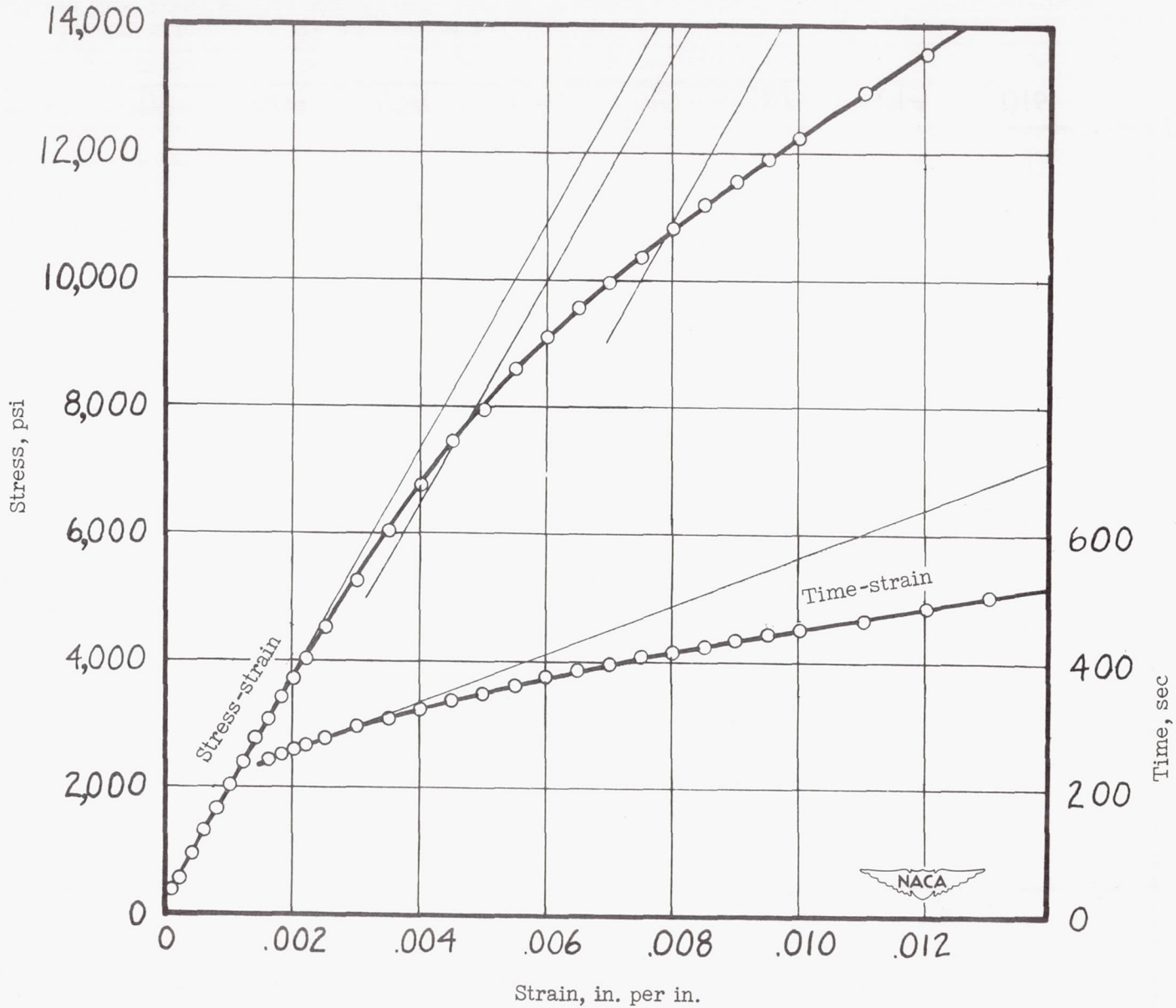


Figure 14.- Static tension test of rayon laminate. Elastic modulus E, 1,780,000 psi; yield strength at 0.05-percent offset, 7800 psi; yield strength at 0.2-percent offset, 10,700 psi; rate of strain, 0.0016 inch per inch per minute; specimen B-4.

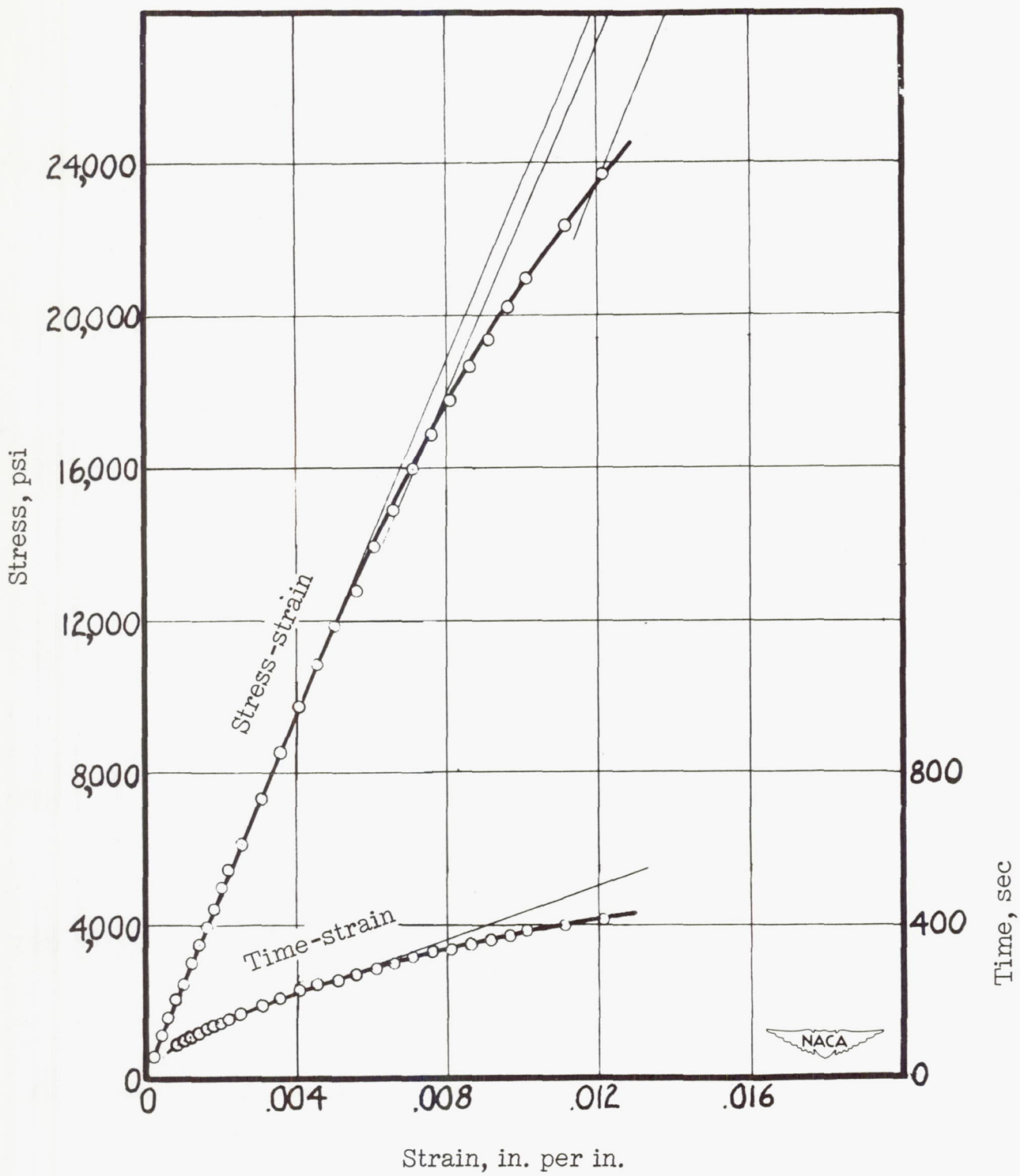


Figure 15.- Static tension test of paper laminate. Elastic modulus E, 2,340,000 psi; yield strength at 0.05-percent offset, 17,100 psi; yield strength at 0.2-percent offset, 23,600 psi; rate of strain, 0.0017 inch per inch per minute; specimen B-6.

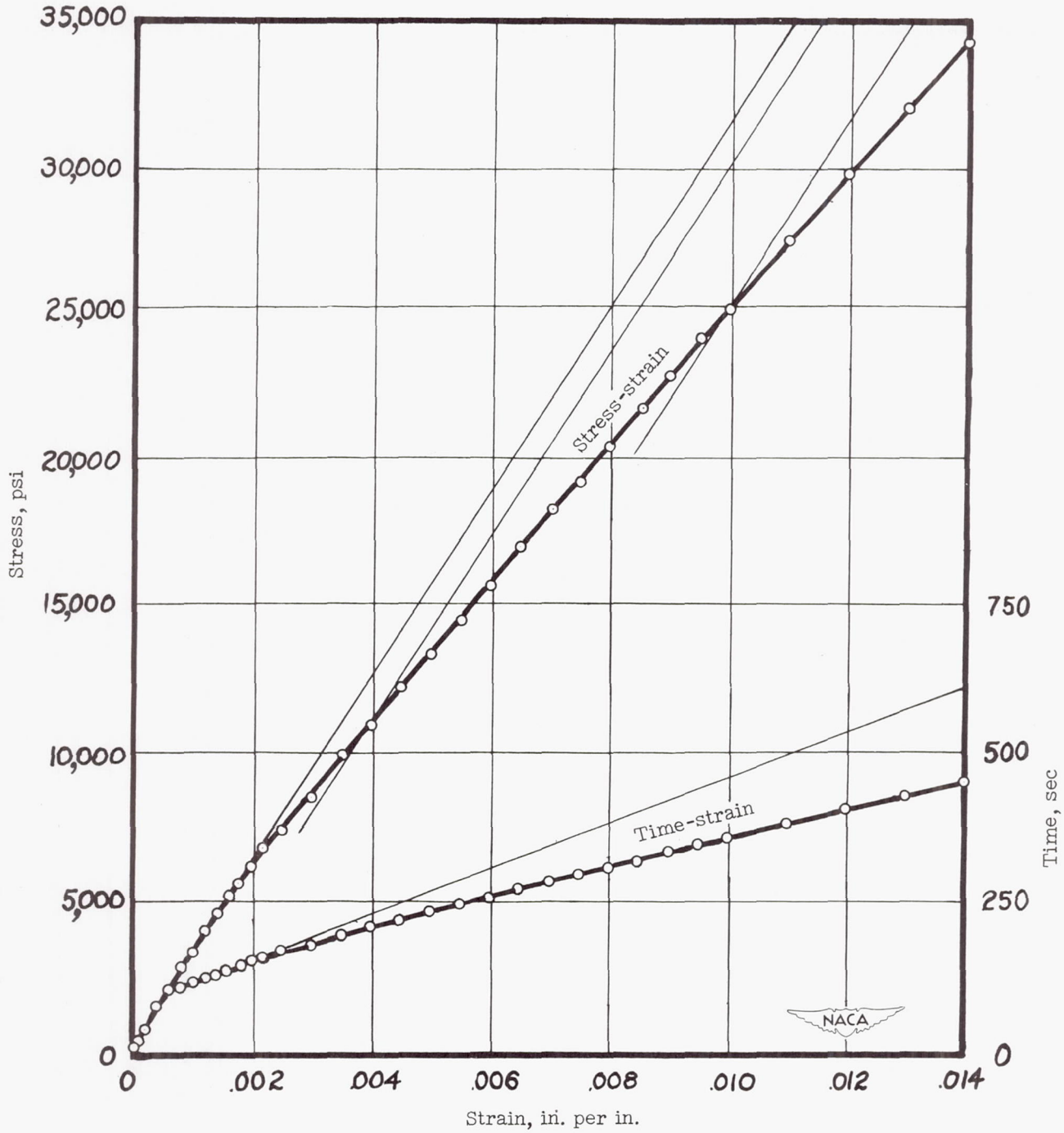


Figure 16.- Static tension test of glass-fabric laminate. Elastic modulus E, 3,130,000 psi; yield strength at 0.05-percent offset, 11,300 psi; yield strength at 0.2-percent offset, 25,100 psi; rate of strain, 0.0016 inch per inch per minute; specimen B-5.

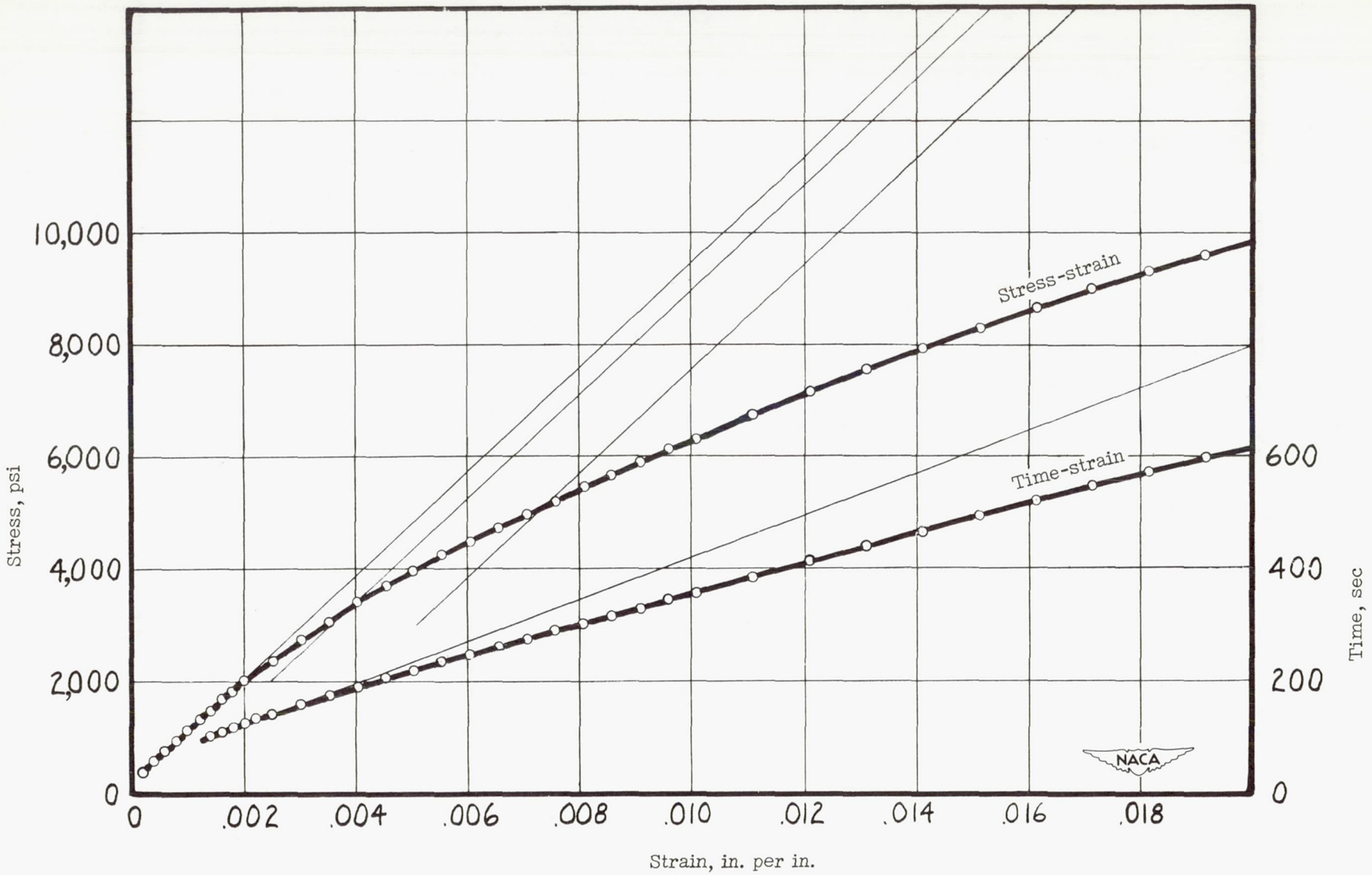


Figure 17.- Static compression test of low-pressure-molded canvas laminate. Elastic modulus E, 930,000 psi; yield strength at 0.05-percent offset, 3200 psi; yield strength at 0.2-percent offset, 5100 psi; rate of strain, 0.0016 inch per inch per minute; specimen A-5.

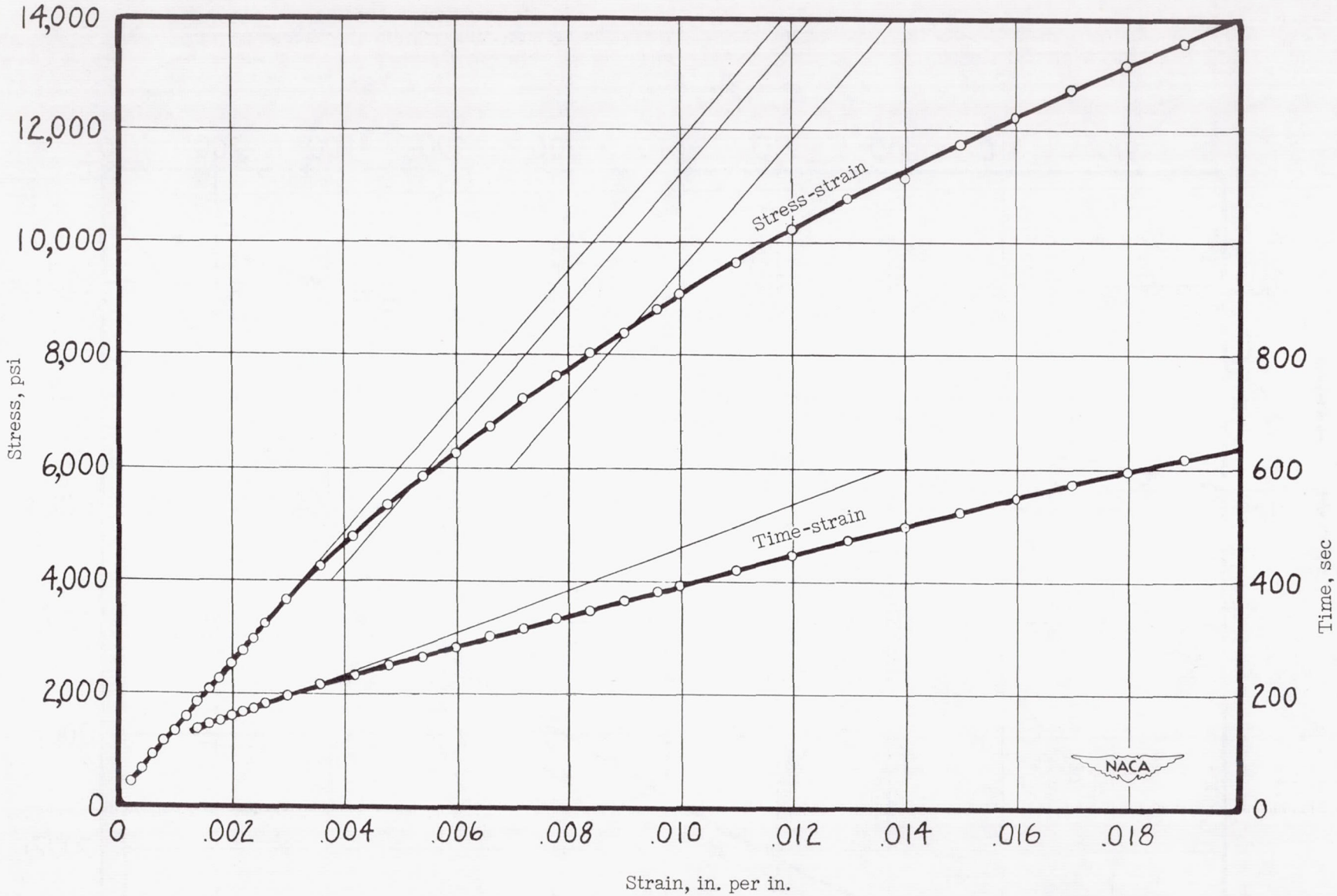


Figure 18.- Static compression test of grade-C canvas laminate. Elastic modulus E, 1,160,000 psi; yield strength at 0.05-percent offset, 5700 psi; yield strength at 0.2-percent offset, 8500 psi; rate of strain, 0.0016 inch per inch per minute; specimen A-11.

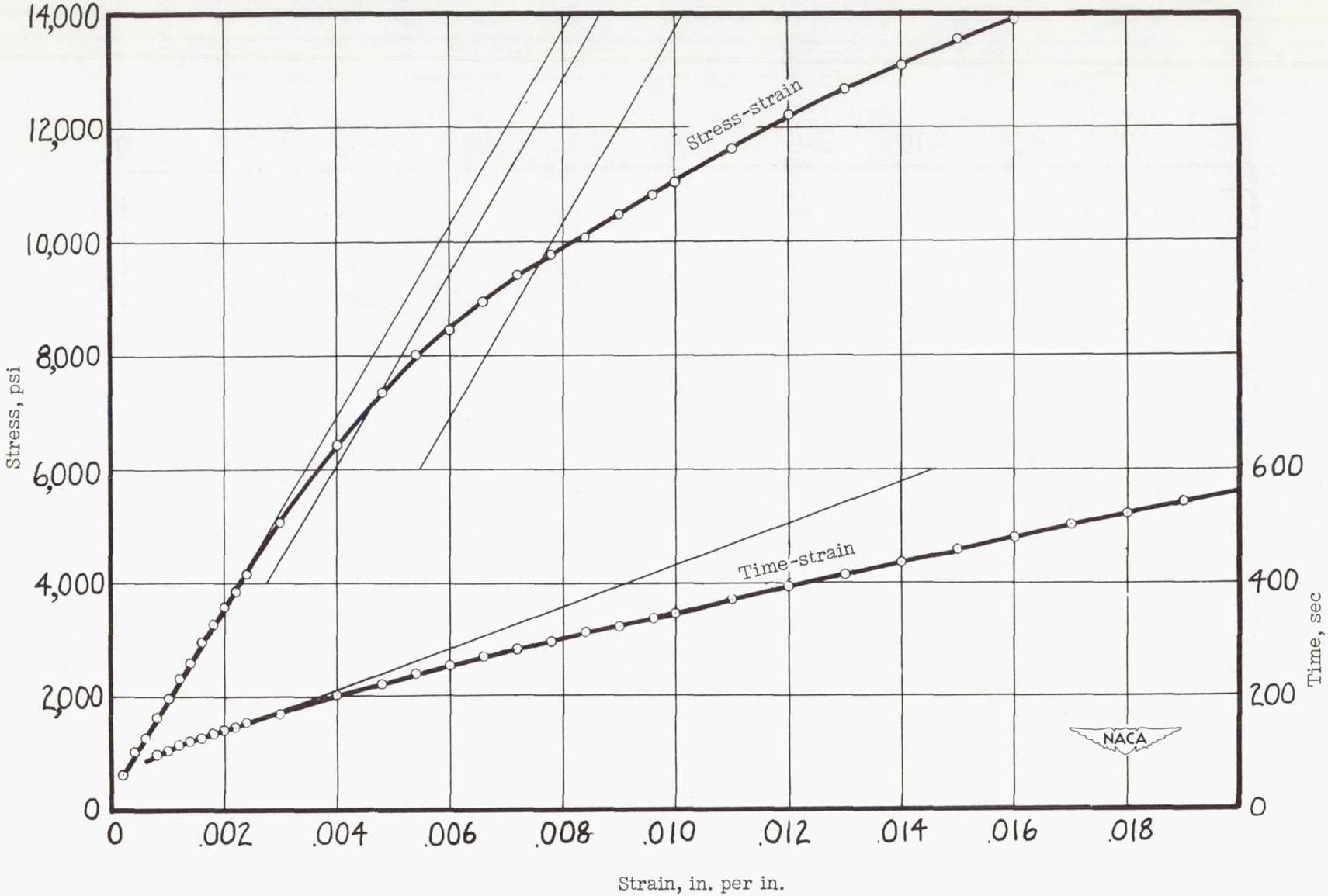


Figure 19.- Static compression test of rayon laminate. Elastic modulus E, 1,680,000 psi; yield strength at 0.05-percent offset, 7200 psi; yield strength at 0.2-percent offset, 9630 psi; rate of strain, 0.0016 inch per inch per minute; specimen A-4.

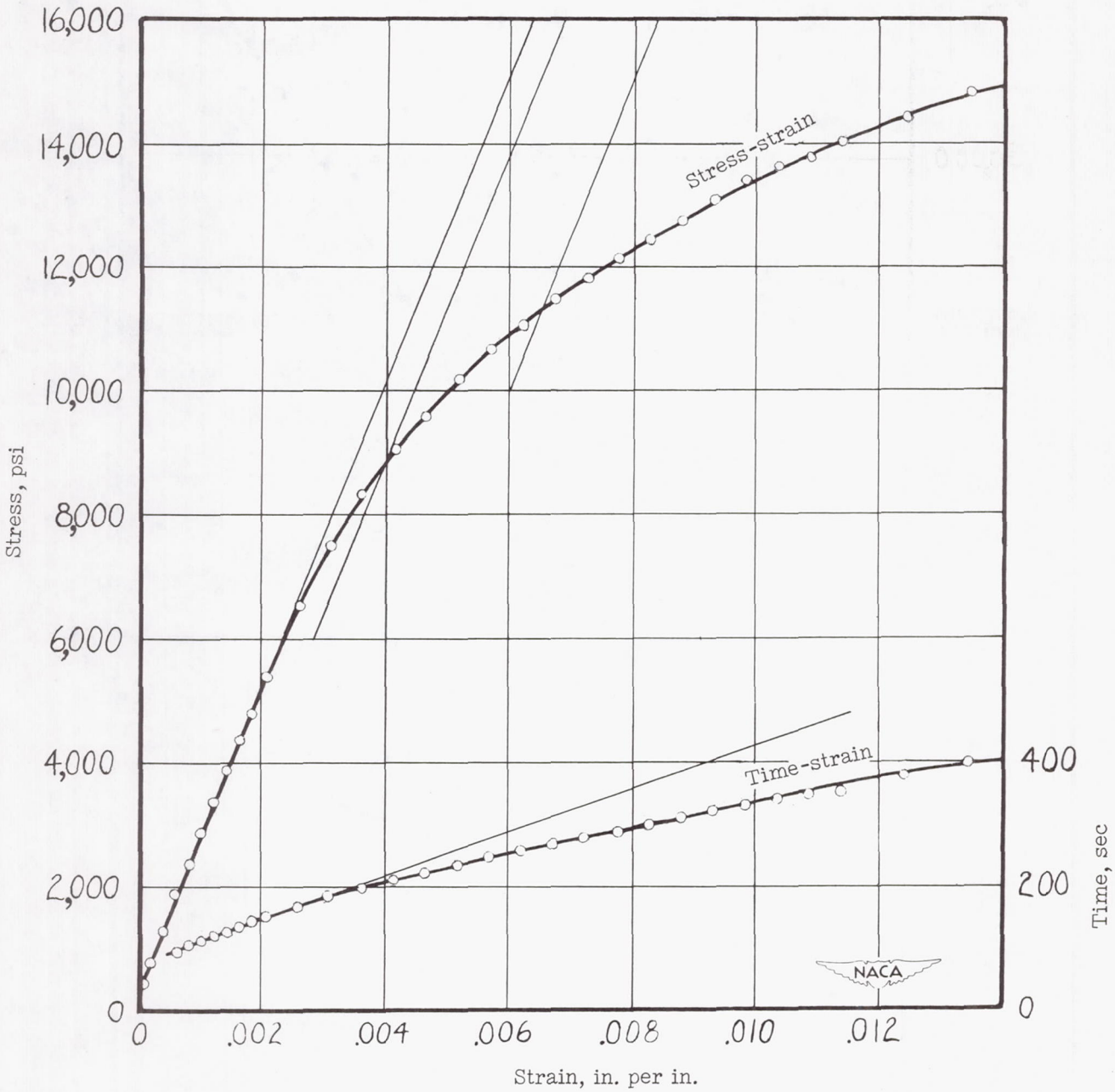


Figure 20.- Static compression test of paper laminate. Elastic modulus E, 2,480,000 psi; yield strength at 0.05-percent offset, 8900 psi; yield strength at 0.2-percent offset, 11,300 psi; rate of strain, 0.0017 inch per inch per minute; specimen A-7.

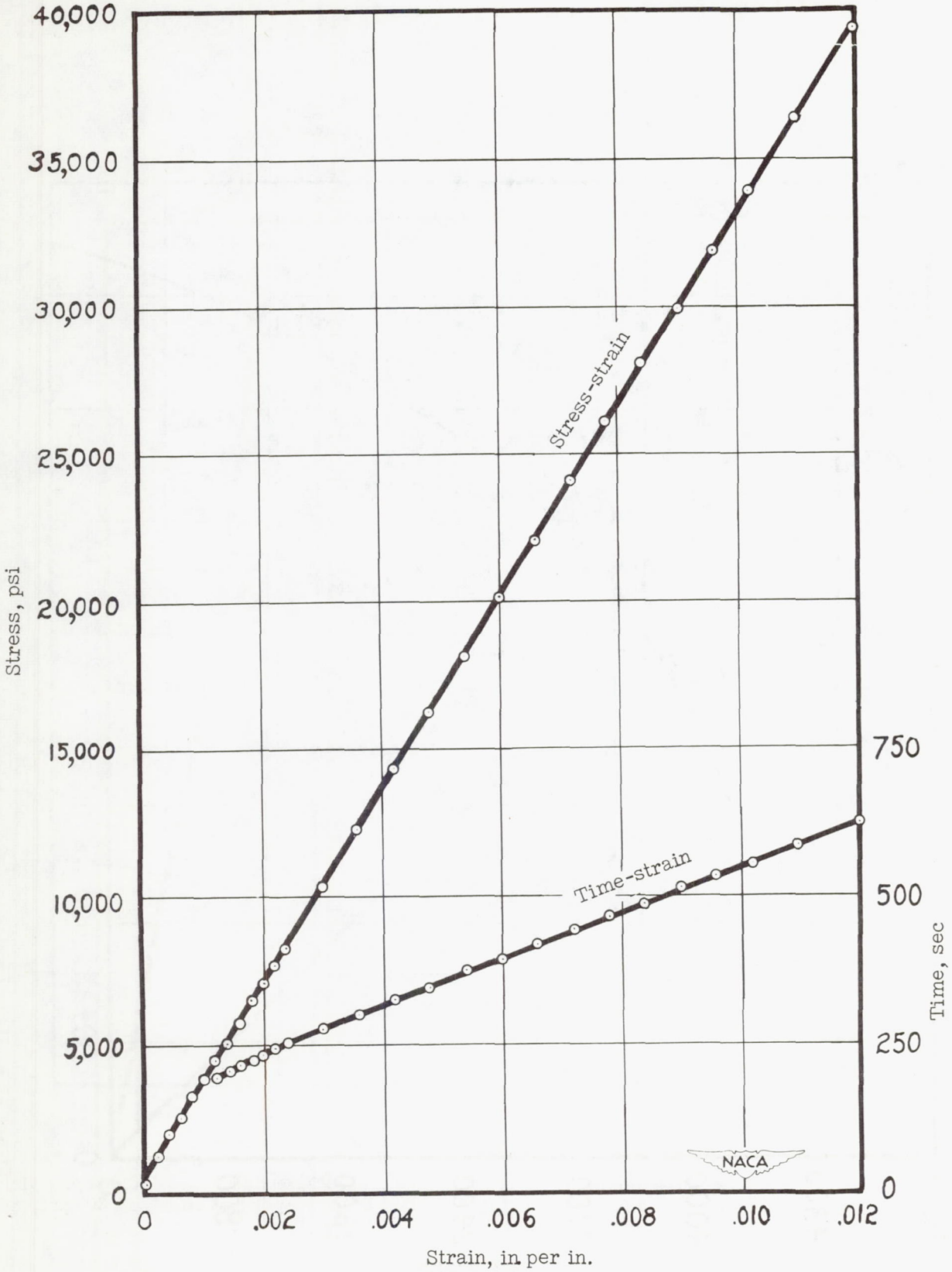


Figure 21.- Static compression test of glass-fabric laminate. Elastic modulus E, 3,260,000 psi; rate of strain, 0.0016 inch per inch per minute; specimen A-6.

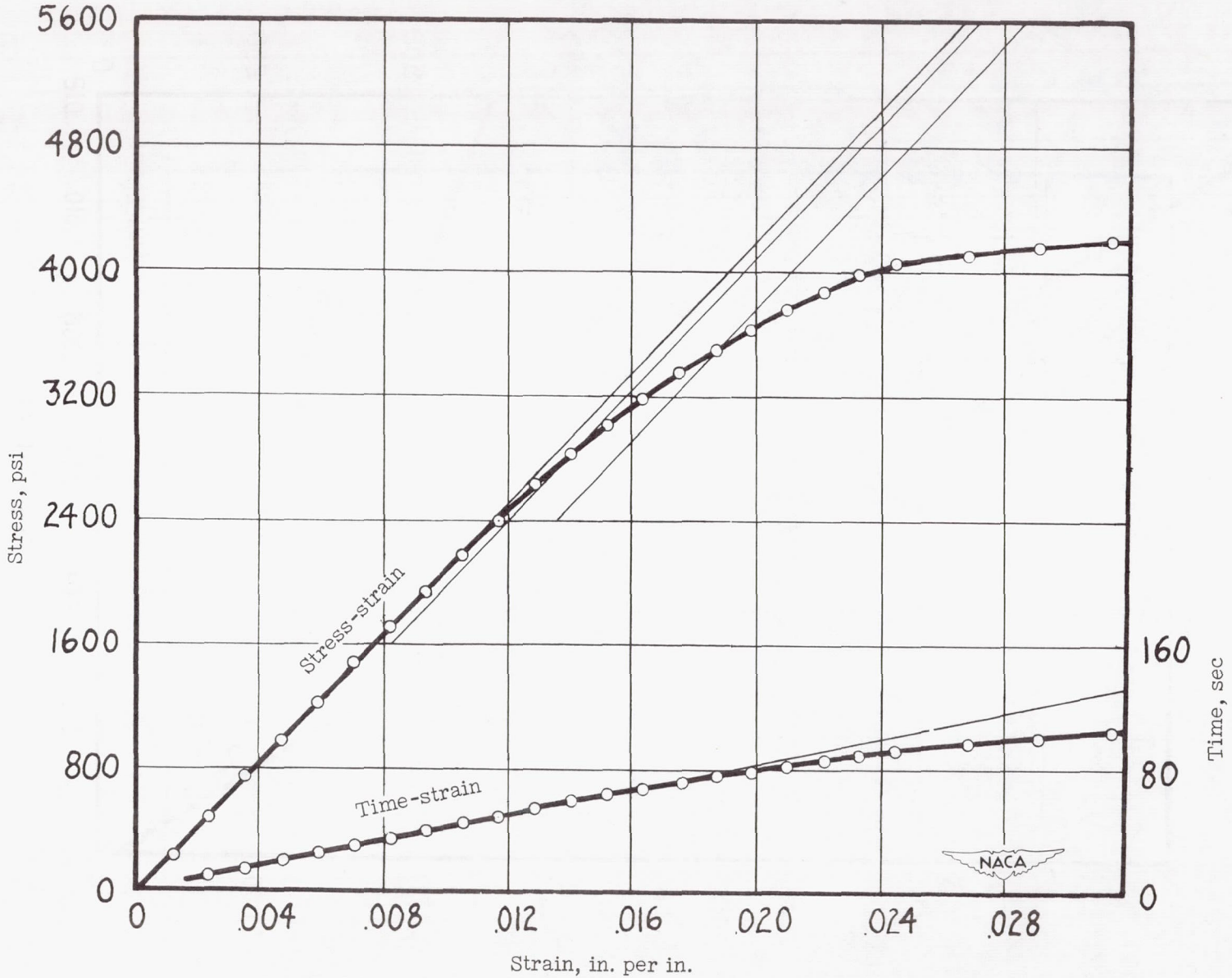


Figure 22.- Static torsion test of rayon laminate. Elastic modulus G, 210,000 psi; yield strength at 0.05-percent offset, 2800 psi; yield strength at 0.2-percent offset, 3500 psi; rate of strain, 0.015 inch per inch per minute; specimen T-2.

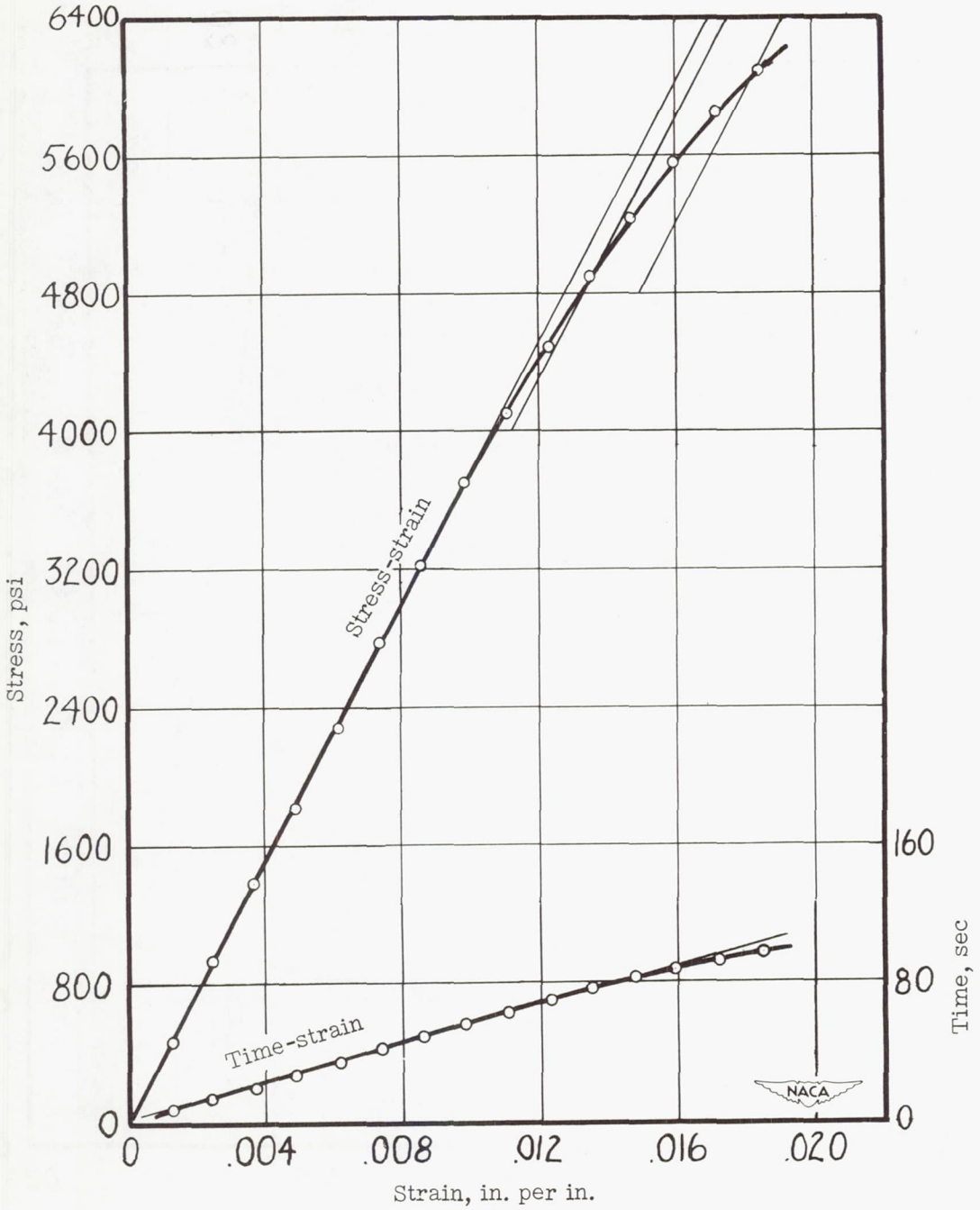


Figure 23.- Static torsion test of paper laminate. Elastic modulus G, 376,000 psi; yield strength at 0.05-percent offset, 4900 psi; yield strength at 0.2-percent offset, 6100 psi; rate of strain, 0.011 inch per inch per minute; specimen T-9.

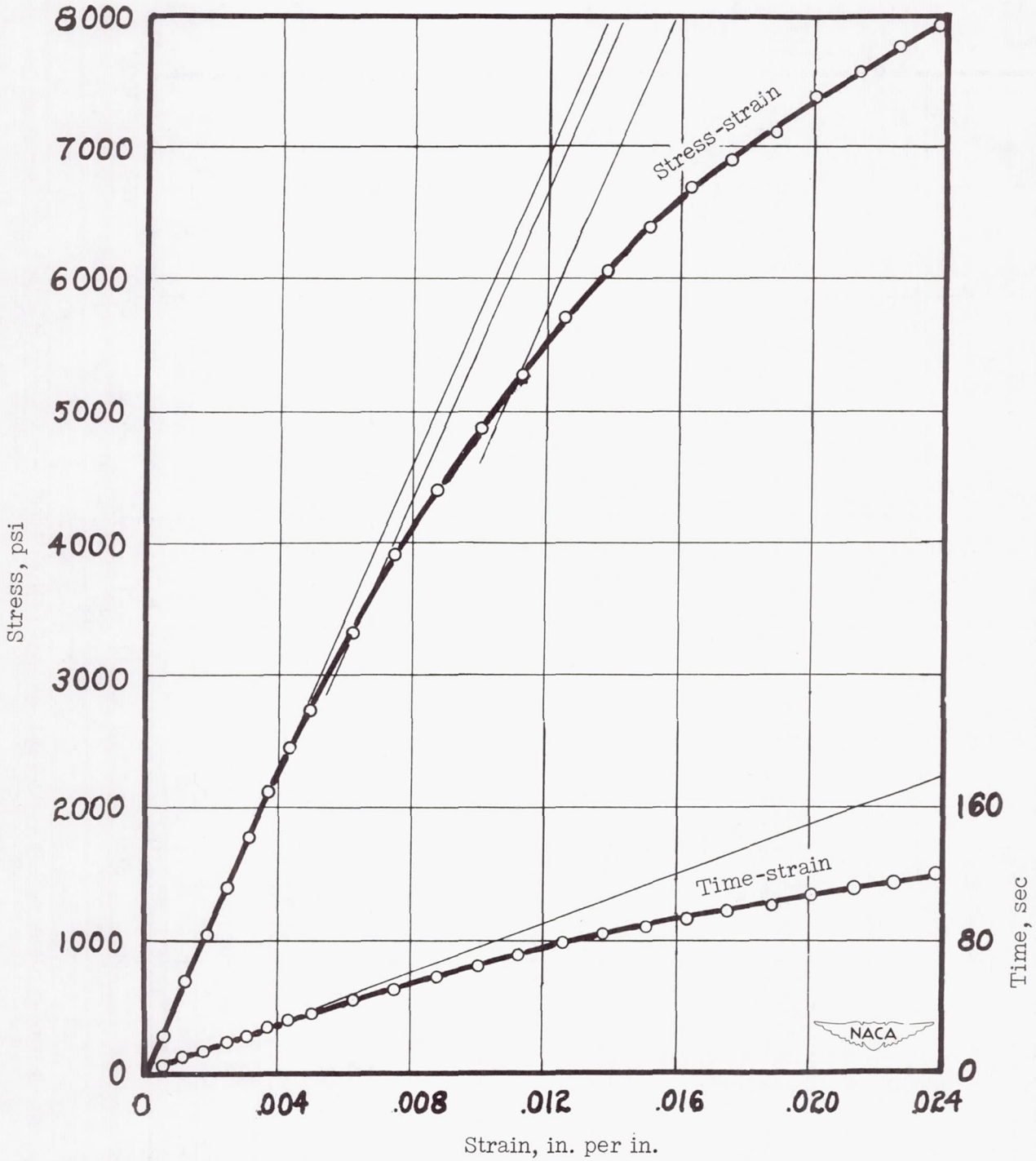


Figure 24.- Static torsion test of glass-fabric laminate. Elastic modulus G, 578,000 psi; yield strength at 0.05-percent offset, 3500 psi; yield strength at 0.2-percent offset, 5300 psi; rate of strain, 0.008 inch per inch per minute; specimen T-4.

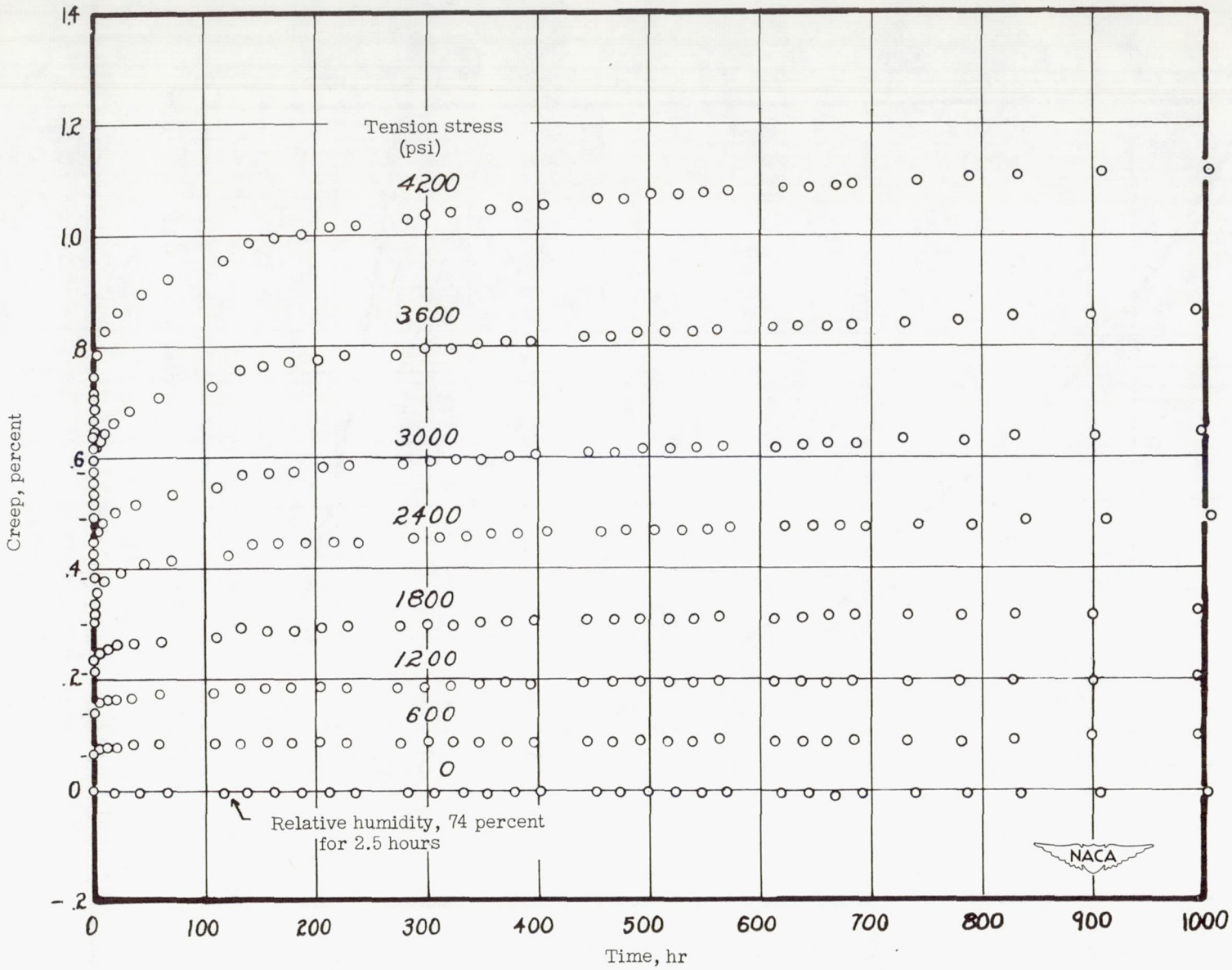


Figure 25.- Creep against time for tension creep tests of low-pressure-molded canvas laminate for 1000 hours at constant load. Temperature, 77° F; relative humidity, 50 percent. First test point for each specimen in a series of creep tests is indicated by a short dash line.

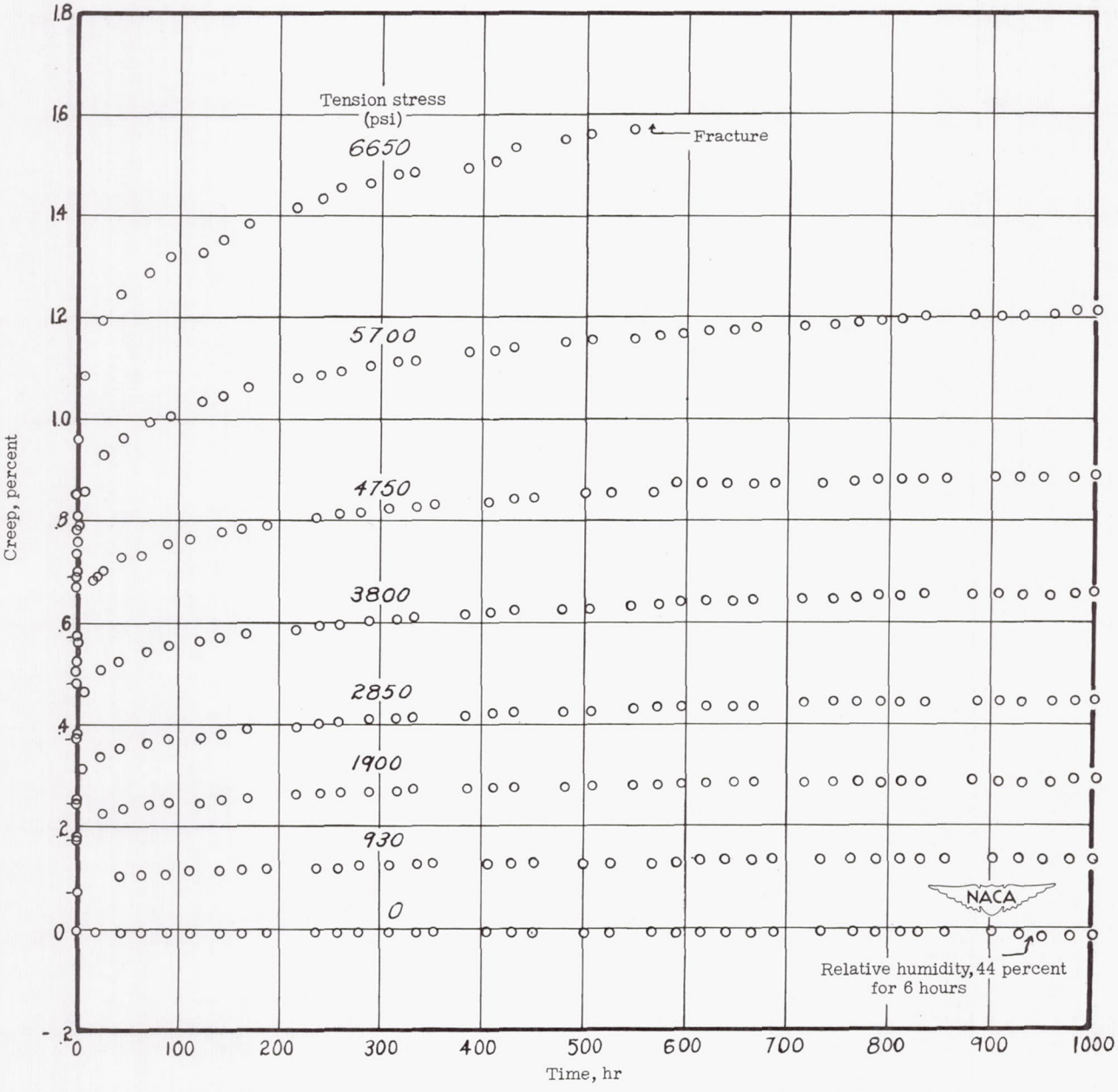


Figure 26.- Creep against time for tension creep tests of grade-C canvas laminate for 1000 hours at constant load. Temperature, 77° F; relative humidity, 50 percent. First test point for each specimen in a series of creep tests is indicated by a short dash line.

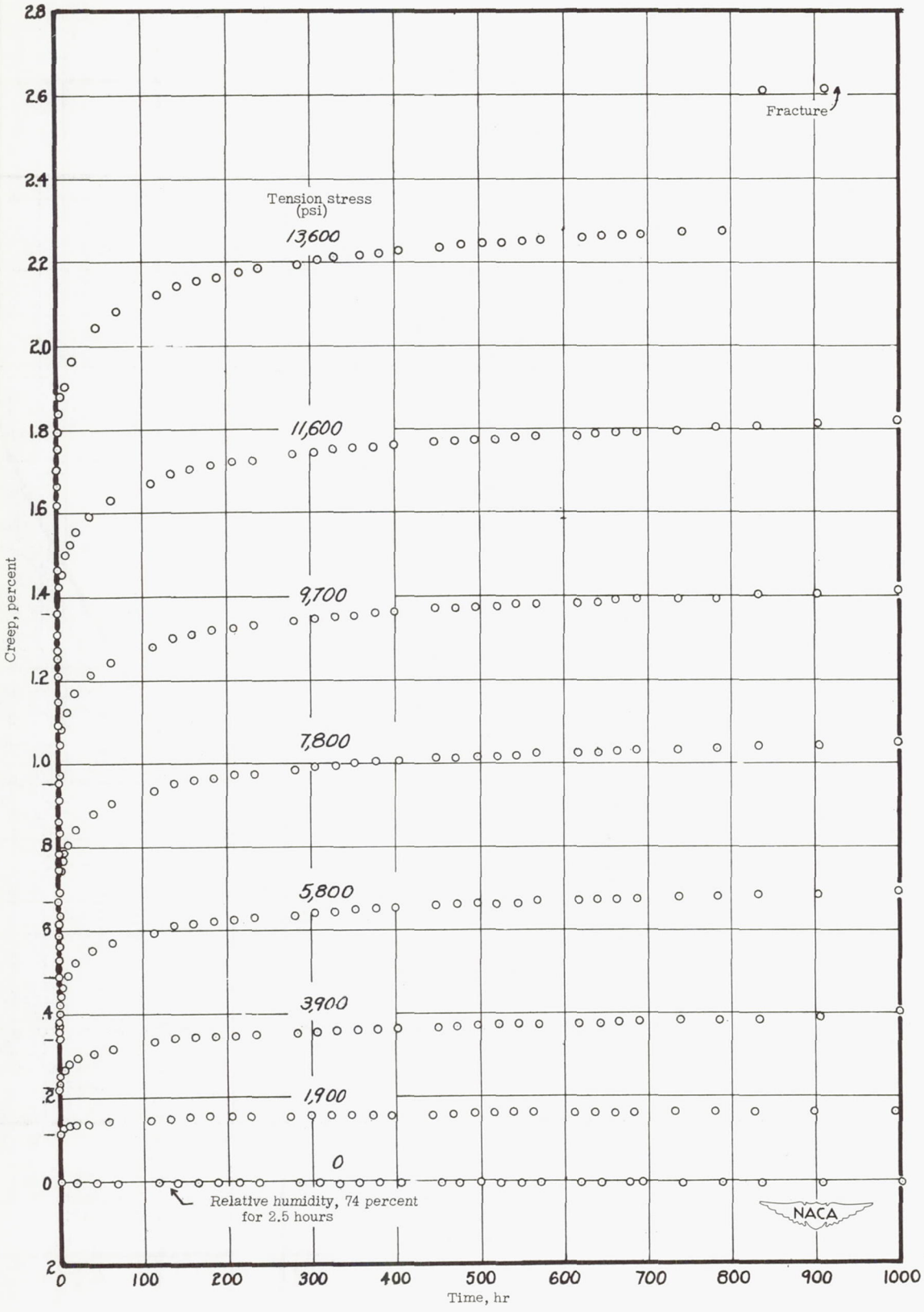


Figure 27.- Creep against time for tension creep tests of rayon laminate for 1000 hours at constant load. Temperature, 77° F; relative humidity, 50 percent. First test point for each specimen in a series of creep tests is indicated by a short dash line.

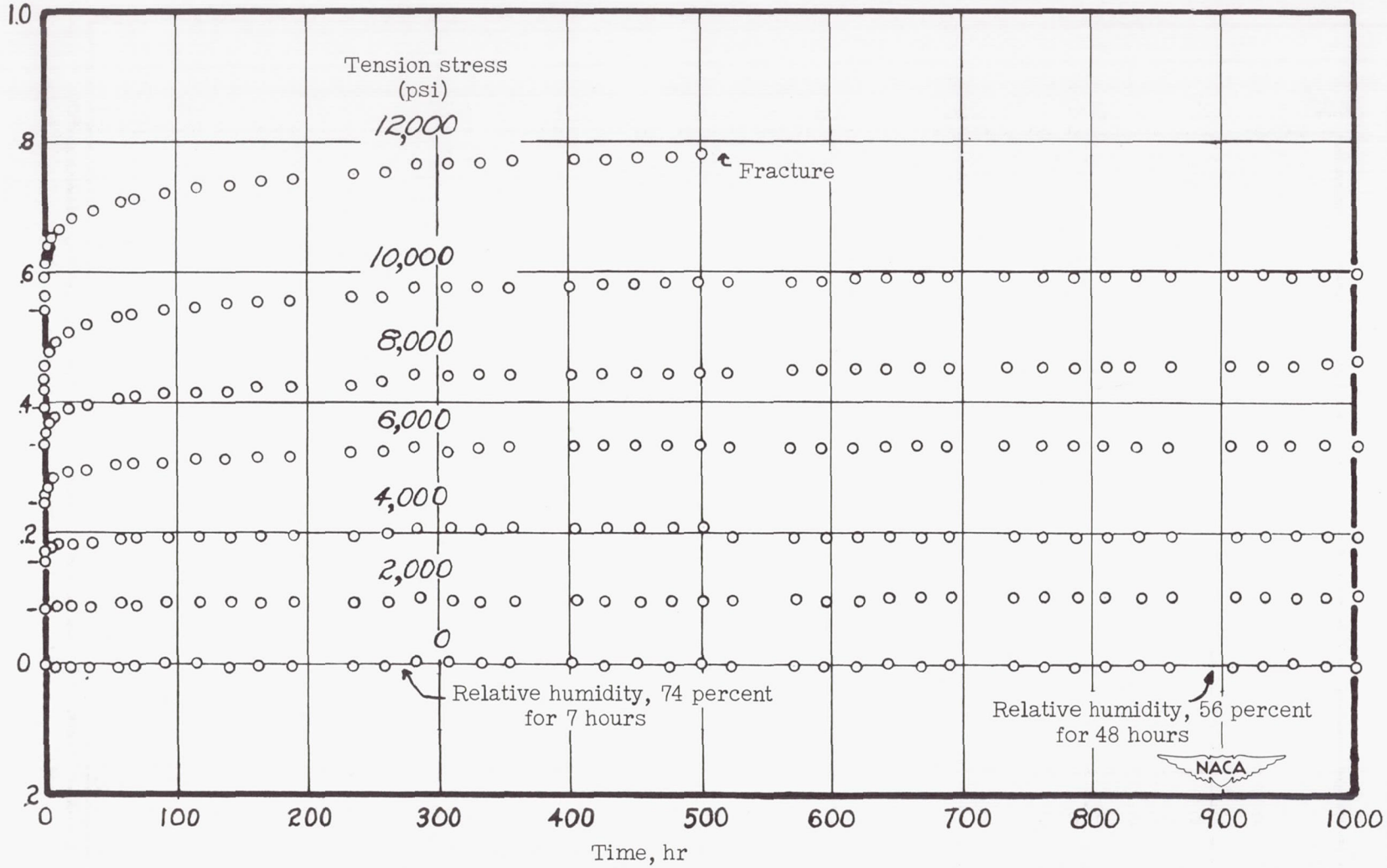


Figure 28.- Creep against time for tension creep tests of paper laminate for 1000 hours at constant load. Temperature, 77° F; relative humidity, 50 percent. First test point for each specimen in a series of creep tests is indicated by a short dash line.

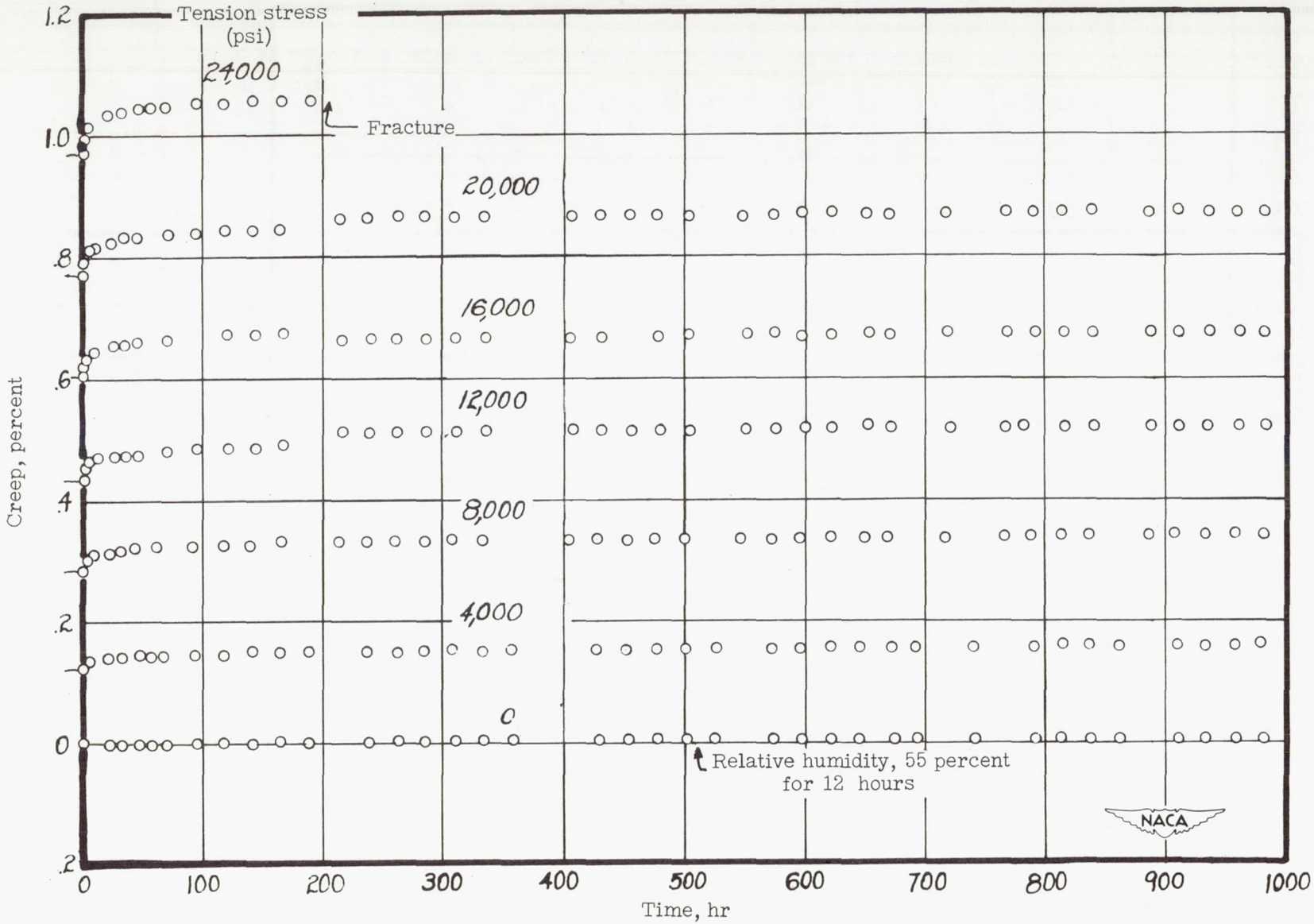


Figure 29.- Creep against time for tension creep tests of glass-fabric laminate for 1000 hours at constant load. Temperature, 77° F; relative humidity, 50 percent. First test point for each specimen in a series of creep tests is indicated by a short dash line.

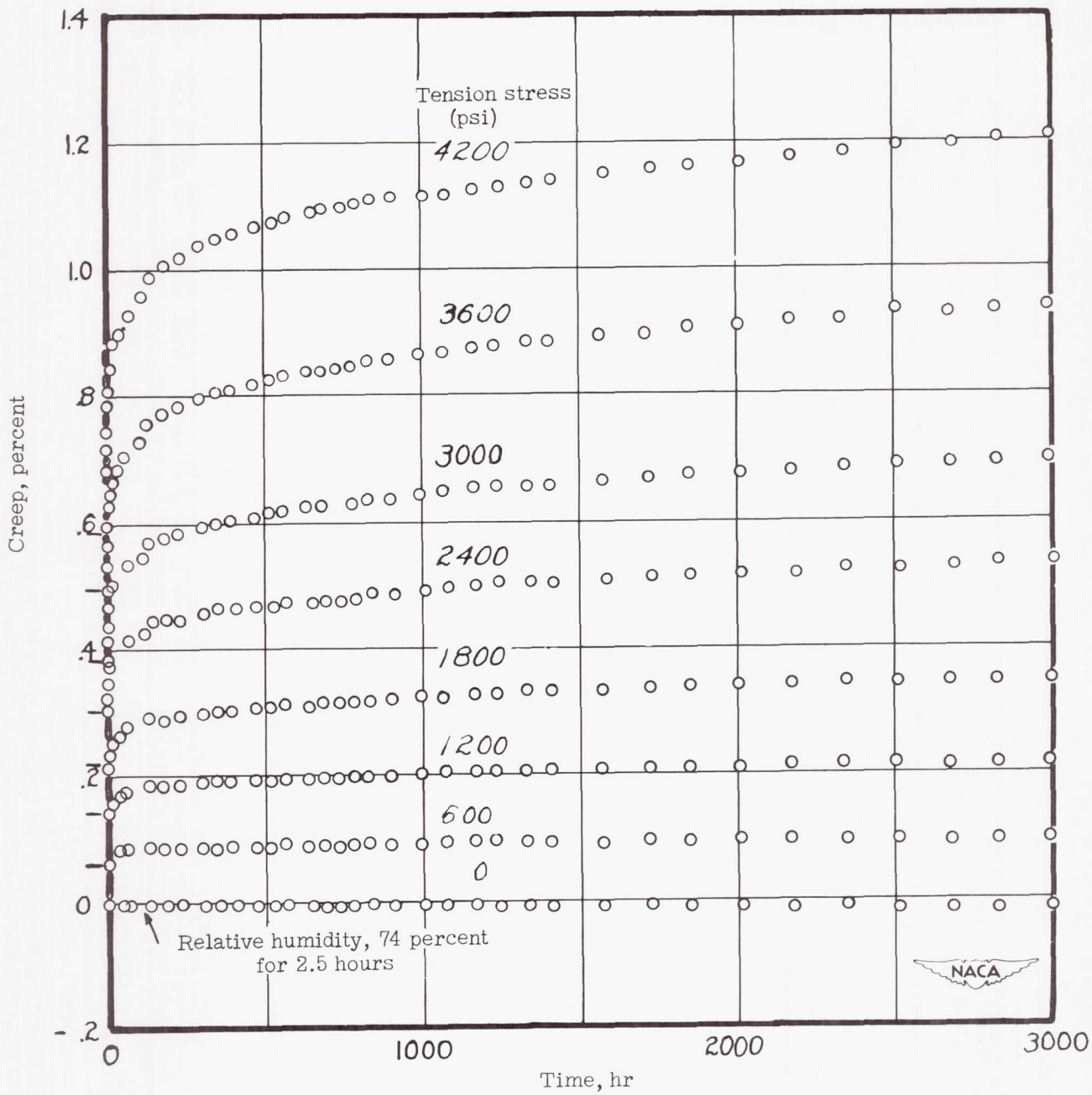


Figure 30.- Creep against time for tension creep tests of low-pressure-molded canvas laminate for 3000 hours at constant load. Temperature, 77° F; relative humidity, 50 percent. First test point for each specimen in a series of creep tests is indicated by a short dash line.

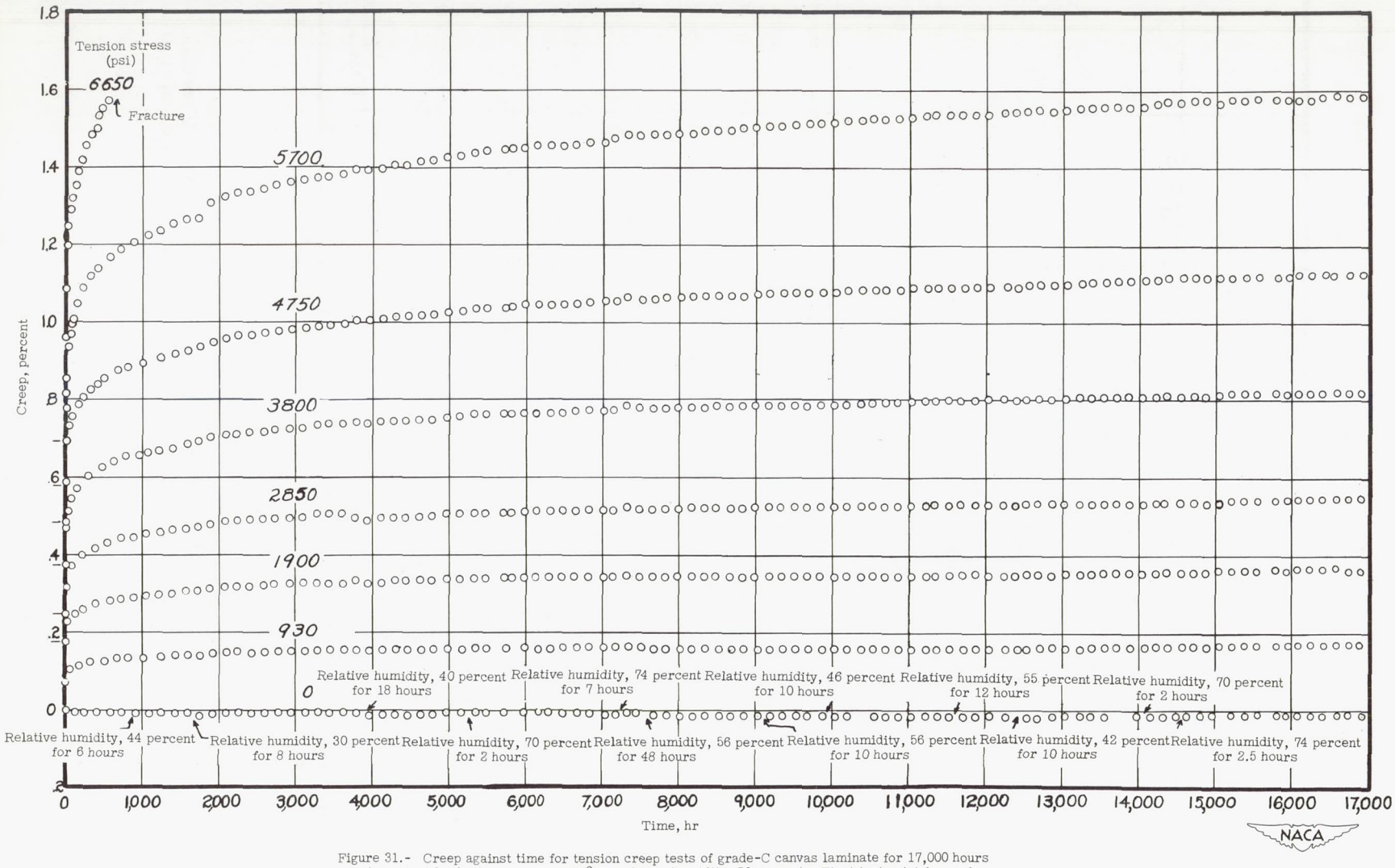


Figure 31.- Creep against time for tension creep tests of grade-C canvas laminate for 17,000 hours at constant load. Temperature, 77° F; relative humidity, 50 percent. First test point for each specimen in a series of creep tests is indicated by a short dash line.

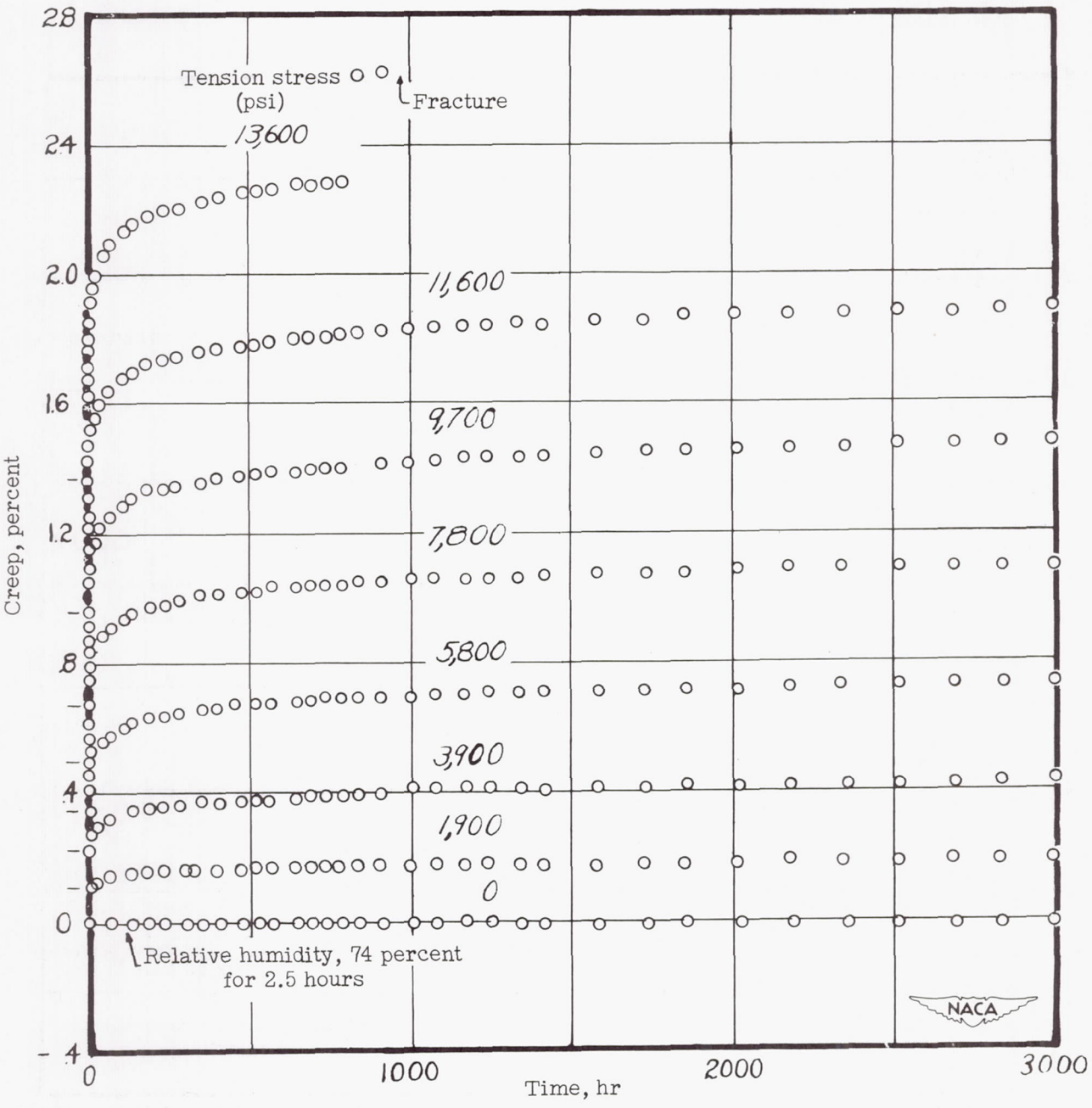


Figure 32.- Creep against time for tension creep tests of rayon laminate for 3000 hours at constant load. Temperature, 77° F; relative humidity, 50 percent. First test point for each specimen in a series of creep tests is indicated by a short dash line.

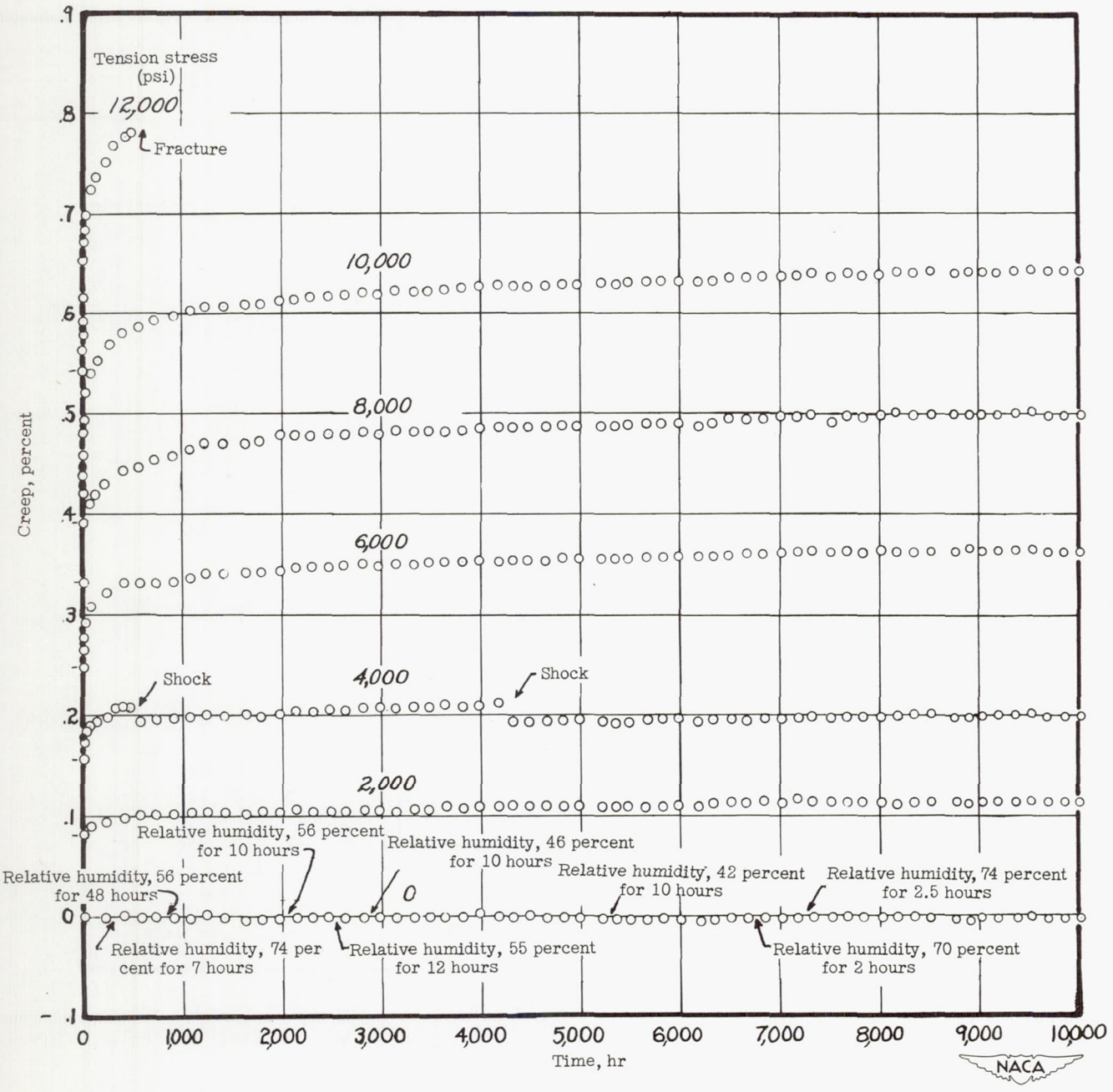


Figure 33.- Creep against time for tension creep tests of paper laminate for 10,000 hours at constant load. Temperature, 77° F; relative humidity, 50 percent. First test point for each specimen in a series of creep tests is indicated by a short dash line.

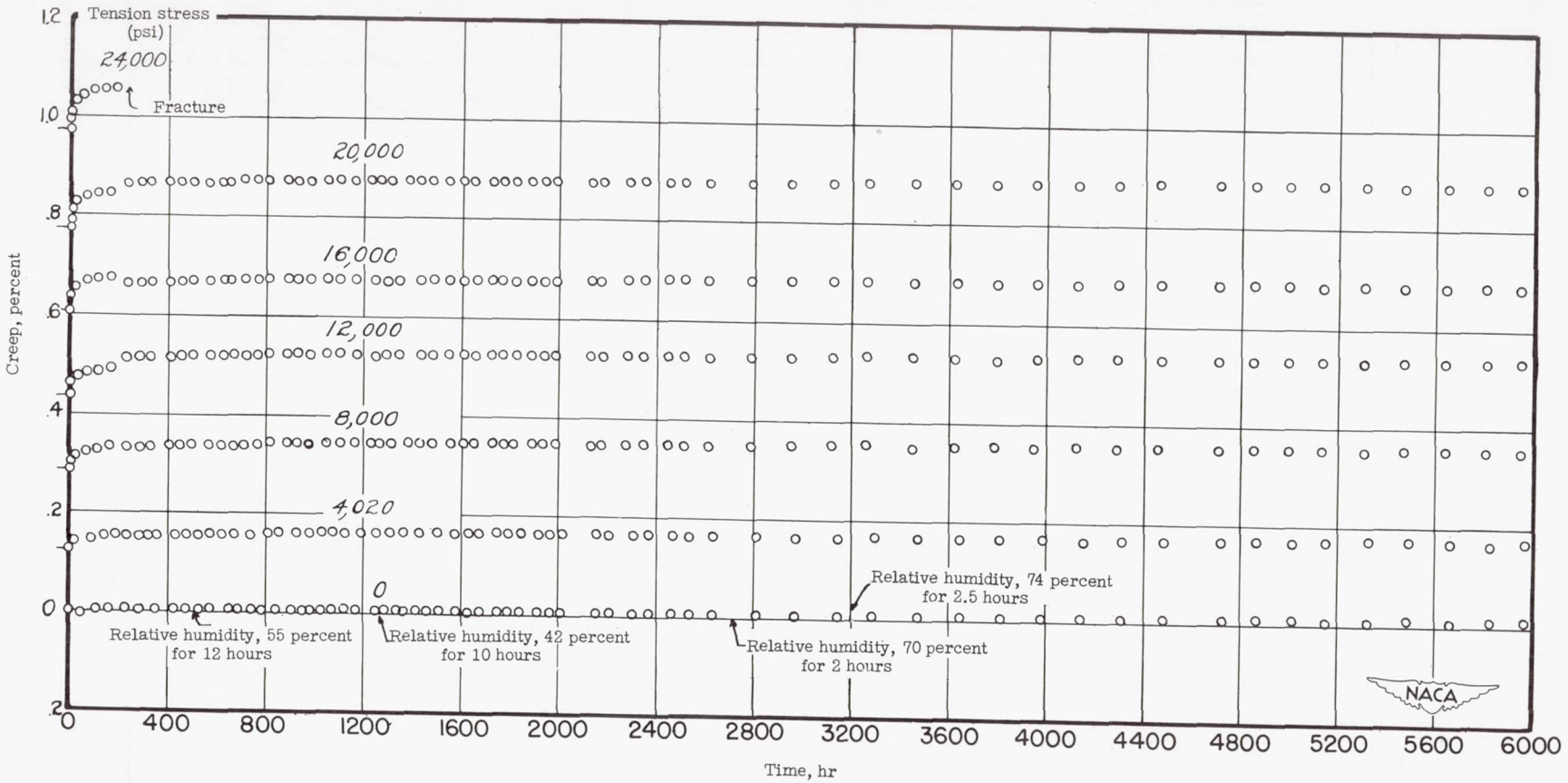


Figure 34.- Creep against time for tension creep tests of glass-fabric laminate for 6000 hours at constant load. Temperature, 77° F; relative humidity, 50 percent. First test point for each specimen in a series of creep tests is indicated by a short dash line.

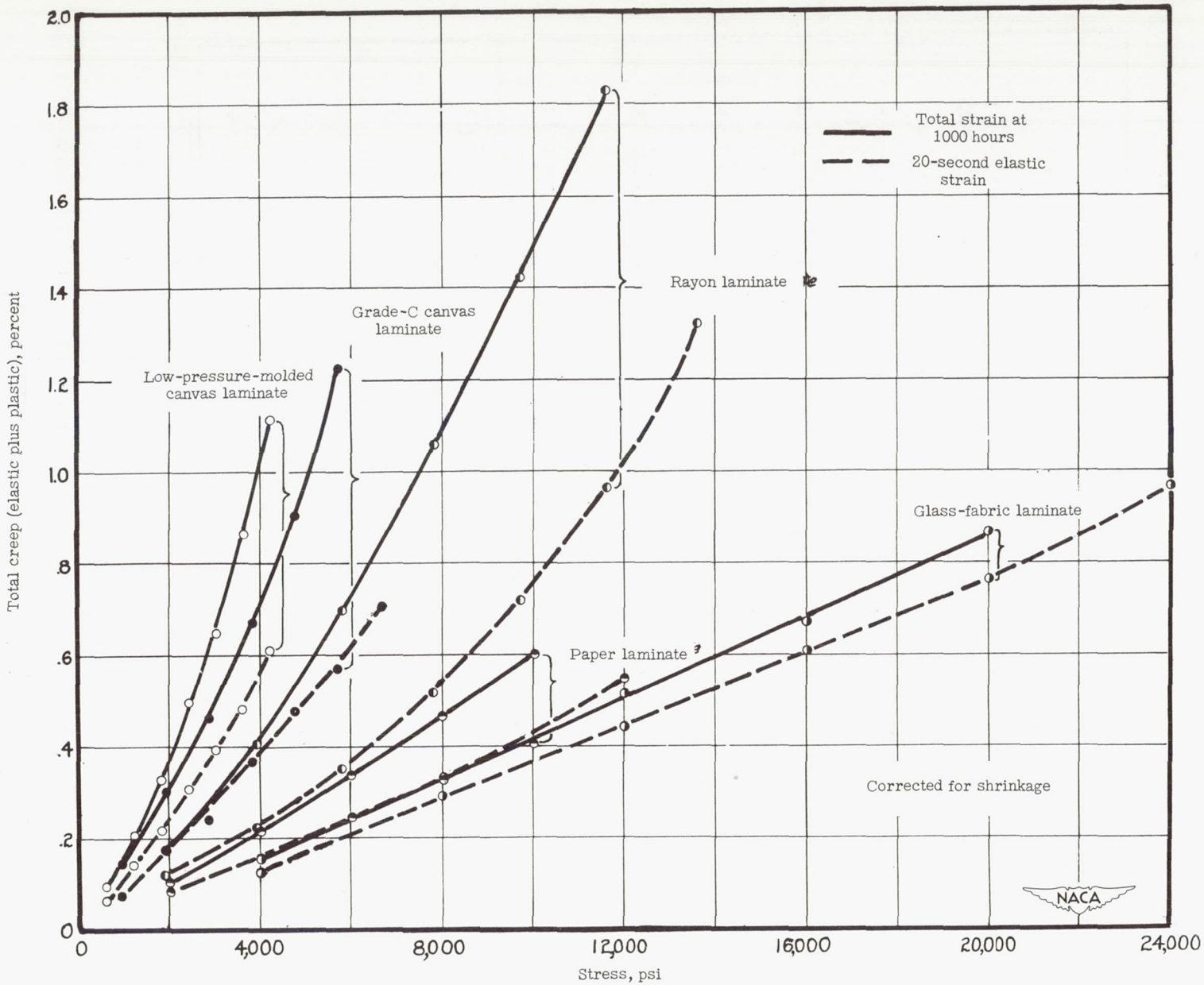


Figure 35.- Effect of stress on 20-second elastic strain and on total creep at 1000 hours for all five laminates.

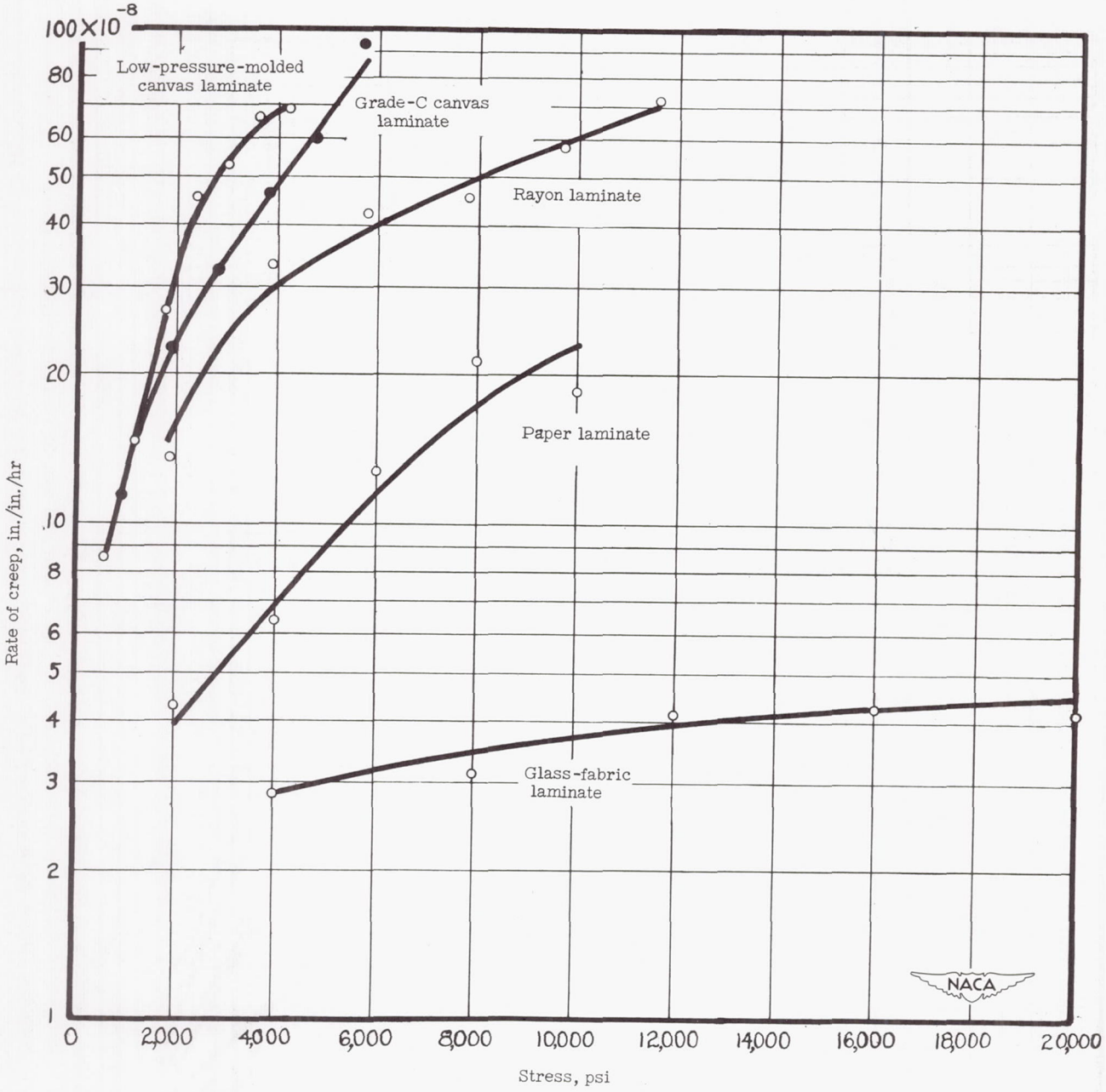


Figure 36.- Rate of creep at 1000 hours against stress for all five laminates.

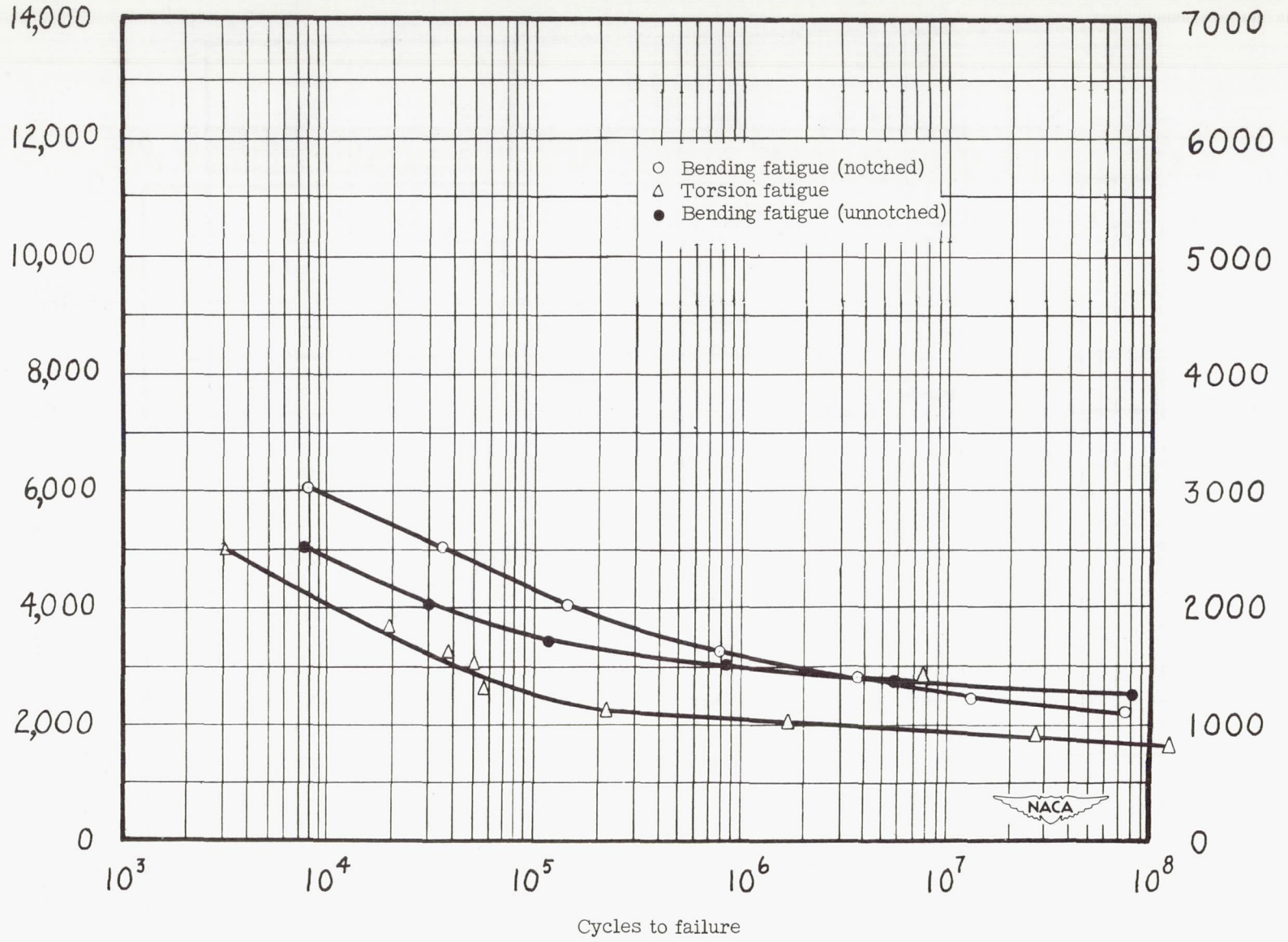


Figure 37.- S-N diagrams for tests of low-pressure-molded canvas laminate obtained from rotating-cantilever-beam fatigue tests of notched and unnotched specimens and from torsion fatigue tests of unnotched specimens.

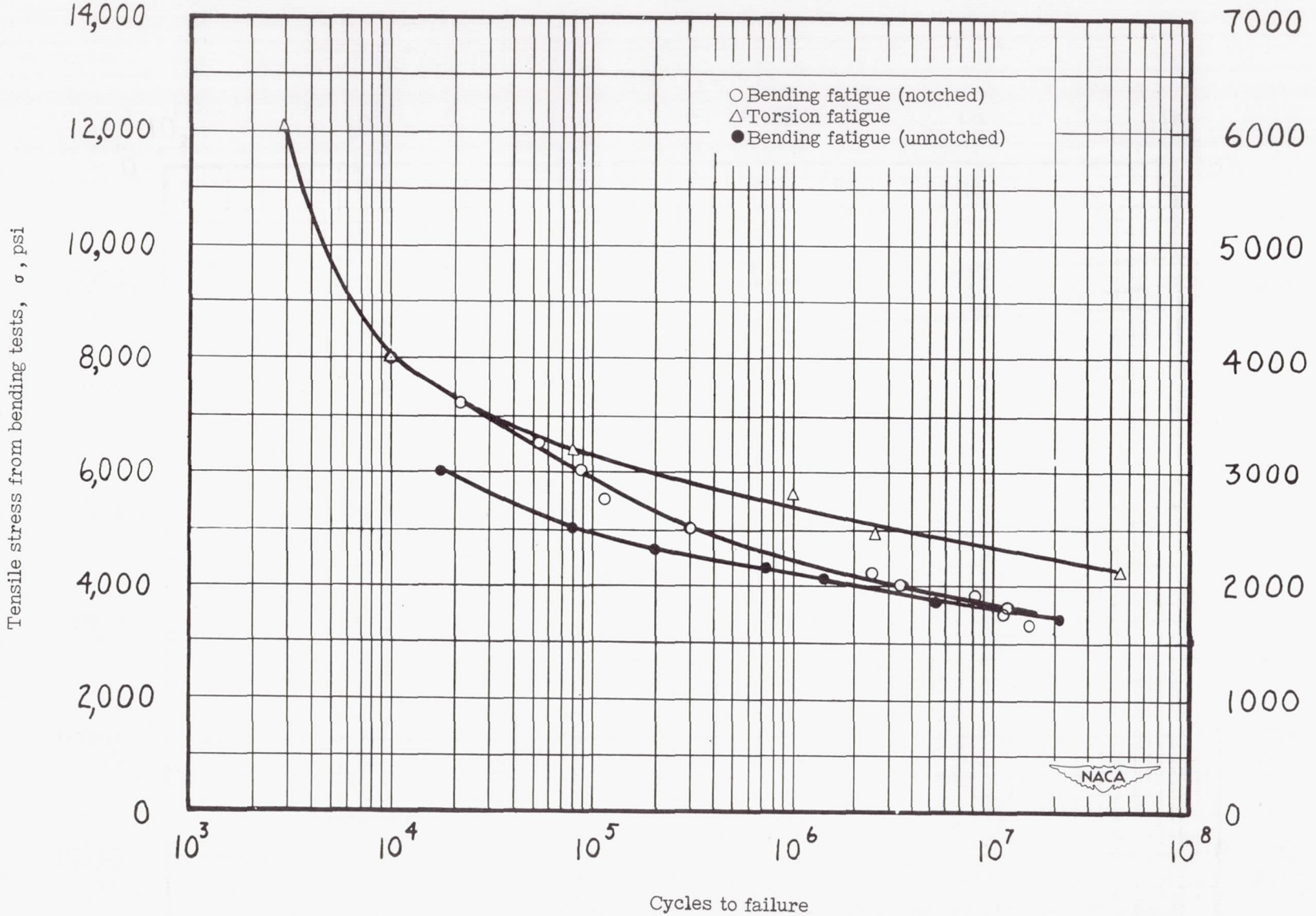


Figure 38.- S-N diagrams for tests of grade-C canvas laminate obtained from rotating-cantilever-beam fatigue tests of notched and unnotched specimens and from torsion fatigue tests of unnotched specimens.

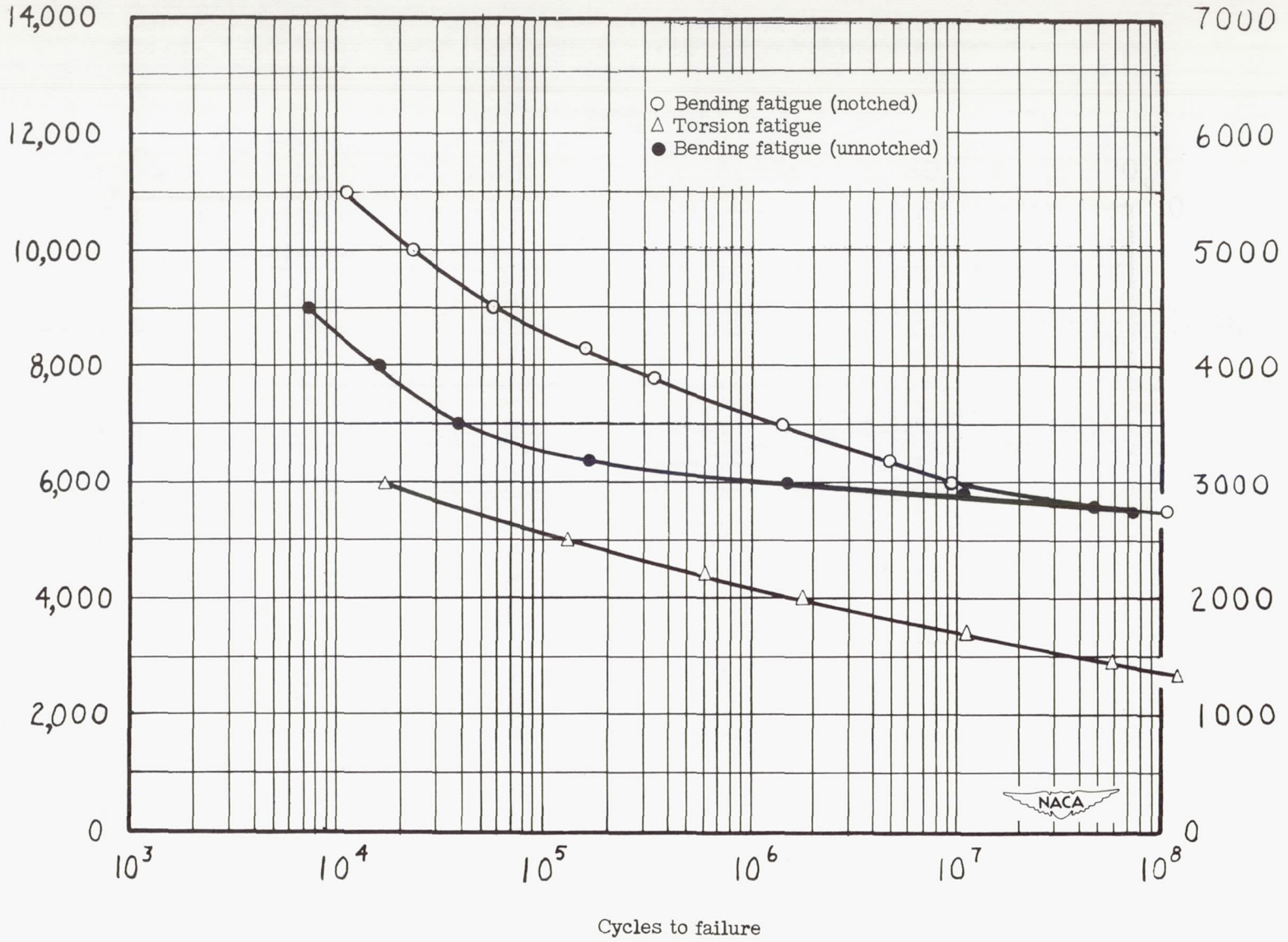


Figure 39.- S-N diagrams for tests of rayon laminate obtained from rotating-cantilever-beam fatigue tests of notched and unnotched specimens and from torsion fatigue tests of unnotched specimens.

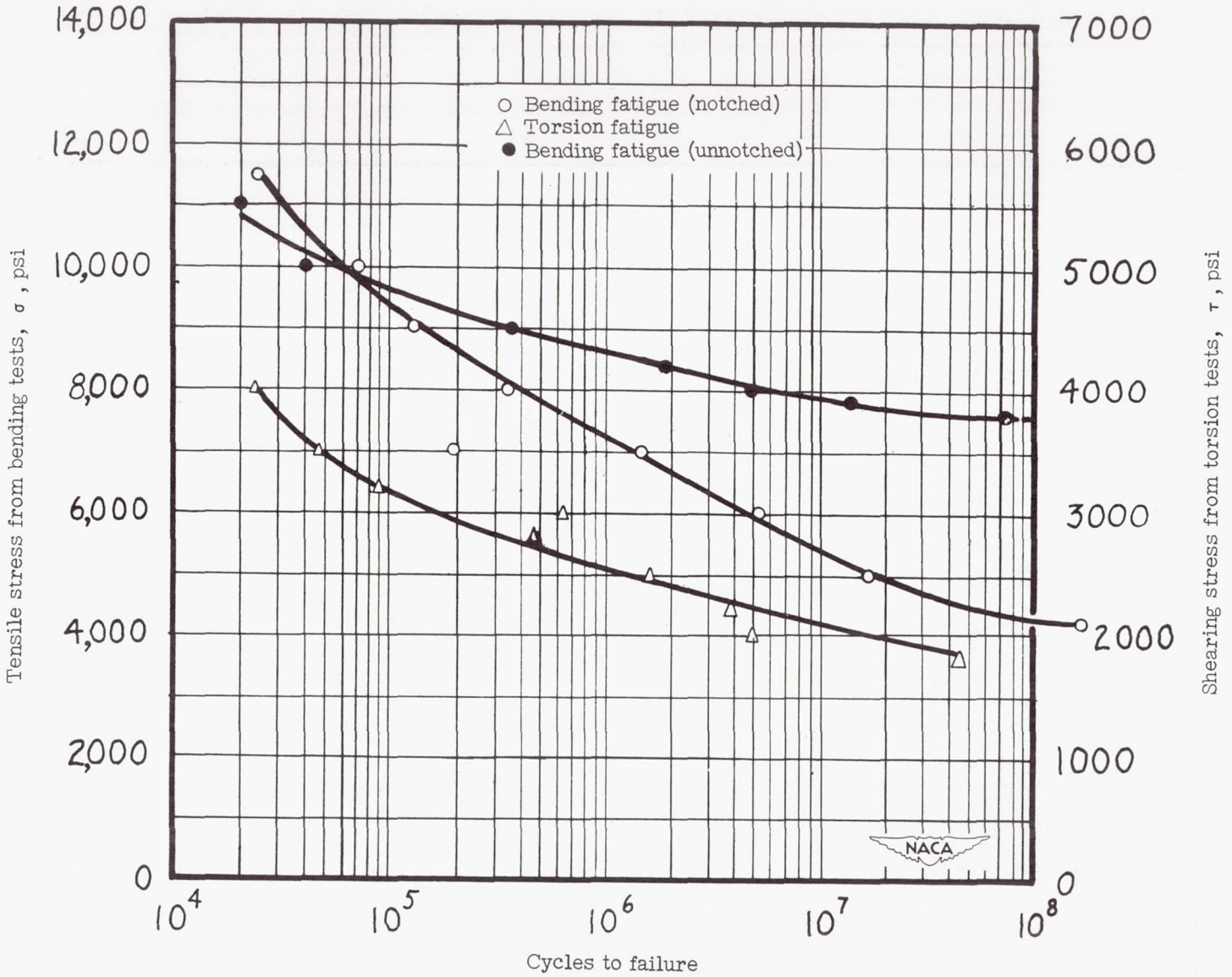


Figure 40.- S-N diagrams for tests of paper laminate obtained from rotating-cantilever-beam fatigue tests of notched and unnotched specimens and from torsion fatigue tests of unnotched specimens.

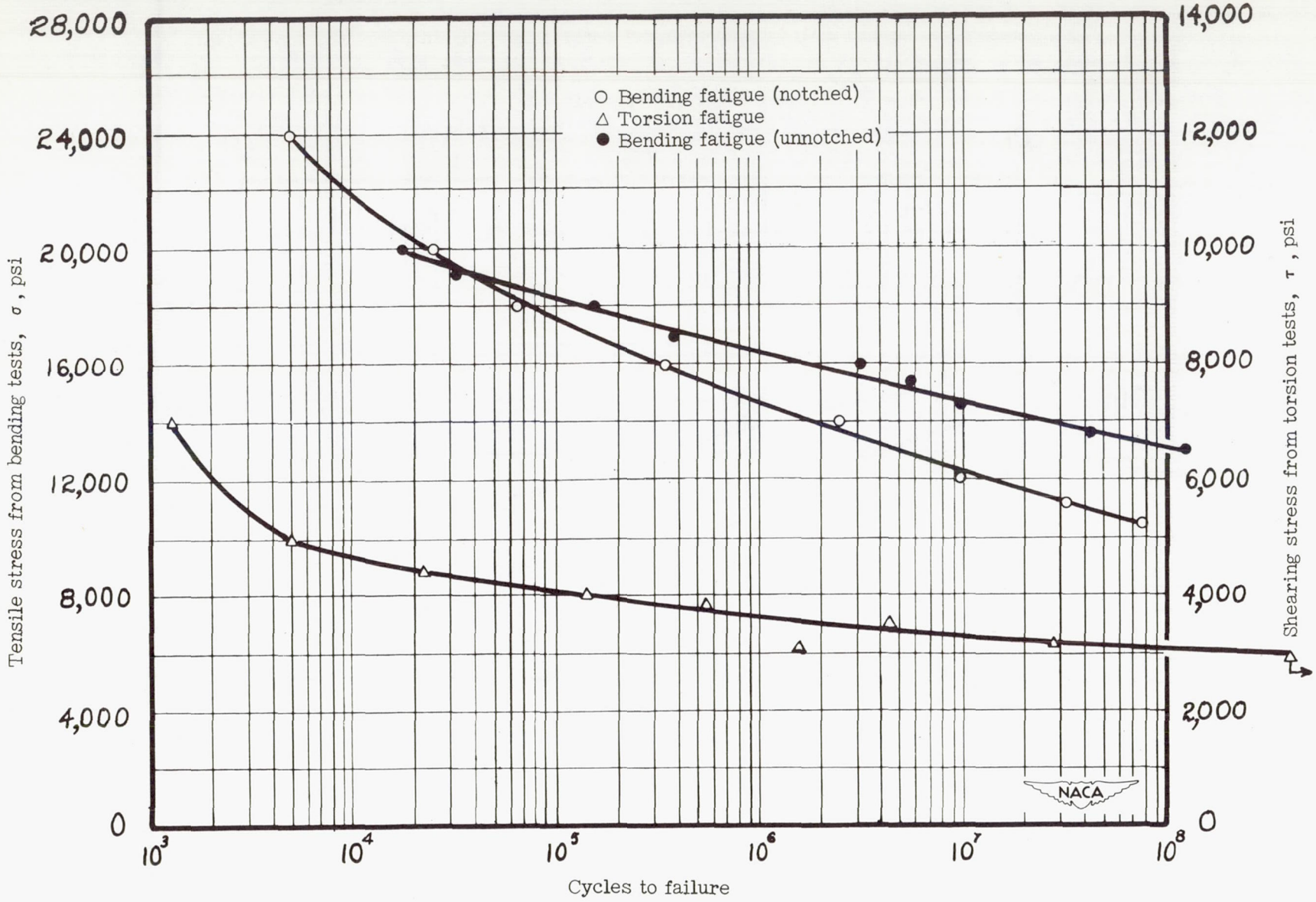


Figure 41.- S-N diagrams for tests of glass-fabric laminate obtained from rotating-cantilever-beam fatigue tests of notched and unnotched specimens and from torsion fatigue tests of unnotched specimens.

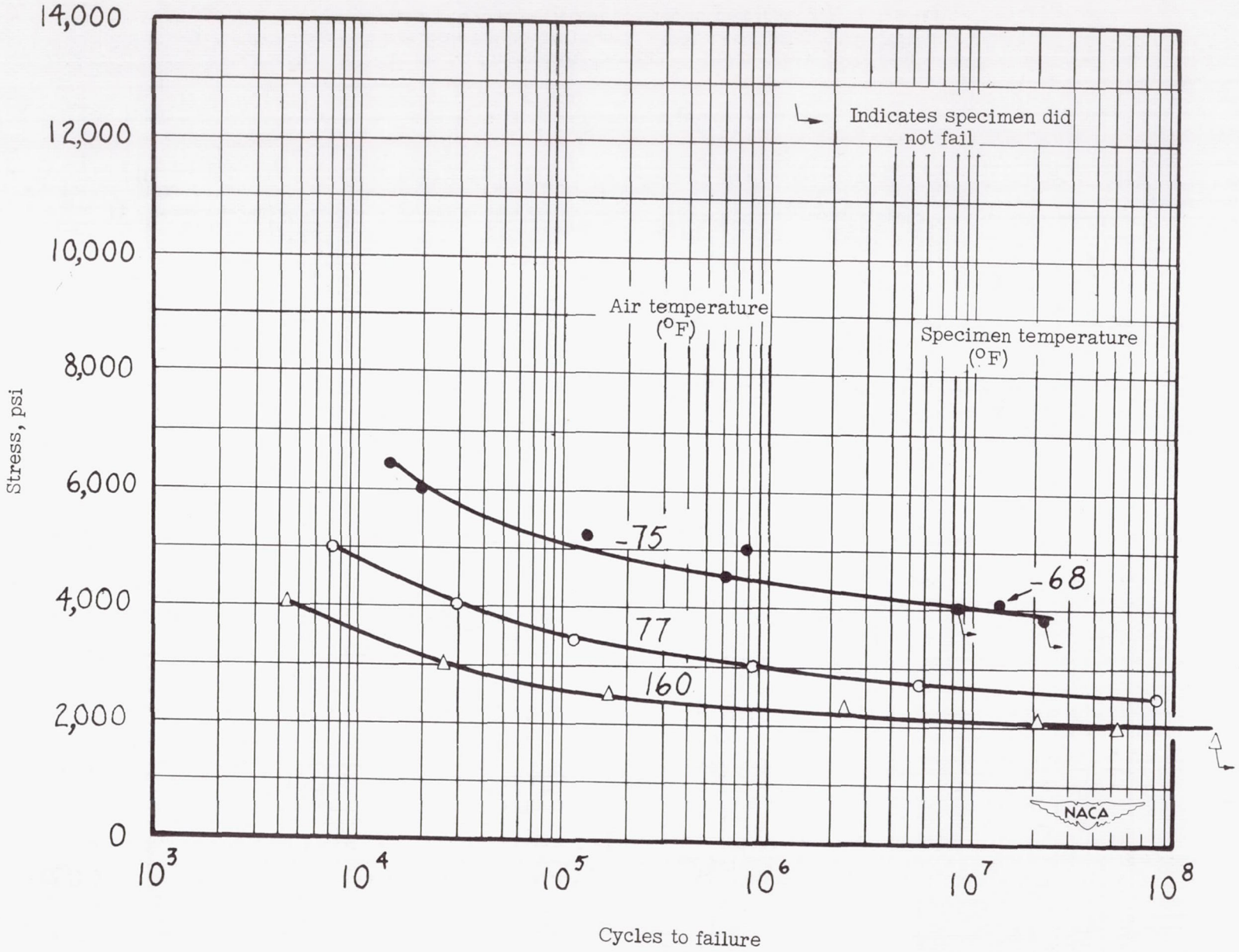


Figure 42.- S-N diagrams for rotating-cantilever-beam fatigue tests of low-pressure-molded canvas laminate at three different temperatures.

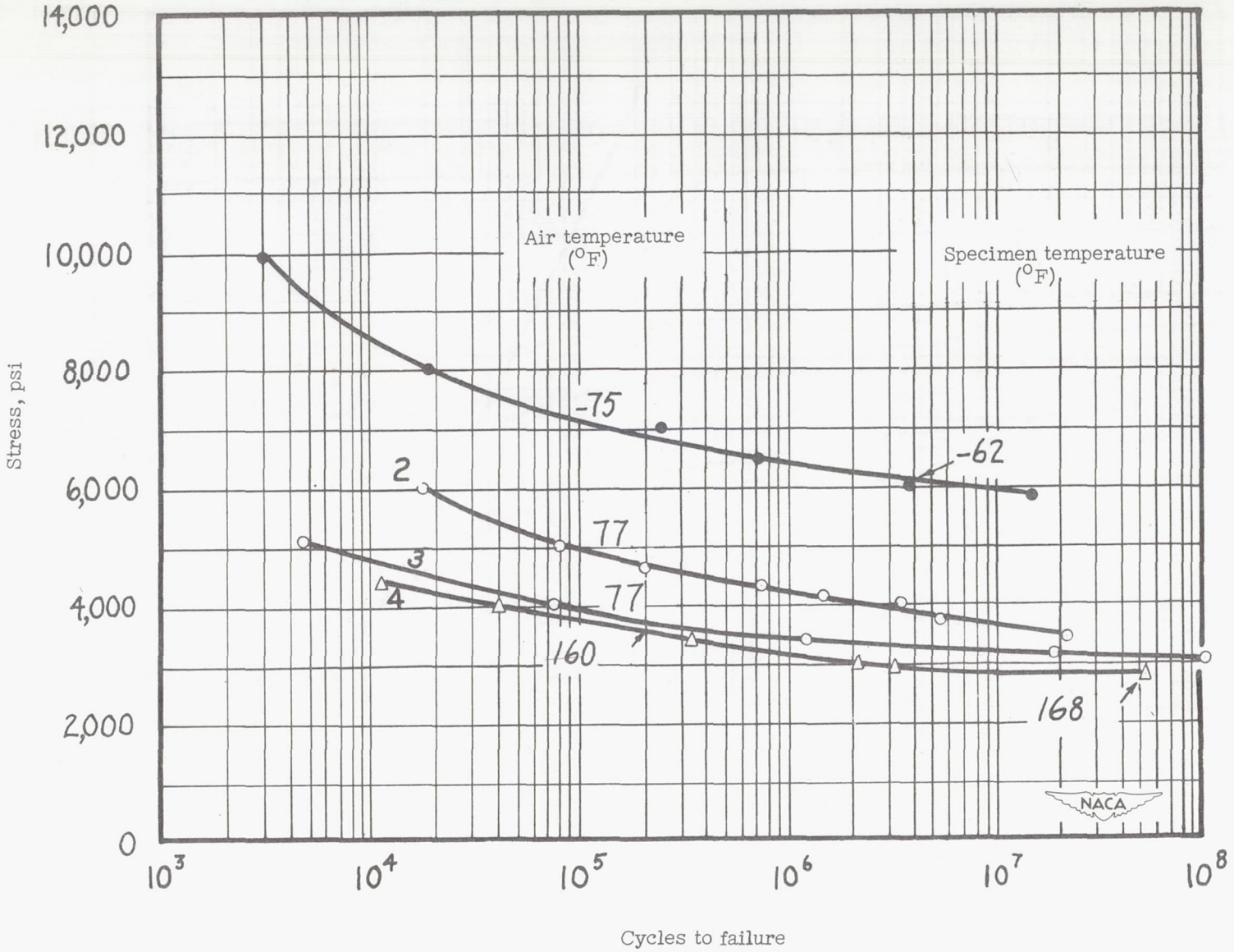


Figure 43.- S-N diagrams for rotating-cantilever-beam fatigue tests of grade-C canvas laminate at three different temperatures. Specimens for curve 3 were machined and tested approximately 1 year earlier than specimens for curves 1, 2, and 4.

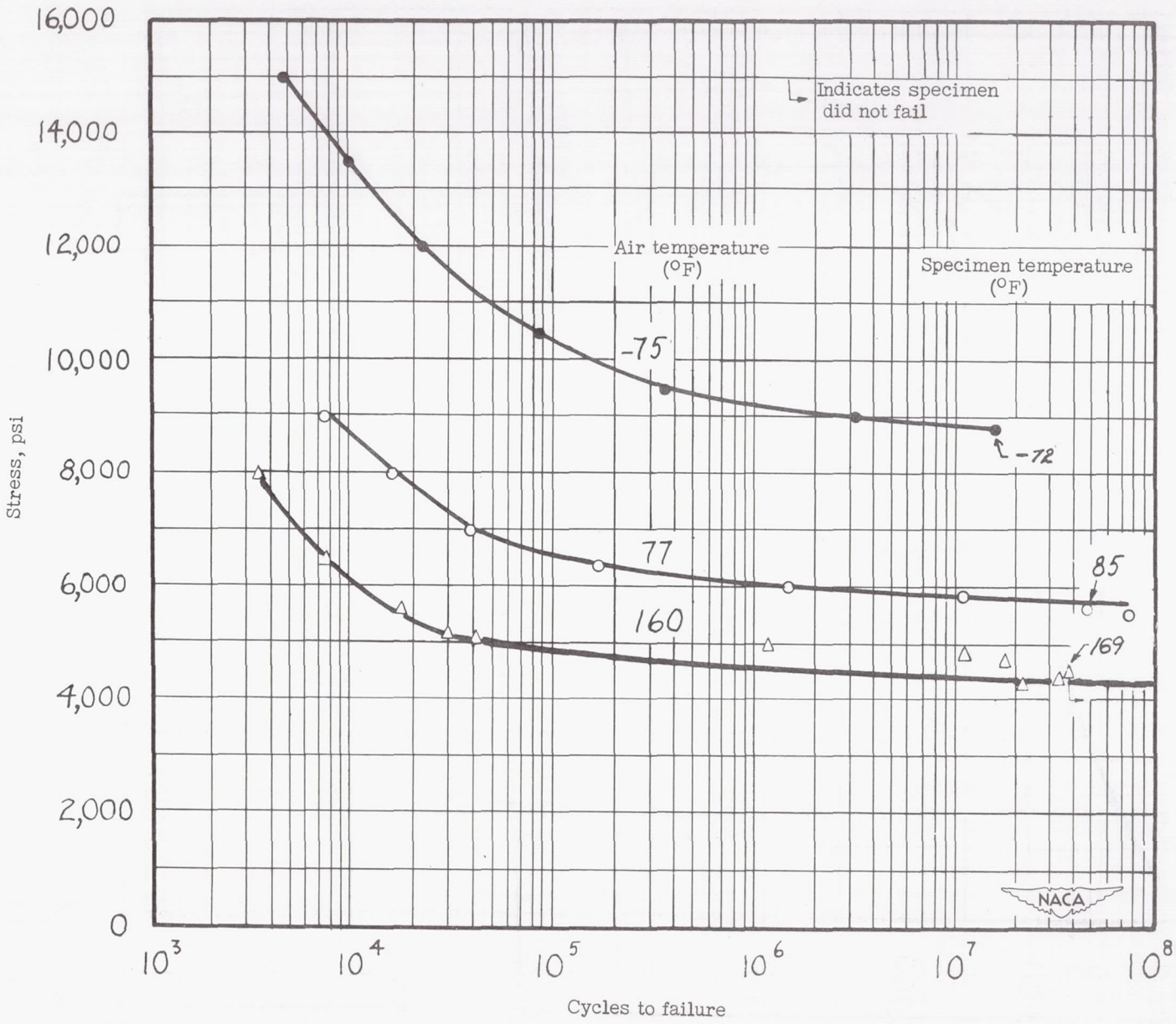


Figure 44.- S-N diagrams for rotating-cantilever-beam fatigue tests of rayon laminate

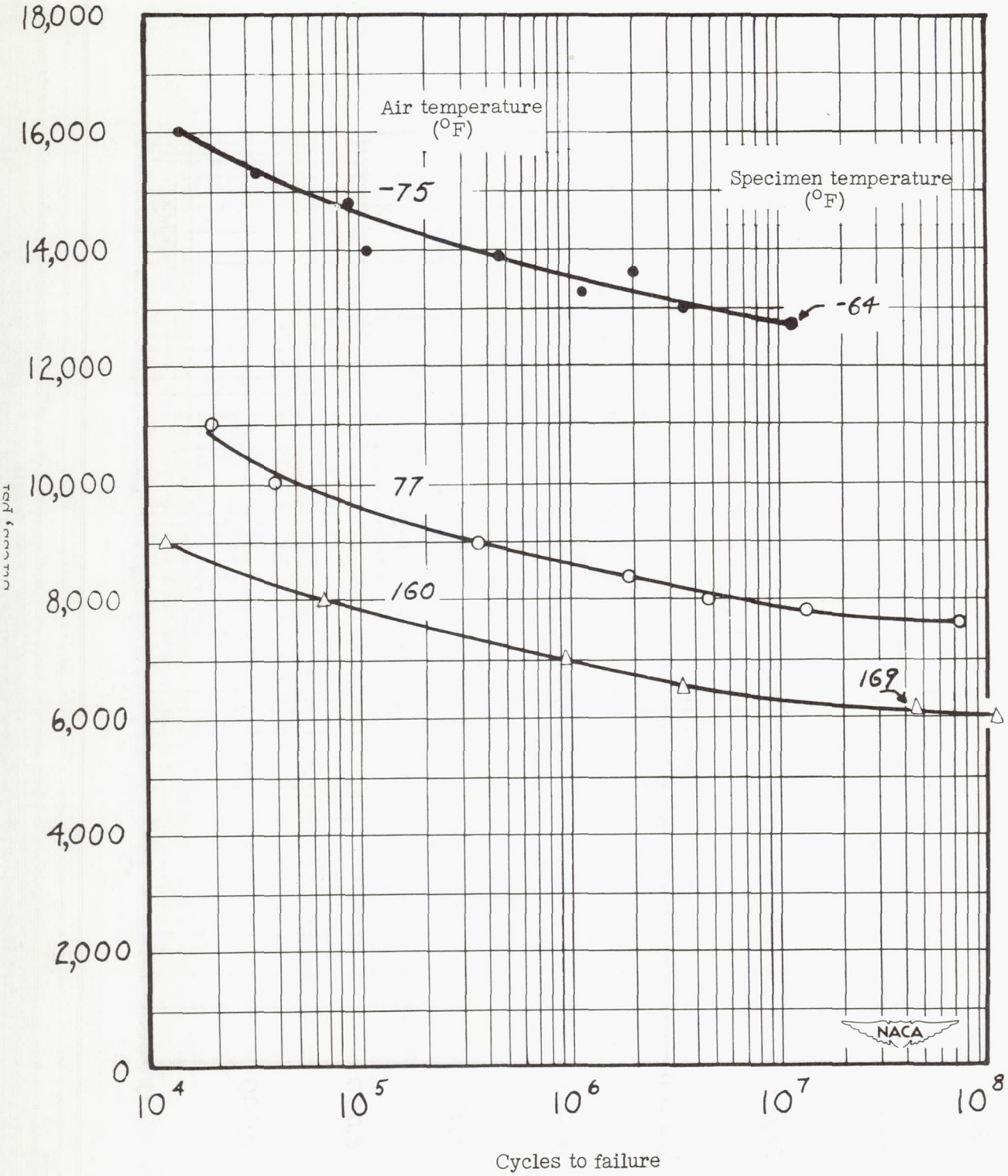


Figure 45.- S-N diagrams for rotating-cantilever-beam fatigue tests of paper laminate at three different temperatures.

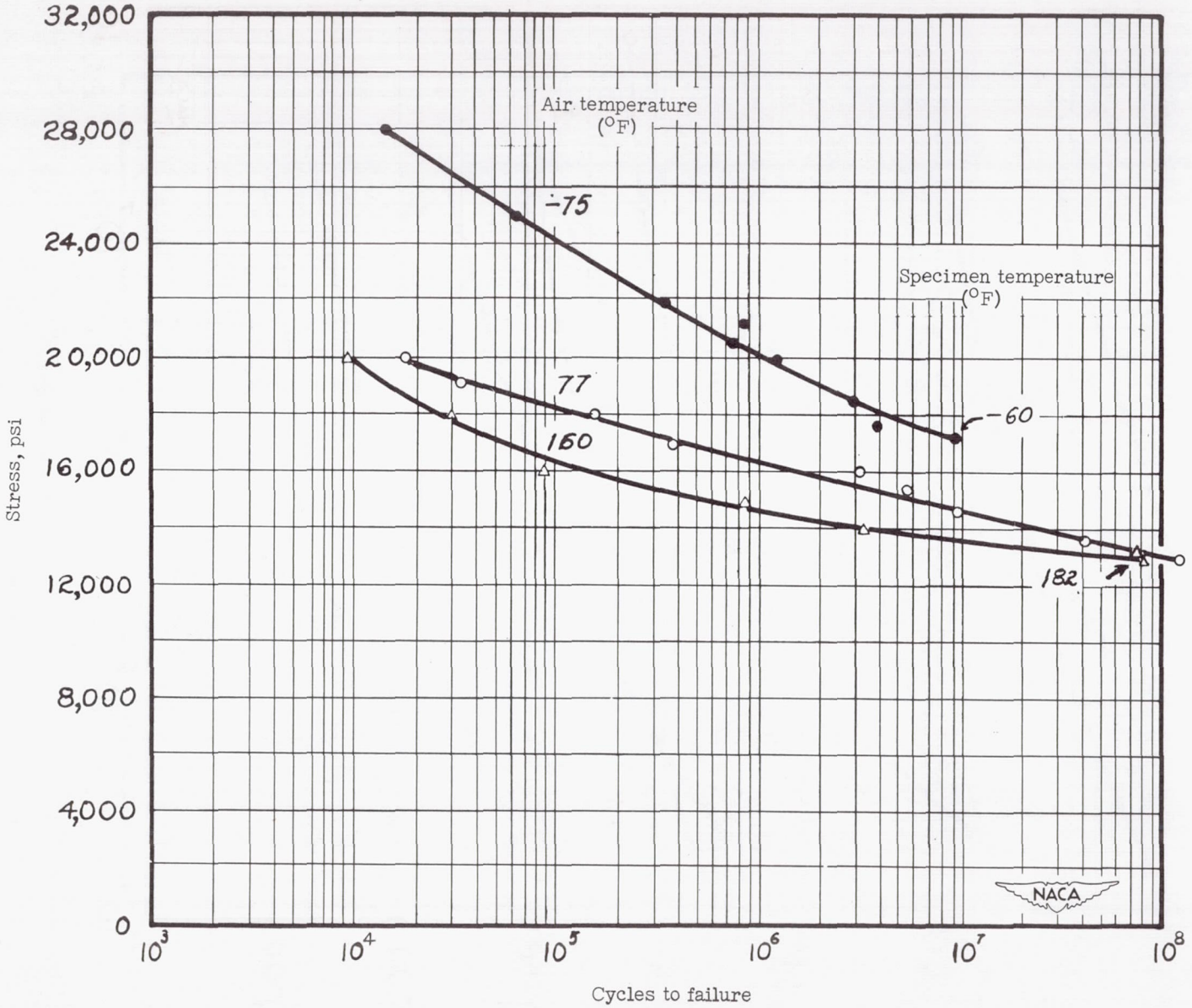


Figure 46.- S-N diagrams for rotating-cantilever-beam fatigue tests of glass-fabric laminate at three different temperatures.

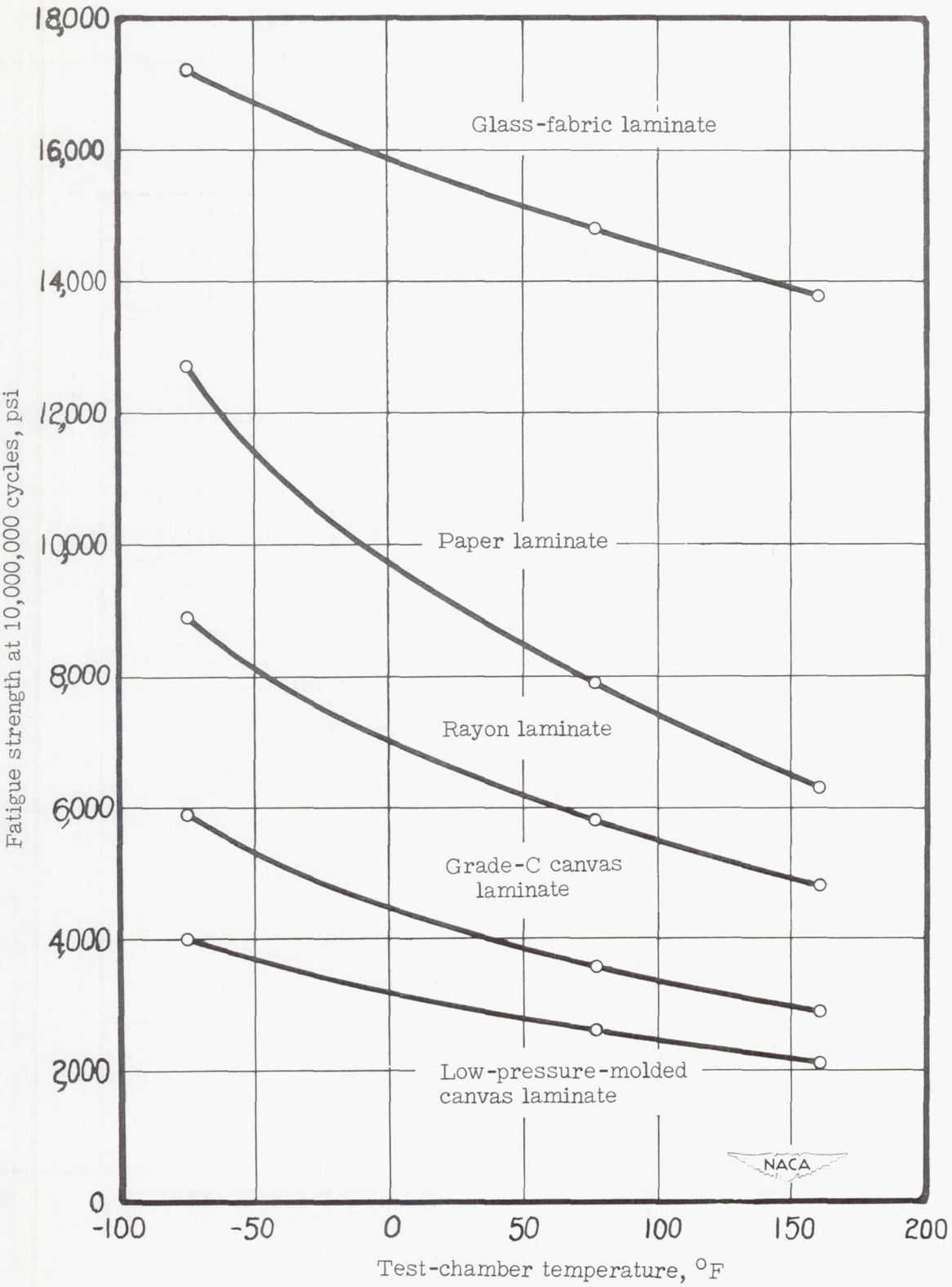


Figure 47.- Effect of temperature on fatigue strength at 10,000,000 cycles for all five laminates.

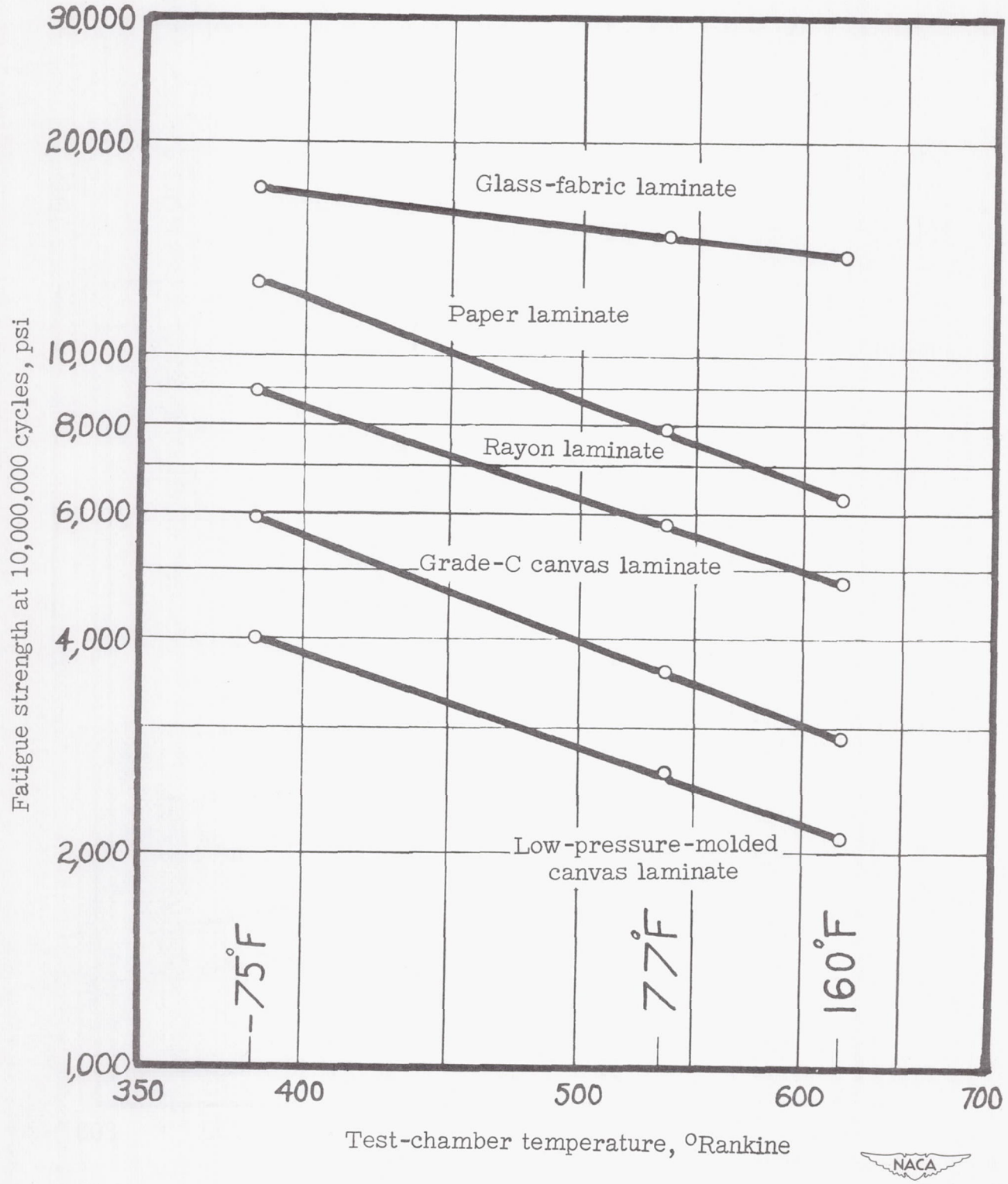


Figure 48.- Effect of temperature on fatigue strength at 10,000,000 cycles for all five laminates.

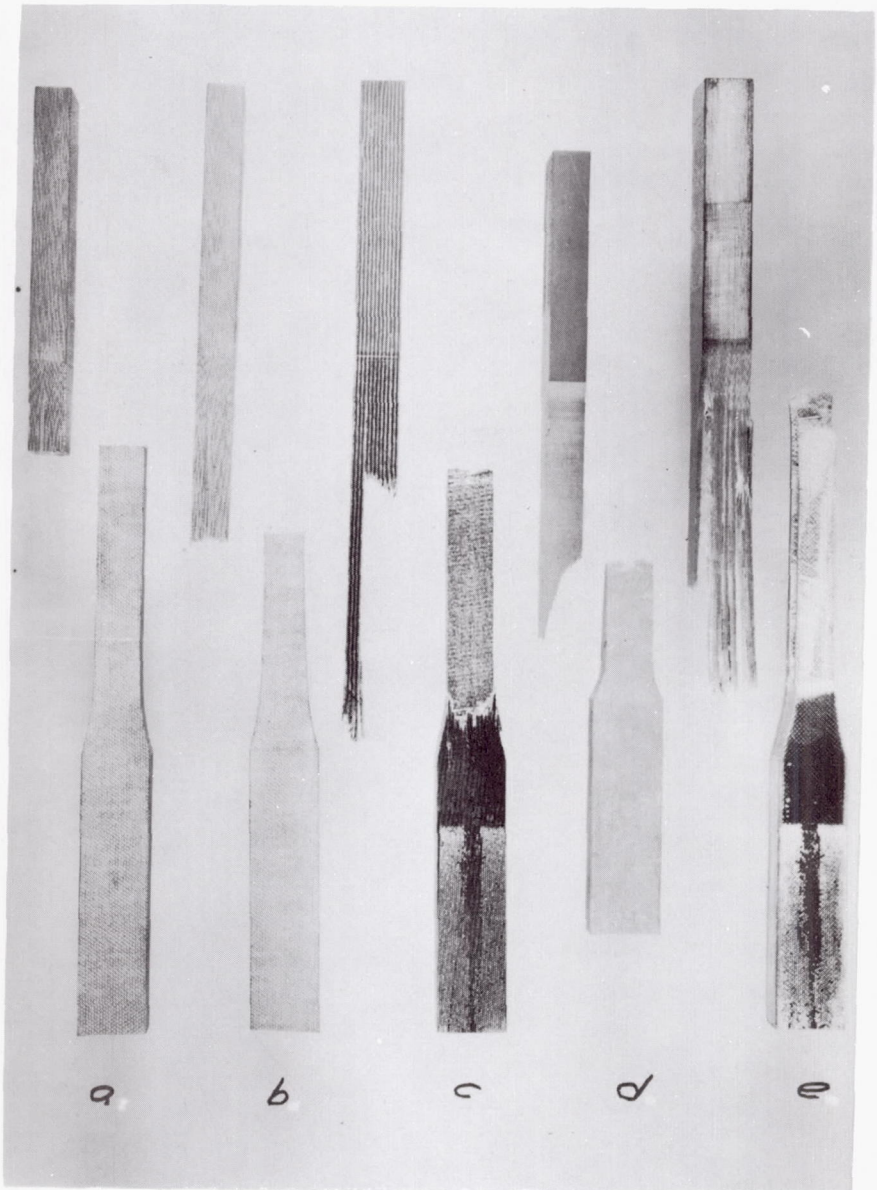


Figure 49.- Fractured tension specimens. a, low-pressure-molded canvas laminate; b, grade-C canvas laminate; c, rayon laminate; d, paper laminate; e, glass-fabric laminate.

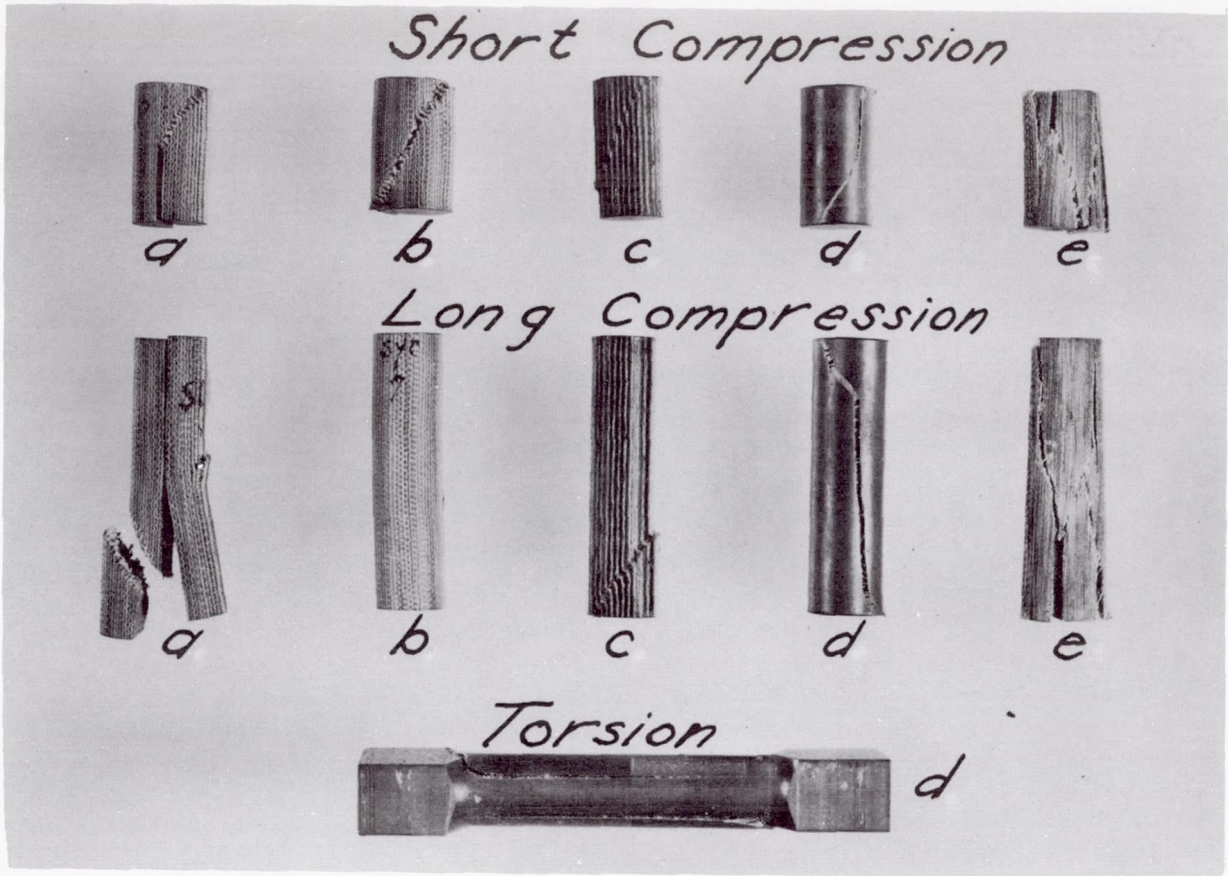


Figure 50.- Fractured compression and torsion specimens. a, low-pressure-molded canvas laminate; b, grade-C canvas laminate; c, rayon laminate; d, paper laminate; e, glass-fabric laminate.

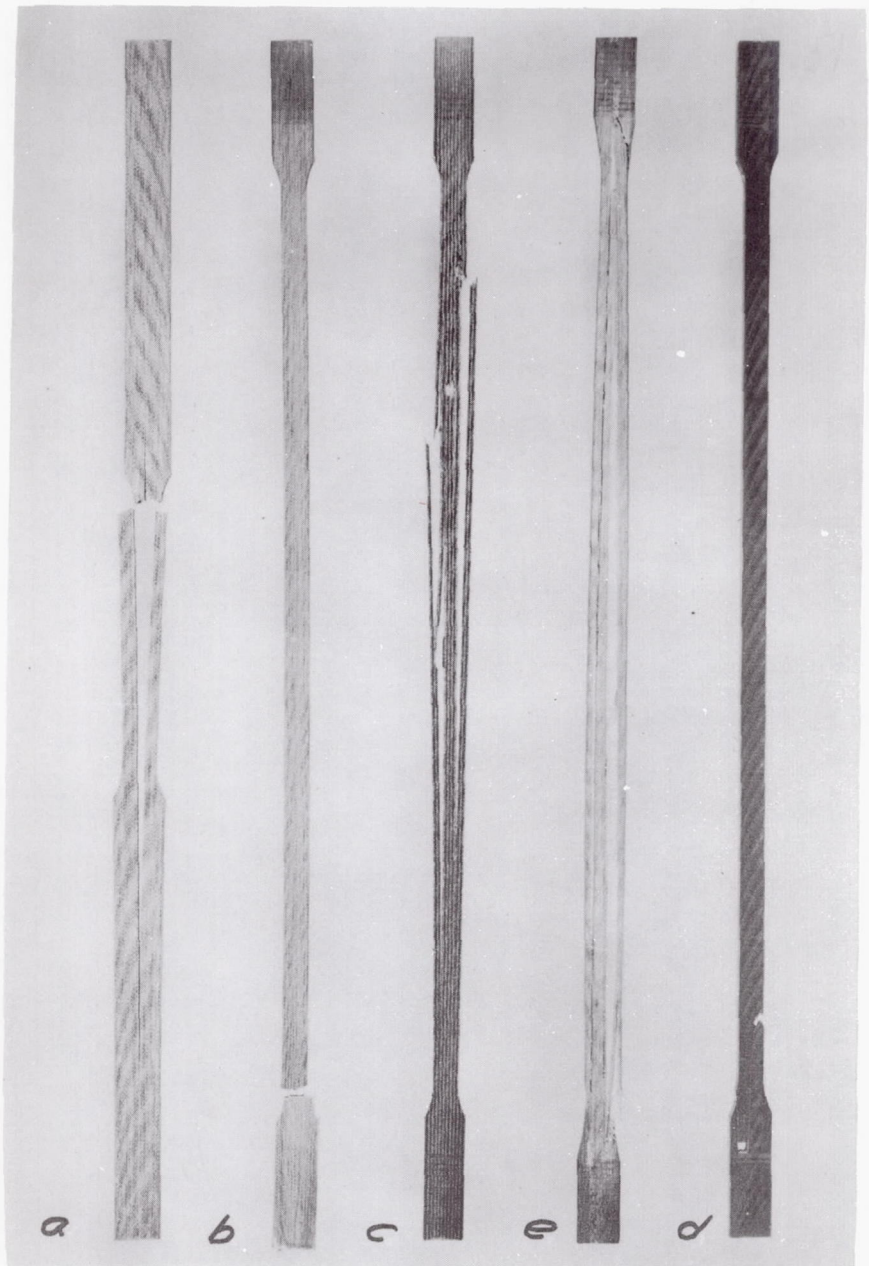


Figure 51.- Fractured creep specimens. a, low-pressure-molded canvas laminate; b, grade-C canvas laminate; c, rayon laminate; d, paper laminate; e, glass-fabric laminate.

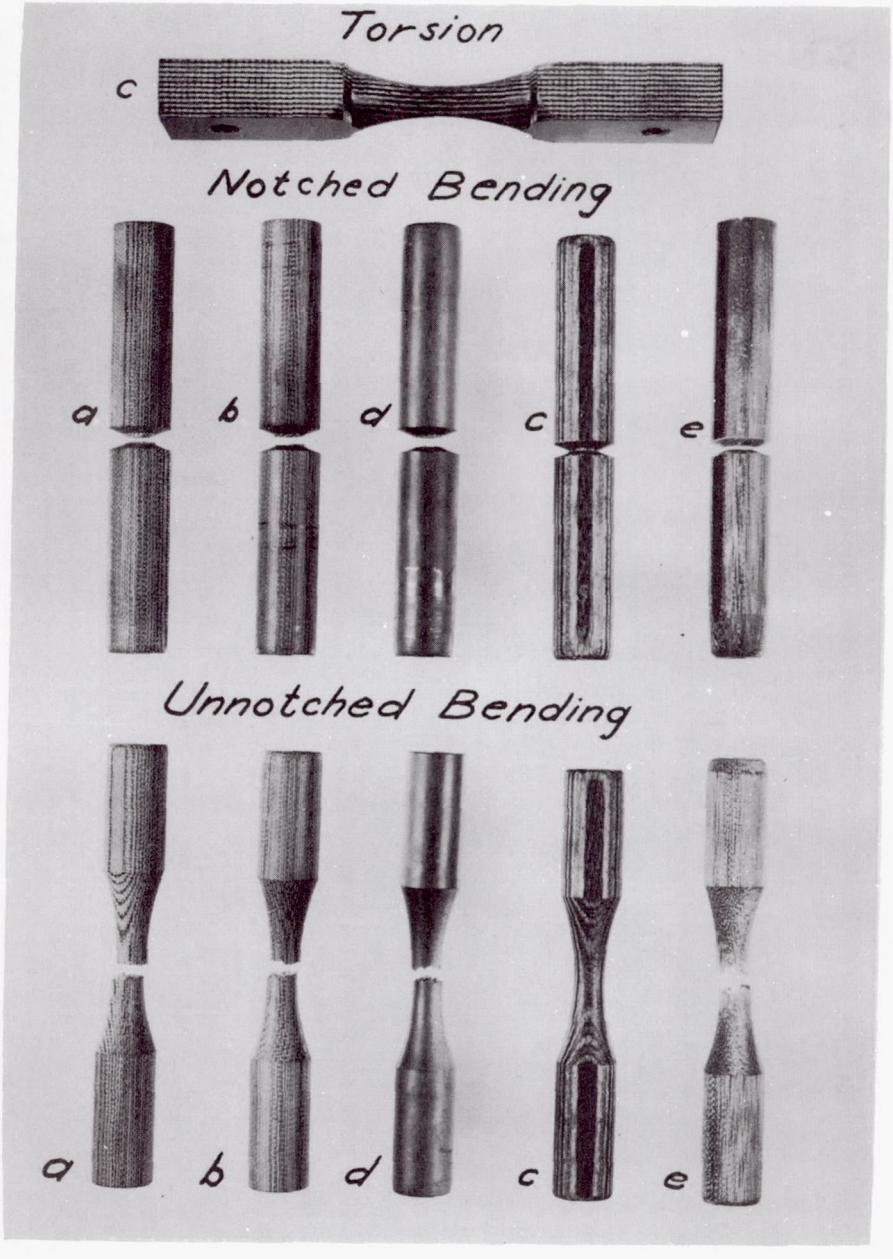


Figure 52.- Fractured and failed fatigue specimens. a, low-pressure-molded canvas laminate; b, grade-C canvas laminate; c, rayon laminate; d, paper laminate; e, glass-fabric laminate.