THE EFFECTS OF ELEVATED TEMPERATURE, THICKNESS, AND FABRIC ORIENTATION ON THE FLEXURAL FATIGUE PROPERTIES OF CTL-91-LD PHENOLIC RESIN FIBERGLASS REINFORCED LAMINATES

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SUMMARY

A review of the literature concerning the mechanical properties of fiberglass reinforced plastics revealed that little information was available on the fatigue strength properties, either under room or under elevated temperature testing conditions. Therefore, a heat resistant phenolic resin, CTL-91-LD, glass fabric laminate was selected for evaluation, and a testing program was begun. A 500° F. upper temperature limit for testing was set arbitrarily.

In order to determine the flexural fatigue properties of CTL-91-LD laminates at elevated temperatures it was first necessary to devise a test machine with elevated temperature capability. This was done by converting a standard Sonntag Scientific Corporation Flexure Testing Machine, Model SF-2, through the addition of an elevated temperature oven to the standard assembly. The principle of inertia compensation employed in the Sonntag machine made other changes unnecessary, since any changes in specimen stiffness (modulus of elasticity), resulting from temperature exposure, were automatically cancelled in the machine.

During the course of investigation of the flexure fatigue properties it became necessary to conduct side studies and additional tests to determine the effects of specimen thickness on the static tensile and reversed flexural properties. These correlary investigations were undertaken when, early in the program, a noticeable difference was observed in the flexural strength of 3/32 in. specimens compared to 1/16 in. specimens being tested under the same conditions.

It was found that the static tensile strength of 3/32 in. specimens averaged 22,000 psi, while the static tensile strength of the 1/16 in. specimens averaged 43,200 psi, both results based on room temperature testing conditions. The 1/16 in. specimens were not from the same lot of material as was used to prepare the flexural test specimens; however, all specimens were fabricated to the same specifications by the Cincinnati Testing and Research Laboratories, manufacturer of the CTL-91-LD resin. No satisfactory explanation for the difference in properties could be found.

The flexural fatigue properties of 1/16 in. specimens, under room temperature testing conditions, were different from the properties of the 3/32 in. specimens, with 1/16 in. specimens showing approximately ten per cent higher strength at 5×10^6 cycles to failure.

The fatigue strength at elevated temperature for CTL-91-LD laminates was determined with 1/16 in. specimens. The fatigue strength at 5×10^6 cycles increased with temperature from room temperature to 207° F. From 207° F. to 500° F. there was a decrease in strength with temperature. At 500° F. the strength at 5×10^6 cycles was 40.1 per cent of the room temperature value of 17,200 psi.

It was determined that the fatigue strength of the CTL-91-LD specimens tested (1/16 in. nominal thickness) was higher when the specimens were stressed parallel to the direction of the warp of the fabric than when tested perpendicular to the warp. These tests were conducted at room temperature only. A comparison of fatigue strength at 5×10^6 cycles shows that the specimens stressed parallel have approximately 32 per cent more strength than those stressed perpendicular. The difference is more than could be predicted based on the fabric construction of the 181/114 cloths used to fabricate the laminate (57 threads per inch in the warp and 54 threads per inch in the fill).

CHAPTER I

INTRODUCTION

General.--The primary purpose of this study was to determine the elevated temperature fatigue properties of a heat resistant glass-fabric laminate. Prior to 1953, when the testing reported herein was done, a number of studies had provided much information concerning the static properties of fiberglass reinforced plastics at elevated temperatures (References 1 through 15). A review of the literature on the fatigue properties, however, showed that almost no testing had been reported, either under room or elevated temperature conditions (References 16 and 17).

Although some years have passed since the fatigue testing program was completed, the author is not aware of any data reported during this period on the fatigue properties of CTL-91-LD laminates. This lack of information on such an important design property seems strange since the CTL-91-LD laminates are now in general use in the aircraft and missile industries, and other evaluations of this and similar resins have been reported during the interim period (References 18 through 21).

Material Description.--The CTL-91-LD laminates tested were prepared by the Cincinnati Testing and Research Laboratories. All specimens were prepared with the fabrics orientated parallel to each other in the warp direction. The fabricator describes the laminates as follows (Reference 22):

> The fiberglass used was identification number grade 181 with a 114 finish. Both the fabric and the finish are standard, with

the 114 commonly known as the chrome finish. The weave used is a standard harness or satin weave, with a thread count in the warp of 57, and in the fill of 54. The thickness of the raw glass per lamination is 0.0085 in. and seven laminations were required for the 1/16 in. laminate, and 11 for the 3/32 in. laminate. The density, insofar as we can determine from literature studies is 0.4 grams per cubic inch.

The resin used in preparation of your panels was of our own design and manufacture and is known to the trade as CTL-91-LD. This is a straight phenolic resin which meets the one stage category. Therefore, no additional catalyst is required or was employed. This resin is generally not sold in liquid form, but in the form of a preimpregnated fiberglass fabric. However, the method normally used is as follows: The resin is applied in a Waldren-type impregnating apparatus, which involves dipping the glass into a resin tank, then through adjustment squeeze rolls to meter the resin to the proper content and then to a traveling slat-type conveyor oven. The material is carefully controlled to adjust the percentage pick-up of the resin after drying and the flow or pre-cure, by means of measuring a small laminate of one in. by one in. plies pressed at 325°F. at five minutes under 15 psi pressure. The exudation from the tiny laminate is scrapped off; the difference in weight between the raw laminations and the cured laminations is known as "flow". A third control is the "drape". This term is used to describe the flexibility of the treated fabric and is controlled by careful adjustment of oven temperatures, but we do not use this data for control purposes, since it is unreliable. The preimpregnated material used in the panel submitted to you had a weight pick-up of 42 plus or minus 2-1/2 percent and a flow of 28 plus or minus 2-1/2 percent, and a drape of "75". The "75" drape material is well advanced into the B stage and is suitable only for the moderate and higher pressure molding in the range of 160 psi and up. The standard material designation is 42/75/28.

The molding process is as follows: The preimpregnated fabric is cut into the proper sizes to achieve the laminate required. The dry lay-up is wrapped in cellophane to serve as a releasing agent and inserted into a press already preheated to 250°F. Pressure at 160 to 200 psi was applied and the material was allowed to cure 30 minutes. The press was then cooled to 100°F. and the laminate removed. After the cellophane is stripped from the laminate, it is placed in a post-curing oven. The post-cure cycle, for the laminate submitted, was 18 hours at 250°F., 18 hours at 300°F., and 18 hours at 350°F. If thicker laminations are required, the post-cure cycle is increased.

The resin content by weight of the laminate is approximately 28 percent. The resin weight of the cured panel is determined by burning-off in a muffle furnace at temperatures not to exceed 900°F.

Typical physical properties of a CTL-91-LD laminate pressed at 100 psi are shown in Table 1 (Reference 23). Data were not available for laminates pressed at 160 psi.

CHAPTER II

INSTRUMENTATION AND EQUIPMENT

Tensile Test Machine

Tensile tests were conducted at room temperature using a standard Rhiele Precision Hydraulic Universal Testing Machine. The zero to 4,000 pound loading range was used for all tests reported herein. In this range the least scale reading is five pounds, and the accuracy is plus or minus ten pounds (Reference 24).

Flexure Fatigue Test Machine

A Sonntag Scientific Corporation Flexure Fatigue Machine, model SF-2, was adapted for elevated temperature testing and was used to test the materials described herein. This machine was designed for testing sheet materials in 100 percent reversed flexural stress under room temperature conditions; however, the geometry of the unit and the principle of inertia compensation employed in its operation made it possible to convert it to an accurate elevated temperature testing machine.

Description.--Front and right side views of the standard SF-2 machine are shown in Figures 1 and 2, respectively. It is to be noted that all of the parts which affect the force settings, speed of operation, and inertia compensation are located within the housing. The pedestal on which the test specimens are mounted is that portion of the machine which extends above the housing. The test oven, shown in Figures 3 and 4, was designed to fit above the housing to include the pedestal, the test specimen, the loading yoke, and about half of the length of the loading rod. The loading yoke and loading rod are identified as parts labelled AA and B, respectively, in Figure 1. All other parts of the test machine are thermally insulated from the heat source.

Operation.--Parts labelled in Figures 1 and 2 are referred to in the following discussion of the operation of the fatigue machine:

A one-quarter horsepower synchronous electric motor operates the tapered drive shaft, S, at a constant rate of 1800 revolutions per minute. The eccentric mass, A, at the free end of the rotating drive shaft sets up an inertia force which is transmitted through rod, B, to the load yoke, AA. The force is then transmitted to the free end of the cantilever beam specimen (Figure 5) through needle bearings, LL, the pivot bar, BB, clamp bar, CC, and clamping bolts, DD. The fixed end of the specimen is clamped between clamping bar, FF, and the pedestal, EE, with clamping bolts, GG. The magnitude of the force is determined by the eccentricity of the mass, A, as measured on scale, H, which is calibrated at the factory for each machine and shows the force on the yoke in pounds and ranges from zero to twenty pounds. The least scale reading is 0.5 pounds, but since the rim of the cylindrical eccentric mass, A, is further calibrated in 0.10 pound divisions, it is possible to obtain good approximations to readings such as 7.37 pounds.

Side motion of the test specimen is prevented by the side rod, C, which is attached to bearings at L and at the drive shaft. Rod C also supports variable poise weights, G, which are manually adjusted to compensate for variations in the masses of different test specimens. The accuracy of the machine depends on maintaining a constant effective mass for the vibrating system.

The machine automatically stops when the deflection of the test specimen reaches plus or minus one half inch and causes the microswitch, D, to be tripped. The automatic counter, PP, which gives readings in thousands of cycles, is also stopped when the microswitch is tripped. The microswitch is reset with the button, JJ, before the machine is to be started again with the starter button, HH.

The principle of operation of the flexure machine is discussed in the appendix.

Elevated Temperature Oven

The heating unit consisted of the following parts (see Figures 3 and 4):

(1) Outer and inner oven walls, a, of 0.032 in. thick aluminum sheets separated by one and one-half inches of fiberglass insulation,

(2) A one-quarter inch thickness of asbestos and a one and one-half inch thick fiberglass blanket, b, between the bottom of the oven and the fatigue machine housing,

(3) Six tubular heating elements, c; three on either side of the inside oven walls,

(4) One fast heating coiled heating element, d, located in front of the circulating fan, f,

(5) One fan assembly, f, consisting of a motor mounted on the back side of the oven (not visible in Figures 3 or 4), a shaft passing through holes in the outer and inner walls and the insulation between, and a fan blade within the oven,

(6) One thermometer, g, calibrated to 300° C., with a least scale reading of one degree Centigrade, and located so that the mercury reservoir would be one half inch from the test specimen,

(7) One oven temperature range selector control, h, with settings of "HIGH", "MEDIUM", and "LOW" corresponding approximately to oven temperature ranges of from 400° F. to 600° F., 200° F. to 400° F., and below 200° F., respectively,

(8) An electric fan starting switch, j, and

(9) One "Fenwal" thermoswitch control unit to maintain the oven temperature to within plus or minus five degrees Fahrenheit.

CHAPTER III

PROCEDURE

Sampling Procedure

The original plan for sampling of the fatigue test specimens called for a random selection from any of the four 1/16 in. (nominal thickness) or of the four 3/32 in. (nominal thickness) sheets supplied for testing. These specimens would then be used as required so that the fatigue machine could be operated at the highest force settings consistent with the desired stress level. By following this procedure the possible error due to friction losses would be minimized.

It was estimated that 48 specimens would be required to conduct the fatigue tests at room temperature, 200°F., 350°F., and 500°F., for those specimens to be stressed so that the direction of the warp of the fabric would be parallel to the direction of the bending stresses. The blanks for these specimens, 2.0 in. by 3.1 in., were then cut, half from the 1/16 in. thick sheets and half from the 3/32 in. sheets. At the end of each sheet sufficient material remained so that two blanks could be cut for specimens whose direction of the warp of the fabric would be perpendicular to the direction of stressing. The remaining two sheets in each thickness were to be used for tensile tests.

After the sheets were cut into blanks it was noted that there was a substantial variation in the thicknesses, even when comparing blanks cut from the same sheet. Nevertheless, they were thoroughly mixed, and after being routed to the final shape each specimen was measured with a micrometer to establish the average thickness in the test section. They were then graded according to thickness, numbered, and divided into four groups, one for each test temperature.

During the test run at 207°F. it was found that the specimens having thicknesses of approximately 3/32 in. did not give results consistent with those being obtained using the 1/16 in. material. The scatter was greater than had been anticipated and seemed to be of a higher order than the scatter reported in the literature. A change in sampling procedure was made as follows:

All of the specimens having a nominal thickness of 3/32 in. were removed from those groups not tested and were set aside for further investigation. From the remaining two sheets having a nominal thickness of 1/16 in., 21 samples were cut to replace those removed. From one of these sheets a strip 2.0 in. by 12 in. was saved for tensile tests. The material on the ends of each sheet was sufficient to obtain four more specimens for determining the effects of fabric orientation on the fatigue properties.

The single strip 2.0 in. by 12 in. did not prove to be enough for tensile testing, since the original type of test coupon, similar to those used to test metal specimens, caused failures to occur outside the test section as a result of stress concentrations in the small radii in the transition area. Another sheet of the 1/16 in. CTL-91-LD laminate was requested of the manufacturer and arrived late during the program. Tensile tests of the 1/16 in. laminates were conducted using samples taken from this sheet. Tensile tests of the 3/32 in. thick material were made from specimens taken from the original lot of the CTL-91-LD panels.

Preparation of Test Specimens

Fatigue Test Specimens.--The dimensions of the fatigue test specimens are shown in Figure 5. This specimen corresponds to the "Specimen No. 1" type as recommended by the manufacturer of the fatigue test machine (Reference 25). Through the following procedure in preparing specimens it was possible to meet the critical width dimensions throughout the tapered test section to tolerances of minus zero, plus 0.005 in. at any point, and equally as important, to keep the variation from specimen to specimen to within plus or minus 0.001 in.

The fatigue specimen blanks, 2.0 in. by 3.1 in., were trimmed oversize with a diamond saw, and then eight to ten specimens at a time were clamped in a routing fixture made especially for holding the specimens while they were being routed to final shape with a high-speed routing machine.

The routing operation was accomplished using a carbide-tipped router bit. The shank and flute of the bit were ground to the same diameter on a centerless grinder so that the smooth portion of the shank could be used as a guide along the tool steel template in the routing fixture. The specimens were compared periodically with a master template not used to form parts. In this way it was possible to detect any wear of the working template or of the router bit.

Since the specimens were clamped tightly while being routed, the edges were relatively free of frayed material; however, when the edges were wiped clean with cotton rovings it was noticed that small pieces of lint would adhere. The edges were sanded lightly with number 000 sandpaper, and given the lint test. When no more lint would adhere the specimens were considered smooth. No sanding whatever was done to the manufactured surfaces. These were left in the "as-received" condition, and care was taken to prevent these surfaces from becoming scratched.

Tensile Test Specimens.--The dimensions of the tensile test specimens are given in Figure 6. They correspond closely to the government specifications for tensile test coupons of plastic materials (Reference 26, Method 1011). A tool steel template was made to these dimensions and was used in a routing jig to shape the specimens in a manner similar to the procedure used to shape the fatigue specimens.

Testing Procedure

Fatigue Tests.--The procedure for conducting tests with the Sonntag machine is outlined in the operating manual (Reference 25). Seven basic steps are involved, as follows:

(1) The stress range and the thickness of material to be used are selected. The specimen thickness is selected to give the proper stress range for force settings of from two to twenty pounds - the operating limits of the machine. This is done by referring to Figure 90447-S of the operating manual, which is a graph of "Specimen Thickness" versus "Maximum and Minimum Machine Force". This step, of course, was made before the laminated sheets were requested from the manufacturer.

(2) The specimen pedestal (Figure 2) is adjusted, and the specimen is inserted into position, aligned, and clamped.

(3) The effective weight of the specimen is determined using the following equation:

$$W_e = 0.385\ \delta t$$

where,

W_e = effective weight (pounds)

δ = density (pounds/in.^{3})

t = specimen thickness (inches)

(4) The adjustable poise weight (part G, Figure 1) is set to the correct position. This is determined by referring to Figure 90452-S of the operating manual which shows "Effective Weight" versus "Poise Distance from the Pivot Shaft". The poise weight is locked, and no further adjustment is made unless the specimen material or thickness is changed.

(5) The final adjustment is made by setting the eccentric mass at the proper position for the desired stress level. Figure 90446-S of the operating manual gives the "Specimen Stress" for a one-pound force versus "Specimen Thickness".

(6) The counter on the side of the machine is set to zero.

(7) The test is started by pushing the starting button and continues until the specimen fails or until the deflection reaches one half inch.

For elevated temperature testing only a slight variation in the above procedure is required. Between steps six and seven there are the following additional steps:

(6a) The oven is closed.

(6b) The air circulating fan is started.

(6c) The oven heating units are turned on.

(6d) After waiting thirty minutes, the thermometer is checked for the proper temperature setting.

Step seven then follows.

The procedure used in calibrating the test oven for temperature control is as follows:

Assume that the oven is to be adjusted to maintain 350°F.

(1) The Fenwall Thermoswitch is adjusted according to the instructions in the operating manual (Reference 27) so that it will be set to open the electric circuits at approximately 350°F.

(2) The oven temperature range selector switch is set to the "Medium" position for operating in the 200°F. to 400°F. range.

(3) After thirty minutes a reading is taken with the oven thermometer. If the temperature is higher or lower than 350°F. a correction is made in the setting of the thermoswitch.

(4) Step three is repeated as often as necessary until the temperature remains at 350°F. plus or minus 5°F. After this is done no further adjustments are necessary until it is desired to conduct tests at some other temperature.

Tensile Tests.--Standard procedure was followed in conducting tensile tests at room temperature using the Rhiele Universal Testing Machine previously described. Since it was necessary to retighten the grips of the tension heads frequently during the tests, the rate of strain was not constant, but was estimated to be 0.005 in./in./minute with approximately five second stops at each of the test data-reading points.

CHAPTER IV

DISCUSSION OF RESULTS

Tensile Tests

The tensile test data are presented in Tables 2 and 3 for specimens having nominal thicknesses of 3/32 in. and 1/16 in., respectively. Figures 7 through 10 show conventional tensile stress-strain curves plotted from these data. From the slopes of the stress-strain curves the primary and secondary elastic moduli, the primary and secondary proportional limits, and the yield strength at 0.05 per cent offset from the primary modulus line were determined. A summary of these results is given in Table 4.

Only two specimens in each of the two thicknesses, 1/16 in. and 3/32 in., were tested, and in the 3/32 in. group one specimen failed outside the test section. The 1/16 in. specimens are from a different lot of material than the lot from which the flexural fatigue specimens were prepared.

All of the stress-strain curves show some curvature at stress levels from zero to 4,000 psi. In this low stress range it was difficult to obtain readings because of slippage of the specimens in the test machine grips. With one specimen, however, it was possible to obtain one good reading at the 2,000 psi stress level (see Table 2), which confirmed, at least for this specimen, the existence of an initial nonlinearity in the stress-strain curve.

The primary and secondary elastic moduli are not greatly different for any of the four specimens tested; however, a great difference is seen to exist between the tensile ultimate strength of the 1/16 in. specimens compared to the 3/32 in. specimens. The 3/32 in. specimens failed at an average stress of 22,000 psi while the 1/16 in. specimens failed at an average stress of 43,200 psi (see Table 4).

The large variation of failing stress between the 3/32 in. and the 1/16 in. specimens caused the author some concern, since all of the specimens were prepared in exactly the same manner. Actually, the manufacturer acknowledges that there is to be anticipated some variation in the properties of CTL-91-LD laminates, but not of the order of magnitude noted herein. Shown in Figure 11 are curves of the flexural strength of CTL-91-LD laminates of 1/8 in. and 1/2 in. thicknesses. These curves were provided by the Cincinnati Testing and Research Laboratories (Reference 23) and show that the room temperature flexural strength for 1/8 in. material is 52,500 psi compared to 35,500 psi for 1/2 in. material. Even assuming, conservatively, that a linear relationship exists, and extrapolating for thicknesses of 1/16 in. and 3/32 in., not more than a few per cent difference would be anticipated in the flexural strengths of 1/16 in. and 3/32 in. specimens. It is likely that a similar relationship would exist for the variation of tensile strength with specimen thickness, although such data were not available for direct comparison.

Others have also noted substantial differences in the properties of fiberglass laminates prepared under similar conditions. VanEcho, Garrabrant, and Simmons (Reference 19) report - "It is, generally, well known that plastic-glass laminates of uniform properties are difficult to reproduce. They can have considerably different properties from one manufacturer to another, from one batch to another, quite often from sheet to sheet and even within one sheet of the same material." It is noteworthy that this statement was made in particular with regard to the laminate NA-91-LD, which is a laminate fabricated by the North American Aviation Corporation with the same basic CTL-91-LD resin.

In an earlier report VanEcho, Remely, and Simmons (Reference 20) found that the room temperature tensile strength of two different lots of CTL-91-LD laminates varied from 13,000 psi for one lot to 23,000 psi for the other. The sheets from which the specimens were prepared were of the same thickness and material and were prepared in the same manner, with the exception that the postcure was longer for those specimens which failed at the lower stresses.

Boller (Reference 21) evaluated the effect of thickness of CTL-91-LD laminates on the tensile strength for thicknesses ranging from 0.010 in. through 0.107 in. The fabric used in the evaluation was number 112 and had a Volan A finish. The molding conditions were not stated. Boller found that the relationship between the ultimate tensile strength and thickness could be expressed by the following empirical equation:

$$S_t = 46,300 - 57.3/t$$

where, S_t = ultimate tensile strength, psi

t = thickness of the material, in.

For the present study the predicted difference between the failing stresses of the 1/16 in. and 3/32 in. specimens could not be explained by Boller's equation, since it would not show more than a two per cent difference.

Fatigue Tests

Effects of Elevated Temperature.--The results of the flexural fatigue testing of 1/16 in. specimens of CTL-91-LD material are summarized in Figure 12. Shown in this figure are the standard S-N curves for 80° F., 207° F., 350° F., and 500° F., compiled from the test data shown in Tables 5, 6, and 7. These data were further reduced to show the variation of flexural strength with temperature when the parameter, "the number of cycles to failure", is held constant (see Fig. 13). Shown are curves for 1,000, 10,000, 100,000, 1,000,000, and 5,000,000 cycles to failure. For this series of tests the bending stresses were applied parallel to the warp direction of the fabric.

Figure 13 shows that the fatigue strength at 1,000,000 and at 5,000,000 cycles at 190° F. are higher than the fatigue strength for the same number of cycles at room temperature. At 5,000,000 cycles the 500° F. fatigue strength of 6,900 psi is 40.1 per cent of the corresponding room temperature value of 17,200 psi.

When comparisons are made with regard to the number of cycles of reversed stress it is important to keep in mind the time at temperature represented by a given number of cycles. The testing speed was constant for all test runs so that 108,000 cycles represented one hour of test time in each instance. In addition, there was a thirty minutes waiting period at the test temperature before cycling was begun. Thus, specimens which had been given 5,000,000 cycles at elevated temperature had been exposed to this temperature continuously for 46.8 hours.

In Table 8 three specimens with a nominal thickness of 3/32 in. are listed separately. One of these had been run at 207° F. with the other specimens, which, up to this time, had all been of 1/16 in. nominal thickness. A marked difference was observed in the fatigue properties of this particular specimen - it failed at 847,000 cycles at a stress of 17,750 psi, whereas other specimens being tested at the same stress level were running approximately 5,000,000 cycles. Two more of the 3/32 in. thick specimens were then tested at the same temperature and at the same stress level for comparison. They failed at even lower numbers of cycles than did the first. The second ran only 273,000 cycles and the third only 244,000 cycles. It was at this time that the decision was made to continue the elevated temperature fatigue testing with the 1/16 in. nominal thickness specimens only.

Major Ramke (Reference 15) has stated: "It has been found that in general the fatigue strength at 10,000,000 cycles of an unnotched laminate specimen in axial loading, when tested at standard conditions with a mean stress of zero, is approximately 25 per cent of the static or short time tensile strength." While the present work was limited to 5,000,000 cycles to failure, and the tests were conducted with flexural stresses rather than axial stresses, the following comparison tends to confirm Major Ramke's generalization, even when applied to elevated temperature tests.

No static flexural tests were conducted during the course of this study so that no direct comparison can be made of the flexural fatigue strength at given temperatures and the static flexural strength for the same number of hours of exposure prior to testing. However, data provided by the manufacturer on the static flexural strength of the CTL-91-LD laminates after 1/2 hour and after 200 hours of exposure time at temperature, prior to testing at temperature (see Fig. 11), can be compared on a qualitative basis. This was done as follows:

The static flexural strength for 46.8 hours exposure time at room temperature, 207° F., 350° F., and 500° F. were interpolated from the 1/2 hour and 200 hour exposure curves of Figure 11, assuming a linear variation (see Table 9). From Figure 13, which shows the effects of elevated temperature on the flexural fatigue strength, the fatigue strengths at 5,000,000 cycles were listed for the same temperatures. Since 5,000,000 cycles represents 46.8 hours exposure time the comparison is for the same number of hours of temperature exposure in each case. The ratios of the flexural fatigue strength at 5,000,000 cycles divided by the ultimate static flexural strength were then plotted in Figure 14 to show the variation of this parameter with temperature. The resultant curve shows that from room temperature to 207° F. there is an increase in the ratio from 0.33 to 0.36. Above 207° F. there is an almost linear decrease up to 500° F. where the value is 0.20.

Effects of Thickness.--As explained previously it was suspected that there was a basic difference in the flexural fatigue properties of the 3/32 in. specimens as compared to the 1/16 in. specimens. To establish whether the difference was generally applicable to the material on hand, or whether it was applicable to only a few of the specimens, room temperature flexural fatigue tests were conducted with the 3/32 in. thick specimens. As with the room and elevated tests for the 1/16 in. specimens, the stresses were applied parallel to the warp direction of the of the fabric.

The results of the room temperature fatigue tests with the 3/32 in. material are shown in Figure 15, where for comparison, the curves for room temperature and 207° F. tests with the 1/16 in. material are also shown. The curves confirm that there is a basic difference of at least ten per cent in the fatigue properties of 1/16 in. specimens and 3/32 in. specimens, with the 1/16 in. specimens showing the higher strength. However, the difference was not of the order of magnitude which had been expected, and is not in keeping with the order of magnitude of difference noted in the tensile ultimate properties.

Effect of Fabric Orientation.--Figure 16 is a conventional S-N curve showing the effect of fabric orientation on the flexural fatigue properties of 1/16 in. specimens of CTL-91-LD laminates. The points for this curve were plotted based on the test data listed in Table 5. For this series of tests the specimens were orientated so that the stresses would be applied either parallel or perpendicular to the warp direction of the fabric.

Figure 16 shows that there is a noticeable difference in the fatigue properties of specimens stressed parallel as compared to those stressed perpendicular to the warp. For any given number of cycles to failure strength is higher for the specimens stressed parallel to the warp direction. This difference is greater than would be predicted based on the thread count of the 181/114 fabric, which is 57 threads/in. in the warp direction and 54 threads/in. in the fill, or woof, direction.

CHAPTER V

CONCLUSIONS

1. The variation in thickness throughout the sheets of CTL-91-LD laminates was four to five times as great as standard tolerances for metal sheets of the same nominal thicknesses.

2. The recognition of primary and secondary slopes of the tensile stress-strain curves is in agreement with this observed characteristic for fiberglass laminates by others.

3. The effect of thickness on the ultimate tensile strength of the CTL-91-LD laminates tested is greater than has been observed by others.

4. The tensile properties of the 1/16 in. specimens as determined herein cannot be related directly to the tensile properties of the 1/16 in. specimens used for the flexural fatigue tests.

5. In general, the effect of elevated temperature on the flexural fatigue properties of the CTL-91-LD laminates tested is to reduce the allowable stress for any given number of cycles to failure; however, up to 207° F., for comparisons made at less than 100,000 cycles to failure, the fatigue strength at temperature is higher.

6. The flexural fatigue strength of 1/16 in. specimens of the CTL-91-LD laminates tested at both room temperature and at 207° F. is greater than the strength of the 3/32 in. specimens for comparisons made at any given number of cycles to failure.

7. The effect of fabric orientation on the flexural fatigue strength of 1/16 in. specimens of the CTL-91-LD laminate tested is such that when stressed parallel to the warp direction of the fabric the strength is from 0.21 to 0.36 higher than when stressed perpendicular to the warp direction.

8. The generalization made by Major Ramke that the fatigue strength at 10×10^6 cycles for 100 per cent reversed axial loadings is approximately 25 per cent of the short time static tensile stress for fiberglass laminates may be applied to flexural stress fatigue and static flexural stress even when the effects of temperature are included, provided that the static flexural stress allowable is corrected for exposure time at temperature.

APPENDIX

Table 1. Physical Properties of CTL-91-LD Fiberglass Laminates Pressed at 100 Psi[x]

	Room Temp. Strength (psi)	500° F. Strength [xx] (psi)
Flexural Strength	55,000	40,000
Tensile Strength	45,000	40,000
Block Compression Strength (one inch cube vertical lamination)	50,000	---
Yzod Impact Strength (notched specimen)	15 (ft./lb.)	15 (ft./lb.)
Young's Modulus in Flexure	3.5×10^6	3.25×10^6
Single Shear Strength (vertical to laminations)	33,000	---

[x] Data supplied by the Cincinnati Testing and Research Laboratories.

[xx] Specimens conditioned 1/2 hour at 500° F. prior to tests.

Table 2. Static Tensile Stress-Strain Test Data for

3/32 in. Thick CTL-91-LD Laminate

Force (lb.)	Extensometer Reading (in.)	Stress (psi)	Strain (in./in.)
		Specimen No. 3 [x]	
0	-0.0002	0	0
210	0.0013	4,770	0.00075
300	0.0023	6,810	0.00125
410	0.0036	9,290	0.00190
510	0.0048	11,550	0.00250
600	0.0059	13,600	0.00305
700	0.0070	15,850	0.00360
800	0.0083	18,150	0.00425
915	0.0094	20,800	0.00480

Failure occurred 1/2 in. outside test section. Stress at failure is average stress - the same as for the other values.

Force (lb.)	Extensometer Reading (in.)	Stress (psi)	Strain (in./in.)
		Specimen No. 5 [xx]	
0	-0.0001	0	0
105	0.0010	2,290	0.00055
200	0.0015	4,350	0.00080
300	0.0026	6,530	0.00135
408	0.0038	8,900	0.00195
500	0.00505	10,900	0.00258
600	0.00645	13,000	0.00328
704	0.00755	15,300	0.00383
800	0.00885	17,400	0.00448
900	0.0101	19,500	0.0052
1,005	0.0115	21,900	0.00625
1,067	------	23,200	Failure

Normal failure at minimum test cross-section. Stress at failure based on minimum area.

[x] 2 in. gage length, average thickness = 0.0891 in., average area = 0.0441 in.^{2}, minimum area = 0.0434 in.^{2}

[xx] 2 in. gage length, average thickness = 0.0908 in., average area = 0.0460 in.^{2}, minimum area = 0.0457 in.^{2}

Table 3. Static Tensile Stress-Strain Test Data for

1/16 in. Thick CTL-91-LD Laminate

Force (lb.)	Extensometer Reading (in.)	Stress (psi)	Strain (in./in.)
	Specimen No. 10 [x]		
0	0	0	0
200	0.0021	4,930	0.00105
300	0.0032	7,390	0.00160
405	0.0045	9,990	0.00225
505	0.0057	12,400	0.00285
610	0.0074	15,000	0.00370
700	0.0089	17,200	0.00445
800	0.0105	19,700	0.00525
1,135	0.0145	27,900	0.00725
1,250	0.0160	30,800	0.00800
1,400	0.0178	34,500	0.00890
1,480	0.0190	36,500	0.00950
1,780	------	44,500 [xx]	Failure
	Specimen No. 11 [x]		
0	0.0001	0	0
215	0.0016	5,300	0.00075
295	0.0025	7,270	0.00120
400	0.0037	9,860	0.00180
490	0.0048	12,100	0.00235
595	0.0061	14,700	0.00300
715	0.0078	17,600	0.00385
965	0.0112	23,700	0.00555
1,050	0.0123	25,900	0.00610
1,160	0.0138	28,600	0.00685
1,255	0.0150	30,900	0.00745
1,350	0.0161	33,300	0.00800
1,455	0.0176	35,900	0.00875
1,545	0.0188	38,100	0.00935
1,680	------	42,100 [xx]	Failure

[x]2 in. gage length, average thickness over test section of 0.0820 in., average width = 0.0495 in., average area = 0.0406 in.^{2}, minimum area = 0.0400 in.^{2}

[xx]Stress at failure based on the minimum cross-sectional area.

Table 4. Summary of Static Tensile Stress-Strain Test Data

Specimen Number	Nominal Thickness (in.)	Actual Thickness (in.)	Primary Elastic Modulus (lb./in.²) x 10⁻⁶	Secondary Elastic Modulus (lb./in.²) x 10⁻⁶	Primary Proportional Limit (lb./in.²)	Secondary Proportional Limit (lb./in.²)	Yield Strength at 0.05 Per Cent Offset (lb./in.²)	Ultimate Strength (lb./in.²)
3	3/32	0.0891	3.80	----	20,800	------	------	20,800 x
5	3/32	0.0908	3.97	3.88	8,800	17,400	18,600	23,200
Average			3.89	3.88	14,800	17,400	18,600	22,000
10	1/16	0.0820	4.09	3.96	11,750	44,500	18,500	44,500
11	1/16	0.0820	4.17	3.92	14,700	33,000	31,000	42,100
Average			4.13	3.94	13,075	38,750	24,750	43,300

x Specimen failed 1/2 in. outside of test section.

Table 5. Room Temperature Flexural Fatigue Test Data

for 1/16 in. Thick CTL-91-LD Laminate

Average Thickness in Test Section (in.)	Force on Yoke (lb.)	S, Bending Stress per Pound of Force on Yoke (psi/lb.)	S (psi)	N, Number of Cycles to Failure
		(80 ± 5)° F. Stress applied parallel to warp		
0.0571	17.00	2,740	46,500	1,000
0.0583	16.00	2,640	46,200	4,000
0.0583	15.00	2,540	39,600	5,000
0.0596	14.00	2,540	35,600	6,000
0.0604	13.00	2,490	32,400	17,000
0.0594	12.00	2,540	30,500	14,000 [x]
0.0613	11.00	2,450	27,000	43,000
0.0619	10.00	2,350	23,000	181,000
0.0631	9.00	2,250	20,200	805,000
0.0636	8.50	2,180	18,500	1,455,000
0.0636	8.00	2,180	17,400	5,702,000
		(86 ± 5)° F. Stress applied perpendicular to warp		
0.0593	13.73	2,550	35,000	2,000
0.0595	11.97	2,540	30,000	4,000
0.0616	10.42	2,400	25,000	21,000
0.0618	7.08	2,350	16,700	363,000
0.0600	5.10	2,520	12,800	5,613,000 [xx]

[x]Removed for inspection after noting first evidence of failure.

[xx]Did not fail.

Table 6. 207° F. and 350° F. Flexural Fatigue Test Data

for 1/16 in. Thick CTL-91-LD Laminate

Average Thickness in Test Section (in.)	Force on Yoke (lb.)	S, Bending Stress per Pound of Force on Yoke (psi/lb.)	S (psi)	N, Number of Cycles to Failure	
		(207 ± 5)° F.			
0.0656	19.00	2,080	39,500	1,000	
0.0694	19.00	1,860	35,300	2,000	
0.0756	20.00	1,580	21,600	7,000	
0.0711	14.30	1,750	25,000	41,000	
0.0735	14.50	1,670	22,400	237,000	
0.0637	9.00	2,200	19,800	741,000	(a)
0.0640	8.50	2,190	18,600	3,242,000	
0.0642	8.07	2,190	17,700	5,015,000	(b)
0.0638	6.00	2,160	13,000	4,557,000	(c)
		(350 ± 5)° F.			
0.0624	13.33	2,250	30,100	2,000	
0.0624	11.10	2,250	25,000	12,000	
0.0625	10.66	2,250	24,000	12,000	
0.0635	9.88	2,220	22,000	79,000	
0.0640	9.10	2,200	20,000	241,000	(d)
0.0679	10.00	1,920	19,200	123,000	
0.0641	8.65	2,200	19,000	15,000	
0.0645	8.65	2,160	18,700	331,000	
0.0647	8.37	2,150	18,000	374,000	(e)
0.0652	8.00	2,110	16,900	492,000	
0.0652	7.53	2,110	15,900	1,166,000	
0.0653	7.30	2,110	15,400	1,138,000	
0.0670	7.38	2,000	14,800	2,493,000	
0.0677	7.34	1,980	14,500	1,547,000	(f)
0.0688	7.22	1,930	13,900	4,573,000	

(a) Noticeably warped.
(b) Overheat 20° F.
(c) Did not fail.
(d) Possibly overheated.
(e) Two 1/64 in. diameter surface defects (pits).
(f) Bearing retainer loose.

Table 7. 500° F. Flexural Fatigue Test Data for

1/16 in. Thick CTL-91-LD Laminate

Average Thickness in Test Section (in.)	Force on Yoke (lb.)	S, Bending Stress per Pound of Force on Yoke (psi/lb.)	S (psi)	N, Number of Cycles to Failure
		(500 ± 5)° F.		
0.0697	13.33	1,860	24,800	1,000
0.0706	12.34	1,800	22,100	2,000
0.0688	10.35	1,900	20,000	27,000 x
0.0596	7.00	2,510	17,600	39,000
0.0600	6.00	2,500	15,000	140,000
0.0611	5.71	2,420	13,800	311,000
0.0613	3.75	2,370	8,900	1,420,000
0.0617	3.33	2,360	7,860	2,282,000
0.0645	3.33	2,160	7,220	4,565,000

[x] Failure due to maximum allowable deflection of ± 0.5 in.

Table 8. Room Temperature and 207° F. Flexural Fatigue Test Data for 3/32 in. Thick CTL-91-LD Laminate

Average Thickness in Test Section (in.)	Force on Yoke (lb.)	S, Bending Stress per Pound of Force on Yoke (psi/lb.)	S (psi)	N, Number of Cycles to Failure
		$(86 \pm 5)^{\circ}$ F.		
0.0868	18.50	1,180	21,800	60,000 (a)
0.0927	20.00	1,030	20,600	178,000 (a)
0.0911	17.50	1,070	18,700	660,000
0.0925	17.07	1,030	17,600	961,000
0.0902	14.88	1,090	16,200	5,143,000 (b)
0.0873	13.05	1,160	15,100	5,374,000 (b)
		$(207 \pm 5)^{\circ}$ F.		
0.0952	18.20	975	17,750	847,000 (c)
0.0952	18.20	975	17,750	273,000 (d)
0.0941	17.75	1,000	17,750	244,000 (e)

(a) Removed for inspection just prior to failure.

(b) Did not fail. Noted evidence of fatigue at 2,000,000 cycles.

(c), (d), (e) These specimens were run with those having a nominal thickness of 0.0625 in. before any difference in properties was observed. All three specimens were run at the same stress level for comparison with each other and with the thinner specimens in the same material.

Table 9. The Effects of Temperature to 500° F. on the Ratio of Flexural Fatigue Strength at 5×10^6 Cycles to the Static Flexural Strength at Temperature

Temperature	Ultimate Static Flexural Strength			Flexural Fatigue Strength at 5×10^6 Cycles	Flexural Fatigue Strength at 5×10^6 Cycles Divided by Static Ultimate Strength after 46.8 Hours Exposure
	1/2 Hour	200 Hours	46.8 Hours		
Room	52,500	52,500	52,500	17,200	0.327
207° F.	49,000	50,400	49,300	17,500	0.355
350° F.	46,500	46,400	46,500	13,500	0.290
500° F.	39,600	17,600	34,300	6,900	0.201

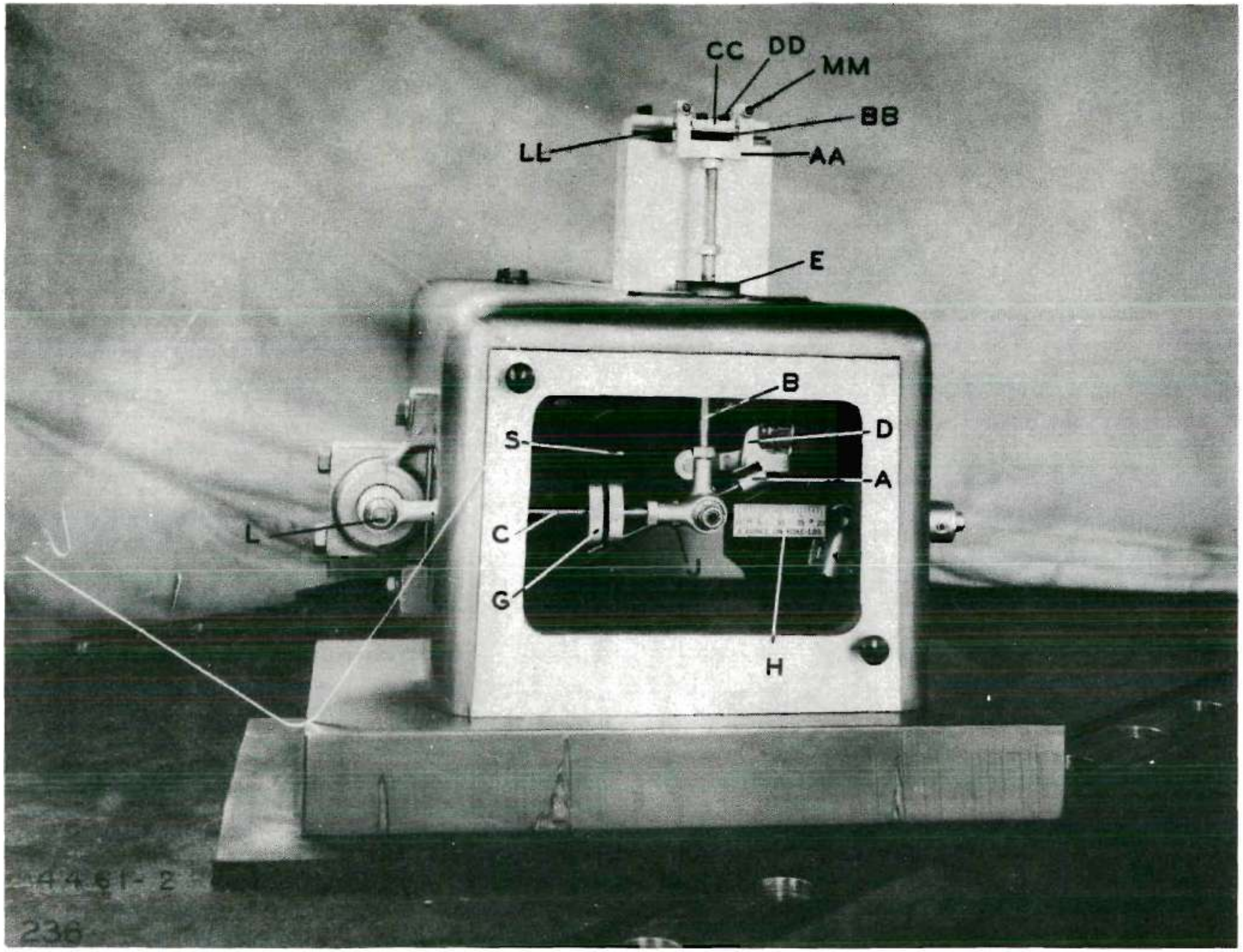


Figure 1. Front View SF-2.

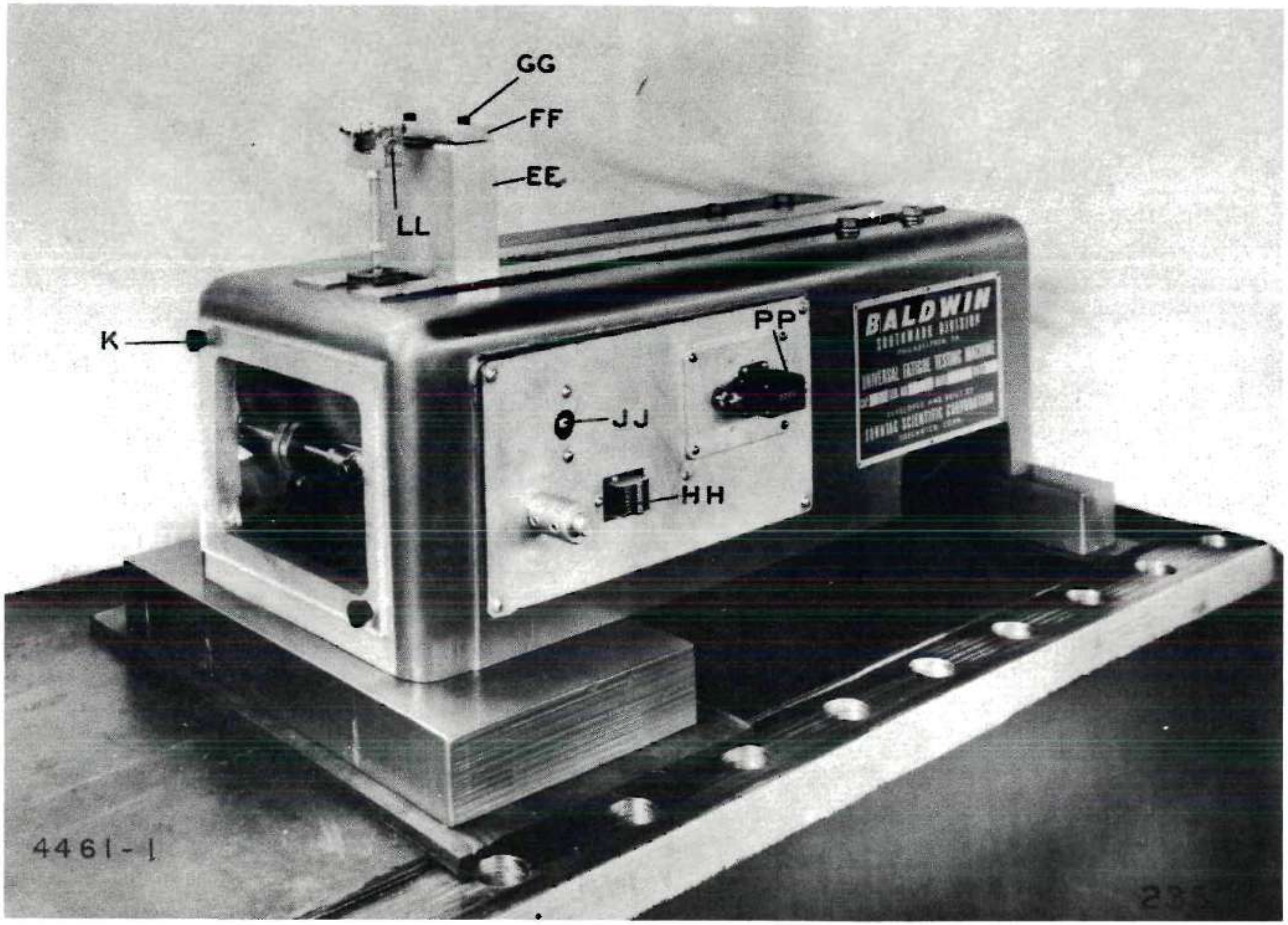


Figure 2. Side View SF-2.

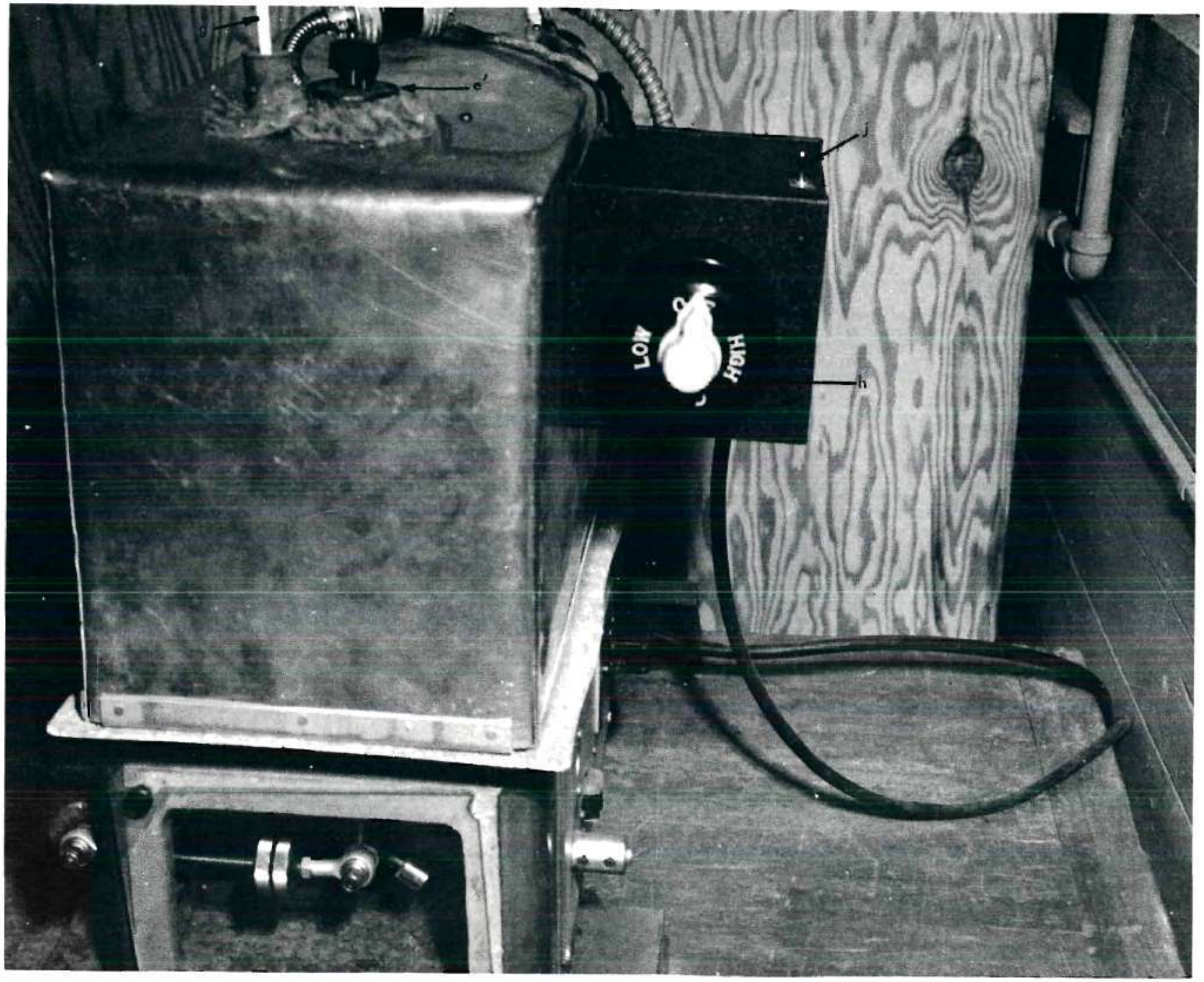


Figure 3. Sonntag Flexure Fatigue Testing Machine SF-2 with the Elevated Temperature Oven Shown in the Closed Position.

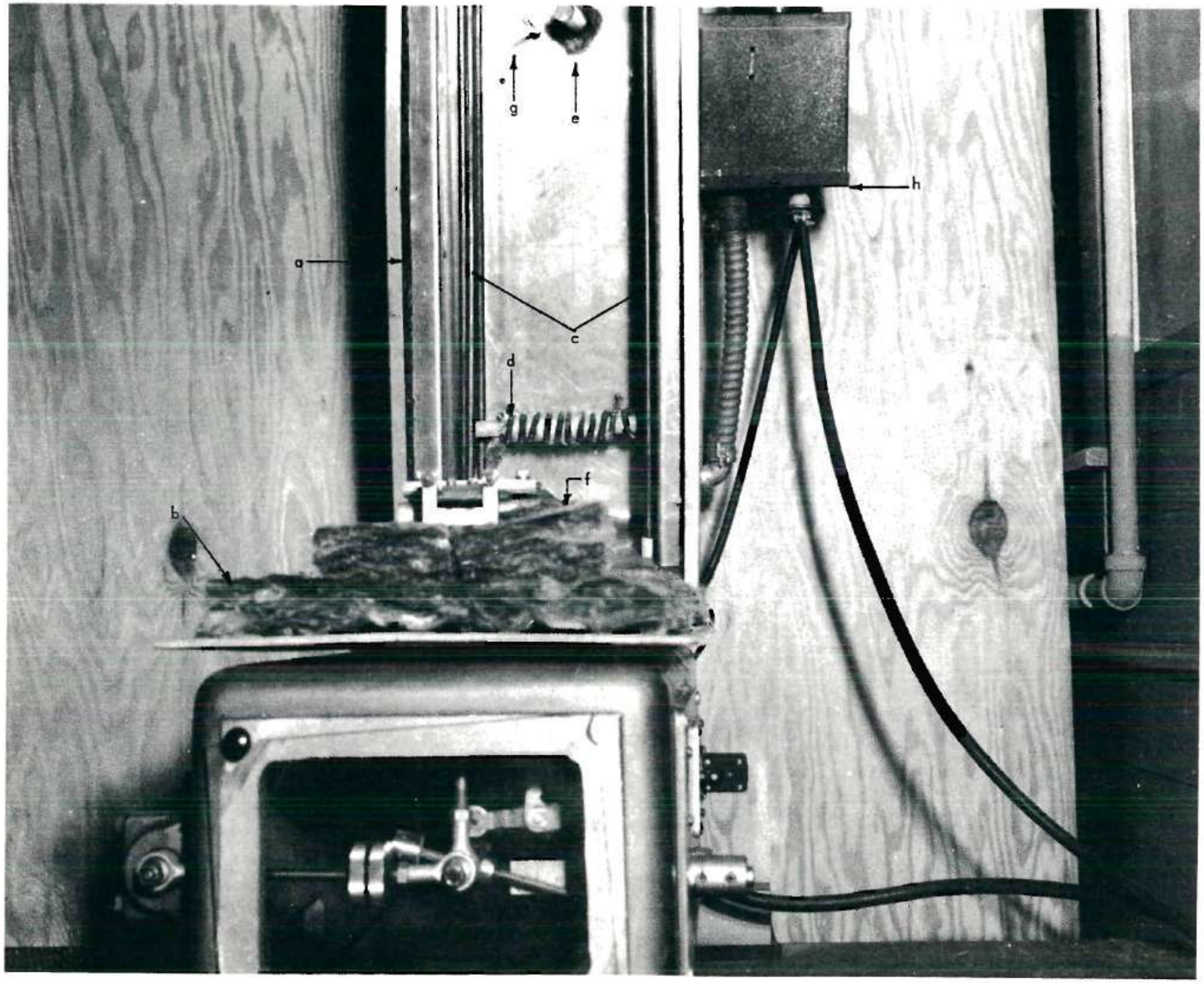
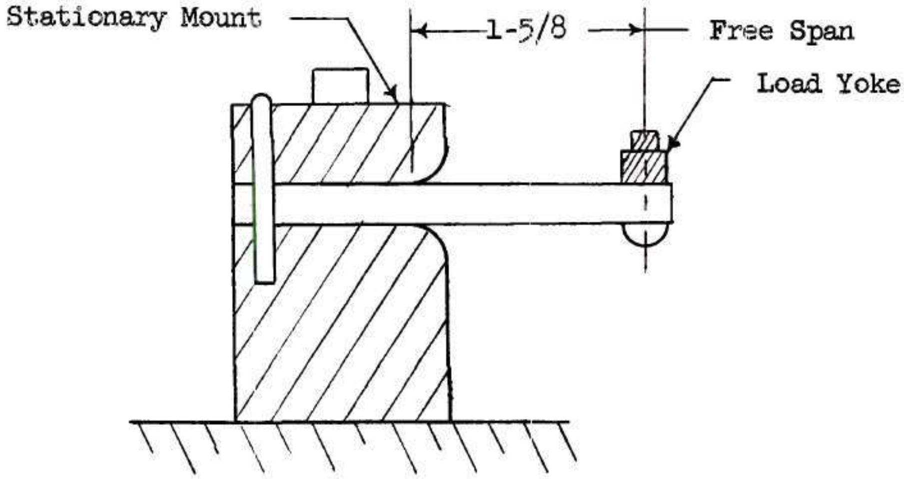
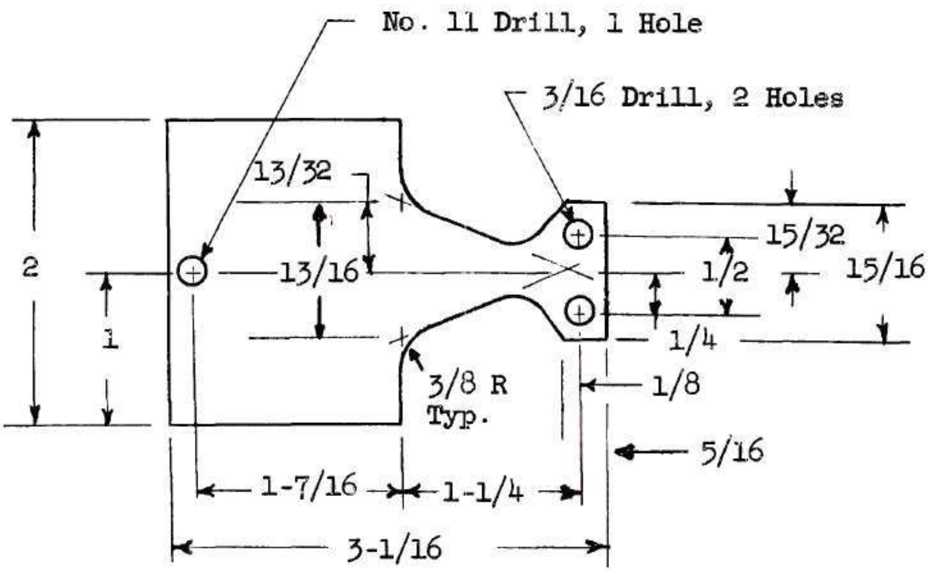


Figure 4. Sonntag Flexure Fatigue Testing Machine SF-2 with the Elevated Temperature Oven Shown in the Open Position.



Cross Sectional View of Specimen Mounting



Specimen Details

(All dimensions in inches)

Figure 5. Fatigue Specimen and Mounting Details

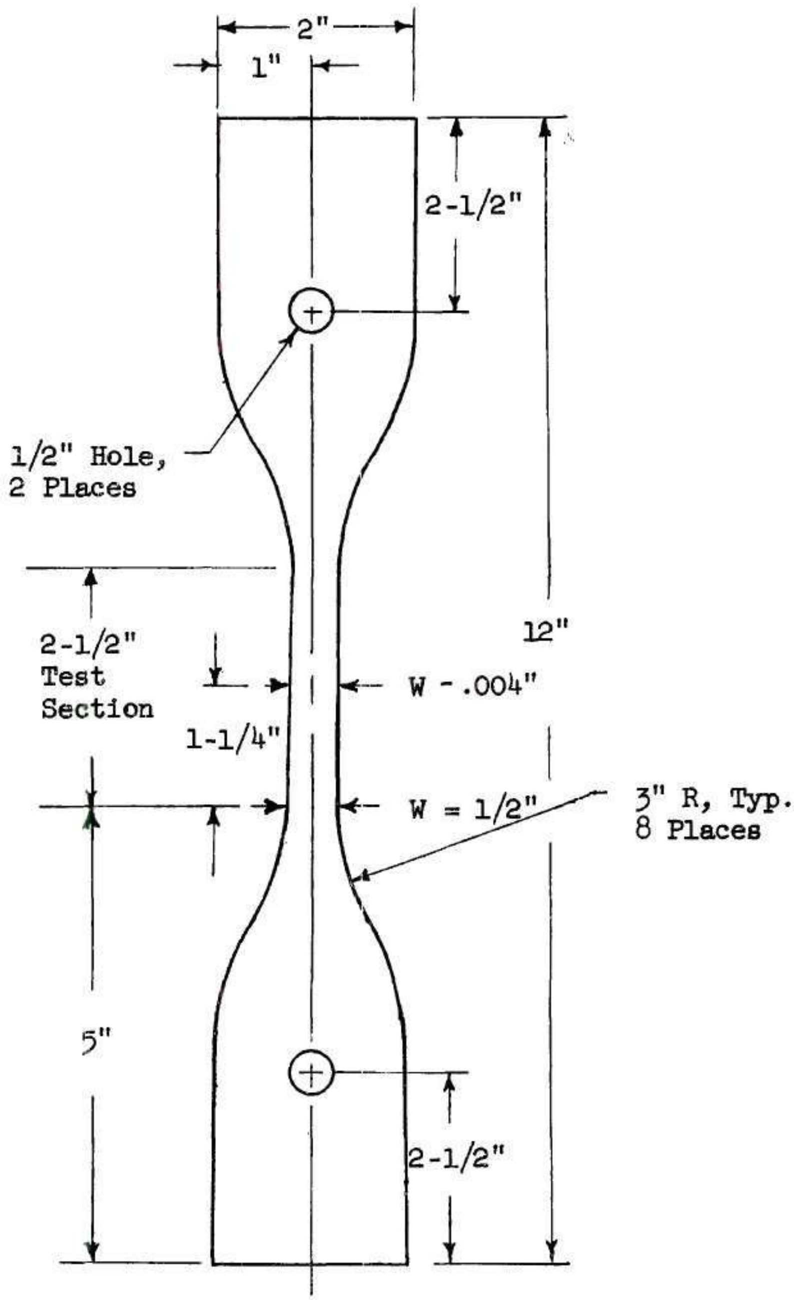


Figure 6. Tensile Test Specimen Details

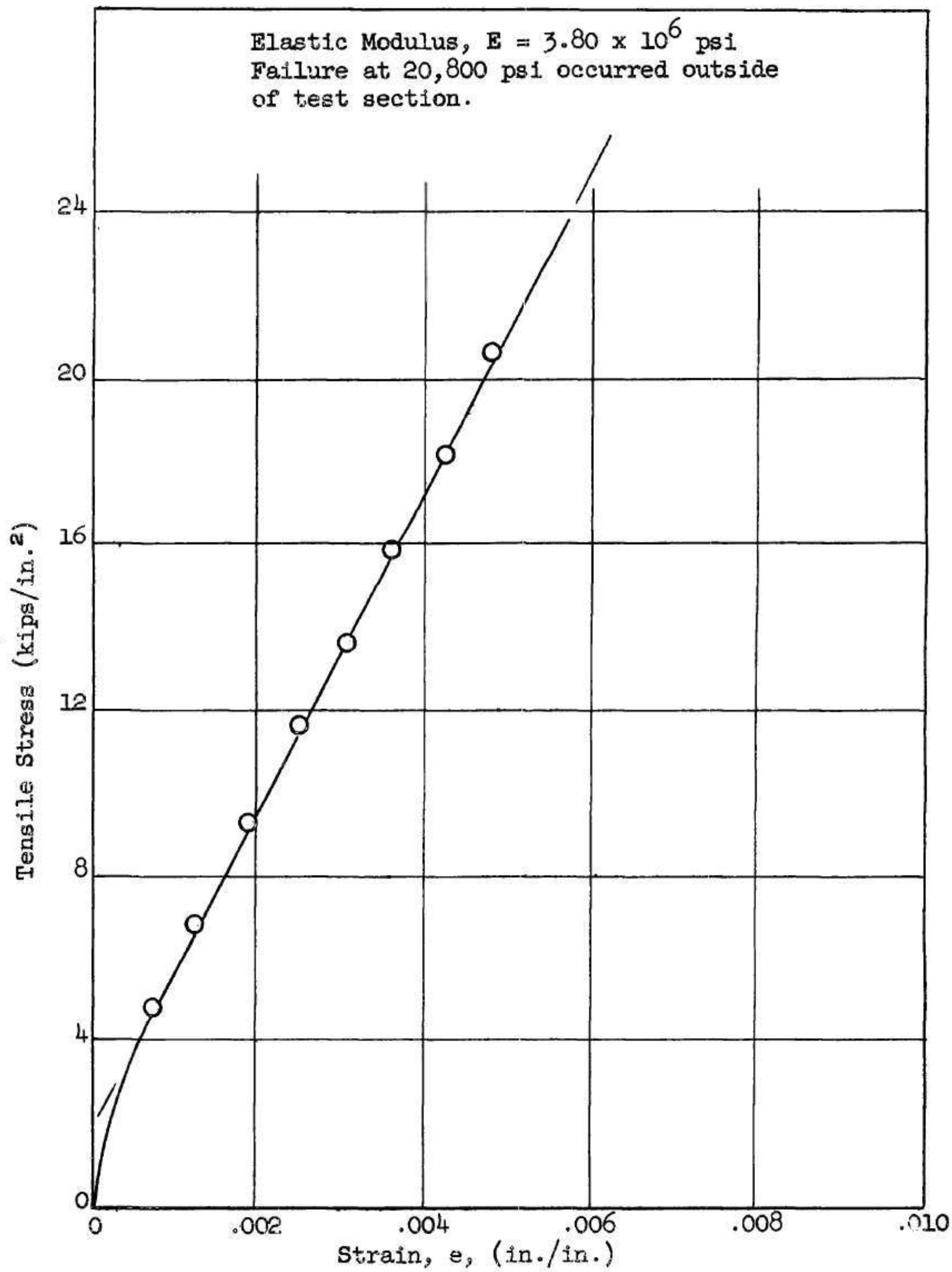


Figure 7. Grade CTL-91-LD Static Tensile Stress-Strain Curve for Specimen No. 3 (Nominal Thickness = 0.09375 in.)

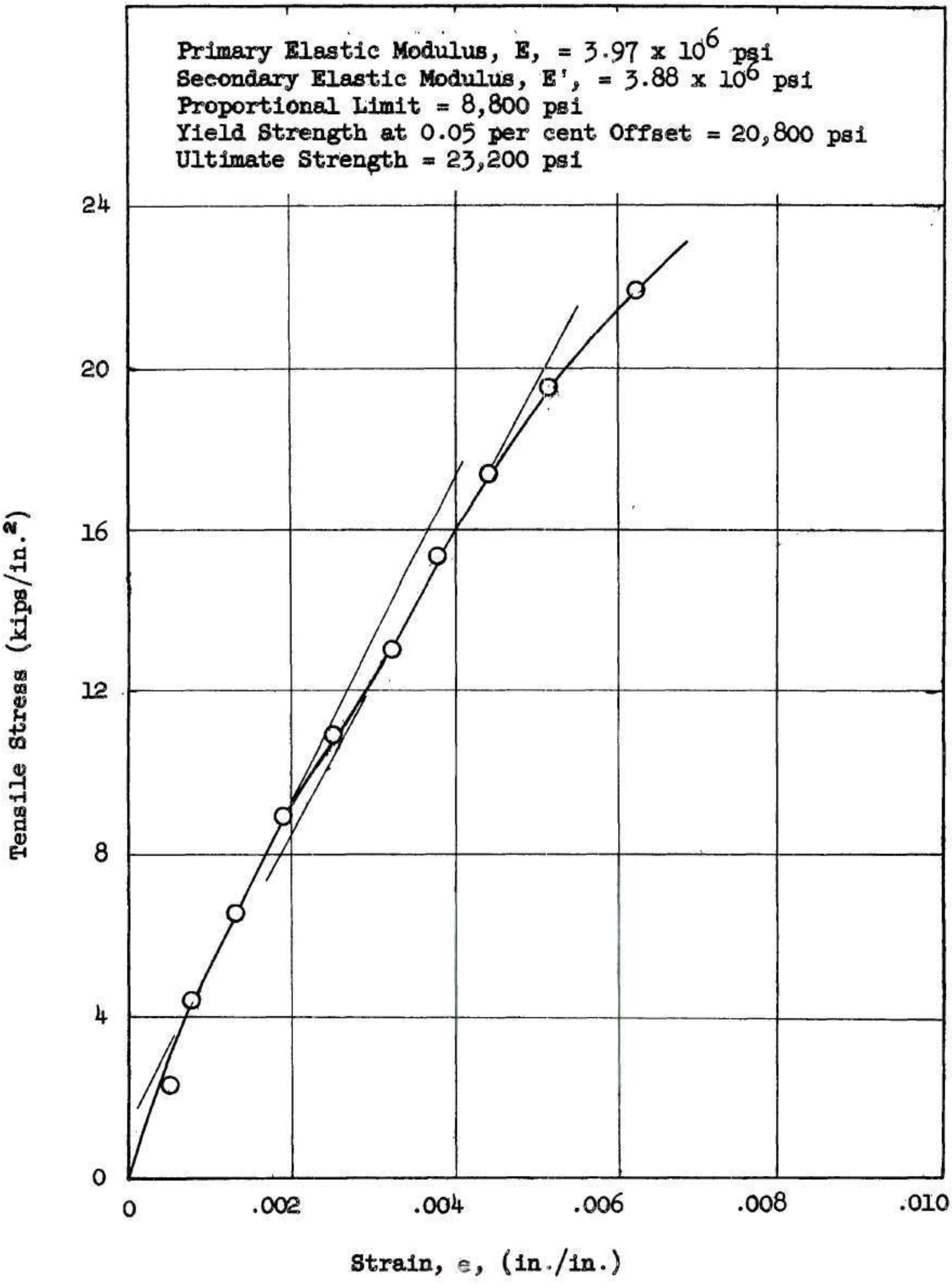


Figure 8. Grade CTL-91-LD Static Tensile Stress-Strain Curve for Specimen No. 5 (Nominal Thickness = 0.09375 in.)

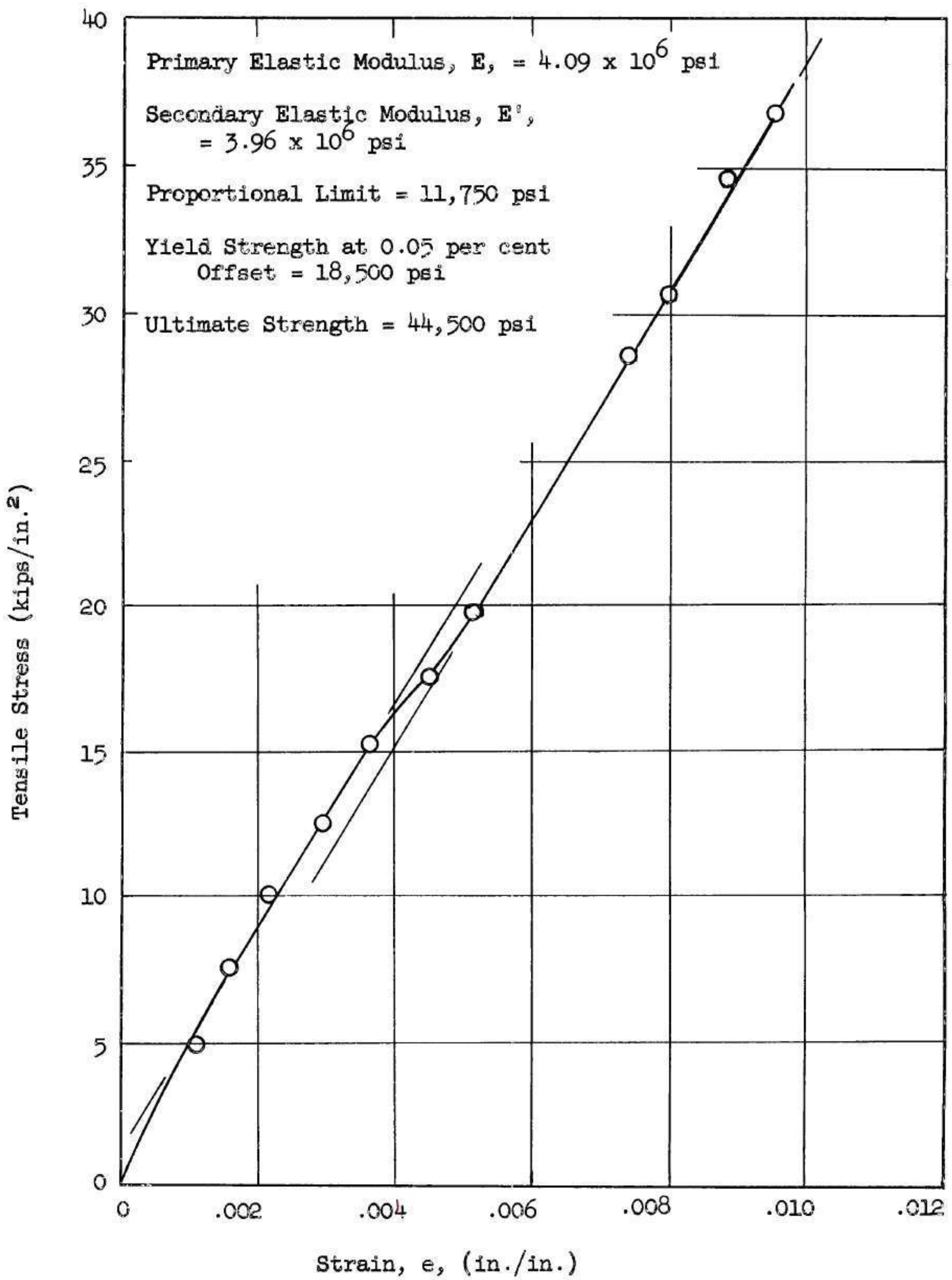


Figure 9. Grade CTL-91-LD Static Tensile Stress-Strain Curve for Specimen No. 10 (Nominal Thickness = 0.0625 in.)

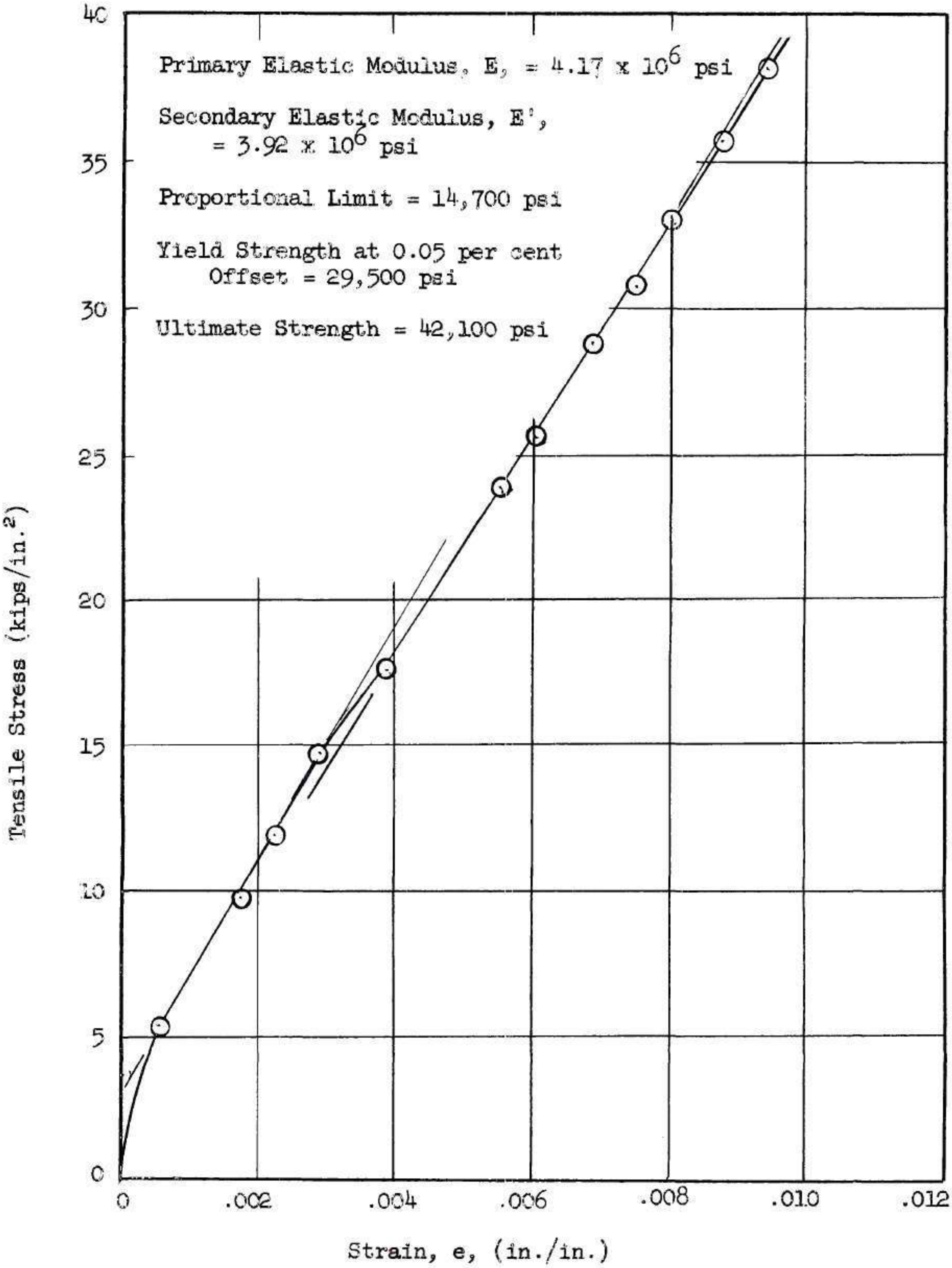


Figure 10. Grade CTL-91-LD Static Tensile Stress-Strain Curve for Specimen No. 10 (Nominal Thickness = 0.0625 in.)

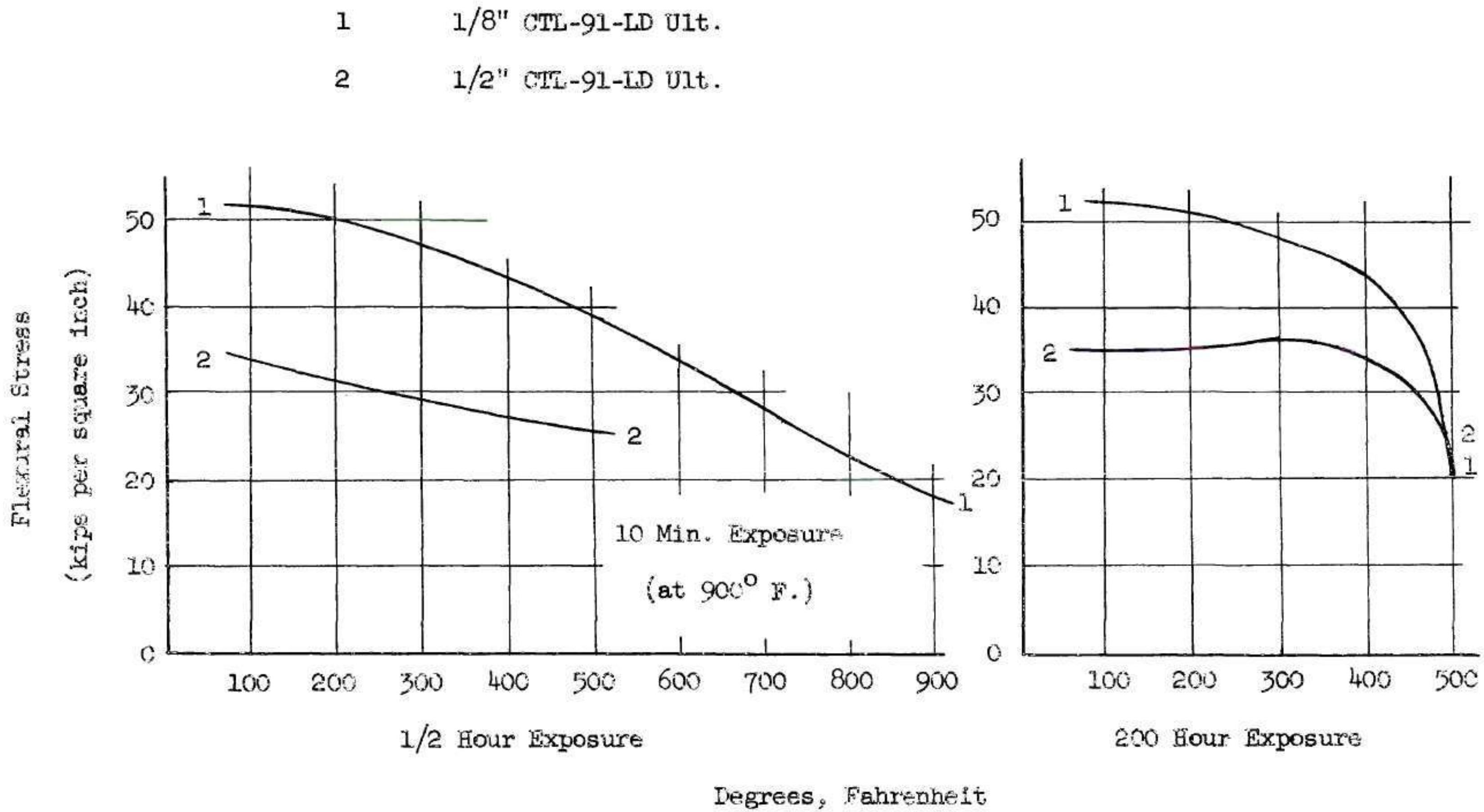


Figure 11. Elevated Temperature Static Flexural Properties of CTL-91-LD
(Data Supplied by the Cincinnati Testing and Research Laboratories)

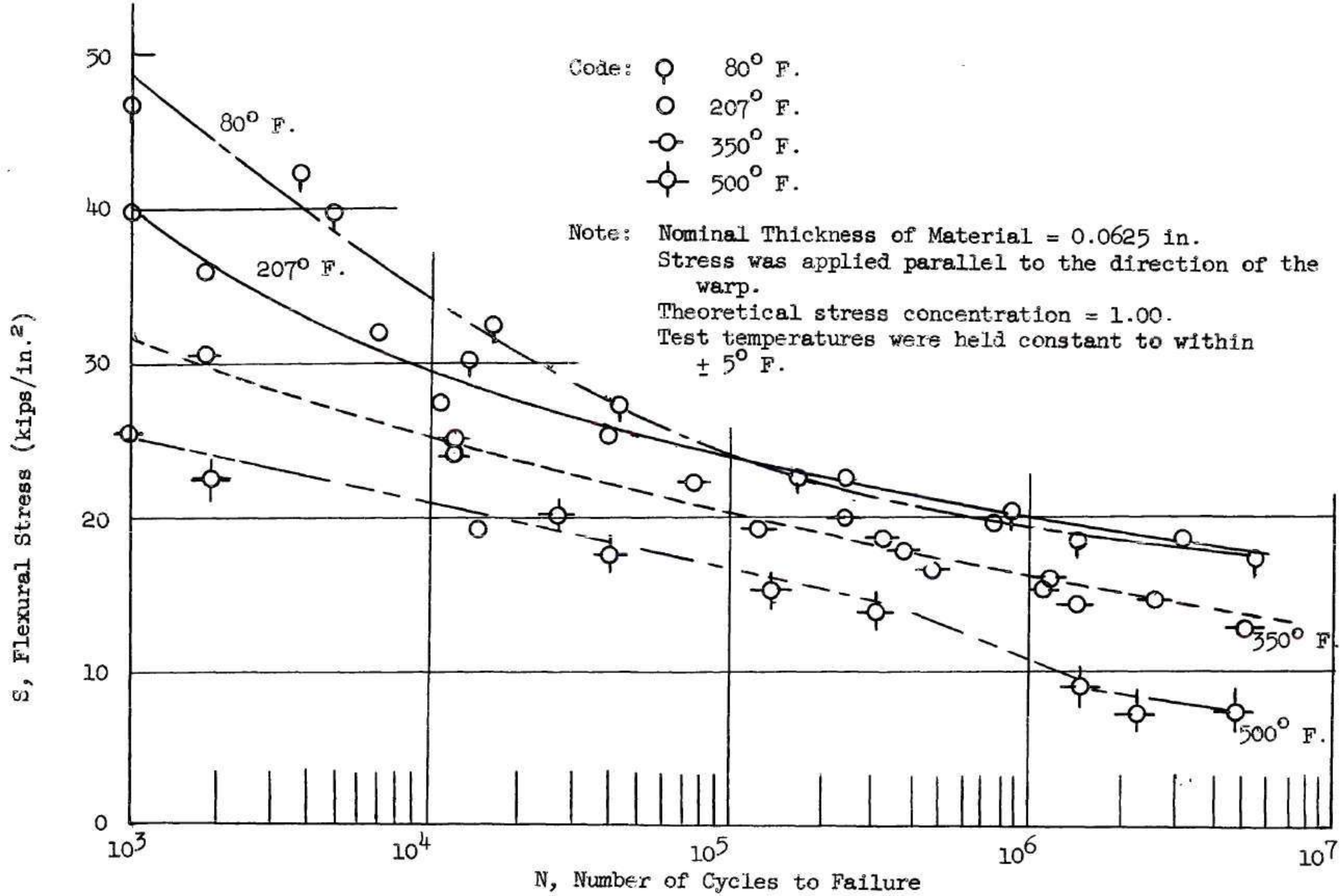


Figure 12. Grade CTL-91-LD Flexural Fatigue at Elevated Temperatures

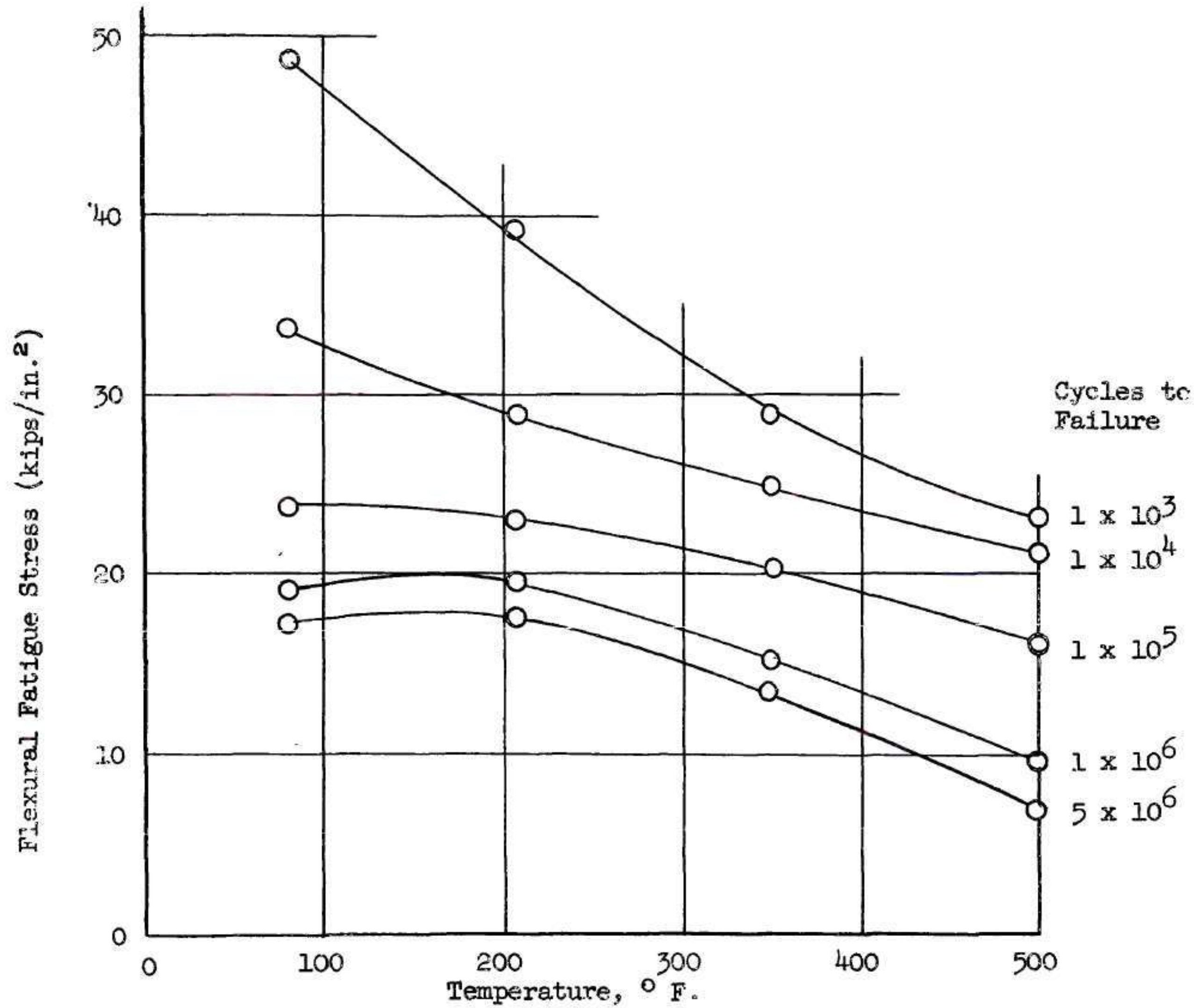


Figure 13. A Cross-Plot of Figure 12 Showing the Effect of Temperature on the Flexural Fatigue Life of Grade CTL-91-LD Fiberglass Plastic Laminate (Nominal Thickness = 0.0625 in.)

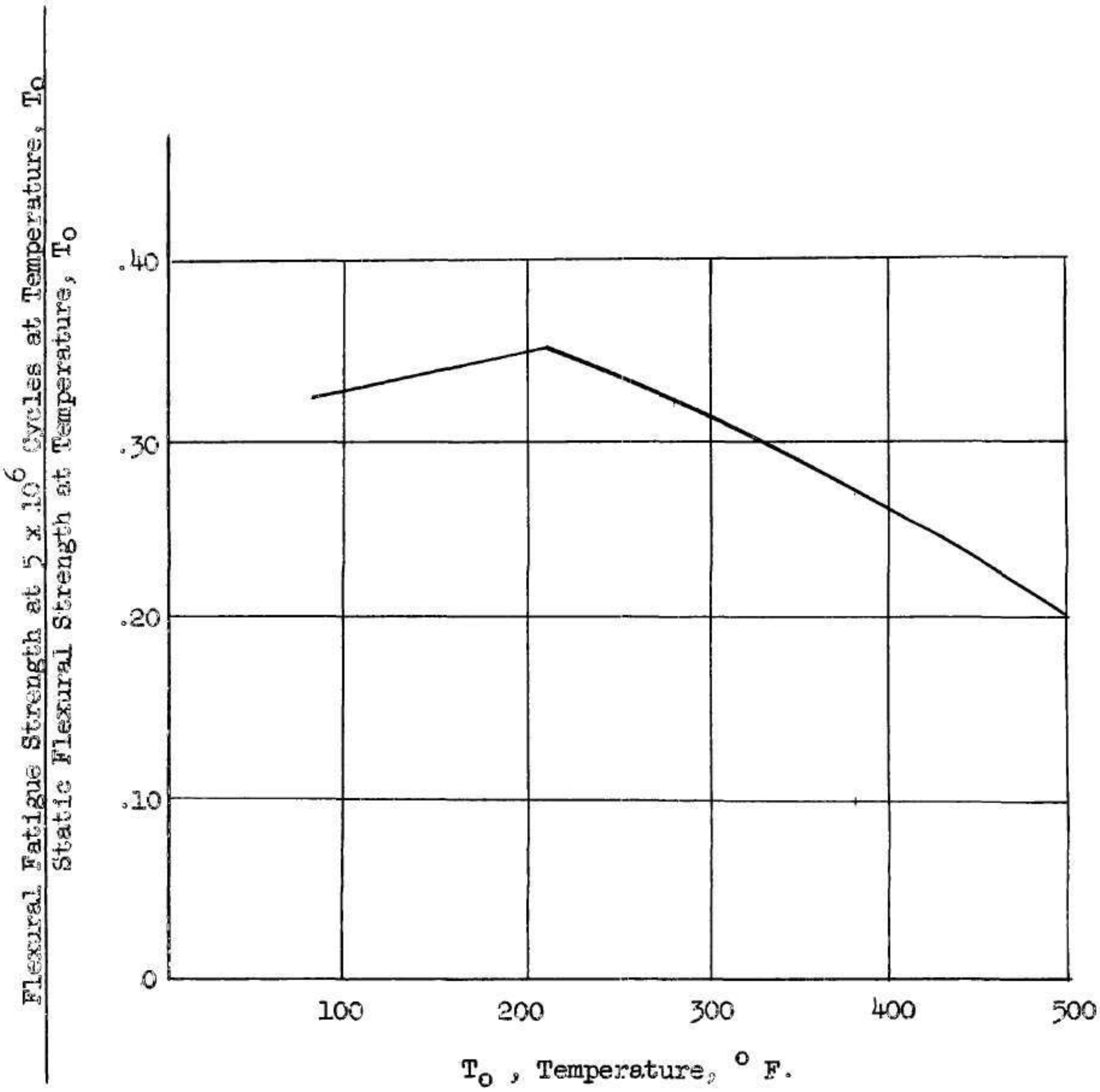


Figure 14. The Effect of Temperature on the Ratio of Flexural Fatigue Strength at 5×10^6 Cycles to the Static Flexural Strength at Temperature (see Table 9)

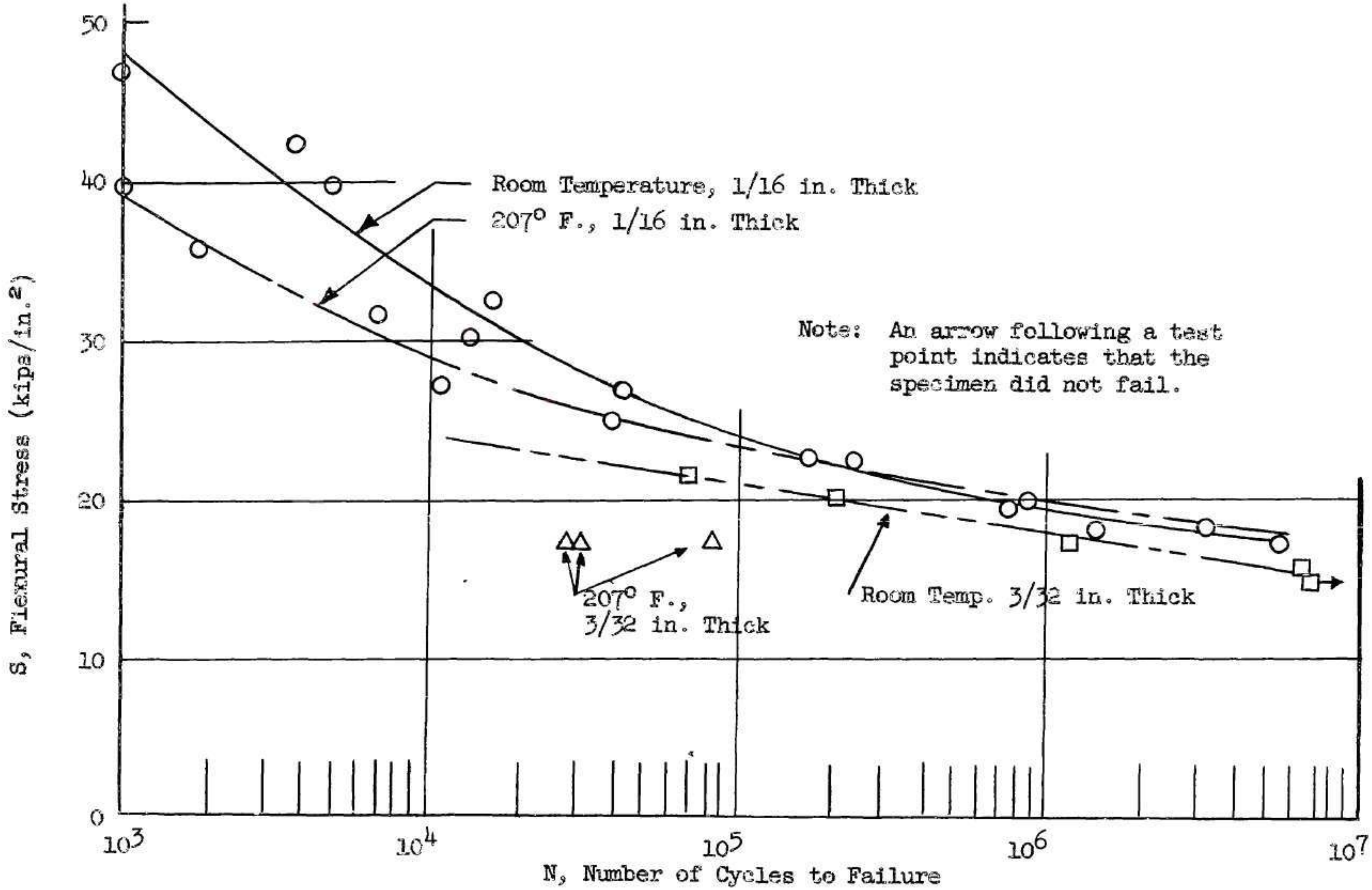


Figure 15. The Effect of Specimen Thickness on the Flexural Fatigue Strength of 1/16 in. Nominal Thickness CTL-91-LD Laminate

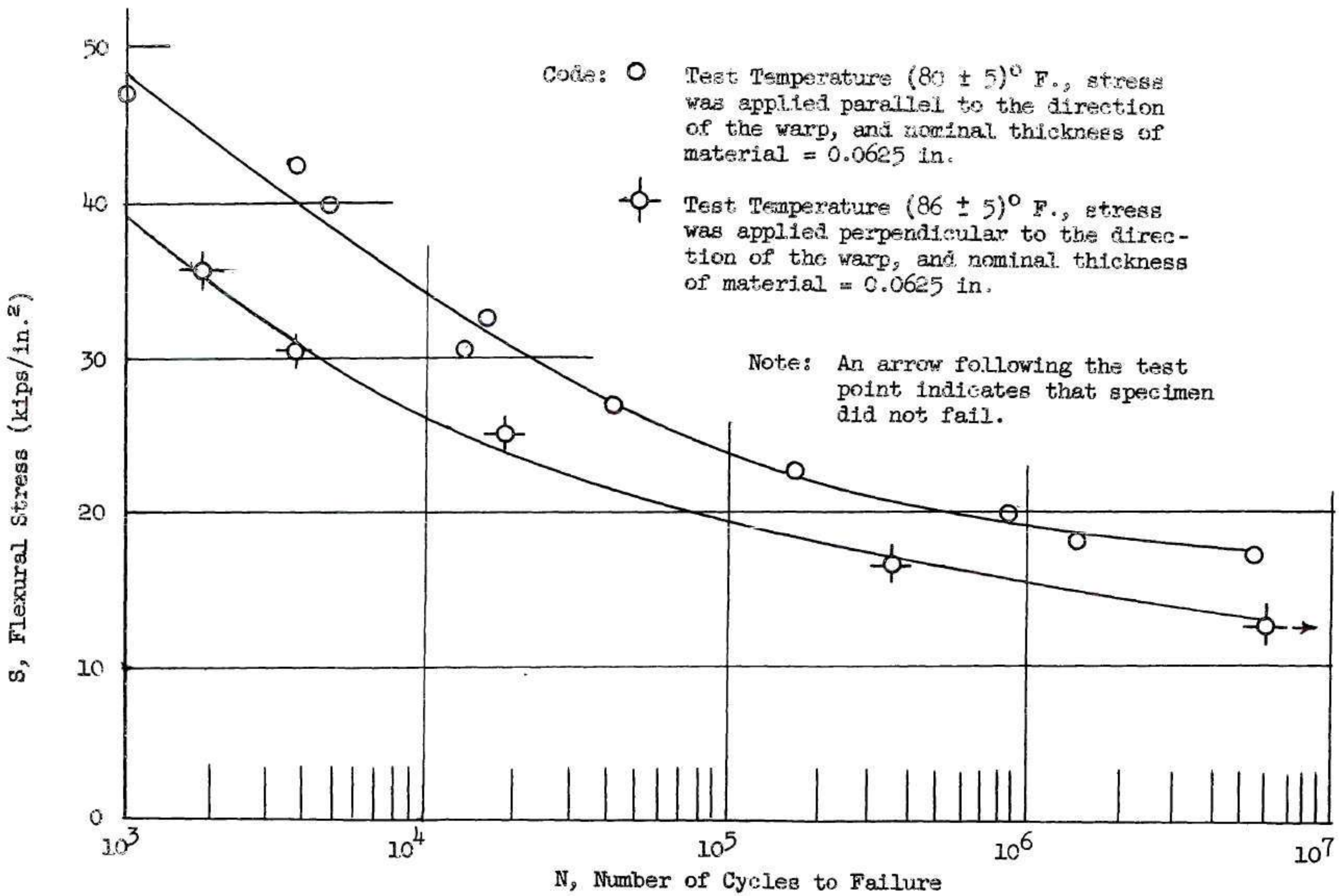


Figure 16. Grade CTL-91-LD Flexural Fatigue at Room Temperature Showing the Effect of Fabric Orientation

Principle of Operation of the Sonntag

Flexural Testing Machine Model SF-2

The SF-2 machine applies force to the test specimens by a rotating mass. The peak values of the force remain constant throughout a test run regardless of any change in the rigidity of the test specimen. This feature is made possible through a system of inertia compensation which absorbs all inertia forces in the vibrating system except those produced by the rotating eccentric mass.

Inertia compensation is accomplished by using a spring (the tapered drive shaft, S, shown in Figure 1) whose deflection constant, K_c, is equal to the inertia forces, M, of the vibrating system, where:

M = the total mass of the vibrating system including the equivalent mass of the test specimen

ω = the resonant circular frequency of the vibrating mass, M, and the spring, K_c, with the specimen out

In the Sonntag machine the frequency, ω, is held at a constant value by the synchronous electric motor operating at 1800 revolutions per minute. Since the spring effect of the specimen, K_s, is additive to that of the compensator spring, K_c, the system as a whole operates at a non-resonant frequency.

The system is one of forced vibrations with a single degree of freedom which can be described by the following equation (Reference 25):

$$X = \frac{P_o \sin \omega t}{K - M \omega^2} \tag{1}$$

where: X = displacement of mass, M (inches)

P_o = peak force (pounds)

K = $K_c + K_s$, the overall spring constant (pounds/inch)

K_c = the spring constant of the compensator spring, S, (pounds/inch)

K_s = the spring constant of the test specimen (pounds/inch)

t = time (seconds)

With the substitutions $K_c = M \omega^2$ and $K = K_c + K_s$ into equation (1) and considering only the peak values of force, the following relationship is obtained:

$$X_o = \frac{P_o}{(K_c + K_s) - K_c} = \frac{P_o}{K_s} \tag{2}$$

or,

$$P_o = X_o K_s \tag{3}$$

Recalling that $P_o = M \omega^2$, with both M and ω being fixed constants, it must be concluded that P_o will also have a fixed constant value. Therefore, if the specimen rigidity, K_s, varies during a test run, the specimen deflection, X_o, will increase or decrease so that the product $X_o K_s$ (equal to P_o) will remain constant.

Thus, although elevated temperature specimens were set up in the machine at room temperature before the oven was turned on, the fact that the modulus of elasticity, and consequently, the spring constant of the specimen, K_s, was different at elevated temperatures, had no effect on the accuracy of the test results.

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