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AN APPRAISAL OF THE PROT METHOD OF FATIGUE TESTING

by

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AN APPRAISAL OF THE PROT METHOD

OF

FATIGUE TESTING

(Part I)

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Project Director, T. J. Dolan

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ABSTRACT

A recent proposal by Prot suggests that both the expense and the duration of fatigue tests may be lessened by a progressive load method which consists of subjecting a test specimen to a completely reversed stress whose amplitude increases regularly with time until the specimen fails. By assuming (a) that the ordinary S-N curve, when plotted on a linear scale, becomes an approximate hyperbola which is asymptotic to the vertical axis and to the endurance limit, and (b) that the material is not affected by the completely reversed stress until the amplitude of the stress is greater than the endurance limit, Prot shows that the stress at failure, S_R, may be expressed as

$$S_R = E + K\alpha^{0.50}$$

where E is the endurance limit, K is a constant for a particular material and α is the loading rate usually in psi/cycle. Plotting S_R as a function of $\alpha^{0.50}$, a straight line results; the intersection of this line with the stress axis indicates the value of the endurance limit. A logical modification of the above formula proposed by Henry is

$$S_R = E + K\alpha^{\frac{1}{m+1}}$$

where m is a constant dependent on the material.

In this paper the validity of the above equations has been investigated for two materials, ingot-iron and 75S-T aluminum alloy. Conventional fatigue test data were also obtained for comparison with the values of E predicted by the progressive loading tests. In general, it was found that the exponent of α that gave the best approximation to a linear plot of the experimental data was not 0.50 but approximately 0.371 and 0.1786 for the ingot-iron and 75S-T aluminum alloy, respectively. Further, the value of the endurance limit for these materials as determined by the above equations was affected by completely reversed stresses whose amplitudes were smaller than the endurance limit. Nevertheless, the method has certain inherent advantages of correlating the data for every specimen tested to determine the most probable endurance limit. Further studies are therefore being made of the method that will be reported at a later date.

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ACKNOWLEDGMENT

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I. INTRODUCTION

At present the conventional method used to evaluate the fatigue strength of material involves the determination of the fatigue life of a number of specimens, each of which is subjected to repeated loading at a different stress level. From the S-N diagram thus obtained the endurance limit of the material is estimated. Another method which is sometimes employed when only a few expensive specimens are available consists of testing at some low stress level for a predetermined number of cycles of stress. If the specimens do not fail at this stress level before the predetermined number of cycles, the stress level is raised. The testing is continued in this manner until failure occurs. The lowest stress level at which failure occurs is considered the endurance limit. The predetermined number of cycles for each stress level is usually set at about 10^7 for steel and 10^8 for aluminum.

In recent years it has become increasingly apparent that these methods are costly and time consuming. As a result, various attempts to eliminate these objectionable features in the evaluation of fatigue strength have been undertaken.

It is clear that the time required in the general methods of fatigue strength determination can be reduced by the use of several testing machines or multi-head machines. However, the cost of numerous or multi-head machines may be excessive. This is particularly true when testing large specimens or full-sized components. In addition, the number of specimens required in conventional fatigue tests frequently makes the expense of large models prohibitive.

Another obvious method of reducing the time required would be to increase the speed of the testing machines; it has been established experimentally, within certain limits, that the frequency of stressing has little influence on the endurance limit. However because of the mechanical limitations, it does not appear that the duration of the tests can be reduced significantly in this manner. A further objection is that metals with appreciable hysteresis effect develop excessive heat from high frequency stressing. In cases of high hysteresis materials, it is sometimes preferable not to exceed 2000 cycles/min. These facts place a limit upon the speed of testing as a satisfactory means of reducing the time element in fatigue testing.

Recently, Prot (1)* proposed a new method of fatigue testing to remedy the two objectionable features of the ordinary fatigue tests. The Prot method consists of submitting specimens to a reversed stress, whose amplitude increases regularly with time. According to Prot, within the limits of the basic assumptions of the theory, the method is completely independent of materials tested, method of testing (rotating beam, plane flexure, etc.) or method of applying load. The stress may be increased according to any function of time, a linear function being chosen primarily because of its simplicity.

In theory** the Prot method is based on the assumption that the ordinary S-N curve, when plotted on a linear scale becomes an approximate hyperbola which is asymptotic to the vertical axis and to the endurance limit. From this basic assumption, Prot shows that the stress at failure, S_R, may be expressed as

$$S_R = E + K\sqrt{\alpha} \qquad \text{Eq. 1}$$

where E is the endurance or fatigue limit***, K is a constant for a particular material and α is the loading rate (psi/cycle). Thus

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* Numbers in parentheses refer to the references listed in the Bibliography.

** See Appendix A.

*** For materials having S-N diagrams consisting of two straight lines one of which is parallel to the N-axis, the endurance limit as determined by Prot's method and by the conventional method are equivalent. For materials such as aluminum alloys which exhibit S-N diagrams that are non-linear (and with no tangent parallel to the N-axis), the endurance limit determined by the Prot method corresponds to a fatigue strength at an infinite number of cycles. Hence in this paper, regardless of type material, the value E as determined in the Prot method will be called the endurance or fatigue limit.

to determine the fatigue strength for any material theoretically, it is necessary only to determine the failure stress, S_R, for two different loading rates, α. Practically, because of "scatter", it is usually necessary to test at several different loading rates α. Such a method would greatly reduce the time required to determine the endurance limit and, in the case of large models, would greatly reduce the number (and cost) of specimens. Furthermore the data from all specimens are utilized in the final determination of the most probable value of the endurance limit, E. However it should be emphasized that the Prot method is applicable only to the determination of a fatigue strength corresponding to a very long fatigue life; the method is not applicable to the determination of the "finite life" strengths corresponding to the upper portion of the conventional S-N curve.

II. PURPOSE AND SCOPE

A laboratory study was made to investigate the accuracy of the Prot accelerated method as compared with the conventional S-N diagram for determination of the fatigue strength of metals. Some doubt exists as to the adequacy of the theory on which Eq. 1 is based (particularly for metals which may "coax"* during the test). For example, a more general form of Eq. 1 is

$$S_R = E + K\alpha^n \qquad \text{Eq. 2}$$

in which the exponent, n, may be computed from experimental data (see Appendix B).

Thus, it was also desired to investigate several modifications of the Prot theory to determine an optimum method of interpretation of the experimental data. Sufficient tests were run to indicate the relative "scatter" in fracture stress and thus to indicate the variability to be expected from the Prot method.

In order to appraise the effect of widely different metals, Armco ingot-iron was tested as representative of a metal with a definite fatigue limit, whereas 75S-T aluminum alloy was utilized as a non-ferrous metal exhibiting no clear-cut fatigue limit. Three groups of experiments were conducted for each of these metals, namely: (a) conventional fatigue tests at constant stress amplitude; (b) tests with a uniform increase in loading rate α, starting from a relatively low initial stress; (c) tests similar to (b), but starting from a relatively high initial stress level. The initial stress levels were 10,000 and 30,000 psi for the ingot-iron and were 10,000 and 20,000 psi for the aluminum alloy.

This report has been prepared as Part I of a more general appraisal of the Prot method; further studies are being conducted

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* The fatigue resistance of some metals may be improved by understressing followed by a process of gradually increasing the amplitude of the alternating stress in small increments, a procedure ordinarily called "coaxing". (5)

of other metals and will include the influence of other variables such as the presence of a stress raiser in the form of a semi-circular notch. It is anticipated that a later report (Part II) will be prepared under the same title to summarize more completely a final appraisal of the Prot method. It was, however, felt desirable to outline at this time the results of the preliminary experiments in this report.

III. MATERIALS AND METHOD OF TESTING

[redacted]. The 75S-T was received in the form of 7/8" round rolled rod and the ingot-iron in 5/8" diameter hot rolled bars. The fatigue specimens were machined to the dimensions shown in Fig. 1; the test pieces were not given any subsequent heat treatment. The test sections of the fatigue specimens were finished with 2/0 emery polishing paper in accordance with previously established procedures (6).

Tests were conducted in rotating cantilever beam machines of the type utilized in past work (2). The gradual increase in loading was accomplished by means of water supplied from a standpipe which maintained a constant pressure on a needle control valve. The water passed through the needle control valve into a container, and this water load was transmitted through a spring to the free end of the cantilever specimen. Automatic shut-off of the water flow was effected by means of a solenoid valve which closed when the specimen failed (Fig. 2).

Two series each of the iron and of the aluminum specimens were tested with uniform increase in load. Each series consisted of from 22 to 32 specimens; in general, two or more specimens were tested at several different values of loading rate. Conventional tests under constant load were also completed for each metal.

IV. RESULTS OF TESTS AND DISCUSSION

In general the data indicate that the fracture stress was not always a linear function of $\alpha^{0.50}$ as indicated by Eq. 1. Hence it was found desirable to replot the data in accordance with Eq. 2, and to select values of the exponent, n, of the loading rate that would result in a linear relationship between S_F and α^n. This then permits an extrapolation of the data to values of $\alpha = 0$, at which abscissa the ordinate represents the endurance limit, E. The original theory on which the Prot method is based is discussed in Appendix A and the modified theory in Appendix B. The test data for each method have, therefore, been plotted in terms of two different values of n to show the deviations from the original Prot theory in method of plotting the results.

The results are shown in graphical form in Figs. 3 to 10. In these figures a straight line has been drawn in to indicate the relationship represented by Eq. 1 or Eq. 2 and to determine the value of fatigue limit by extrapolation as indicated above. The location of these lines has been determined by use of the principle of "least squares" (7) to obtain a best fit to the experimental data.

In Figs. 3 and 4 the data for ingot-iron are plotted with the exponent of the loading rate taken as 0.371*, and for initial stress levels of 10,000 and 30,000 psi. The values of the endurance limit, E (observed as the ordinate at $\alpha = 0$) for the ingot-iron for this exponent are 35,400 and 36,200 psi for initial stress levels of $\sigma_o = 10,000$ and $\sigma_o = 30,000$ psi, respectively.

In Figs. 5 and 6 the same data are plotted but with the exponent of the loading rate as 0.50 as suggested by Prot, and the values of the endurance limit were 36,700 and 38,500 psi for initial stress levels $\sigma_o = 10,000$ and 30,000 psi respectively.

Good straight-line plots of the data were obtained with both the 0.371 and 0.50 power exponents; the variation of the endurance limit in the two cases being 1,300 psi and 2,300 psi for the initial stress levels of 10,000 psi and 30,000 psi, respectively.

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* See Appendix B.

Thus it appears that the value of the endurance limit of ingot-iron as determined by the Prot method is sensitive to both the exponent of the loading rate and to the initial stress level at which loading was started. A change of 34.8% in the exponent of the loading rate resulted in changes of the endurance limit amounting to 3.67% and 6.35% for initial stress levels of 10,000 and 30,000 psi. Changing the initial stress level from 10,000 to 30,000 psi resulted in an increase in the endurance limit of 2.26% and 4.90% for the 0.371 and 0.50 exponents, respectively.

Under high rates of increase in load, the ingot-iron exhibited a tendency to yield before a visible fatigue crack appeared. Occasionally yielding occurred in a specimen tested at a lower rate of loading for which other specimens failed by fracturing as indicated in Fig. 7.

In Figs. 8 and 9 are plotted the conventional S-N curves for the ingot-iron tested under constant stress amplitude ($\alpha = 0$). These data (plotted with open circles) indicate the fatigue limit to be about 34,000 psi as compared with the values of 35,400 to 36,200 predicted by the Prot method. Thus the method appears to give a close approximation to the ordinarily accepted methods and is within the scatter that might be expected upon successive retesting. (Incidentally, previous conventional tests on another type of flexural fatigue machine indicated a fatigue limit of 37,000 psi for the same iron.)

Also shown in Figs. 8 and 9 are the data obtained in testing by the Prot method; the final fracture stress has been plotted at the corresponding total number of cycles to failure. As would be expected, these data fall above the conventional S-N curve, but tend to become asymptotic to the fatigue limit at a very large number of cycles to failure (corresponding to the tests for which the loading rate α was small).

In Figs. 10 and 11 the results for the 75S-T aluminum are shown. With an exponent of 0.1786* for the loading rate, α, a good straight-line plot of the data was obtained. However when

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* See Appendix B.

plotted as a function of $\alpha^{0.50}$(as suggested by Prot), the large curvature in Fig. 12 was obtained.

The values of the fatigue limit (as obtained with n = 0.1786) were 17,000 and 20,500 psi for initial stress levels of 10,000 and 20,000 psi, respectively. This represents an increase of 20.6% in the fatigue limit. However the value of the fatigue strength at 10^8 cycles for the 75S-T aluminum alloy as indicated by the conventional fatigue test data in Fig. 13 was approximately 25,000 psi. Thus the values from the Prot method were considerably lower than the fatigue strength as usually determined. This is consistent with the fact that the value determined in the Prot method corresponds to an infinite number of cycles.

Considering the above results, it appears that before the Prot method of fatigue testing will be applicable to materials such as 75S-T aluminum alloy (i.e., for materials which do not exhibit linear plots of the fatigue data with the exponent n = 0.50) it will be necessary to determine suitable exponents for the loading rate. Once the exponents have been determined for particular materials, the Prot method has possibilities of being a satisfactory approach to commercial fatigue testing. However for exacting research investigation, the Prot method is limited. To determine the correct exponent of the loading rate for a given material to insure a linear plot, conventional S-N fatigue test data can be utilized as explained in Appendix B. For materials subjected to various heat-treating and other metallurgical processes, the task of determining the corresponding loading rate exponents might offer a serious handicap to the Prot method. However several mathematical methods are being investigated for determining the correct exponent directly from the data obtained in the tests under uniformly increasing load. They appear promising in offering a means of obtaining not only the most probable fatigue limit, but also may be used to estimate the probable error and statistical deviation that may be expected from data of this type.

The scatter of the data obtained in the Prot method needs further investigation both at high and low rates of loading. At high rates of loading the amount of scatter is of particular significance since the time element in testing becomes important in determining the efficiency of the process. Investigation of additional materials by the Prot method is needed, particularly for metals exhibiting no well defined fatigue limit, and a study of the effect of stress concentrations (notches, keyways, grooves, etc.) on the fatigue limit as determined by the Prot method would be of interest for design applications.

Further experimental studies are, therefore, being conducted as a part of this general research program. Notched and unnotched specimens will be investigated for an ingot-iron, an alloy steel, and a boron steel of relatively high hardness. These will be representative of a wide range in hardness and strain-aging characteristics for ferrous metals and thus furnish data for a more extensive appraisal of the Prot method.

V. CONCLUSIONS

1. For ingot-iron the Prot method of fatigue testing using either 0.371 or 0.50 as the exponent of the loading rate, gave results which compared favorably with the ordinary methods of fatigue testing. For high rates of load increase, the ingot-iron failed by yielding before a crack appeared.

2. The value of the endurance limit of ingot-iron was only slightly affected by changes in the exponent used in plotting the loading rate; a change of 34.8% in the exponent resulted in changes of 3.67% and 6.35% in the endurance limit for tests started at initial stress levels of 10,000 psi and 30,000 psi, respectively.

3. Raising the initial stress level from 10,000 psi to 30,000 psi raised the endurance limit of the ingot-iron by only 800 to 1800 psi, the amount depending upon which value of the exponent n was used to interpret the data.

4. For 75S-T aluminum alloy, the 0.50 exponent as proposed by Prot gave a non-linear function that could not be satisfactorily extrapolated to obtain the fatigue strength. Only for one exponent of the loading rate ($n = 0.1786$) did the Prot method give results that could readily be interpreted. Changing the initial stress level of the 75S-T aluminum alloy from 10,000 psi to 20,000 psi increased the indicated fatigue limit from 17,000 psi to 20,500 psi; as values determined by the Prot method corresponds to an infinite number of cycles, these values were somewhat below the fatigue strength of 25,000 psi at 10^8 cycles as determined from the conventional S-N diagram.

5. The Prot method of fatigue testing appears applicable for rapid estimation of the fatigue strength in certain types of commercial testing, particularly for materials for which a linear plot is obtained with the exponent n assumed to be 0.50 or for materials for which an accurate value for n may be obtained readily.

APPENDIX A

THEORY OF PROT METHOD OF FATIGUE TESTING

The S-N curve for a material is obtained by drawing a curve through a series of experimental test points found from conventional fatigue tests at constant stress amplitudes. These experimental test points are plotted usually with the log of the cycles as the abscissa and the stress as the ordinate, the resulting curve consisting ordinarily of two straight lines.

For the case of small scatter, Prot assumes that if a linear scale is used to plot the cycles, the fatigue curve may be assumed without large error to be asymptotic to both the vertical axis and the endurance limit and, in addition, to be a hyperbola in the region of the endurance limit.

Assuming the endurance limit is one axis of the hyperbola, the equation of the fatigue curve is then:

$$pN = K \qquad \text{Eq. A-1}$$

where p is the amount by which the stress in the specimen exceeds the endurance limit, N is the number of cycles to failure and K is a constant. When the usual notations are used, the equation can then be written

$$(S-E)N = K \qquad \text{Eq. A-2}$$

In the progressive loading fatigue test, suppose the stress S has an initial value S_o at the time the test is started, and increases linearly with time. Then at any time

$$S = S_o + \alpha N \qquad \text{Eq. A-3}$$

where N = cycles, and α is the amount the stress increases each cycle. Equation A-1 may then be rewritten

$$\int_o^N p dN = K \qquad \text{Eq. A-4}$$

When p is a constant, this equation represents the rectangle S_oABE, Fig. 14, a constant area with the position A on the curve.

Prot assumes that the above assumptions are still true when p is not constant, but is a function of time, of the form

$$p = p_o + \alpha N \qquad \text{Eq. A-5}$$

Substituting this value of p into Eq. A-4 gives

$$\alpha N^2/2 + p_o N - k' = 0 \qquad \text{Eq. A-6}$$

valid only for $p_o \geqq E$. This result simply means that the trapezoid ES_oRC, Fig. 14, has a constant area equal to K' for all possible positions of the point R.

Prot assumes that when the initial stress S_o is less than E, no damage of the material occurs until the stress S is greater than the endurance limit E. The value p_o considered above, is then zero, and using the notation from Fig. 15

$$\frac{\alpha N^2_R}{2} = K' \qquad \text{Eq. A-7}$$

This shows the area of the triangle ERC is constant and that the point R is also on an hyperbola with the equation

$$(S_R - E)N_R = 2K' \qquad \text{Eq. A-8}$$

Since $p_R = S_R - E$, and $p_R = \alpha N_R$, then from Eq. A-7

$$p^2_R = 2\alpha K' \qquad \text{Eq. A-9}$$

Hence,

$$p_R = \sqrt{\alpha} \;.\; \sqrt{2K'} = K\sqrt{\alpha} \qquad \text{Eq. A-10}$$

or by substituting for p its equivalent value S-E, at fracture we have

$$S_R = E + K\sqrt{\alpha} \qquad \text{Eq. A-11}$$

This is the equation of a straight line intersecting the ordinate axis at the endurance limit, E, corresponding to $\alpha = 0$. From Eq. A-11 it is seen that the stress S_R varies linearly with $\sqrt{\alpha}$.

APPENDIX B

DETERMINATION OF EXPONENTS OF LOADING RATE

If a repeated stress, S, which is less than the endurance limit, E, is applied to a specimen, the life of the specimen will be infinite. If a repeated stress, S, which is greater than the endurance limit, E, is applied, the fatigue life is finite. The greater the difference (S-E) the small the fatigue life, N. Therefore we may write, in the manner of Weibull (3), a close approximation to the shape of the S-N curve as

$$N = k(S-E)^{-m} \qquad \text{Eq. B-1}$$

which indicates that a plot of log N vs. log (S-E) will be a straight line. In this notationship m and k are constants which Weibull has shown to be dependent on the material. By employing Eq. B-1 (instead of the assumption of Eq. A-1 made by Prot) Henry (4) has shown that m may be related to the exponent of the loading rate α in the following manner

$$S_R = E + K\alpha^{\frac{1}{m+1}} \qquad \text{Eq. B-2}$$

i.e., the exponent of α is equal to $1/(m+1)$. Hence the exponent of the loading rate is not necessarily a constant value of 0.50 as indicated by Prot (which would require $m = 1$) but in general is a function of the material being tested.

A procedure for determining the value of m from conventional fatigue data for a particular material is as follows:

1. Obtain sufficient S-N data to determine an approximate endurance limit, E.

2. With this approximate value of E, plot log N vs. log (S-E). Unless the approximate value of E is fairly accurate, a curved line will result.

3. If a curved line results, adjust the value of E by small amounts until a straight line is obtained. From Eq. B-1, it is seen that the slope of the linear plot of log N vs. log (S-E) determines m.

Proceeding in the manner outlined above, the values of m for ingot-iron and 75S-T aluminum alloy were found to be 1.7 and 4.6, respectively (Figs. 16 and 17). The data shown in these two figures are the same as those previously shown (by open circles) in Figs. 9 and 13. The optimum loading rate exponents for α were therefore 0.371 and 0.1786, respectively, and these values were used for final interpretation of the data obtained in testing by the Prot method. See for example Figs. 3, 4, 10 and 11.

In general, the above procedure would make the Prot method seem tedious and uneconomical because it would require some data to be obtained from the usual types of conventional constant stress-amplitude tests. However the exponents n presumably would be material constants and thus should only need to be determined once for a given type of material. Furthermore it appears probable that a direct method of interpreting the data can be developed that will not necessitate the use of conventional test data for evaluation of the constants of Eq. B-2. Further study of suitable methods of analyzing the data is now underway.

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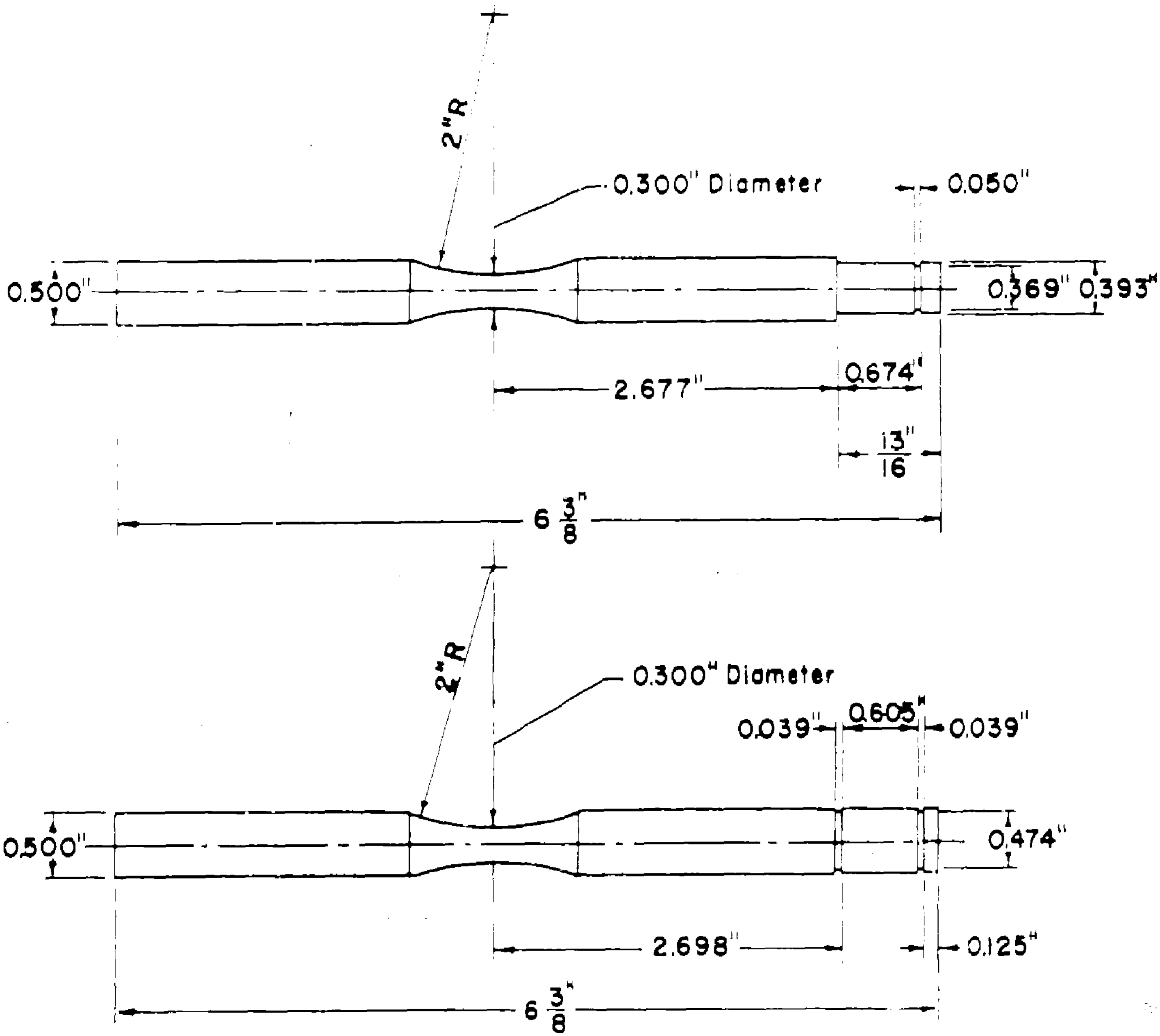
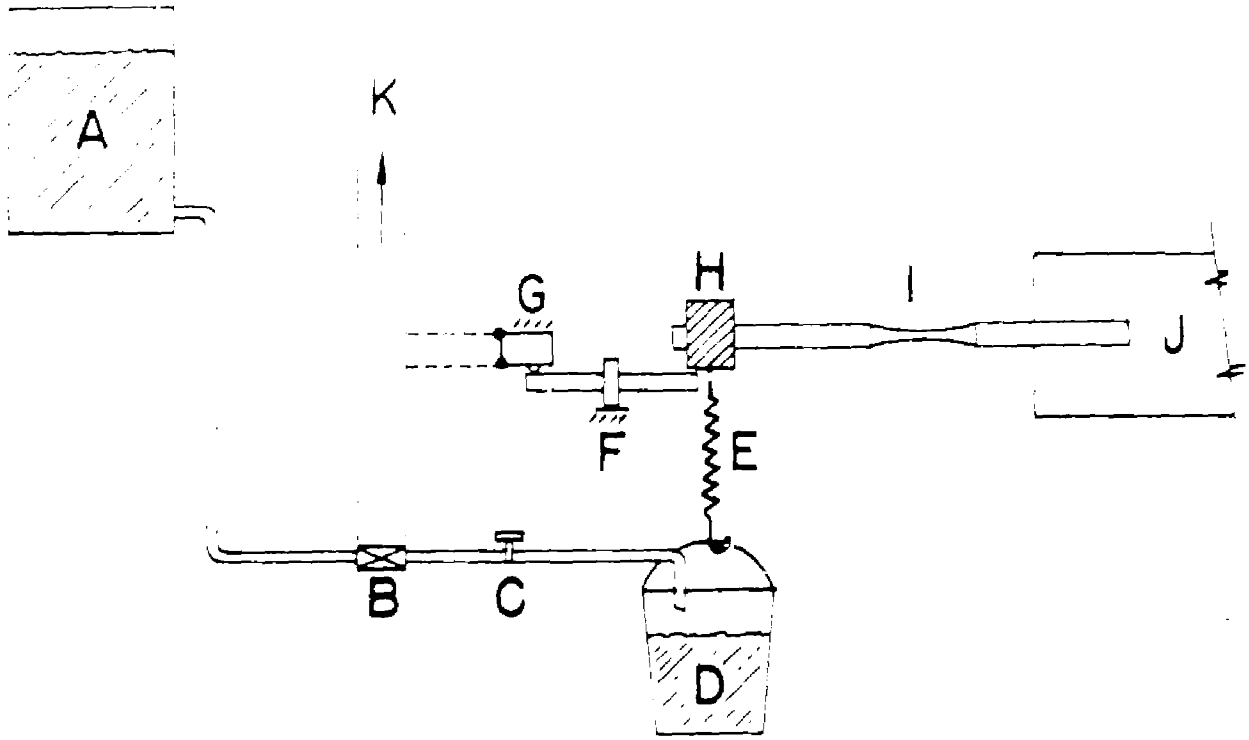


Fig. 1. Dimensional Details of Fatigue Specimens.



A - Standpipe
B - Solenoid Control Valve
C - Needle Control Valve
D - Water Container
E - Spring Hanger
F - Automatic Cutoff Arm
G - Micro-switch, When Specimen Fails Automatically Closes Solenoid Control Valve and Electric Motor
H - Ball Bearing Housing To Transmit Load To Specimen
I - Specimen
J - Specimen Chuck Of Rotating Cantilever Beam Fatigue Machine
K - Electric Wiring To Electric Motor Drive

Fig. 2. Schematic Of Test Apparatus

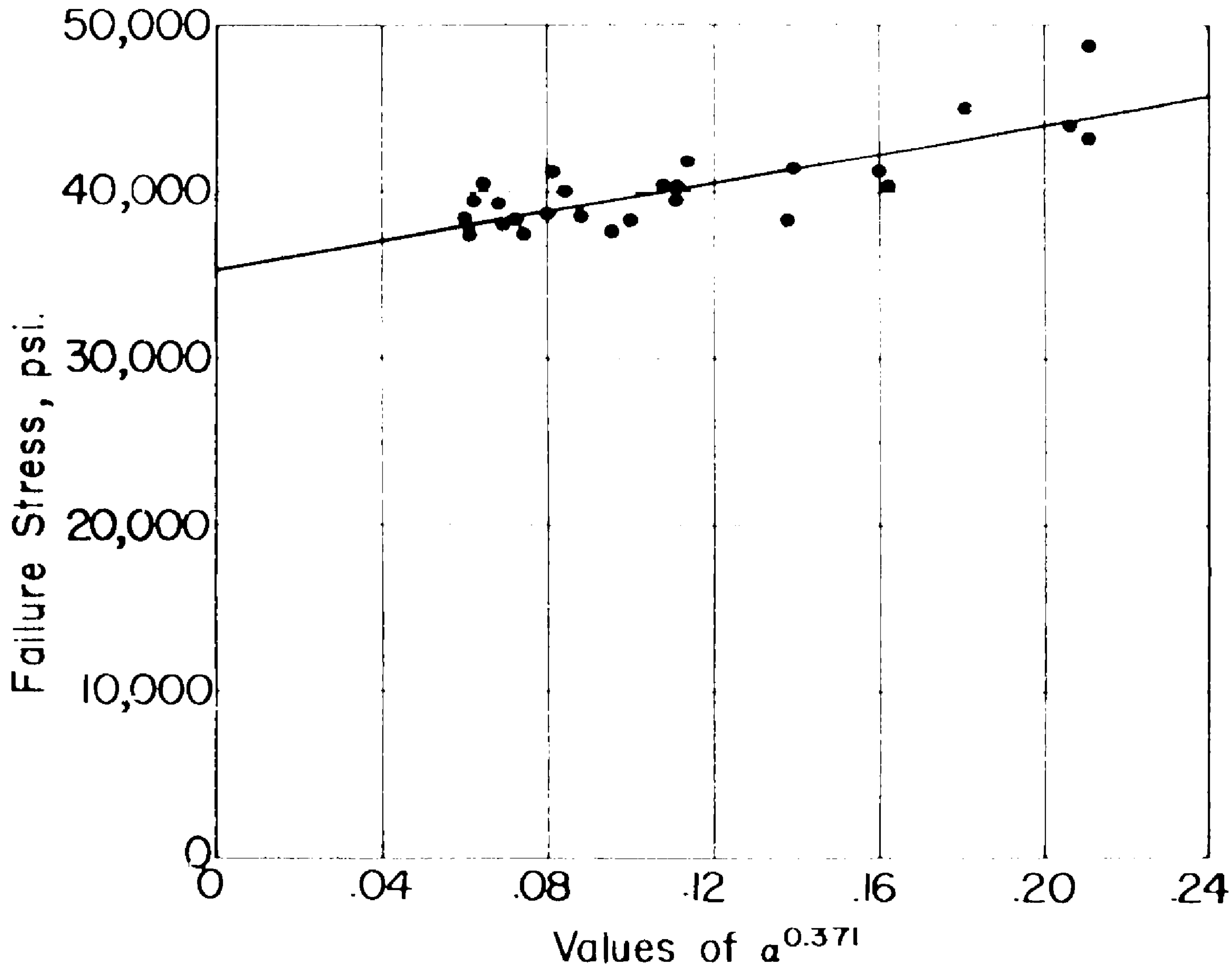


Fig. 3. Fatigue Data for Ingot Iron. (σ_o = 10,000 psi.)
(Omitting specimens that failed by plastic bending)

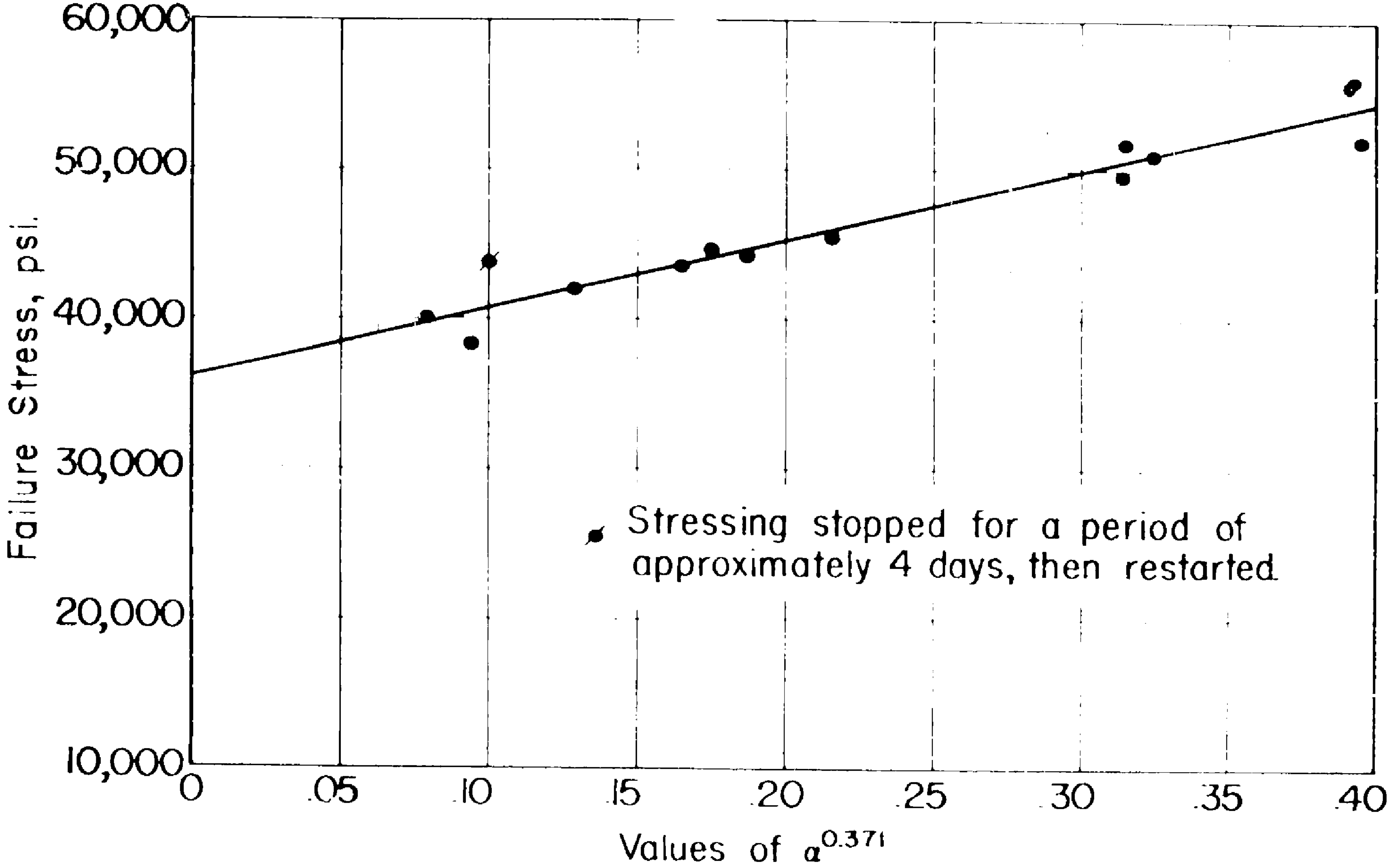


Fig. 4. Fatigue Data for Ingot Iron. (σ_0 = 30,000 psi.)
(Omitting specimens that failed by plastic bending.)

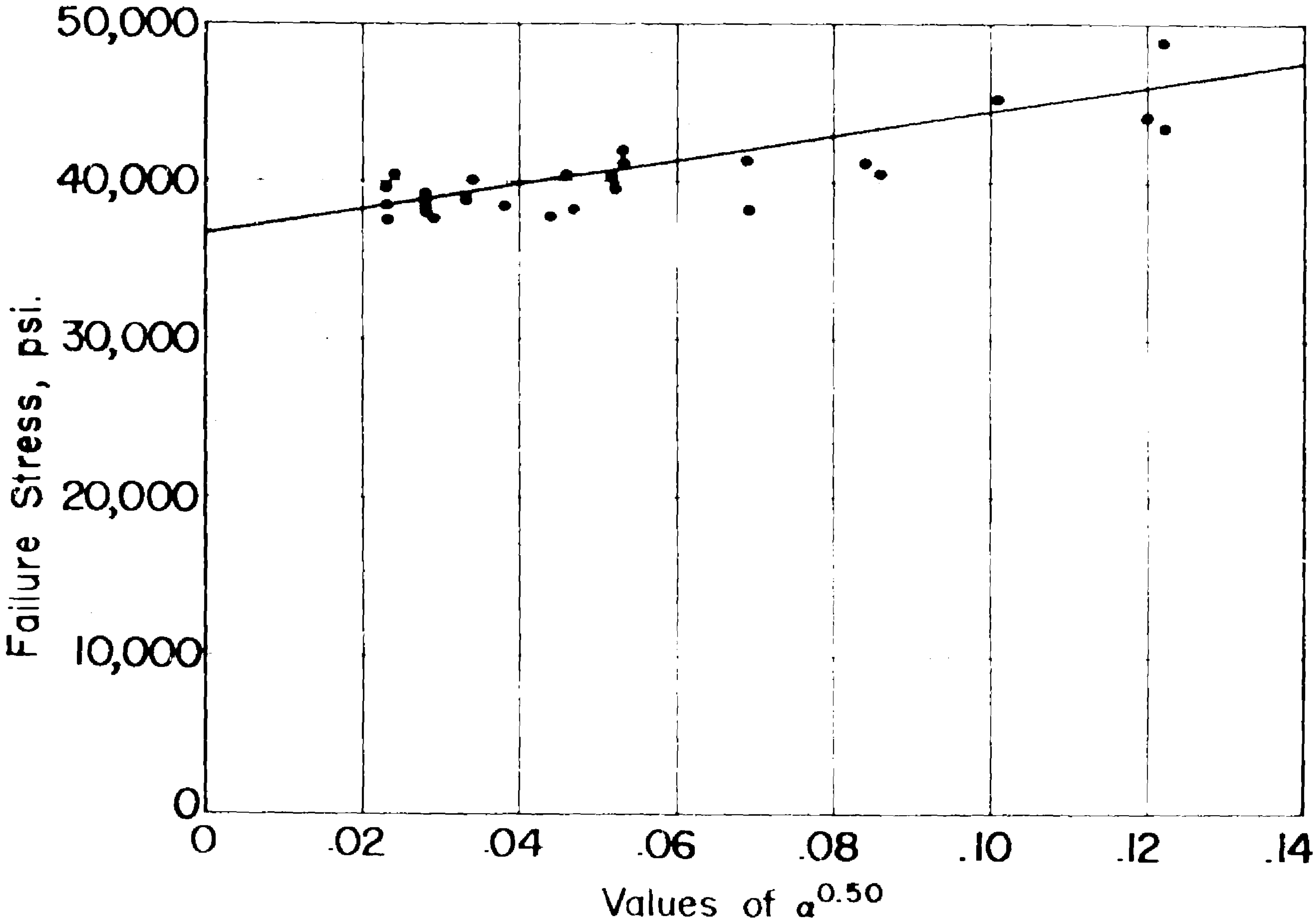


Fig. 5. Fatigue Data for Ingot Iron. ($\sigma_o = 10{,}000$ psi.)
(Omitting specimens that failed by plastic bending.)

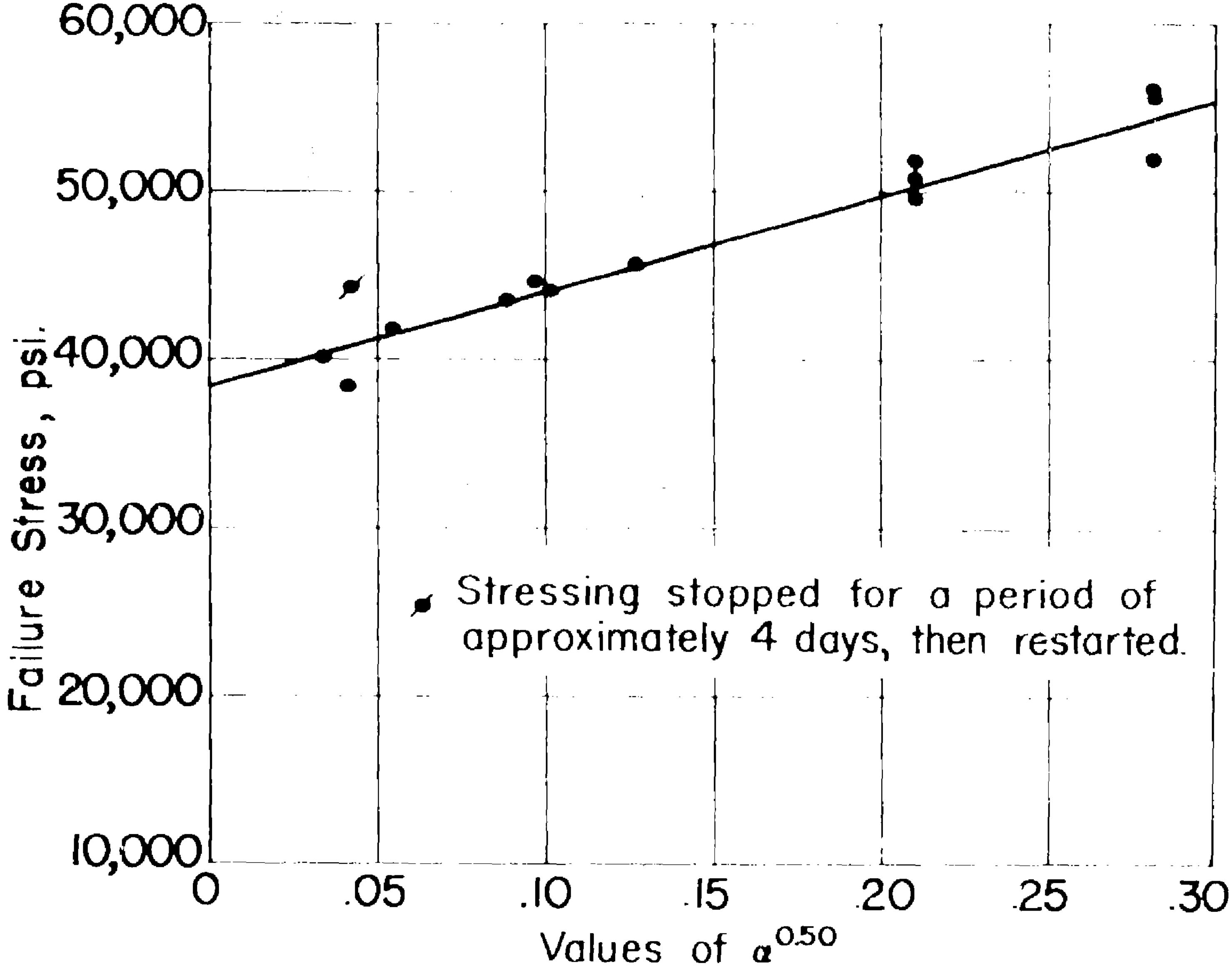


Fig. 6. Fatigue Data for Ingot Iron. (σ_o = 30,000 psi.)
(Omitting specimens that failed by plastic bending.)

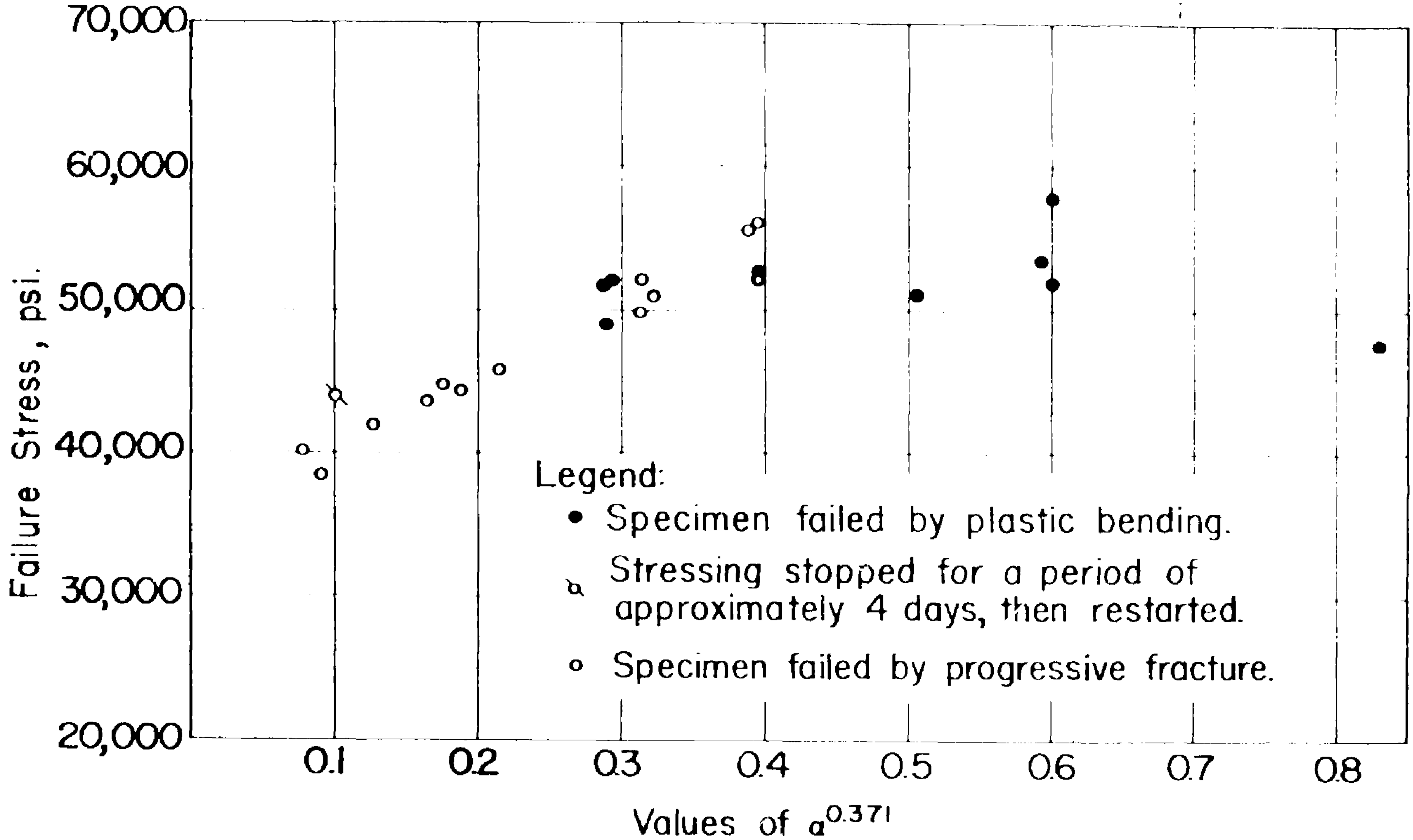


Fig. 7. Appraisal of Prot Method for Ingot Iron. (σ_0 = 30,000 psi.)

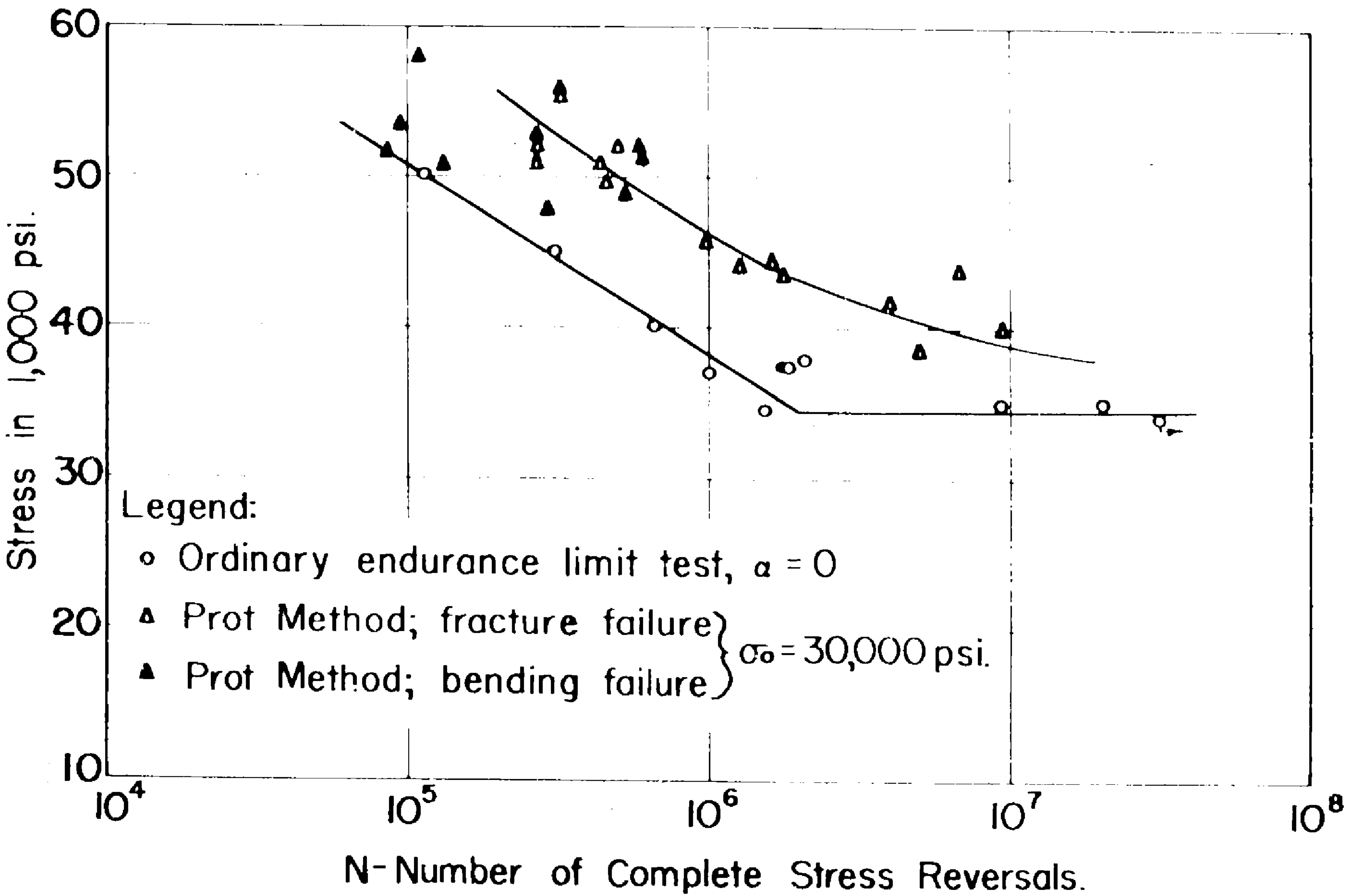


Fig. 8. S-N Curve for Complete Stress Reversals; Ingot Iron Specimens.

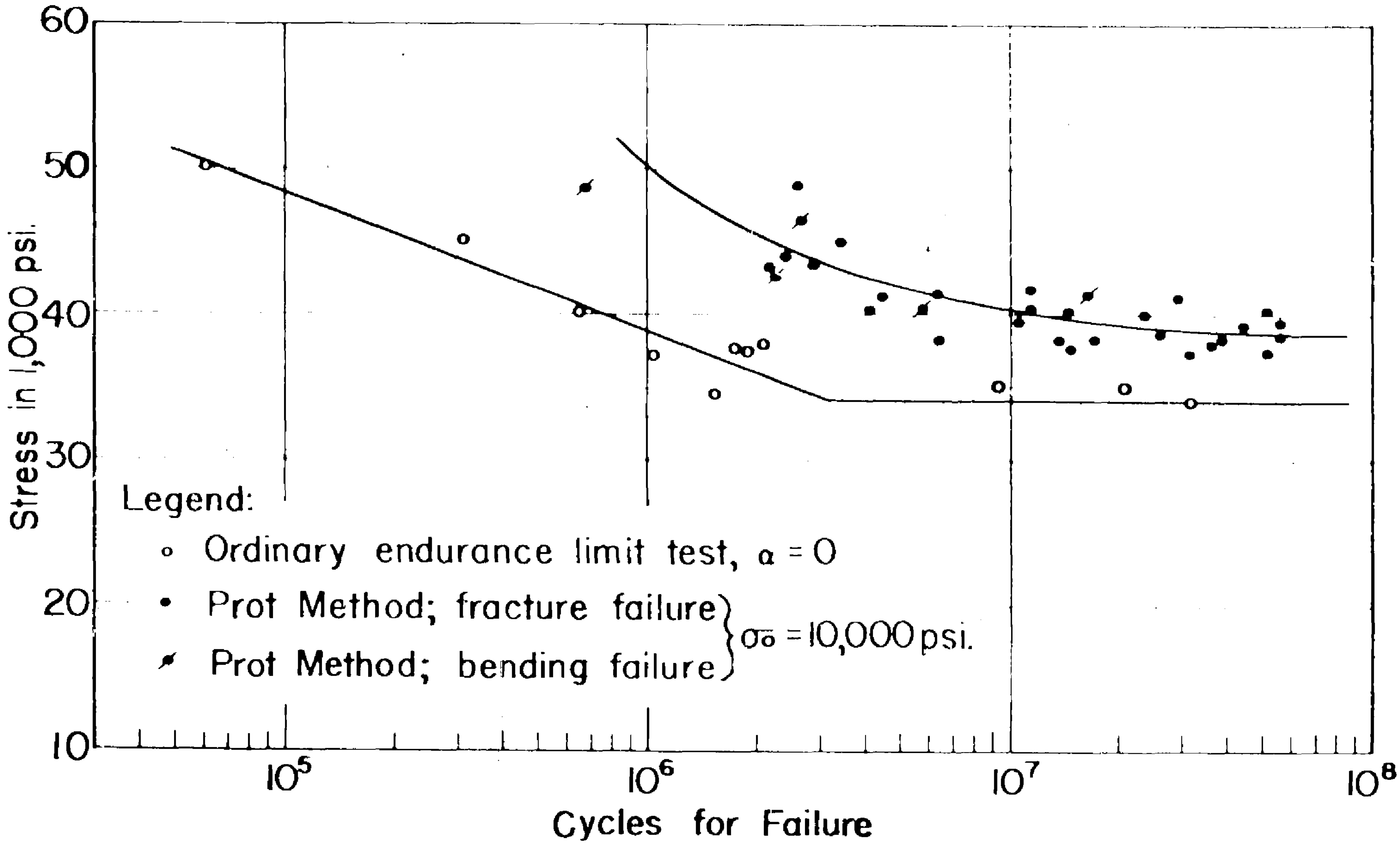


Fig. 9. S-N Curve for Complete Stress Reversals; Ingot Iron Specimens.

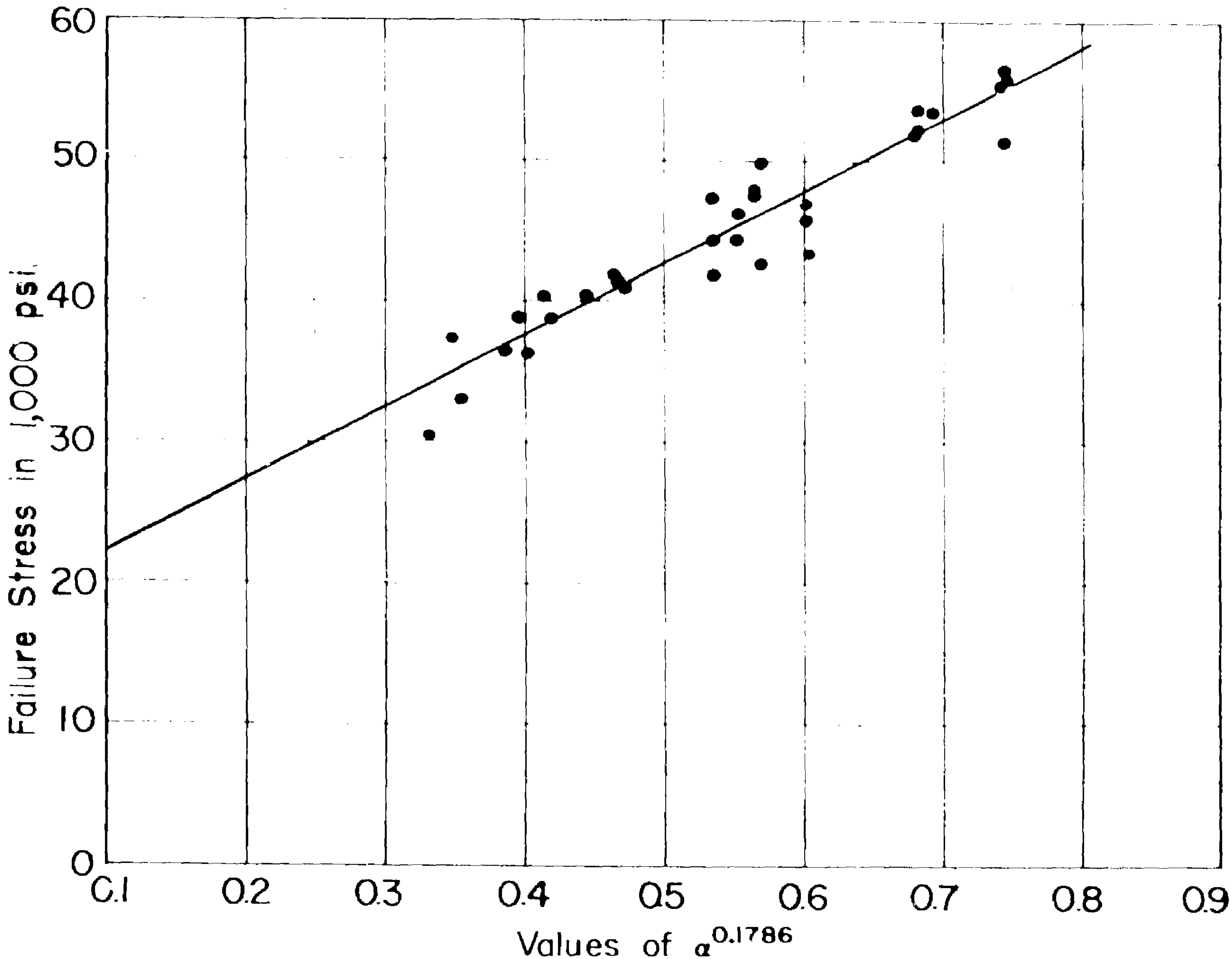


Fig. 10. Fatigue Data for 75S-T Aluminum Alloy. (σ_0 = 10,000 psi.)

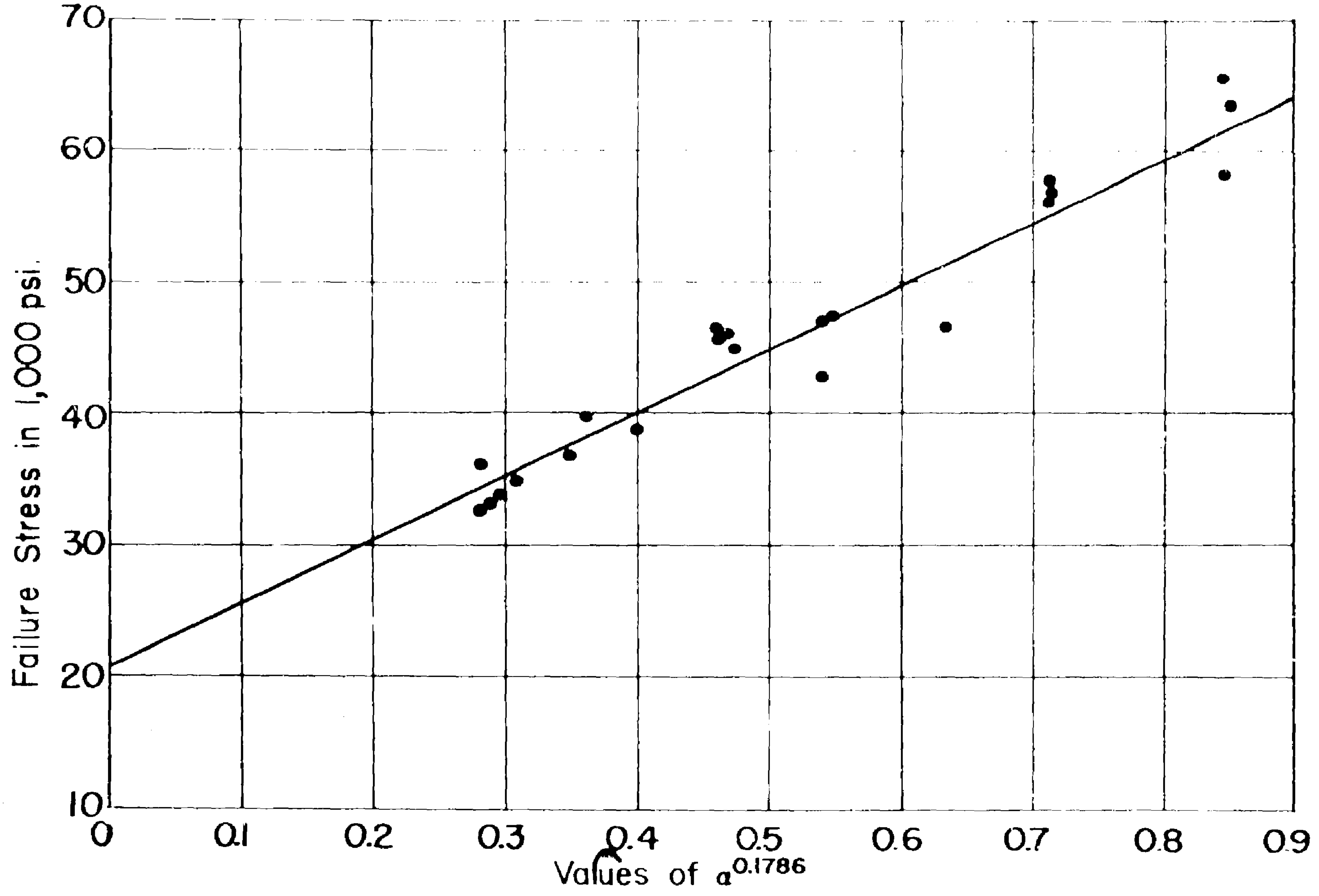


Fig. 11. Fatigue Data for 75S-T Aluminum Alloy. (σ_o = 20,000 psi.)

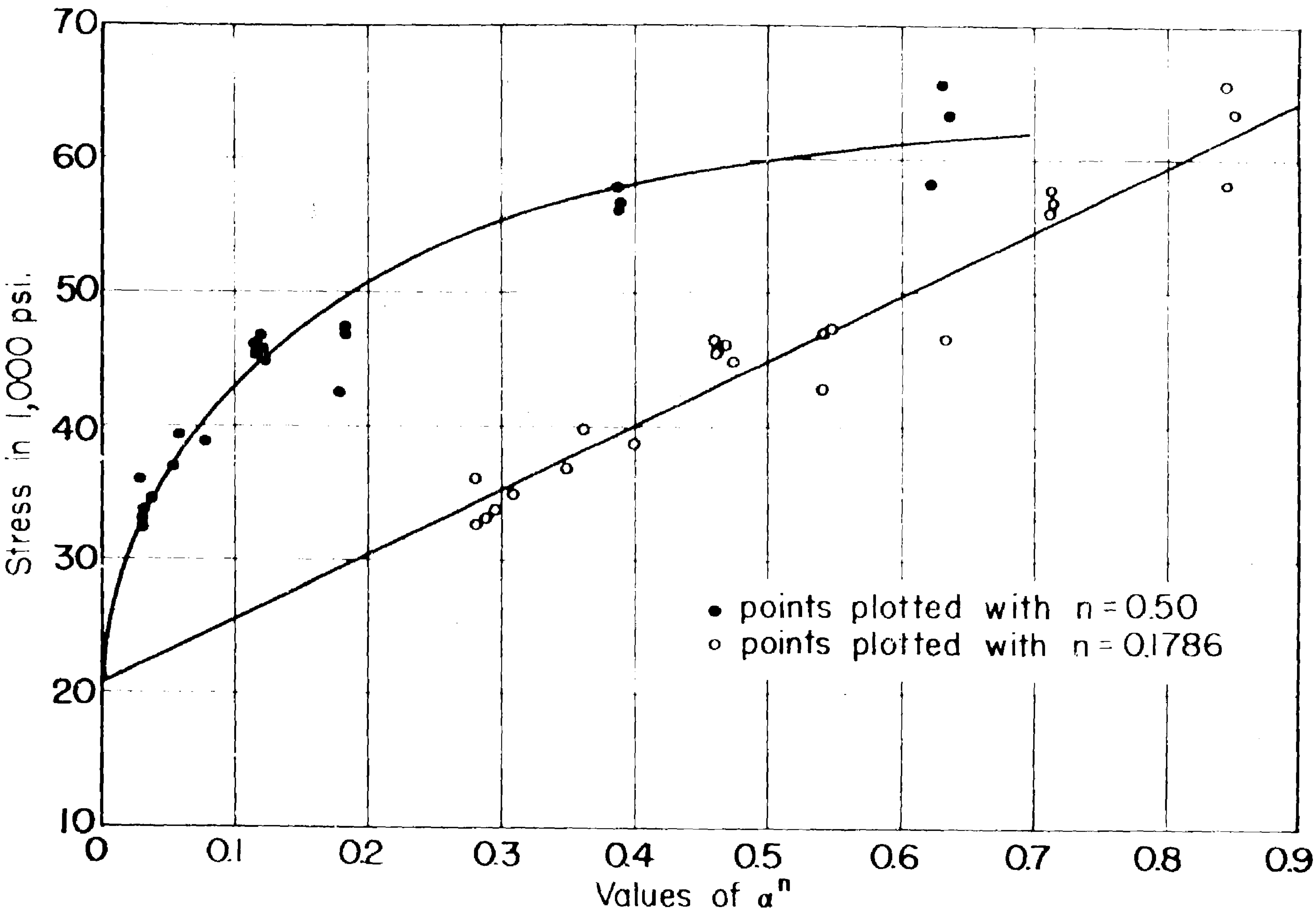


Fig. 12. Appraisal of Prot Method for 75S-T Aluminum Alloy. (σ_o = 20,000 psi.)

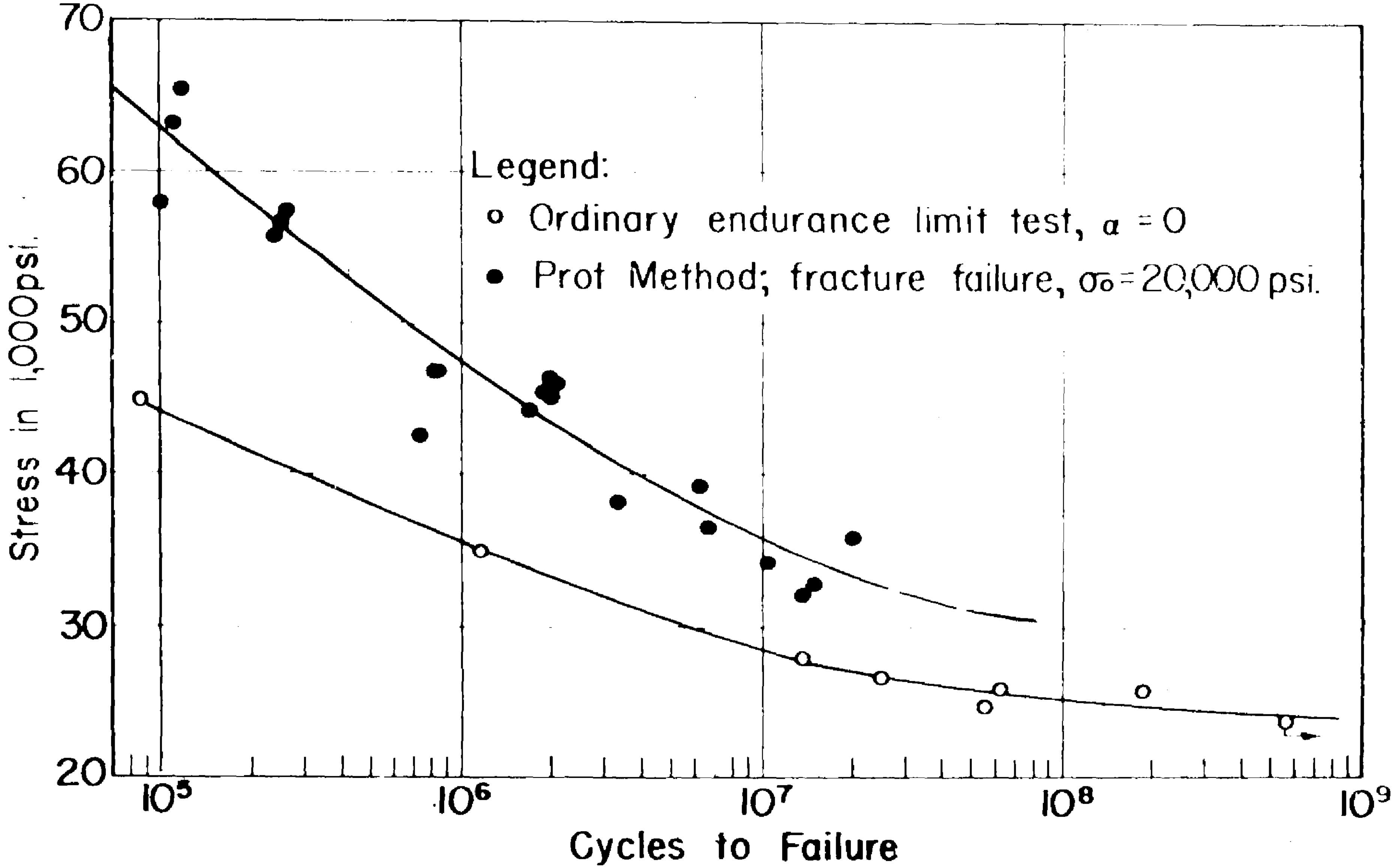


Fig. 13. S-N Curve for Complete Stress Reversals; 75S-T Aluminum Specimens.

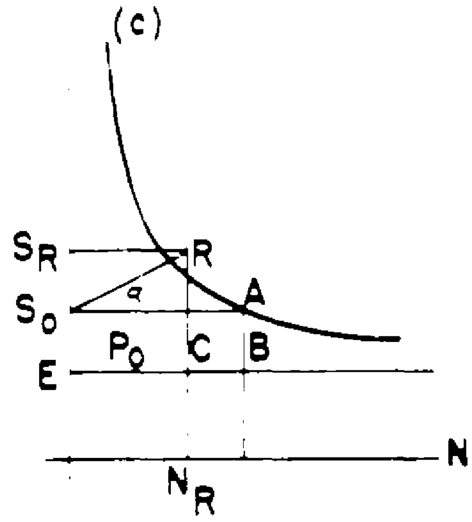


FIG. 14 S-N Diagram **showing** initial stress level S_o above endurance limit E.

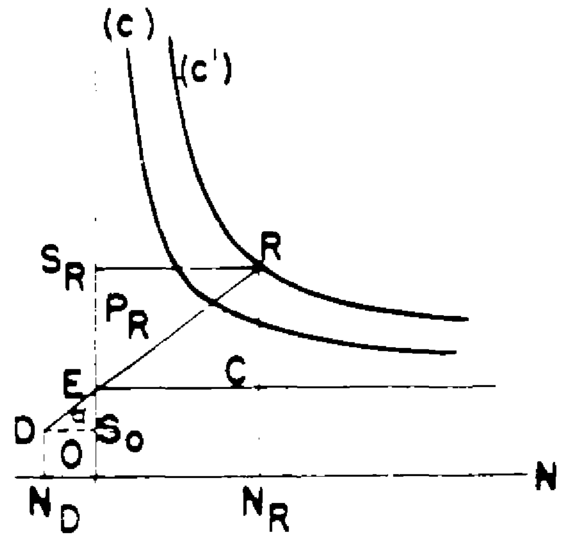


FIG. 15 S-N Diagram **showing initial stress level** S_o **below** endurance **limit** E. In the Prot method the "damage" represented by the area $N_D DECN_R$ is neglected.

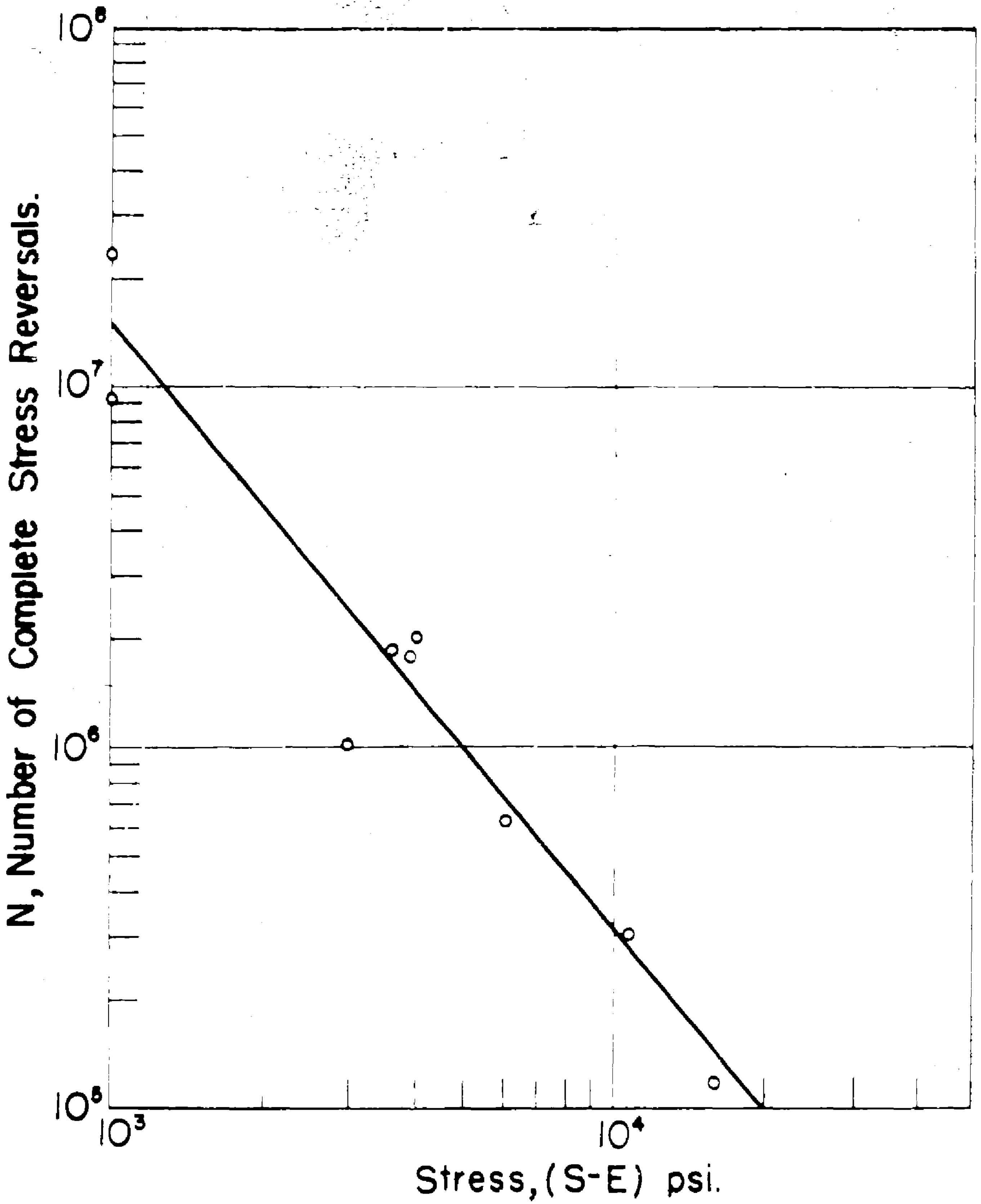


FIG. 16 N vs. (S-E) diagram for Armco Ingot Iron using E = 34,000 psi. The slope of the line is the exponent m used in Eq. B-2, m = 0.371

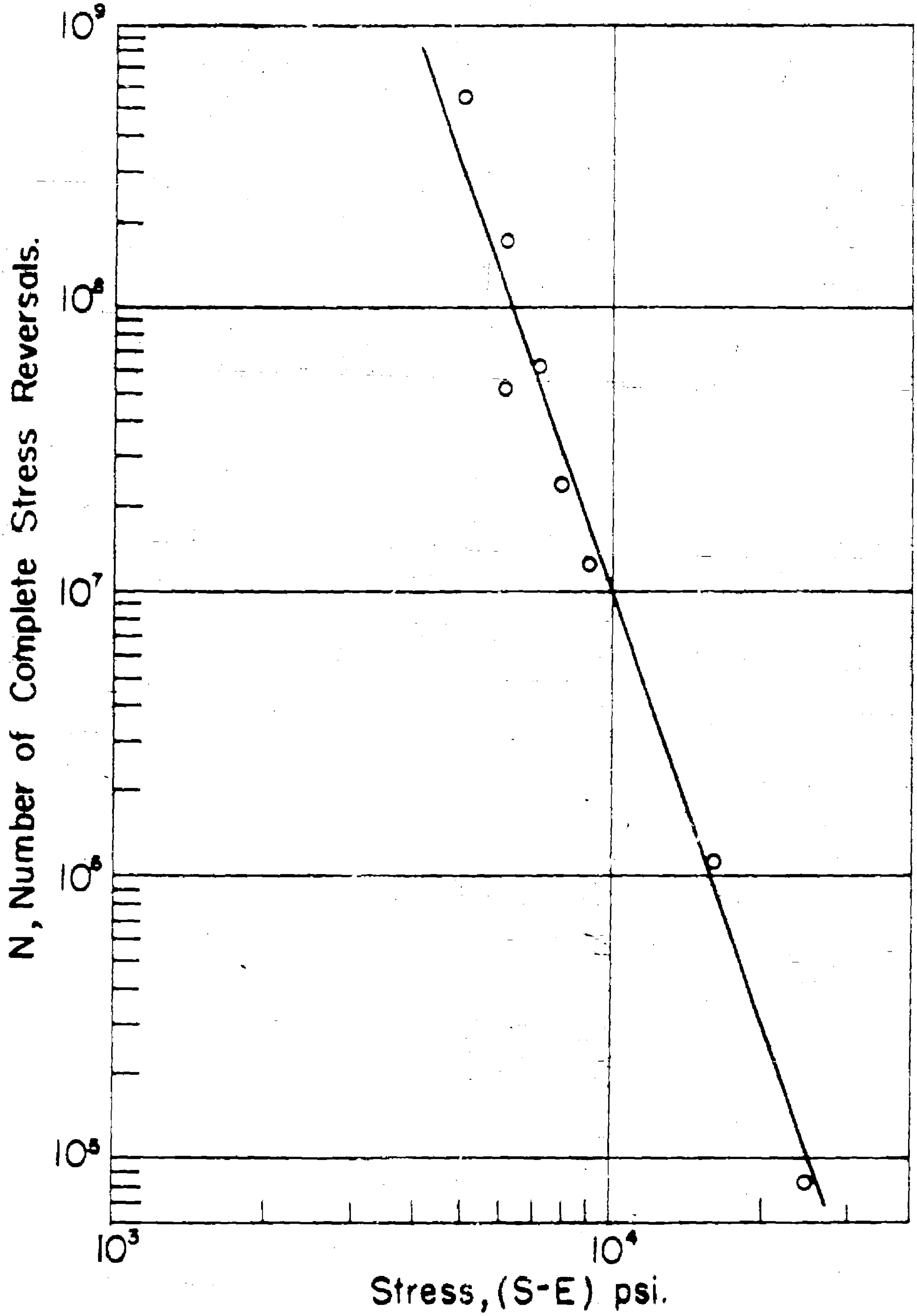


FIG. 17 N vs. (S-E) diagram for 75S-T Aluminum Alloy using E = 19,000 psi. The slope of the line is the exponent m used in Eq. B-2, m = 0.1786

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