1959

Accelerated fatigue tests of butt-welded joints, June 1959

J. Swindlehurst

ACCELERATED FATIGUE TESTS OF BUTT-WELDED JOINTS

by

John Swindlehurst

This study has been made as a Special Problem in Civil Engineering, C. E. 406, in partial fulfillment of requirements for the Degree of Master of Science. This investigation has been carried out under the financial sponsorship of the University Committee of the Welding Research Council.

Fritz Engineering Laboratory
Department of Civil Engineering
Lehigh University
Bethlehem, Pennsylvania

Fritz Laboratory Report No. 265.1

June 1959

TABLE OF CONTENTS

ABSTRACT

Experimental data using an accelerated method of fatigue testing is presented. This method introduced by Prot, calls for testing of specimens under a constantly increasing fluctuating or alternating stress as opposed to conventional methods using a constant stress amplitude. The test specimens were butt-welded joints of A373 steel. Testing was done in an Amsler High Frequency Vibrophore.

Accelerated Fatigue Tests of Butt-Welded Joints

1. INTRODUCTION

In 1947, Marcel Prot (1)* proposed a new technique for an accelerated determination of the Endurance Limit of Materials. Although many short-cuts in fatigue testing have been previously proposed, the Prot method has aroused sufficient interest in technical and scientific circles to be submitted to experimental verification. This program has been organized to investigate the applicability of the method to the testing of butt-welded connections of ASTM A-373 steel.

The conventional approach to fatigue testing involves the determination of the Endurance Limit from a Wöhler or S-N diagram. This method, although universally accepted, has many inherent disadvantages. Generally, to obtain an accurate curve a great many tests must be run, all of which are subject to normal scatter. The statistical confidence limits are sometimes difficult and, for some materials, even impossible to establish. Another difficulty is to set a limit or life to the number of cycles which, at a given stress level, will determine the Endurance Limit.

To overcome these disadvantages, attempts have been made to relate the endurance limit to some of the statical

---

* Refers to list of references.

properties[5] by a special testing technique and to use this as a measure of the endurance limit. The results obtained were not conclusive and found little verification.

Other investigators utilized electrical and magnetic properties[5] of the material to detect the stress level of the Endurance Limit. Changes in the damping capacity and the Modulus of Elasticity[5] have also been studied with considerable success. Some studies have been made on the use of X-rays[5] to determine surface phenomena as related to fatigue life.

Attempts have also been made to reduce testing time by assuming the shape of the S-N curve as a means of extrapolating results, but the necessity of the test results conforming to the assumed mathematical curve limits the value of the method. The Prot method is based on such an assumption.

The total testing time can also be decreased by increasing testing speed. The Amsler High Frequency Vibrophore, which has been used for the tests reported in this paper provides such a possibility. However, there may be serious questions of temperature rise and damping at the higher frequencies for some materials.

The use of more than one machine in a given program will also shorten the total time, but the compilation of results obtained on different machines introduces many new problems.

2. BASIS OF THE PROT METHOD

Many investigators have done extensive work on damage considerations in fatigue.[13][14] They have approached the field from the physical testing point of view, generally staying clear of the complicated theories of crystal and molecular slippage and cleavage. Based mainly on test data, Miner[10] estimated the cumulative damage by the following formula $\Sigma \frac{n}{N} = 1$ - Eq. 4 from Ref. 10 - where N is the number of stress cycles to failure at Stress S, and n is the number of cycles less than N at Stress S. This is to say that the damage done in any cycle at a stress level is a constant for any cycle. Other investigators[11][12][13][14] have determined different relationships.

Prot proposed that the fatigue test should be run at a progressively increasing, fluctuating or alternating stress as opposed to a constant stress amplitude used in the conventional method, the evident advantage of such a progressive loading being that, in all cases, each specimen will fail. As the load is increased linearly, there will be a constant increase of stress amplitude with each cycle, say α psi/cycle. The square root of α is then plotted against the failure stress, S_α . By fitting a straight line through the test points as shown in Fig. 1, the intercept of this line with the S_α ordinate at $\alpha = 0$ is then taken as the value of stress at the endurance limit, S_E.

The above is based on certain theoretical considerations outlined by Prot in the original paper.[1]

Assumptions...(1) The material has an Endurance Limit.

(2) The S-N diagram has the form of a hyperbola, asymptotic to the vertical axis and the Endurance Limit.

(3) The mechanism of failure is manifested by the propagation of microscopic cracks and it can be expressed as the number of ruptured molecules per cycle and it is proportional to the amount of stress above the Endurance Limit.

STOP

Figure 2 is used to illustrate the derivation of the equations used by Prot. Curve C_1 is the ordinary S-N curve represented by $(S-S_E)\ N = K$.* Curve C_2 is similar to C_1 displaced to the right. If D_1 is taken as the damage area required to produce failure of a specimen under a constant stress amplitude, S representing the value of the maximum stress, $D_1 = (S-S_E)\ N$

Similarly D_2 is taken as the damage area required to produce failure of the specimen at stress $S_\alpha = S$ under a constant stress increase of α per cycle.

$$D_2 = \frac{1}{2}\ (S-S_E)\ d$$

---

* For definition of symbols used, see Nomenclature, page 19.

From Miner's hypothesis, equal damage must be done for failure, $D_1 = D_2$

$$2N = d \tag{1}$$

In Fig. 2, from triangle S_E, A, S_m;

$$\alpha = \frac{S_E - S_m}{x}$$

therefore

$$x = \frac{S_E - S_m}{\alpha}$$

$$N_\alpha = \frac{S - S_m}{\alpha}$$

$$d = N_\alpha - x = \frac{S - S_m - S_E + S_m}{\alpha} = \frac{S - S_E}{\alpha}$$

From Eq. 1

$$2N = \frac{S - S_E}{\alpha} \quad \text{or} \quad 2\alpha = \frac{S - S_E}{N}$$

From assumption 2, $(S - S_E)\,N = K$ (2)

$$N = \frac{K}{S - S_E}$$

$$(S - S_E)^2 = 2\alpha K \quad \text{or} \quad S = S_E + \sqrt{2K\alpha}$$

Let $K' = \sqrt{2K}$ $\quad S = S_\alpha = S_E + K'\sqrt{\alpha}$ (3)

The above relation yields a straight line if S is plotted against $\sqrt{\alpha}$.

Henry[2] has developed a somewhat more generalized expression similar to Prot's. He made use of an empirical formula by Weibull for the representation of the S-N curve and applied Miner's[10] hypothesis of cumulative damage. See Fig. 3.

Forming Miner's sum $\sum_{0}^{S_\alpha} \frac{n}{N} = 1$

Now
$$\sum_{0}^{S_\alpha} \frac{n}{N} = \sum_{0}^{S_E} \frac{n}{N} + \sum_{S_E}^{S_\alpha} \frac{n}{N} = 0 + \sum_{S_E}^{S_\alpha} \frac{n}{N} = 1 \qquad (4)$$

but $\Delta S = \alpha n$ or $n = \frac{1}{\alpha} \Delta S$

Therefore
$$\sum_{S_E}^{S_\alpha} \frac{n}{N} = \sum_{S_E}^{S_\alpha} \frac{\Delta S}{\alpha N} \qquad (5)$$

From Eq. (2) $N = K\,(S - S_E)^{-1}$

or since the hyperbolic curve C_1 can vary according to the material, a more general equation can be written,

$$N = K\,(S - S_E)^{-m}$$

From Eq. 5

$$\sum_{S_E}^{S_\alpha} \frac{n}{N} = \sum_{S_E}^{S_\alpha} \frac{\frac{\Delta S}{\alpha}}{K(S-S_E)^{-m}} = \frac{1}{K\alpha} \sum_{S_E}^{S_\alpha} \frac{\Delta S}{(S-S_E)^{-m}} = 1$$

If instead of a step by step stress increase ΔS, a continuous increase dS is used, the above summation must be changed to the following integral

$$\frac{1}{K\alpha} \int_{S_E}^{S_\alpha} (S - S_E)^m \, dS = \frac{(S_\alpha - S_E)^{m+1}}{K\alpha\,(m+1)} = 1$$

$$S_\alpha - S_E = \left[(m+1)\,K\alpha\right]^{\frac{1}{m+1}} \qquad (6)$$

where m can be determined for any material by plotting conventional fatigue data on a graph (Fig. 4). Equation (6) coincides with Eq. (3), developed by Prot, if m = 1.

Previous experimental work(3)(4)(5)(6)(7)(9) using the Prot method has shown that a fairly accurate determination of the Endurance Limit S_E can be made. However, it has been demonstrated that a straight line does not always evolve using an exponent of 1/2 for α. Using a best fit method, the exponents of α have been determined to be from 0.178 for aluminum to 0.717 for 14B50 steel. This would appear to bear out Henry's conclusion that the exponent should depend on the material properties. In fact fairly close agreement to a best fit line on the Prot plot can be obtained from the exponent derived by plotting conventional fatigue data on log-log paper as in Fig. 4.

Equation (3), $S = S_E + K'\alpha^{\frac{1}{2}}$ should then be written in the more general form $S = S_E + K'\alpha^r$ (7)

Previous investigators have studied the Prot method using high strength steels, ingot iron and aluminum, and all these materials gave good agreement with the theory. With the exception of work done by Enomoto(9) of Japan on structural steels, little has been done to determine what happens to mild steel with a relatively low yield point. It was, therefore, decided to test the Prot method on butt-welded specimens of A-373 steel in order to determine its applicability to material like structural steel.

The University of Illinois has accumulated considerable data for welded connections of A-7 steels. Some of these results are shown in Figs. 5 and 6 in form of a Weibull plot. Comparison would show fair agreement of the slope of these straight lines with the slopes of data, on plain steel specimens, obtained in the course of previous Prot investigations.(6)

3. TEST SPECIMENS, APPARATUS, AND PROCEDURE

All test specimens were cut from a single 3/8" plate purchased from the Sparrows Point plant of Bethlehem Steel Company. The physical and chemical properties of the ASTM A373-54T steel plate are given with other information in Tables 1 and 2. The location of the specimen in relation to the original plate is illustrated in Fig. 7. Fatigue specimens were cut out of plates A to H, plate I was used for specimens to determine static properties. Plates A, B, C, D, E and G were cut, beveled and butt-welded as shown in the welding detail, given in Fig. 7. Plates F and H were not welded but cut into plain fatigue specimens.

The welding was performed in the following manner. The individual plates were clamped down flat and the pass was made into the root with a 5/32" DH-6, AWS Class E6014 Electrode at 190 amps. A second pass was made with a 3/16" rod of the same class at 250 amps to complete the weld. The plate was then turned over, reclamped and the root ground to a depth of 1/8". The root was then rewelded with a 3/16" rod at 250 amps. Bend tests were made and no cracks were apparent. Complete X-rays were taken to insure uniformity and quality of welding. All welding was done at the Bethlehem Foundry and Machine Company using one welder to ensure uniformity. The test specimens were machined out of the individual plates by the machine shop in Fritz Engineering Laboratory, type S and X as shown in Fig. 7 and conventional tensile specimens.

Prior to testing, all sharp corners of the specimens were removed and machined surfaces smoothed and polished with coarse and fine emory cloth. This operation removed machine marks and work hardened material and facilitated observation of cracks. Mill scale and weld reinforcements were left on to simulate actual practice. Two types of specimens were cut as shown in Fig. 7. Specimen type S was found to be of inferior design due to its long throat which elongated excessively at yield point stresses. Type X, on the other hand, overcame this tendency but had, of course, larger stress concentration.

All tests were performed on an Amsler High Frequency Vibrophore.(21) This apparatus is a new alternating push-pull type fatigue testing machine operating at high testing speeds. (See diagram Fig. 8 including operating data.) The machine operates on the resonance principle, the frequency always coincides with the natural frequency of the vibrating elements, namely the driving mass, the specimen, the dynamometer, and the counter mass (see Fig. 9). The system is maintained at resonance by a driving magnet, controlled by a feed-back system. The load amplitude is measured by the reflection of a beam of light from a mirror attached to the dynamometer onto a load scale. The magnitude of the load is maintained by means of a photo-cell controlling this optical-electrical feed-back system.

A programming device is also provided with the machine whereby the load can be varied arbitrarily upward or downward in steps. The device runs independently of the operation of the testing machine. A drum rotating at a constant speed has electrical contacts on its surface. If a pointer attached to the photo-cell slide makes contact, an electric drive adjusts the load amplitude according to the given setting of the drum contact.

In general, the Prot method calls for a linearly increasing stress amplitude with time. Two possible programs were tried, (a) in finite steps, and (b) with constant increase per cycle, illustrated in Fig. 10a and 10b respectively. The step program has a disadvantage in that load and cycle corrections must be made depending upon the level and position of the step during which failure occurred.

The linear program was selected in order to avoid such corrections. However, it must be pointed out that the linear program used actually represents extremely small steps due to the operation of the programming device. Variations in the rate of loading are accomplished by variation in the program drum speed, all tests being run at approximately the same loading frequency (see Table 3).

Alignment of the specimen in the gripping heads of the machine was done by eye as recommended by the manufacturer of the machine. The machine has a characteristic to show misalignment very markedly by lateral vibrations, absence of such vibrations giving a good indication of proper alignment. Load and cycle readings were taken at timed intervals during the progress of a test to determine accurately the values of α. Fluctuations in line voltage have a negligible effect on the performance of the testing machine.

It was planned to run three series of tests with mean tensile stresses of 0 psi, 7500 psi, and 15,000 psi respecively, Fig. 11. At each mean stress level both conventional and Prot technique test data was to be obtained. However, certain difficulties were encountered and only the 0 psi and 7500 psi mean stress series were run. The 15,000 psi mean stress series could not be run as there were insufficient damage cycles prior to the specimen elongating excessively at the yield point.

In determining the straight line as plotted on the S_α vs. α^r diagram, the method of least squares was used; the equation of the straight line being:

$$S_\alpha = S_E + K'\alpha^r$$

To obtain the best fit for any value of r, the constants, S_E and K' may be determined from the following formulas:

$$S_E = \frac{\Sigma(\alpha^r)^2 . \Sigma S_\alpha - \Sigma(\alpha^r)\,(\Sigma\alpha^r . S_\alpha)}{m\Sigma(\alpha^r)^2 - \left(\Sigma\alpha^r\right)^2}$$

$$K' = \frac{m\Sigma\alpha^r S_\alpha - \Sigma\alpha^r\,\Sigma S_\alpha}{m\Sigma(\alpha^r)^2 - \left[\Sigma(\alpha^r)\right]^2}$$

A similar procedure was used to determine the value of m from the plot on log-log paper of the conventional fatigue data. This method was not entirely satisfactory, as will be discussed later.

4. TEST RESULTS

Static tensile and hardness properties are given in Table 2. Data as shown are average values obtained from three unwelded tensile coupons and two welded test specimens. All fractures of welded tensile specimens occurred outside the weld. X-ray pictures were taken of all welds to ensure quality and uniformity. Examination of the pictures showed no faults in the welds such that it was not necessary to discard any specimens.

The endurance limit is defined as the highest stress level within the elastic range at which a sufficient number of cycles could be taken without apparent failure. The specimen is said to have failed when it cracked sufficiently through to cause the Vibrophore to cease operations. This was normally at the appearance of a crack on the polished edge for both conventional and Prot testing methods.

Test I - Zero Mean Stress

A series of seven type S specimens were run to determine the conventional Endurance Limit. The results are tabulated (Table 4) and plotted as shown on Fig. 12, in a normal S-N curve. An Endurance Limit of 22,300 psi was determined. The data also was plotted using Weibull's assumption as shown in Fig. 13.

A second series of nine type S specimens were run using the Prot technique. Groups of three specimens were run at each of three values of α. These results are tabulated (Table 5) and plotted on Fig. 14. A straight line was passed through the test points to determine an Endurance Limit of 20,300 psi. Low values of α were used in order to force a fatigue failure prior to excessive plastic deformation. Excessive elongation of the specimen would exceed the limits of the testing machine and change the character of the test.

A third series of six type X specimens were run using the Prot technique. The change in design of specimen was made so that α's of higher values could be used. The change in specimen reduced the length of the test section such that its overall elongation was reduced. Hence, larger values of α could be used producing failure stress beyond yield point. This group was run at four values of α, results are shown in Table 6 and Fig. 15.

Test II - 7500 psi Mean Stress

A first series of six type S specimens were run to determine the Endurance Limit by conventional method. The results as tabulated (Table 7) and plotted on Fig. 16 indicate an Endurance Limit of 24,200 psi. Again the data is also represented on a Weibull plot as shown in Fig. 17.

The second series of nine type S specimens were run using the Prot method. Three specimens were tested at each of three values of α. Again low values of α were used due to the design of the specimens. These results are tabulated (Table 8) and plotted (Fig. 18), yielding an Endurance Limit of 23,000 psi.

Testing of a third series was attempted using a 15,000 psi mean stress level with little success, since the stress level was too high to allow sufficient damage cycles prior to yielding. If yielding of the cross section of the specimen was reached the load did not increase further, actually, the load dropped from the upper yield point to the lower yield point. The specimen then started to heat rapidly due to plastic work followed shortly by a fracture.

5. DISCUSSION OF TEST RESULTS

It is noted that the present tests gave higher Endurance Limits for butt-welded connections than earlier tests at other institutions.(18) This may show an improvement in welding technique or in the quality of welding rods. The back grinding and rewelding of the root may have improved the Endurance Limit. A normal amount of scatter was encountered in the conventional approach, but the result seems to fall within expected limits. The log-log plot of the data from both series of tests show very close agreement in the slopes of the best fit lines, Figs. 13 & 17. Representative earlier data(18) show similar slopes (Figs. 5 & 6).

In testing the type S specimen using the Prot technique, a larger amount of scatter was encountered in both series. This may be due to the greater sensitivity of the approach to variations in physical properties of the specimens. In both the zero psi and 7500 psi mean stress series, the Endurance Limit fell about 1000 psi below that arrived at by the conventional method. However, the scatter of results of either method, conventional or Prot method, is of the same order of magnitude.

It is seen that the type X specimens gave results higher than the conventional Endurance Limit. Although the specimen had a higher stress concentration factor, the rapid increase in cross section provides local restraint to the damaged zone. This in turn could account for the higher Endurance Limit. However, this speculation certainly needs further investigation.

The results presented are far from conclusive. Type S specimens have shown themselves to be of inferior design. A shorter specimen of say 8" length is indicated, with a reduced section of small length. Also, results close to the yield stress must be discarded as they are not indicative of an elastic fracture. The effect of coaxing has not been investigated.

The statistical approach using the method of Least Squares was attempted using the formulation previously indicated. The best fit straight line in the zero mean stress series gave meaningless results, since the scatter was too great. In the 7500 psi mean stress series better agreement was found. On the whole, the method of Least Squares to find a best fit line may be too precise for evaluating a restricted number of test points.

Using Weibull's assumption for the S-N curve, a value of the exponent of α was determined. In both series, an attempt was made to replot Fig. 14 and 18 using α^r as abscissa instead of $\sqrt{\alpha}$. A higher value of the Endurance Limit resulted due to a shift of the test points to the left. Insufficient data is available to draw any conclusion.

6. CONCLUSIONS AND RECOMMENDATIONS

The results as presented, though not conclusive, give some evidence that the method will work. They also show that for mild steel the Prot method saves little time since it is limited to low values of α. This does not rule out the method, as it may be used to make a good estimate of the Endurance Limit if low values of α are used. The stress at fracture could then be used as a starting point for the conventional determination of the Endurance Limit.

The effect of coaxing on the results of Prot tests is uncertain. Its influence could be studied as follows: a series of tests are run using some mean stress S_m and several values of α to determine an Endurance Limit S_E, then a second series of tests are run using the same mean stress and α's, but introducing one change. Instead of starting with a very small or zero fluctuating stress around S_m the test is started with an amplitude $S_E - S_m$ around a mean stress S_m as shown in Fig. 19. Failure would then have to occur at either

1. indicating coaxing,
2. indicating no coaxing or,
3. indicating a lack of damage cycles.

This procedure would seem to point up any effect that coaxing may have on the Endurance Limit.

A greater number of tests should be run such that the data can be treated statistically, this in turn would yield more conclusive results. A change in the geometric shape of the test specimen, as indicated previously, should lead to less scatter in the results.

7. NOMENCLATURE

α - constant stress increase per cycle (psi/cycle)

C_1 - ordinary S-N curve represented by $(S-S_E)\ N = K$

C_2 - a curve similar to C_1 but displaced to the right

d - number of stress cycles, using constant stress increase α per cycle, between endurance limit S_E and failure stress $S_\alpha = S$.

D_1 - damage area required to produce failure of the specimen under a constant stress amplitude, S representing the value of the maximum stress

D_2 - damage area required to produce failure of the specimen at stress $S_\alpha = S$ using constant stress increase (psi/cycle)

K - a material constant: $K = (S - S_E)N$, Eq. (2)

K' - a material constant: $K' = \sqrt{2K}$

m - a material constant, defined on page 6

n - number of stress cycles at stress S $(o < n < N)$

N - number of stress cycles to failure at constant maximum stress S

N_α - number of stress cycles to failure at stress S_α, using constant stress increase α per cycle

r - a material constant: $r = 1/(1 + m)$

S - maximum stress producing failure at N cycles under constant stress cycling

S_α - failure stress at N_α cycles using constant stress increase α (psi/cycle)

ΔS - change in operating stress

Nomenclature (contd.)

S_E - stress at endurance limit

S_o - operating stress - maximum stress in any cycle:
$S_o = S_m + \alpha N$

S_m - mean stress level

8. ACKNOWLEDGEMENT

The author wishes to express sincere appreciation to Dr. Bruno Thürlimann for his supervision, guidance and counsel during this investigation. Thanks are also due Mr. Frank Vickress, instructor in Civil Engineering, for critically reviewing and editing the report draft and preparing the drawings. Miss Lorraine Kisslan typed the manuscript with care. The fine cooperation of Mr. Kenneth Harpel and his staff in preparing the specimens and conducting the tests is appreciated.

The project has been carried out at Fritz Engineering Laboratory of which William J. Eney is Director. Funds were provided by the University Committee of the Welding Research Council.

8. BIBLIOGRAPHY

1. Prot, E. Marcel
   "Fatigue Testing Under Progressive Loading, A New Technique for Testing Material"
   Translated by Edward J. Ward, Capt. USAF., WADC TR 52-148, September 1952

2. Henry, D. L.
   "Predication of Endurance Limit Using Linearly Increasing Loads"
   Unpublished Report, 10 March 1951

3. Stulen, F. B. and Lamson, W. D.
   "Preliminary Report of the Progressive-Load Method of Fatigue Testing"
   Curtiss-Wright Corp., T.N. 270, 12 April 1951

4. Cummings, H. N., Stulen, F. B., and Schulte, W. D.
   "Investigation of Materials Fatigue Problems Applicable to Propellor Design"
   WADC Tech. Report 54-531, May 1955

5. Vitovec, F. H., and Lazan, B. J.
   "Review of Previous Work on Short-Time Tests for Predicting Fatigue Properties of Materials"
   WADC Report 53-122, August 1953

6. Corten, H. T., Dimoff, I., and Dolan, T. J.
   "An Appraisal of the Prot Method of Fatigue Testing"
   ASTM Proc., Vol. 54, 1954, pp. 875-893

7. Ward, E. J., Schwartz, R. T. and Schwartz, D. C.
   "An Investigation of the Prot Accelerated Fatigue Tests"
   ASTM Proc., Vol. 53, 1953, pp. 885-891

8. Vitovec, F. H., and Lazan, J.
   "Strength, Damping, and Elasticity of Materials Under Increasing Reversed Stress with Reference to Accelerated Fatigue Testing"
   ASTM Proc., Vol. 55, 1955, pp. 844-862

9. Nobuske, Enomoto
"On Fatigue Tests Under Progressive Stress"
Vol. 55, 1955, pp. 903-917

10. Miner, M. H.
"Cumulative Damage in Fatigue"
Journal of Applied Mechanics, Vol. 12, No. 3,
September 1945, pp. A159-A164

11. Kommers, J. B.
"The Effect of Over-Stressing and Under-Stressing in Fatigue"
ASTM Proc., Vol. 43, 1943, pp. 743-762

12. Sinclair, G. M.
"An Investigation of the Coaxing Effect in Fatigue of Metals"
ASTM Reprint 92, 1952

13. Richart, F. E., Jr., and Newmark, N. M.
"An Hypothesis for the Determination of Cumulative Damage in Fatigue"
ASTM Proc., Vol. 48, 1948, pp. 767-800

14. Lazan, B. J., and Wu, T.
"Damping, Fatigue, and Dynamic Stress-Strain Properties of Mild Steel"
ASTM Reprint No. 23, 1951

15. Freudenthal, A. M.
"Planning and Interpretation of Fatigue Test"
ASTM Reprint No. 16, 1951

16. Manual on Fatigue Testing, ASTM, STP No. 91, p. 39

17. Epreminn, E., and Mehl, R. F.
"A Statical Interpretation of the Effect of Understressing on Fatigue Stresses"
1952, Reprint No. 90, ASTM

18. University of Illinois
"Fatigue Strength of Welded Joints in Structural Steel Plates"
Exper. Station Bulletin Nos. 310, 327, 344, 384

19. Newman, P. P.
"Influence of Weld Faults on Fatigue Strength with Reference to Butt Joints in Pipe Lines,
The Institute of Marine Engineers, Trans. June 1956, Vol. 68, No. 6

20. Harris, L. A., Nordman, G. E., and Newmark, N. M.
"Fatigue Strength of Butt Welds in Structural Steels"
The Welding Journal, February 1955, pp. 83-96S

21. Russenberger, M., and Földes,
"A New Amsler High-Speed Fatigue Testing Machine"
SESA, Vol. 12, No. 2, 1955, pp. 9-20

Heat No.	Specification	σ_y psi	σ_{ult} psi	Elong. 8" %	Red. %	Chemical Analysis C	M_n	P	S
58J145	ASTM A373-54T	35,400	59,000	28.0	61.6	0.17	0.65	0.010	0.029

Table 1 CHEMICAL AND PHYSICAL PROPERTIES OF 3/8" STEEL PLATE ASTM A-373-54T (From Mill Report)

Specimens	σ_y psi	σ_{ult} psi	Elong. %	Red. %	Rockwell Hardness using "B" scale with 1/16" ball — Plate	Adj. Weld	Root of Weld	Weld Average
Welded	37,100	58,100	16.5%	24.1%	59	71	81	79
Plain	31,900	56,300	31.6%	44.8%	58	--	--	--

Table 2 PHYSICAL PROPERTIES OF SPECIMENS

Program Setting	Time for one revolution of drum, Speed (1) seconds	α psi/cycle	Time for one revolution of drum, Speed (2) seconds	α psi/cycle
250	1645	0.1241	16,450	0.0124
200	1972	0.1035	19,720	0.0104
150	2659	0.0769	26,520	0.0077
100	4033	0.0506	40,330	0.0051
70	5685	0.0359	56,850	0.0036

Load variation - 0 to 11,000 lbs. per drum revolution

Specimen Cross Section = 0.285 in^2

Table 3 RANGE OF PROGRAM FOR PROT METHOD

Specimen	Cycles to Failure	Failure Stress S	S - S_E
Type S	N	psi	psi
D2	2,002 x 10^3	22,600	300
G1	743.5	26,800	4,500
C7*	8,356	21,450	---
E-10	691	24,030	1,730
C-5	958	24,150	1,850
B-1	445	26,900	4,600
C-6	9,043.5	22,400	100

* No failure

S_E = 22,300 psi

Table 4 CONVENTIONAL DATA FOR ZERO MEAN STRESS SERIES

(Type S Specimens)

Specimen	Failure Stress S_α	α	$\sqrt{\alpha}$
Type S	psi	psi/cycle	$\sqrt{\text{psi/cycle}}$
B9	28,000	.00895	.0945
A8	29,300	.00913	.0954
G4	24,100	.00883	.0938
D5	29,250	.01138	.1066
D4	27,250	.01156	.1072
E9	27,560	.01142	.1069
A3	25,000	.01419	.1190
E8	27,850	.01382	.1175
A2	23,900	.01398	.1180

S_E = 20,300 psi

Table 5 PROT METHOD DATA FOR ZERO MEAN STRESS SERIES

(Type S Specimens)

Specimen	Failure Stress S_α	α	$\sqrt{\alpha}$
Type X	psi	psi/cycle	$\sqrt{\text{psi/cycle}}$
D3	31,420	.01282	.113
B4	32,050	.0341	.1848
G5	36,950	.0344	.1853
C3	35,250	.0764	.276
E1	38,850	.0772	.276
A10	41,800	.1231	.350

S_E = 25,600 psi

Table 6 PROT METHOD DATA FOR ZERO MEAN STRESS SERIES

(Type X Specimens)

Specimen Type S	Cycles to Failure N	Failure Stress S psi	$S - S_E$ psi
C10	612.5×10^3	34,300	11,100
B2	304	34,300	11,100
E11	733.5	29,700	5,500
G3	472.5	29,240	5,040
G9	3,517	24,520	320
D8	2,900	24,430	220

S_E = 24,200 psi

Table 7 CONVENTIONAL DATA FOR 7500 PSI MEAN STRESS SERIES (Type S Specimens)

Specimen Type S	Failure Stress S_α psi	α psi/cycle	$\sqrt{\alpha}$ $\sqrt{\text{psi/cycle}}$
C9	38,200	.01492	.1220
B8	35,800	.01407	.1185
D1	35,900	.01388	.1178
E3	31,810	.00837	.0913
B7	33,900	.00852	.0922
G10	30,200	.00850	.0920
E2	28,200	.00558	.0745
A9	30,500	.00549	.0738
D9	34,850	.00557	.0744

S_E = 23,000 psi

Table 8 PROT METHOD DATA FOR 7500 PSI MEAN STRESS SERIES (Type S Specimens)

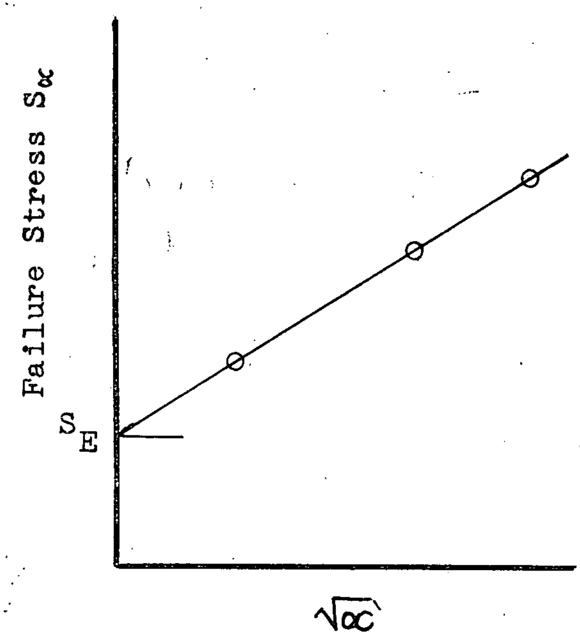


Fig. 1 PROT METHOD

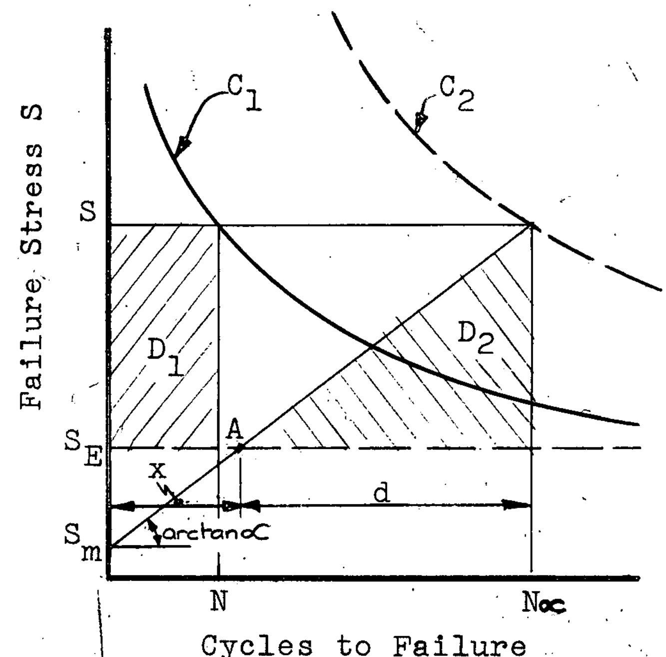


Fig. 2 PROT DERIVATION

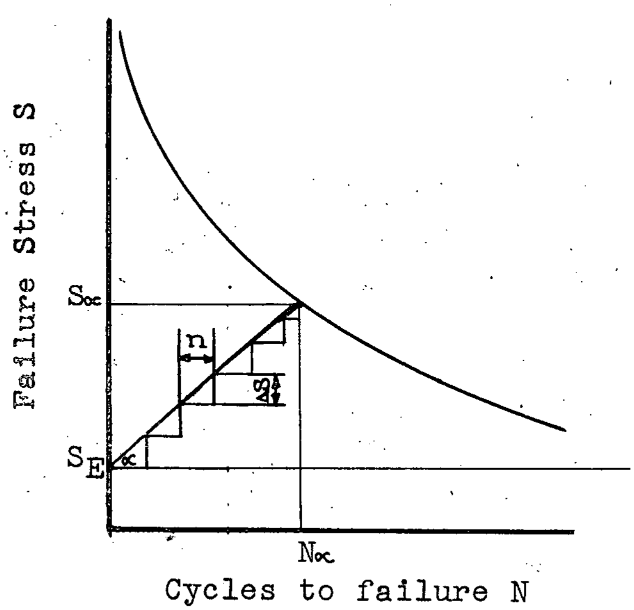


Fig. 3 S-N DIAGRAM

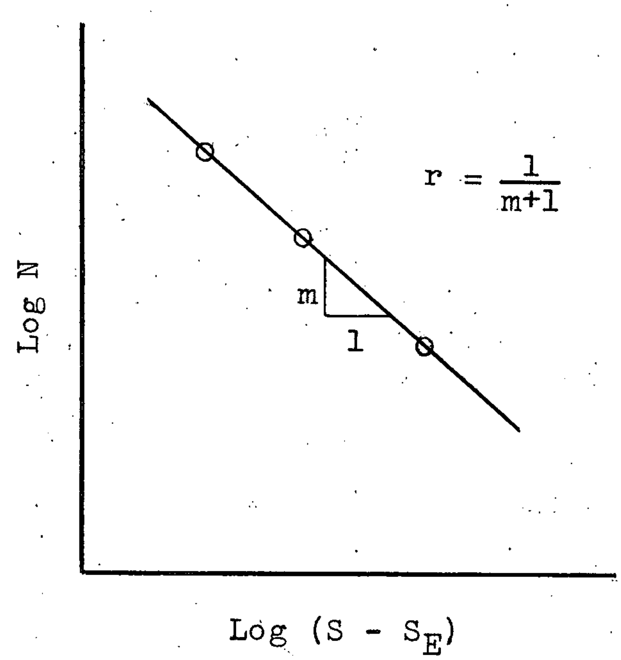


Fig. 4 WEIBULL'S APPROXIMATION

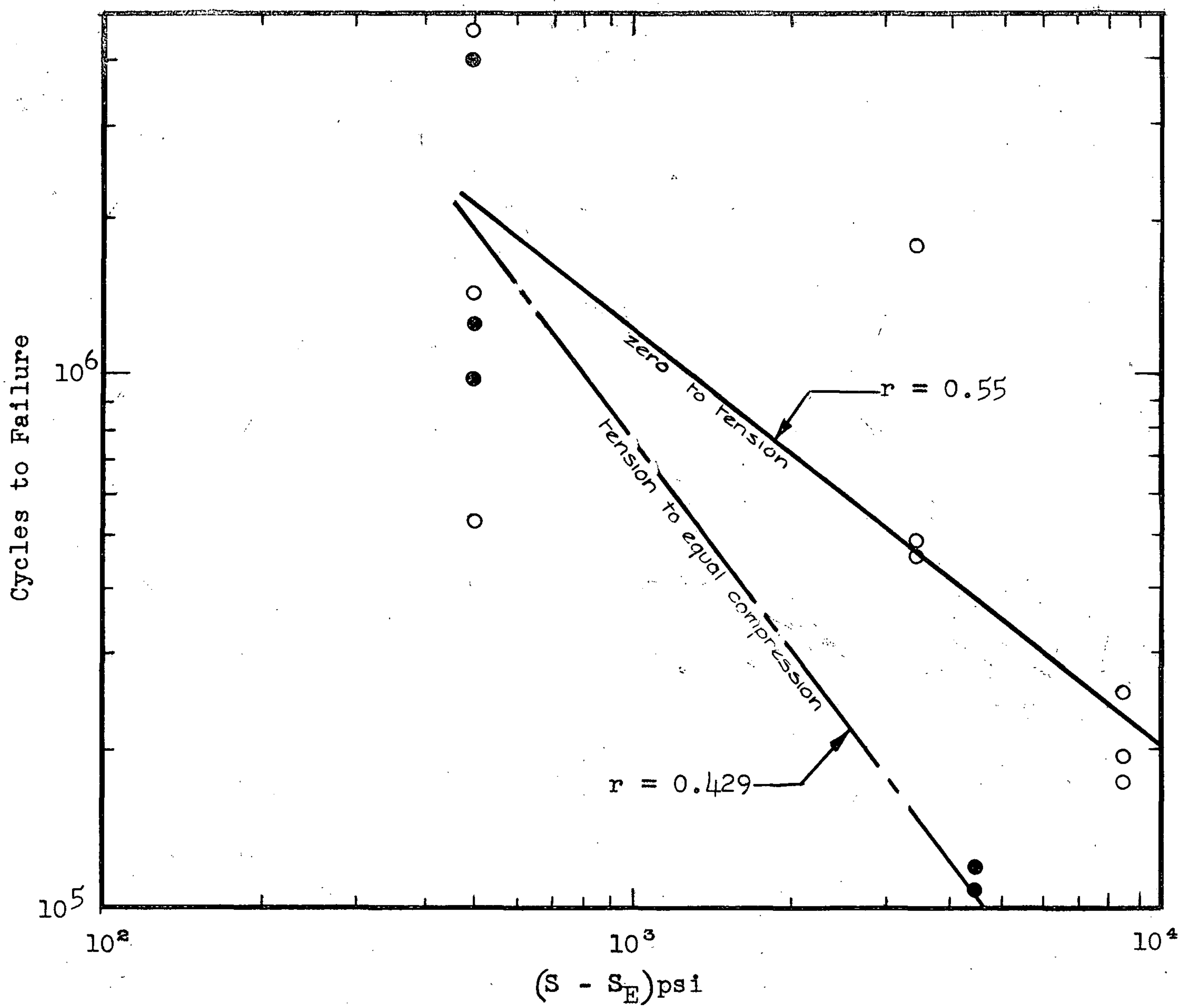


Fig. 5 WEIBULL PLOT OF PREVIOUS BUTT-WELDED FATIGUE DATA[18]

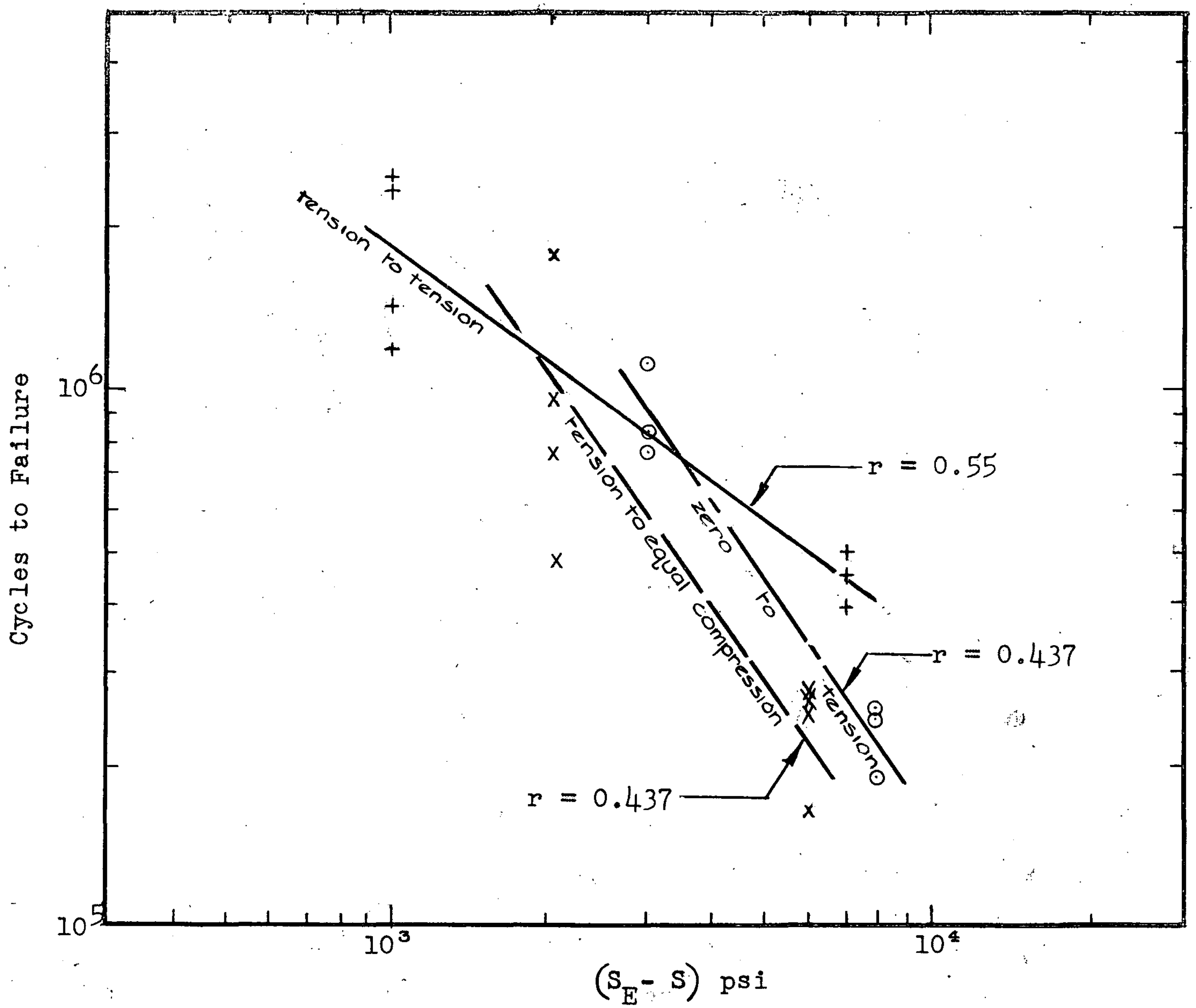
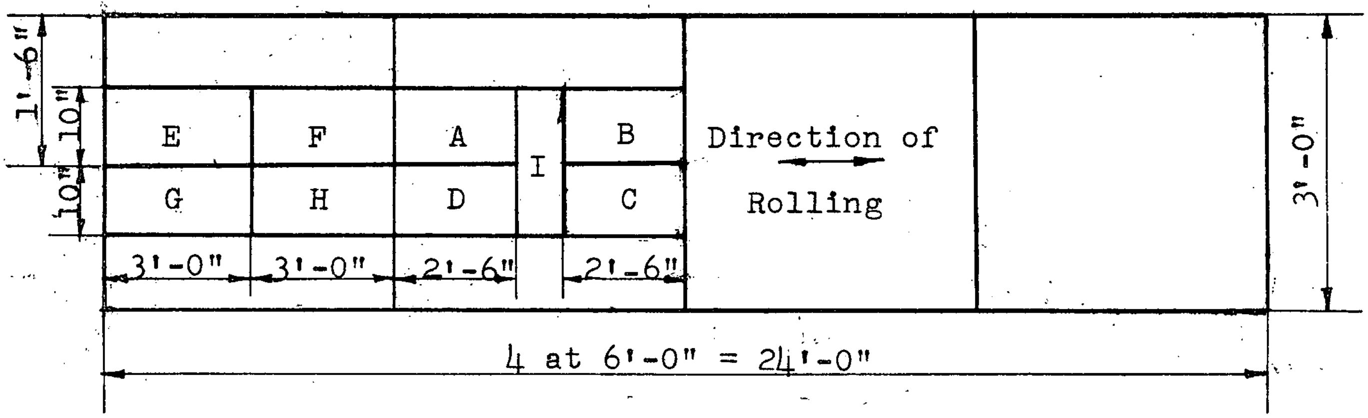
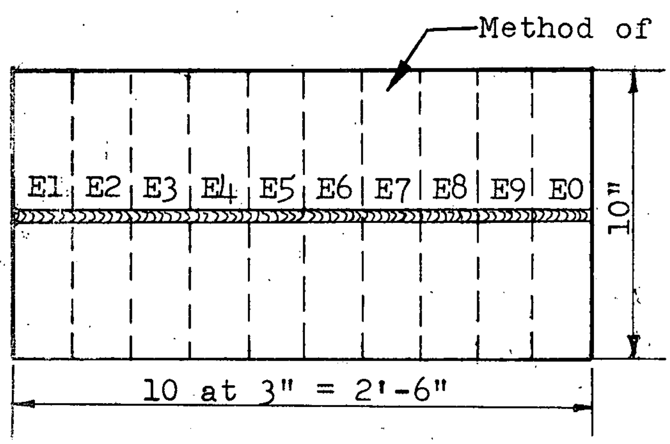


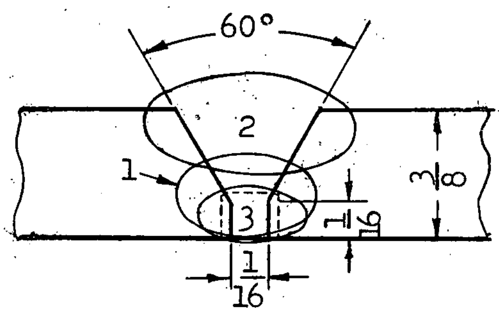
Fig. 6 WEIBULL PLOT OF PREVIOUS BUTT-WELDED FATIGUE DATA[18]



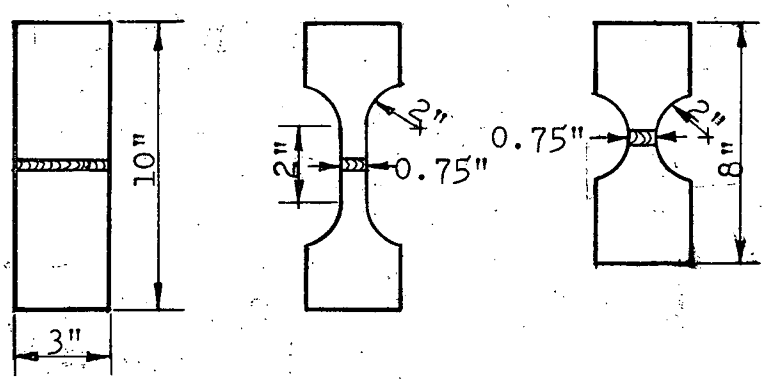
24'x3'x3/8" Steel Plate as Cut



Typical Welded Plate (A,B,C,D,E,G)



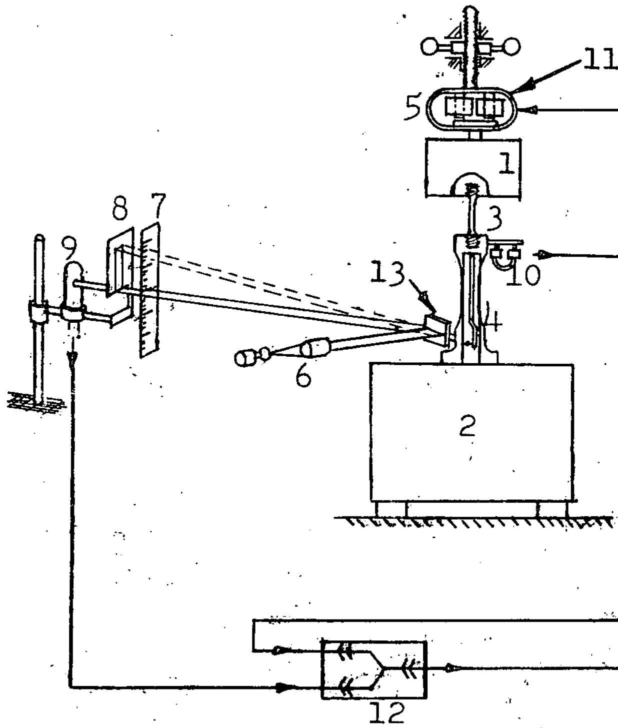
Weld Detail



Blank Type S Type X

Fig. 7 STEEL PLATE AND SPECIMEN DETAILS

[redacted] [redacted]



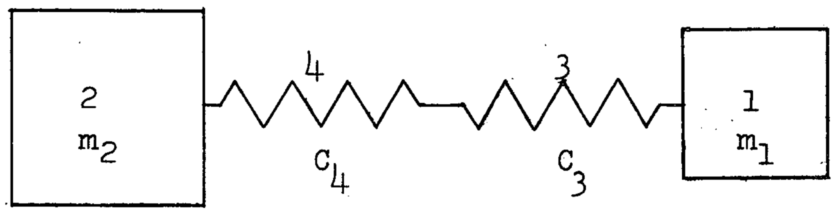
1 - Main moving mass
2 - Opposing mass
3 - Specimen
4 - Dynamometer
5 - Pre-load spring
6 - Optical projector
7 - Dynamometer scale
8 - Diaphragm
9 - Photo-electric cell
10 - Impulse generator
11 - Driving magnet
12 - Amplifier
13 - Oscillating mirror

Diagram showing working principle of the Vibrophore[21]

Vibrophore Operating Data

High Frequency Vibrophore		Serial Number 10HFP422
Maximum alternating load	metric tons	±5
Maximum unilateral tensile or compressive load	metric tons	10
Maximum elastic elongation on specimen	mm	±0.6
Range of frequency	cycles per second	60÷300
Maximum output of amplifier	watt	200
Power input	watt	700
Accuracy of dynamometers	in %	±1.5
Maximum error of dynamometer No. 1	in. kg.	±25
Maximum error of dynamometer No. 2	in. kg.	±5
Load constancy at ± 10% fluctuations of the line voltage: better than		1%
Maximum distance between specimen holders	mm	540
Free space between the columns	mm	400
Total weight without base block	about kg	700
Weight of base block	about kg	1800

Fig. 8 VIBROPHORE WORKING PRINCIPLES AND OPERATING INSTRUCTIONS

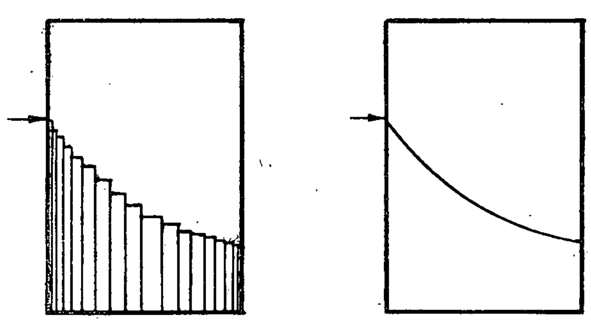


$$\omega = \sqrt{\frac{C}{M}}$$

$$\frac{1}{C} = \frac{1}{C_3} + \frac{1}{C_4}$$

$$f = \frac{1}{2\pi}\sqrt{C\left(\frac{1}{m_1} - \frac{1}{m_2}\right)}$$

Fig. 9 TWO MASS SYSTEM



(a) (b)

Fig. 10 PROGRAMMING DRUMS

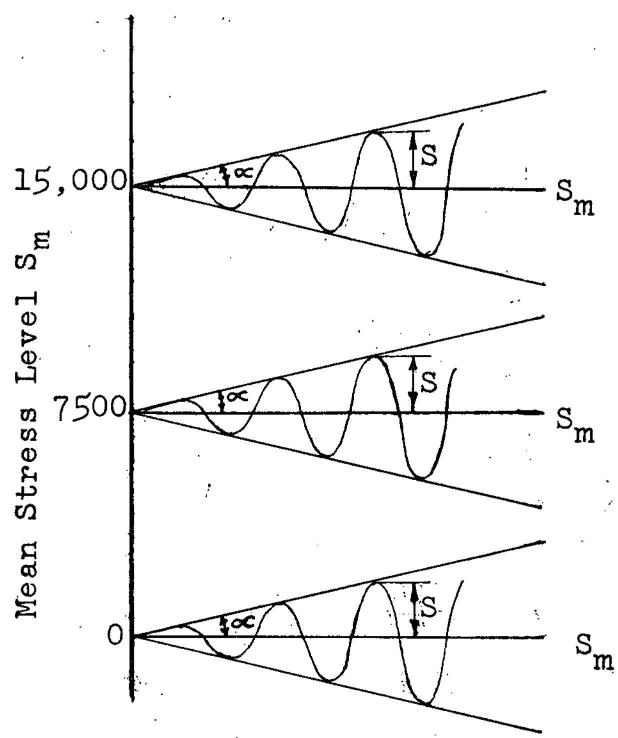


Fig. 11 PROPOSED TESTING

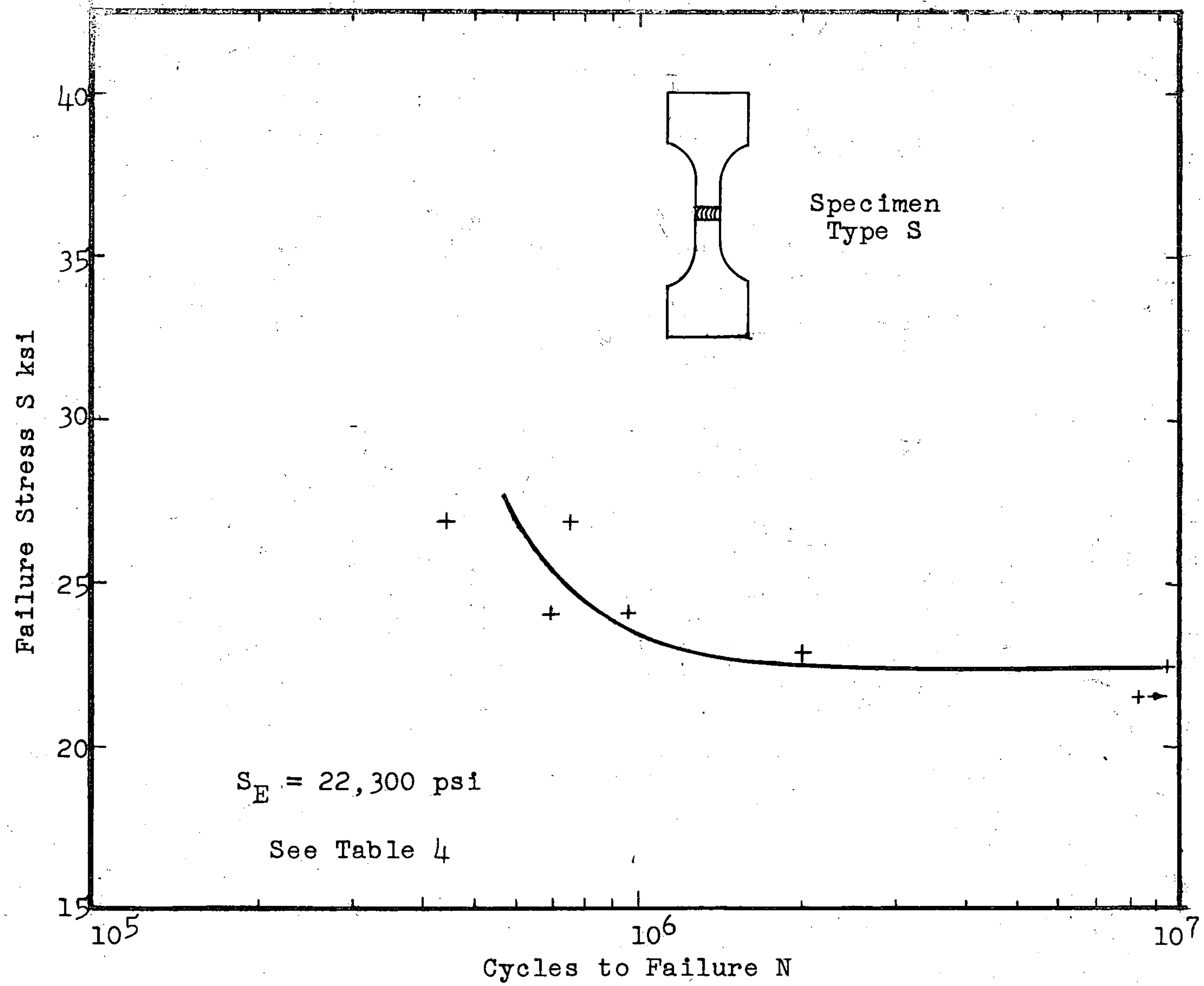


Fig. 12 S-N DIAGRAM FOR ZERO MEAN STRESS SERIES

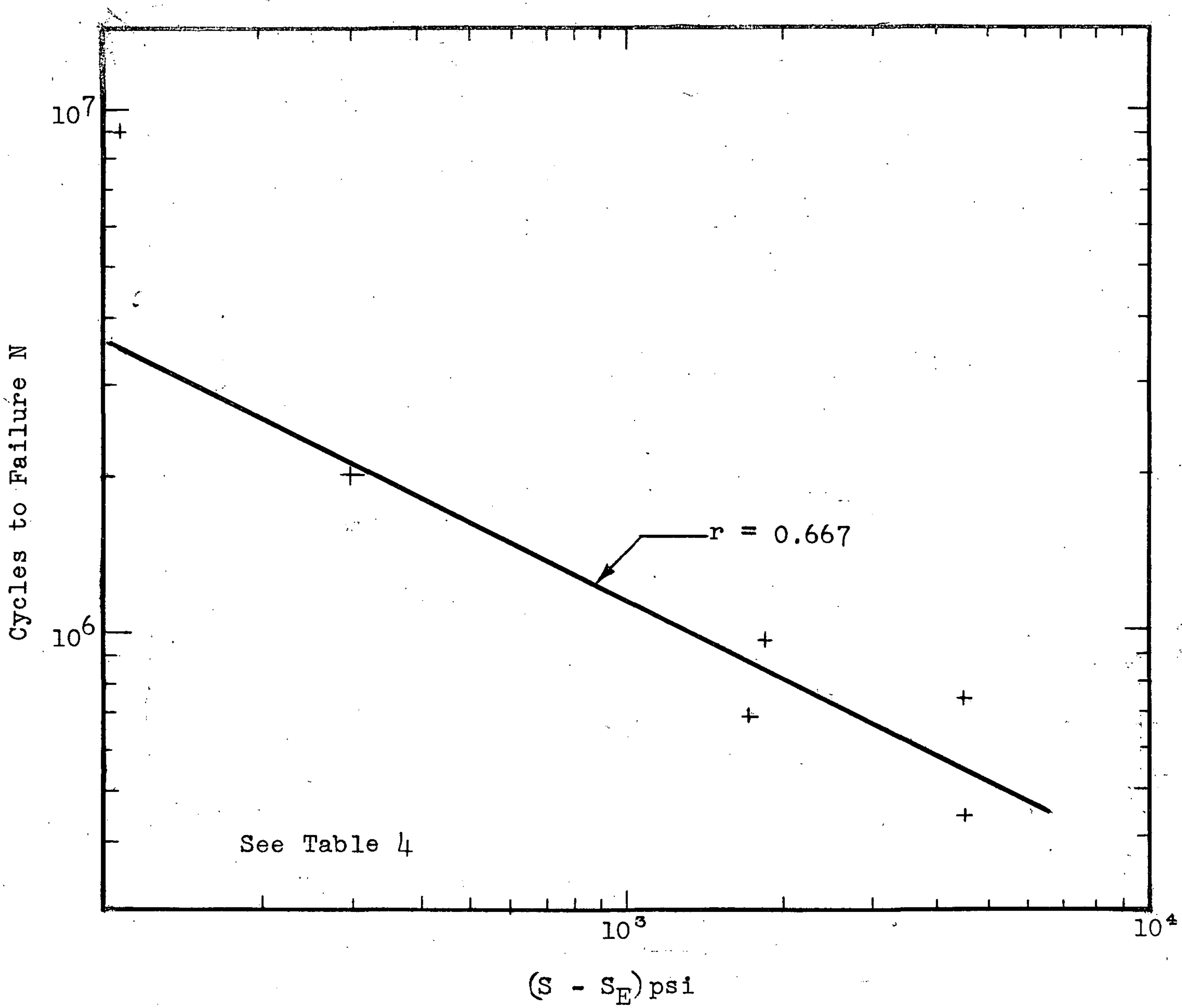


Fig. 13 WEIBULL PLOT FOR ZERO MEAN STRESS SERIES

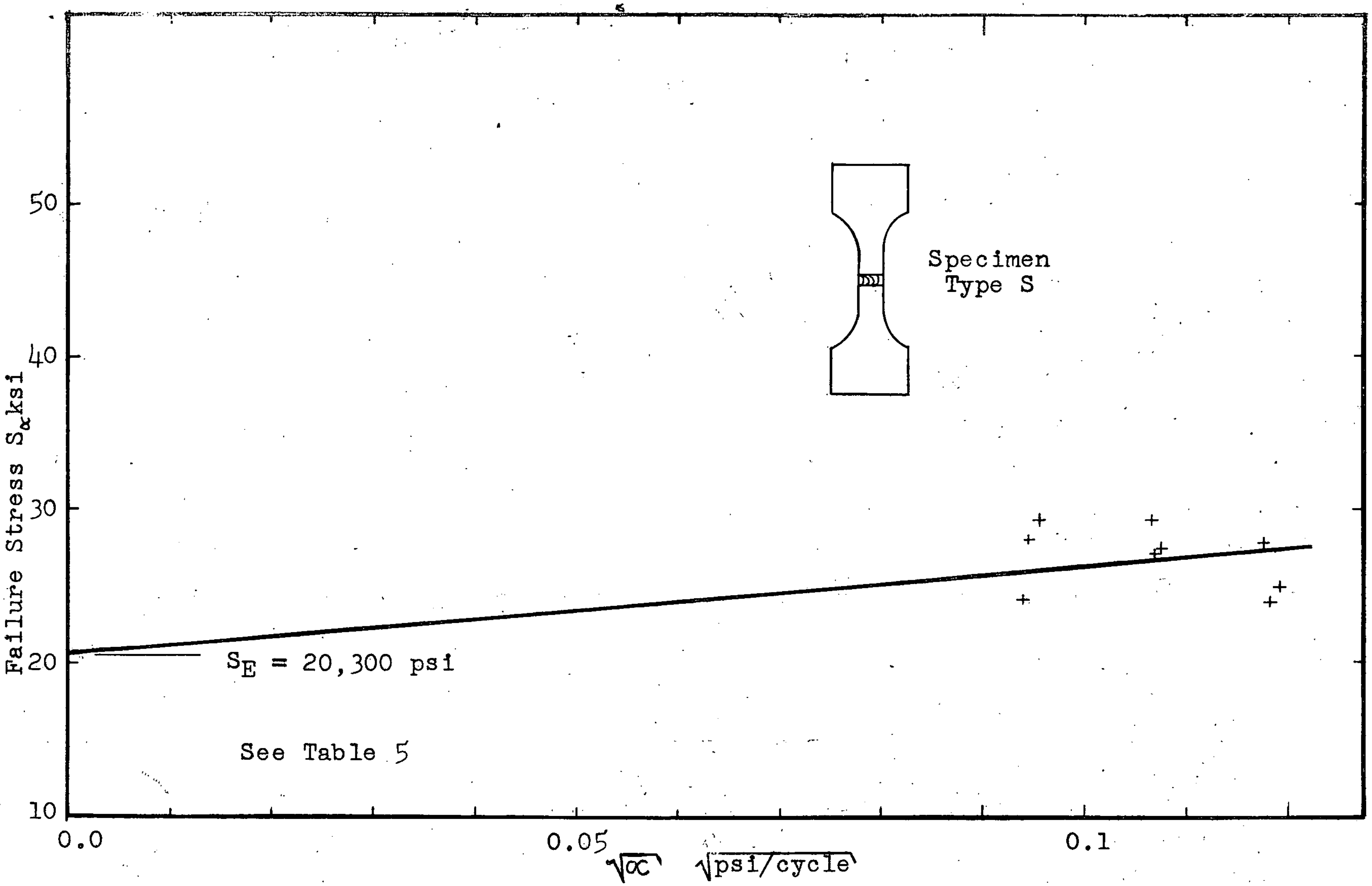


Fig. 14 PROT METHOD DATA FOR ZERO MEAN STRESS

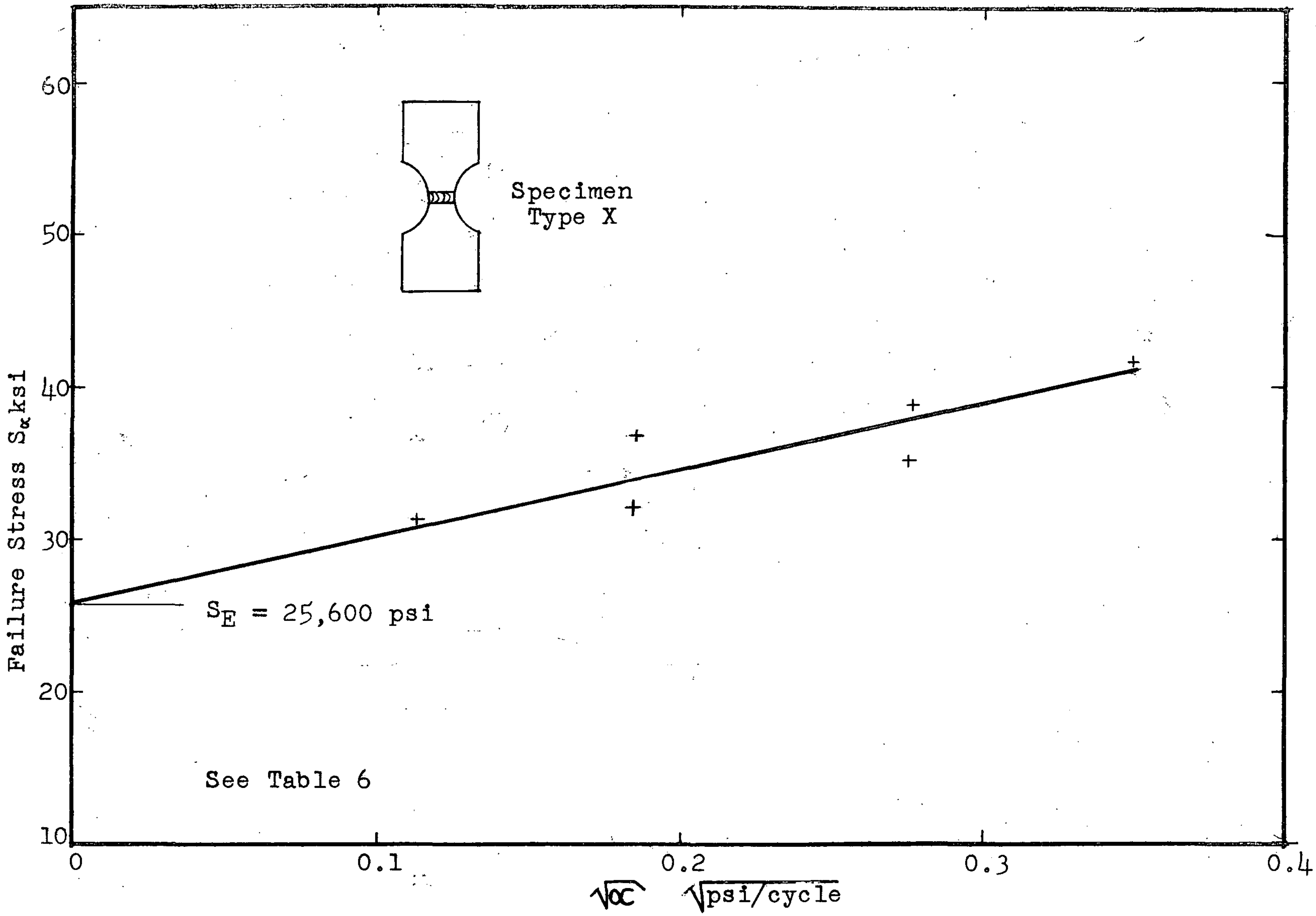


Fig. 15 PROT METHOD DATA FOR ZERO MEAN STRESS

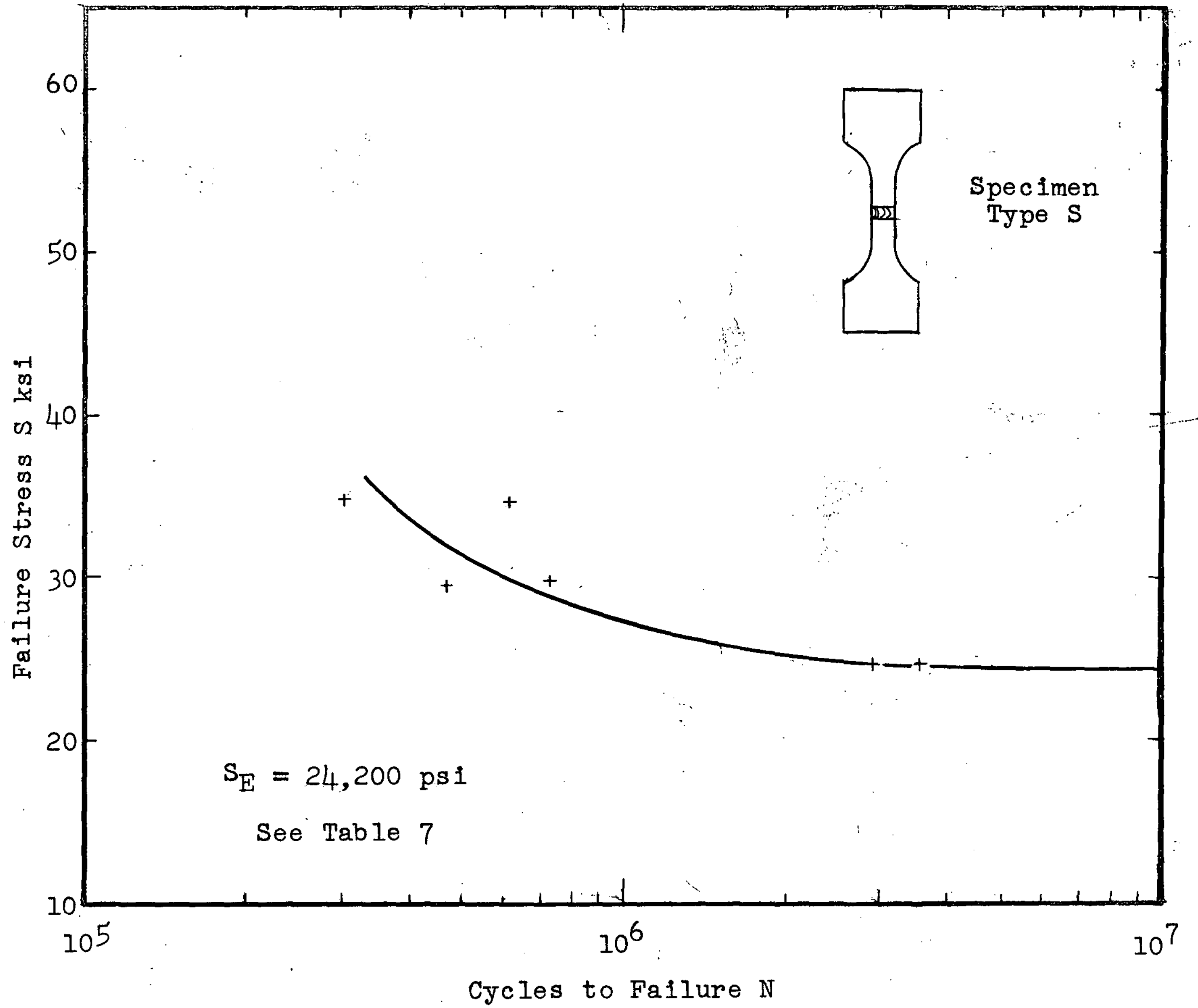


Fig. 16. S-N DISGRAM FOR 7500 PSI FOR MEAN STRESS

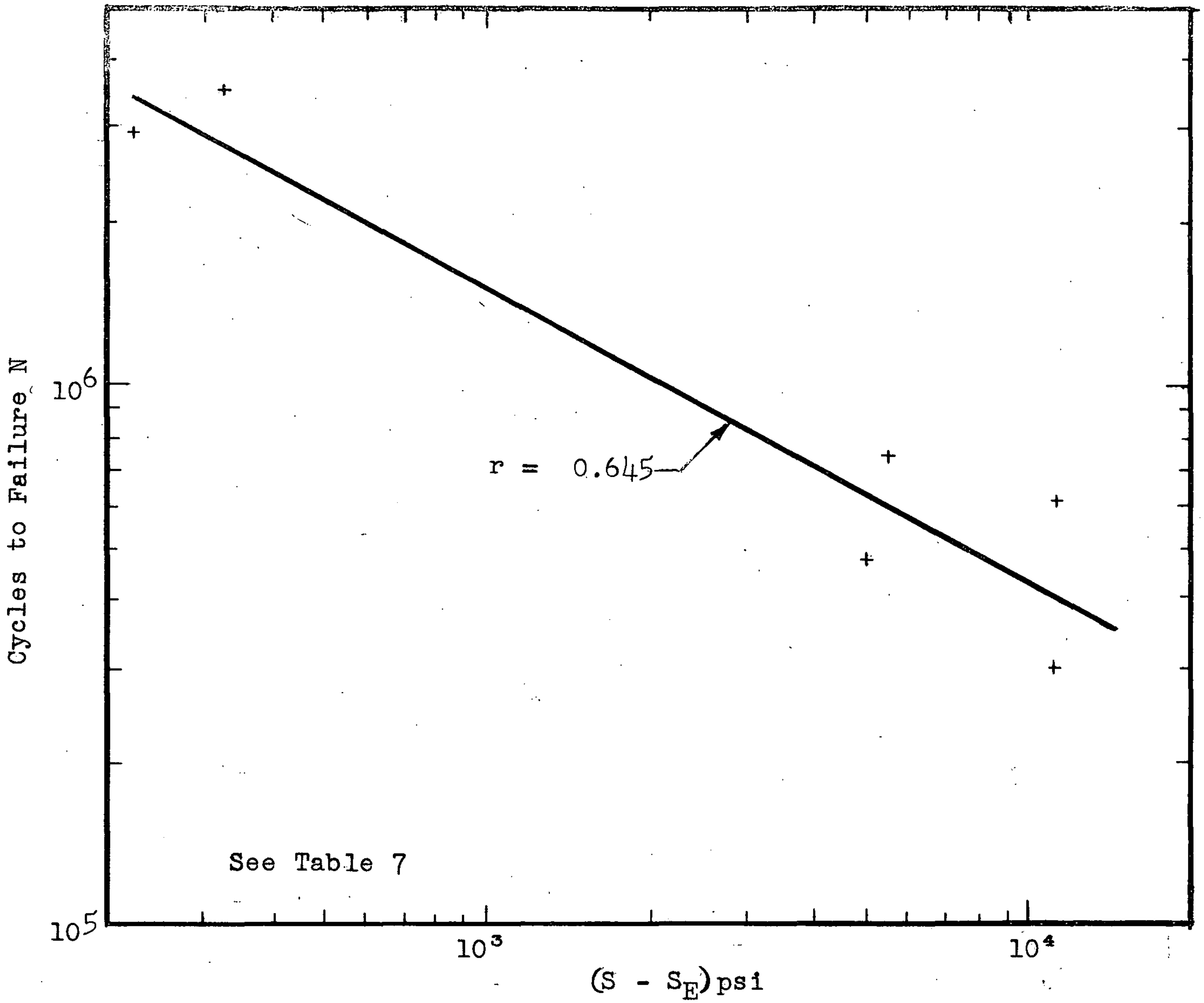


Fig. 17 WEIBULL PLOT FOR 7500 PSI MEAN STRESS

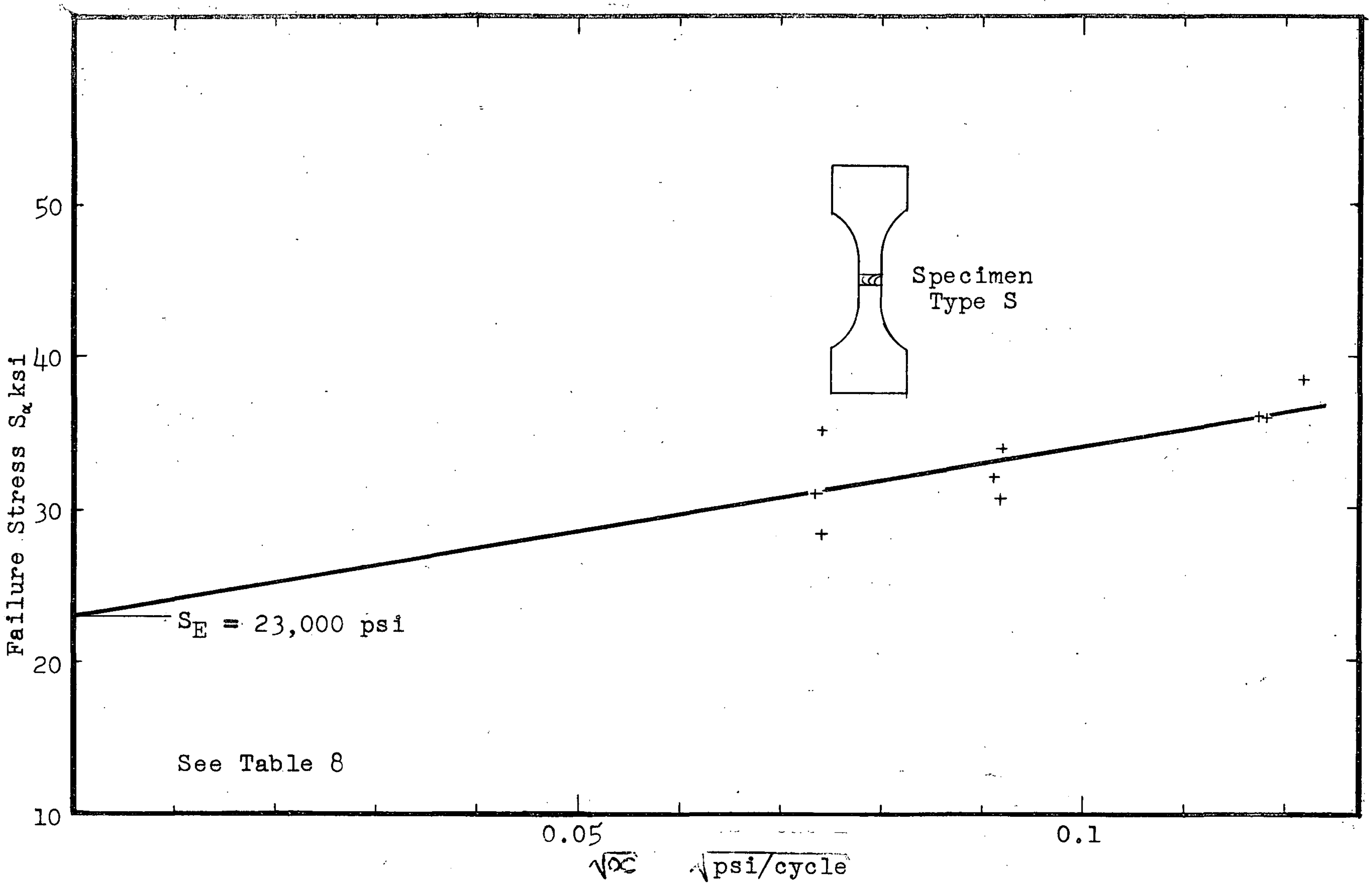


Fig. 18 PROT METHOD DATA FOR 7500 PSI MEAN STRESS

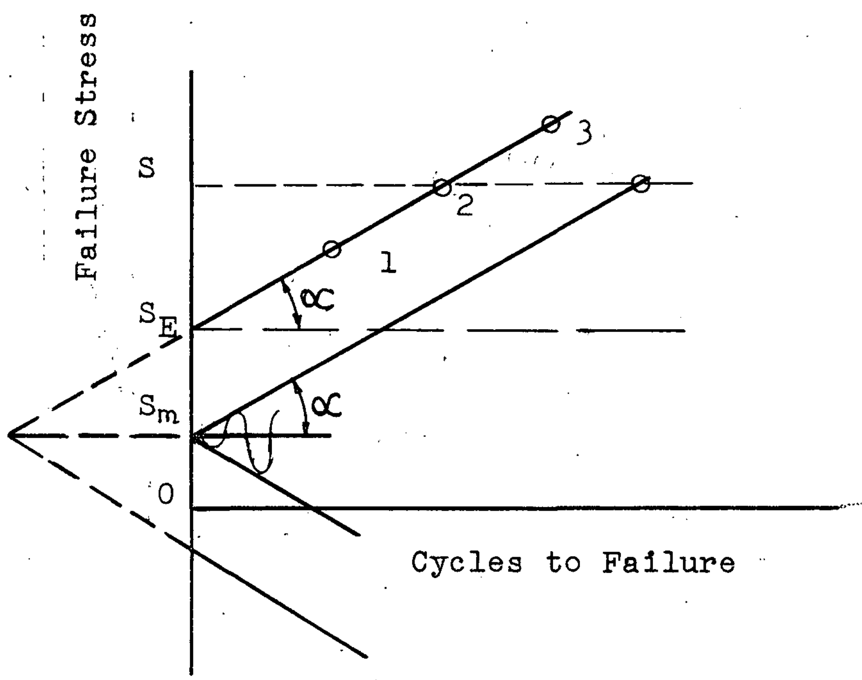


Fig. 19 COAXING EFFECT

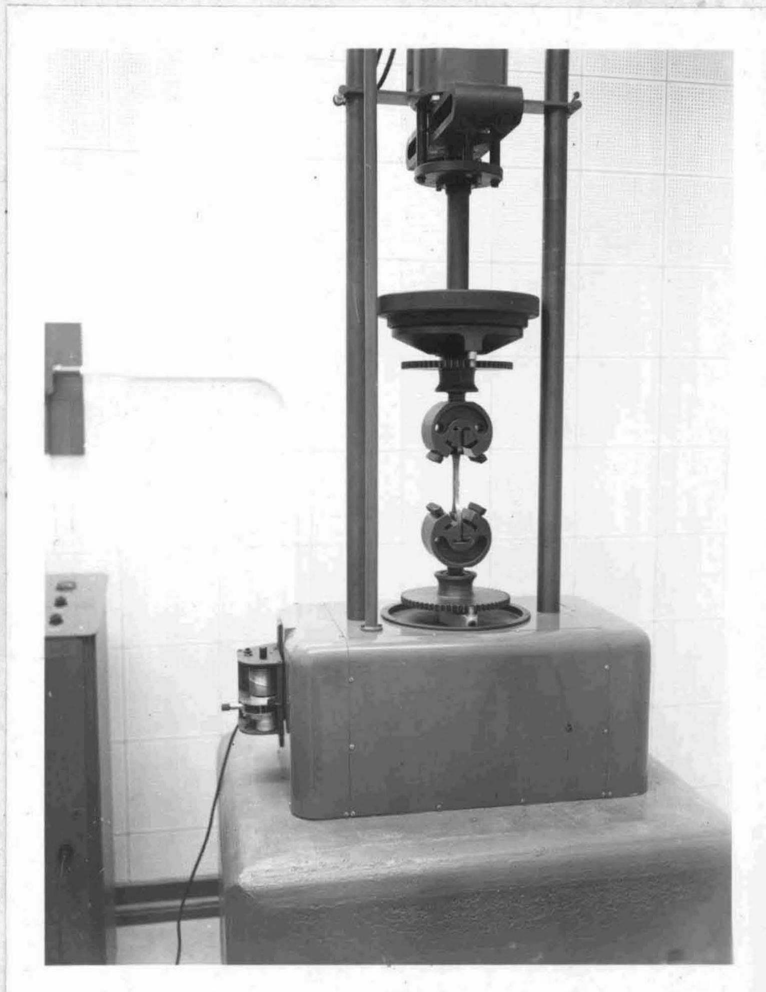


Fig. 20 VIBROPHORE WITH TEST SPECIMEN

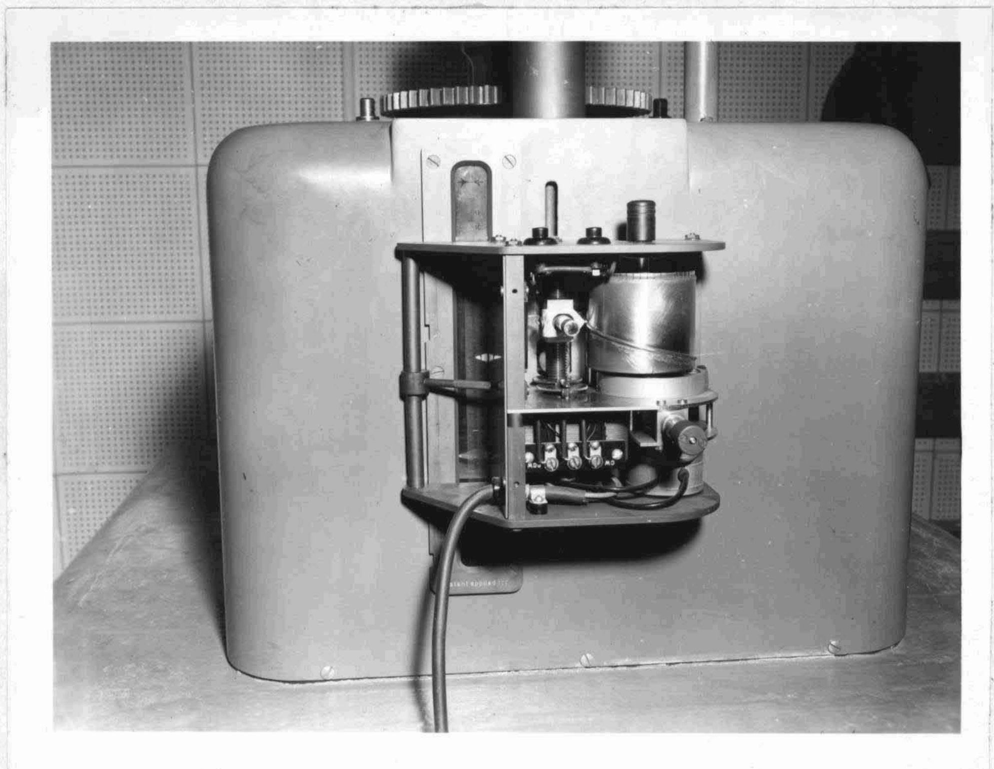


Fig. 21 PROGRAMMING DEVICE

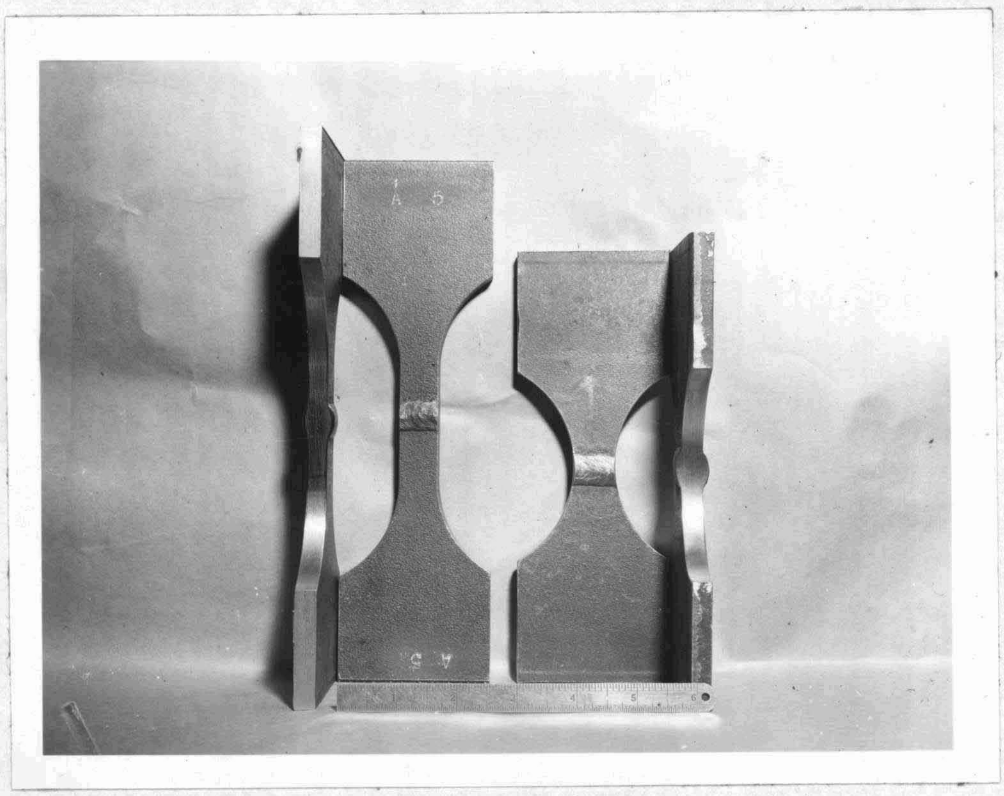


Fig. 22 TYPE S AND X SPECIMENS

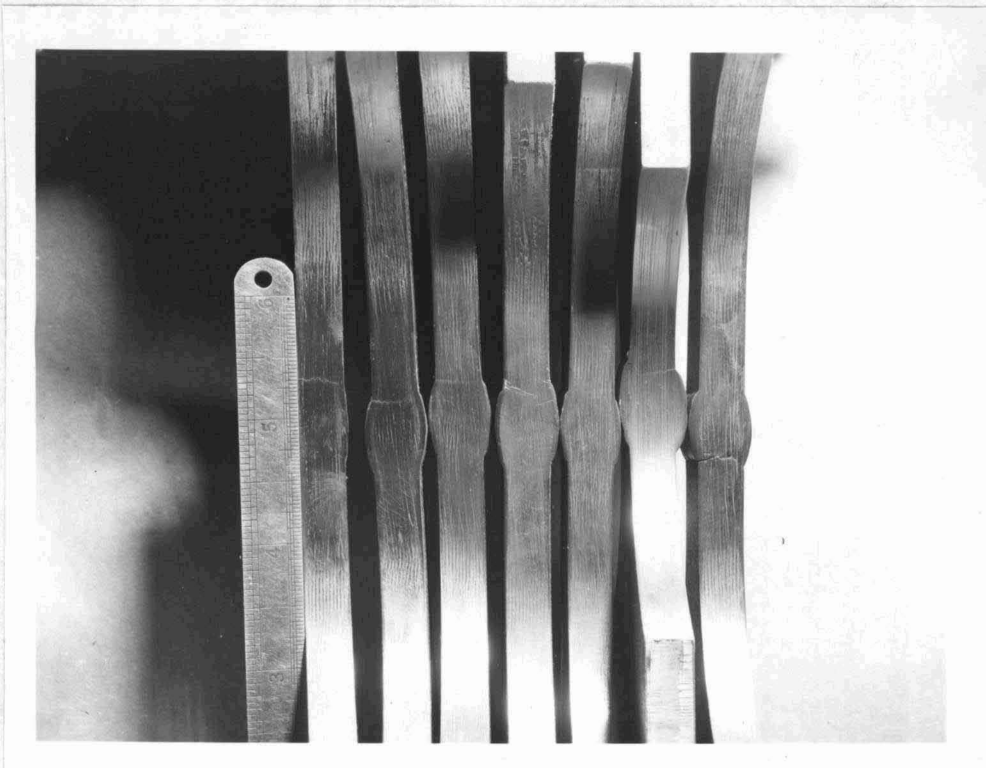


Fig. 23 SPECIMENS WITH INITIAL FRACTURES

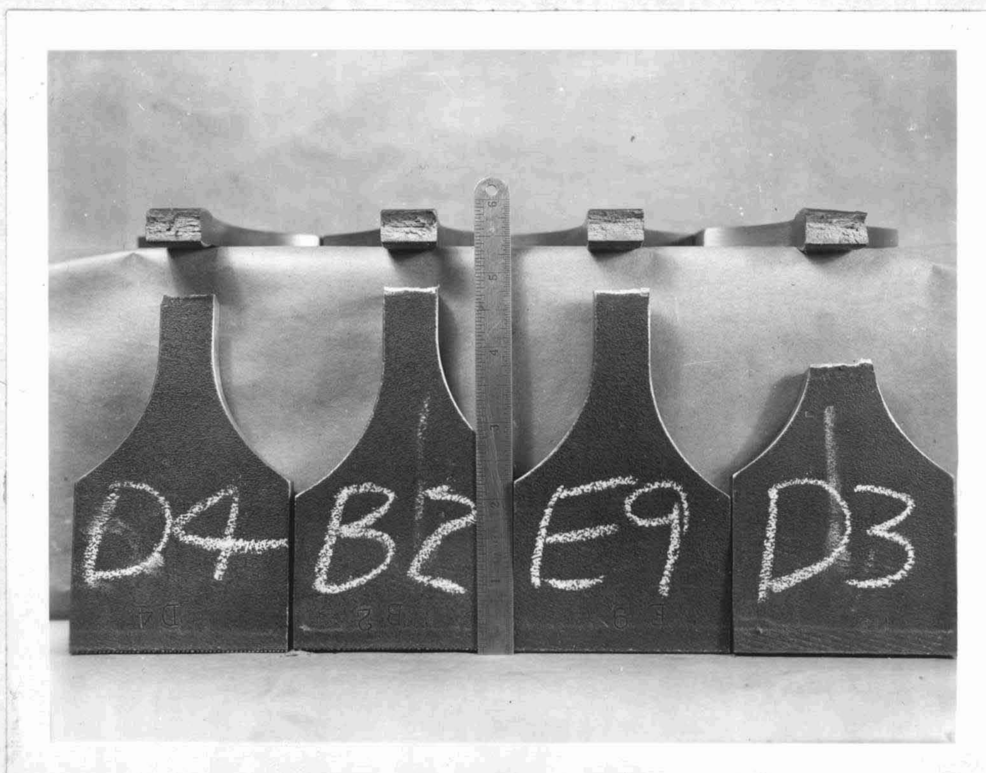


Fig. 24 FRACTURED SPECIMENS