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THE FATIGUE BEHAVIOR OF
PRESTRESSED CONCRETE MEMBERS

Thesis for the Degree of M. S.
MICHIGAN STATE UNIVERSITY
Donald E. Cochran
1964

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thesis entitled

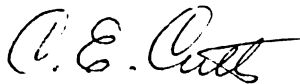
THE FATIGUE BEHAVIOR OF
PRESTRESSED CONCRETE MEMBERS

presented by

Donald E. Cochran

has been accepted towards fulfillment
of the requirements for

M. S. degree in Civil Engineering



Major professor

Date May 8, 1964

O-169



THE FATIGUE BEHAVIOR
OF PRESTRESSED CONCRETE MEMBERS

by

Donald E. Cochran

AN ABSTRACT OF A THESIS

Submitted to

Michigan State University

in partial fulfillment of the requirements

for the degree of

MASTER OF SCIENCE

Department of Civil and Sanitary Engineering

1964

Approved

D. E. Cochran

ABSTRACT

THE FATIGUE BEHAVIOR OF PRESTRESSED CONCRETE MEMBERS

by Donald E. Cochran

The purpose of this study is to investigate the behavior of prestressed concrete when subjected to fatigue loadings. The principal objectives are: to determine what effect, if any, temperature has on the fatigue properties; to study the static strength behavior of members previously subjected to a fatigue loading; and to investigate the possibility of using sonic testing equipment to indicate fatigue damage.

A total of fifteen 3" x 3" x 14 1/2" test beams were tested to fatigue failure in flexure. Four specimens were tested at 55°F, six at 73°F, and five at 90°F. The stress level of the tests varied from 34.1 to 61.0 percent of the ultimate static bending strength. Six other specimens were statically broken after a varying number of stress reversals at 45 percent of the ultimate static bending strength with the temperature held constant at 55°F.

Five similar test beams were statically broken. All static tests were conducted using the third-point loading method.

Temperature was found to affect the fatigue properties of prestressed concrete members. The lower the temperature, the more susceptible the member was to fatigue damage.

Previous reversal loadings at a stress level sufficient to cause failure by fatigue were found to damage the static load-carrying capacity

of the member after 95% of the reversals required to effect failure had been applied.

It is shown that sonic testing equipment may be used to indicate ultimate strength, and that it may be used to indicate fatigue damage, but insufficient data is presented to determine the exact relationships.

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ACKNOWLEDGEMENTS

The author wishes to express his sincere thanks to Dr. Charles E. Cutts, Chairman, Department of Civil Engineering, Michigan State University, for his advice and guidance during this investigation.

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I. INTRODUCTION

Perhaps one of the fastest growing uses of concrete is that of prestressed precast concrete. By using prestressed concrete, smaller members may be utilized, and by precasting the member, forming costs may be reduced and the curing controlled to exacting specifications. In addition, the utilization of prestressed precast members reduces the required construction time.

As in any other field, when a demand and a use for something exist, it may be put into use before complete testing has been performed. Many experiments on prestressed concrete have been made, but there seems to be little continuity in these experiments, and there is limited information as to the behavior of concrete when repeated loads are applied.

Pretensioned prestressed concrete members are formed by tensioning the reinforcing steel, pouring the concrete, then releasing the tension in the reinforcing steel after the concrete has developed sufficient strength for the transfer. In this manner, the concrete is initially in compression, so that a transverse loading which would normally cause tension in the concrete will only cause a reduction in the compression already present. Since in present design practice, the concrete is assumed to carry no tension, a considerably smaller member may be used. The load is transmitted from the steel to the concrete entirely by bond.

It is known that the load-carrying capacity of a member subjected to repetitive loads may be less than that of a member which is not subjected to repetitive loads due to the phenomenon known as fatigue. Fatigue failure may occur in the concrete, or the steel or in the bond between the two materials.

II. REVIEW OF PREVIOUS INVESTIGATIONS

GENERAL INFORMATION CONCERNING FATIGUE

Fatigue is the result of repeatedly changing the stress in a material. It may be due to loading and unloading a member, loading and only partially unloading a member, loading and then reversing the load in a member or a combination of these conditions. Most materials will fail under a number of repeated loads, or fail in fatigue, if the loads are sufficiently high and the number of applications sufficient to complete the failure. This type of failure is known as fatigue failure. Both the concrete and the steel used to reinforce concrete, both conventional and prestressed, exhibit the characteristic of failing gradually under repetition of loads.

The two variables normally present in the fatigue of a material are stress level and number of repetitions. Results of fatigue tests and failure envelopes are generally presented in the form of a S vs N plot. Here, S is the stress level, which may be expressed in a number of ways, and N is the number of cycles required to cause failure plotted on a logarithmic scale. Metals possess an endurance limit. This means that any number of load repetitions of a stress level lower than the endurance limit will not cause failure. In the normal S vs N plot the curve becomes asymptotic to the stress which represents the endurance limit. It does not appear that concrete has an endurance limit, that is, the S vs N plot does not become asymptotic, but continues downward and in fact is generally a straight line when plotted in terms of S vs N.

PLAIN CONCRETE

Since concrete is assumed to carry only compressive stress in present design practice, it is important to concern one's self with the fatigue properties of concrete in compression alone. Fatigue limits for concrete in compression alone range from 40% to 55% of its virgin static compressive strength.

Some (17) (6) of the available literature mentions an endurance limit for concrete in flexure. Kesler (10) states that concrete has no endurance limit, at least up to ten million cycles of loading.

Rest periods appear to help resist failure due to fatigue, and previous loading at a low stress level also helps resist the damaging effects of fatigue.

Nearly all papers state that the failure seems to be in the bond between the binding matrix and the aggregate. Kesler and Murdock (12) in their publication report that the initiation of the fatigue failure is due to progressive deterioration of the bond between the coarse aggregate and the binding matrix, reducing the section of the specimen, and the final fracture is a result of the failure of the paste-fine aggregate bond.

REINFORCED CONCRETE

The majority of the fatigue failures of reinforced beams, as in prestressed beams, occurs in the reinforcing steel. Beams which are critical in longitudinal reinforcement seem to have a fatigue limit of 60-70% of the static ultimate strength at one million cycles. Occasionally, beams were noted to have failed in diagonal tension due

to fatigue, but more generally in a combination of shear and bond. Beams failing in shear as low as 40% of the static ultimate stress have been reported.

In reinforced concrete, as in plain concrete, there is evidence that rest periods and initial fatiguing at a low stress level help resist fatigue failures.

PRESTRESSED CONCRETE

In prestressed concrete, the following types of fatigue failures are possible, as reported in Libby (14):

1. Failure of the concrete due to flexural compression.
2. Failure of the concrete due to diagonal tension or shear.
3. Failure of the prestressing steel due to flexural, or tensile stress variations.
4. Failure of pre-tensioned beams due to loss of bond stress.
5. Failure of the end anchorages of post-tensioned beams.

As yet, fatigue failures due to diagonal tension or shear alone have not been observed in prestressed concrete research.

The majority of fatigue failures found in prestressed concrete testing have resulted from fatigue in the prestressed tendons.

Several fatigue tests conducted abroad found individual wires contained in prestressing tendons failed by fatigue at points where they passed over spacers which were used to hold the wires in position.

Bond failures have been noticed and reported, but principally in very short-span members.

Many reports of fatigue have been made, but there seems to be little continuity in the available data. Some authors (Nordby 17) have attempted to condense the data, but have presented conflicting statements. It seems to be general belief, however, that prestressed beams are superior to conventionally reinforced beams as far as fatigue resistance is concerned. It is also general belief that the ultimate strength for beams which did not fail under repetitive loading is unimpaired by the repetitive loading. Nordby (17) and Patel (22).

T. E. Stelson, (27) has presented the best review of the actual test data conducted to date. In this report he presents a method for predicting a safe design based on fatigue considerations.

In no case, where tests have been made using conventionally prestressed members, has there been a report of failure of the concrete. For this reason, Mr. Vejubhai Gulababhai Patel submitted to Michigan State University in 1961 a Thesis concerned with the action of prestressed concrete under a flexural fatigue loading. By prestressing a test beam at the neutral axis, he was able to study the properties of the concrete itself, as the stress in the prestress wires was not affected by the loading.

Mr. Patel concluded that:

1. The ultimate strength of prestressed beams under static loading was not affected by previous dynamic loading of 2.5 million cycles.
2. That the ratio of failure loads (reversal) in fatigue loadings to that in static ultimate loadings was approximately 45 percent.

3. That under fatigue loading in which the entire cross-section remained in compression, flexural compression failures occurred in the concrete.

SONIC TESTING METHODS

When a test prism supported at its nodal points is driven from the side at one end, the resulting vibration may be picked up at the top at the opposite end, as shown in figure three. By varying the driving frequency and using the equipment shown in figure three, the resonant frequency of the prism may be obtained. It has been shown (19) that there is a relationship between the resonant frequency and the modulus of elasticity. This relationship is as follows: $E = C W n^2$ where E = Young's Modulus, C = a size constant, W = weight, and n = the resonant frequency. This method of non-destructive testing is now almost universally accepted.

III. SCOPE OF INVESTIGATION

QUESTIONS

In reviewing the available current literature and reports of previous investigations, questions arose, and some inconsistencies became apparent. These questions are as follows:

1. Is the ultimate strength of prestressed beams under static loading affected by previous dynamic loading?
2. Will fatigue loading of less than 45% of the static ultimate stress cause failure of the member?
3. Does the temperature of the specimen affect the fatigue properties?
4. If fatigue impairs the static properties of a test specimen, is it possible to use sonic non-destructive testing procedures to indicate the damage?

DISCUSSION OF QUESTIONS

1. It would appear that if a fatigue loading of 45% of the static ultimate load will ultimately cause failure of the specimen, then just before the specimen is destroyed by fatigue, its static properties will also be affected.
2. Since it is reported in many sources that plain concrete does not appear to have an endurance limit, (17) (27) is it not strange that some sources state that a loading of less than 45% will not cause failure?

3. From previous experience, it is known that properties of most materials vary somewhat with temperature. Temperature effects on the fatigue properties of prestressed concrete were not found in the literature. It appears that this is an area where information is lacking.
4. Previous studies (19) (5) have shown that there is a correlation between the sonic transverse resonant frequency of a specimen and the modulus of elasticity of the specimen. Will this equipment also indicate fatigue damage? What would be the outcome if one were to perform sonic tests on a reinforced specimen?

Since it is known that the answers to these questions would require a much more rigorous and time consuming investigation than is now possible, and the questions are somewhat unrelated, complete answers will not be attempted. It is felt, however, that a general investigation would be of significant value in determining the course of future extensive research. Therefore, an investigation of the behavior of prestressed concrete members subjected to dynamic loading, completely reversed, will be made with the objective of providing partial answers to the above questions, and providing a beginning for future investigations.

The size of the test specimen will be 3" x 3" x 14 1/2", since the available equipment is designed to use this size.

Since one of the previous investigations (22) used this size, with two strands of steel wire at the neutral axis, ($A_s = 0.0342 \text{ in.}^2$) with a uniform effective prestress of 473 psi, this investigation will attempt

to deal with that same basic specimen. Since the steel used in that investigation is not readily available, a single seven strand wire cable ($A_s = 0.0356 \text{ in.}^2$) will be used. The design effective prestress will be 473 psi.

Experiments will be performed at three different temperatures. Some members will be destroyed by fatigue, others will be fatigued to various degrees and then statically destroyed. Applicable sonic resonant frequency measurements will be made in conjunction with these experiments.

IV. EXPERIMENTAL PROGRAM

SPECIMENS

The test specimens used were pre-tensioned prestressed concrete beams. The size of each beam was 3" x 3" x 14 1/2". Each beam was prestressed at the geometric center of the cross-section with a single cable.

In Series One, sixteen beams were cast from a single concrete batch. In Series Two, eight beams were cast and in Series Three, ten beams were cast. Series One and Series Two were poured on the same day, and Series Three about five weeks later. The same concrete mix was used for all series.

Six test cylinders of 4" diameter and 8" high were cast with each series.

MATERIALS

PRESTRESSING STEEL

The prestressing steel used was seven strand wire cable of nominal diameter = 0.25 inch. The area of steel given by the manufacturer (Roebling) is 0.0356 square inches. Three 10 inch gage lengths of cable were inspected and tested, and the following data obtained:

Diameter of strand - 0.104"

Area of cable - 0.0343 in.². (A_s)

Modulus of Elasticity - 22×10^6 psi. (E_s)

Yielding load - 9800 lb.

Ultimate load - 9900 lb.

CONCRETE

Natural sand and washed gravel were used as the fine and coarse aggregates, respectively. The maximum size of the aggregate was limited to 1/2 inch due to the small test specimens used. A sieve analysis (Table Eleven) showed the fineness modulus of the sand to be 2.97 and that of the coarse aggregate to be 6.01. The water-cement ratio was 0.400, the cement content was found by a yield test to be 7.0 sacks per cubic yard, and mix proportions of 1: 2.47 : 2.47 were used due to the high fineness moduli of the aggregate. The cement used was type 1 air-entrained.

The cement, sand, and gravel were thoroughly mixed before the water was added, and final mixing time was 2 1/2 minutes in the Lancaster Laboratory Mixer.

The concrete was placed in the forms in two equal layers, and each layer was rodded 25 times. The beams and cylinders were kept wet and covered for 7 days before the release of the prestress, and then moved to the moist room for the remainder of the standard curing. Design strength was 6000 psi, and the average 28 day strength was 5920 psi.

EFFECTIVE PRESTRESS

The effective prestress is equal to the initial calculated prestress minus the prestress losses. Throughout the calculation of prestress losses, the "Tentative Recommendations For Prestressed Concrete," by the ACI-ASCE Joint Committee 323 (2) will be followed. In the calculations, the following terms will be used:

E_{ci} = 1,800,000 / 500 times the cylinder strength at the release of the wires. Modulus of elasticity of the concrete. (Psi)

E_{cf} = 1,800,000 / 500 times the cylinder strength at the end of 28 days. Modulus of elasticity of the concrete. (Psi)

E_s = Modulus of Elasticity of the steel used for prestressing the concrete. (Psi)

ϵ_s = Strain in the steel. (in/in)

ϵ_c = Strain in the concrete. (in/in)

P_{si} = Total load in the prestress wire before release. (lbs.)

P_{sf} = Total load in the prestress wire after release. (lbs.)

P_c = Total load in the concrete after release of the wires. (lbs.)

A_s = Area of the steel. (in.²)

A_c = Area of the concrete. (in.²)

A_g = Gross area = $A_s + A_c$. (in.²)

f_s = Stress in the prestress steel. (Psi)

f_c = Stress in the concrete. (Psi)

f'_c = Ultimate compressive stress in the 28 day old cylinder. (Psi)

C_c = Creep coefficient for the concrete.

δ_s = Unit shrinkage strain for the concrete.

P_t = Change in steel load due to ΔE_s (lbs.)

PRESTRESS LOSSES

(Shown here for Series One and Series Two)

(a) Elastic Shortening of the Concrete.

After release of the wires, $P_{sf} = P_c$

and $\epsilon_c = \Delta\epsilon_s$

Here, $P_{sf} = P_{si} - P$ transferred to the concrete

or, P transferred to the concrete = $P_{si} - P_{sf}$

$$E_{ci} = 1,800,000 + 500 (3925) = 3.763 \times 10^6 \text{ psi}$$

$$E_s = 22 \times 10^6 \text{ psi}$$

f_s initial (before release) = 144,000 psi

$$P_{si} = 5120 \text{ lb.}$$

If we assume elastic conditions

$$\frac{P}{A} = E\epsilon$$

$$\frac{P_t}{A_s} = E_s \Delta\epsilon_s \quad \text{and,} \quad \frac{P_c}{A_c} = E_c \epsilon_c$$

$$\Delta\epsilon_s = \epsilon_c$$

$$\text{so, } \frac{P_t}{A_s E_s} = \frac{P_c}{A_c E_c}$$

$$\text{or, } \frac{P_{si} - P_{sf}}{A_s E_s} = \frac{P_c}{A_c E_c}$$

$$P_{sf} = P_c$$

$$\text{so, } \frac{P_{si} - P_c}{A_s E_s} = \frac{P_c}{A_c E_c}$$

from which

$$\frac{P_c}{A_c} = f_c = \frac{P_{si}}{A_g + A_s \left[\frac{E_s}{E_c} - 1 \right]}$$

$$\begin{aligned} \text{at release} &= \frac{5120}{9 \cdot 0.0356 \left\{ \left(\frac{22 \times 10^6}{3.763 \times 10^6} \right) - 1 \right\}} \\ &= 563 \text{ psi.} \end{aligned}$$

Therefore,

$$\text{since } f_c = E_c \epsilon_c, \text{ and } \epsilon_c = \frac{f_c}{E_c} = \Delta \epsilon_s,$$

the loss of prestress in the steel is

$$\Delta f_s = E_s \frac{f_c}{E_c} = \frac{22 \times 10^6 \times 560}{3.763 \times 10^6} = 3274 \text{ psi}$$

(b) Shrinkage of Concrete:

$$\delta_s = 0.0003 \quad (\text{as recommended})$$

$$\text{since } \Delta \epsilon_c = \Delta \epsilon_s,$$

$$\Delta f_s = \Delta \epsilon_c E_s = \delta_s E_s,$$

$$\text{so, } \Delta f_s = 0.0003 (22 \times 10^6) = 6600 \text{ psi.}$$

(c) Creep of the Concrete:

$$E_{cf} = 1,800,000 + 500 (5980) = 4.790 \times 10^6 \text{ psi.}$$

$$(E_{cf} \text{ sonic} = 6.22 \times 10^6 \text{ psi})$$

A maximum concrete stress under loaded conditions will be assumed to be 563 psi + 0.5 f_c ultimate,

$$= 563 + 487 = 1050 \text{ psi.}$$

$$C_c = 2.5 \quad (\text{as adopted by the committee})$$

for which,

$$f_s = (C_c - 1) f_c \frac{E_s}{E_c}$$

$$\text{so, } f_s = (2.5 - 1) (1050) \left(\frac{22 \times 10^6}{4.79 \times 10^6} \right) = 7234 \text{ psi}$$

(d) Relaxation of Steel Stress:

The committee recommends 2-8% off f_s initial. Since the 7 day creep was found to be 1+%, 4% was assumed for the computations.

$$\text{Therefore, } f_s = 0.04 (144,000) = 5760 \text{ psi}$$

TOTAL PRESTRESS LOSSES:

Loss due to elastic shortening	=	3274 psi
Loss due to concrete shrinkage	=	6600 psi
Loss due to concrete creep	=	7234 psi
Loss due to relaxation of steel	=	<u>5760</u> psi
Total		22,868 psi

Note: This should be compared to the 35,000 as recommended by the committee. The value of 35,000 is judged by many to be excessive, although if considered for a longer period of time than was required for the tests, the 22,868 would undoubtedly be revised upward.

EFFECTIVE PRESTRESS:

Since the steel prestress losses are 22,868 psi or 15.88% f_s initial (say 16%), the effective concrete prestress must also be 16% less than the initial prestress, or 470 psi.

For Series Three, a similar study with:

$$\begin{aligned} E_c \text{ at release} &= 3.738 \times 10^6 & f_c &= 3850 \text{ psi} \\ \text{and } E_c \text{ at 28 days} &= 4.730 \times 10^6 & f_c &= 5860 \text{ psi,} \\ && & \text{yields an effective prestress of 462 psi.} \end{aligned}$$

CASTING OF SPECIMENS

The equipment used to cast the specimens is shown in Figure Three. The prestressing force was applied by threading the end bolts into the gripping fixtures, as shown in Figure Four. A detail of the bolts and fixtures is shown in Figure Six. Due to the fact that the steel used was in the form of a cable, it was impossible to fix a strain gage directly to the cable. If a jack were used, the individual tension would have to be checked and adjusted. Since it was found that the required tension could be obtained without the use of jacks, they were not used.

In order to check the load in each cable, a four inch section of 1 1/4" diameter standard pipe was machined to provide flat ends, and the two strain gages fixed to it, one on either side to eliminate influence due to bending. Since the area of the pipe was known, any indicated strain in the pipe could easily be converted to load in the cable. Each of the fabricated transducers was checked in a universal testing machine and found to be acceptable. These transducers are shown in Figure Seven.

All three cables were loaded at once, and the indicated strain recorded. At the release of the prestress, the indicated strain was again recorded, and the difference between the first strain indication and the last was judged to be the relaxation of steel stress. This was found to be just over 1%.

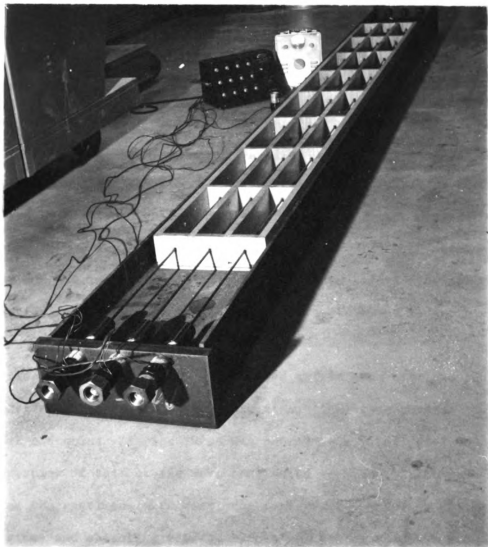


Figure One

General View of Prestress Bed

Two SR-4 strain gages were fixed to one beam in each row just prior to release of the cables, and the actual initial concrete strain recorded. This indicated value was within 1 1/2 percent of that calculated in the section dealing with effective prestress, so the difference was neglected.

During construction of the forms, it became evident that a certain amount of difficulty would be experienced in oiling the forms without getting any oil on the prestress cable. This problem was solved by drilling the holes in the forms to 1/2 inch diameter, oiling the forms, and then inserting a dry sleeve, 1/2 inch outside diameter and 1/4 inch inside diameter in the form before drawing the prestress cable through the forms. This arrangement is shown in Figure Six and Figure Seven

Series One and Series Two were poured at the same time, so they were considered to have the same properties, since they possess identical histories. Series Three was poured at a later date, so the properties of this series were considered separately. About one day after the specimens were cast, the forms were removed by prying up the sides and chiseling out the blocks separating the beam ends. The beams were kept covered and thoroughly wetted throughout the remainder of the seven days before the prestress cables were released. At that time they were moved to the curing room.

FATIGUE EQUIPMENT

The fatigue testing machines used were Baldwin-Lima-Hamilton Sonntag Fatigue Testing Machines, which were equipped with SF-1-U



Figure Three

Apparatus for Obtaining Transverse Resonant Frequency

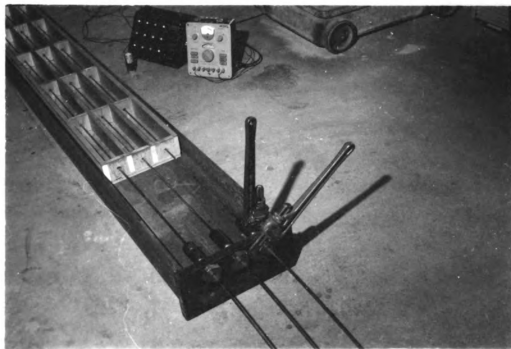


Figure Two

Method of Prestressing the Cables

bending fixtures. A typical view of this machine is shown in Figure Eight. Although the equipment was designed so that a preload could be applied to the specimen, none was applied. The specimen, therefore, was subjected to complete reversal of stress.

The stress was induced by an unbalanced rotating mass which was fixed to the center platen and so caused a vertical vibratory motion of this center platen. The outer platen was stationary, and due to the construction of the bending fixture, the vertical motion of the center platen imparted a constant bending moment to the center portion of the test beam.

The frequency of the applied moment was 1800 cycles per minute and the counter, driven by a synchronous motor, recorded the number of reversals, each unit on the counter being 1000 cycles.

The machine was equipped with a variable transformer which enabled the operator to control the rate of acceleration of the main drive synchronous motor. In this manner, the specimen was not overstressed during either the starting or stopping of the test.

The machine was also equipped with limit switches which limit the vertical motion of the center platen. When a specimen failed during the test, the vertical motion of the center platen became excessive, tripping the limit switch, and stopping both the main driving motor and the counter.

The applied moment was varied by varying the unbalance of the rotating mass. The machine was equipped with a scale so that the mass might be adjusted to give a particular force to the vibrating platen.

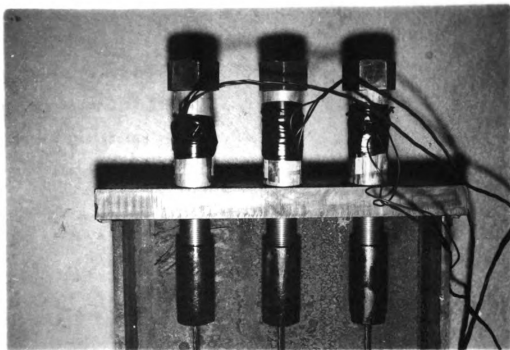


Figure Five

Detail of Transducers

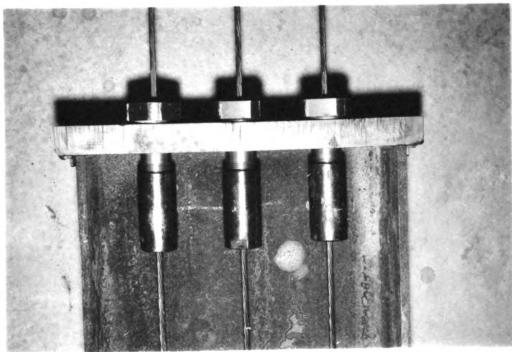


Figure Four

Detail of Bolts and Gripping Fixtures

Since this force was known, and since the dimensions of the bending fixture are known, (length of the bending arm = 6") the required force to produce a particular stress in the specimen was calculated to be

$P = \frac{3}{2} \sigma$ where σ is the maximum stress in the specimen.



Figure Seven

Strain Indicator and Form Detail

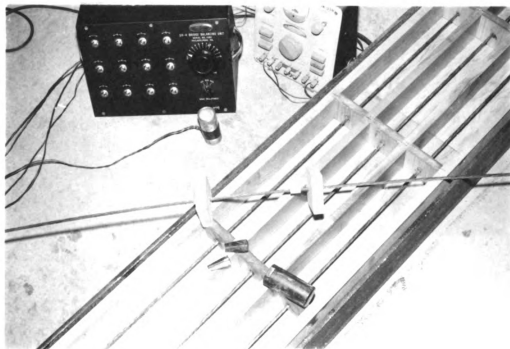


Figure Six

Detail of Gripping Fixtures & Forms

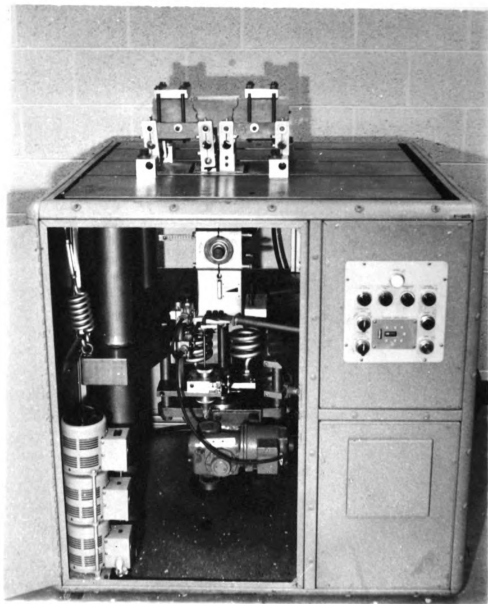


Figure Eight

Fatigue Testing Machine and Bending Fixture

V

**EXPERIMENTAL
DATA
AND
RESULTS**

TABLE 1. Series #1 Test Data

Beam Designation	Effective Pressure (Psi)	Weight (lbs.)	Initial Resonant Frequency	Final Resonant Frequency	Temperature of Test	Loading (In % of static ultimate)	No. of Cycles (millions)	Notes
T1-1	470	11.31	2160	-	*	67.7	0.042	*
T1-2	470	11.31	2170	-	*	50.0	0.020	*
T1-3	470	11.31	2170	-	70°F	-	-	Statically broken at 2,220 lb.
T1-4	470	11.32	2160	-	*	50.0	0.006	* Malfunction of preload equipment
T1-5	470	11.32	2170	-	*	48.0	0.009	* " " "
T1-6	470	11.31	2180	-	55°F	46.8	1.485	Failure
T1-7	470	11.33	2170	-	55°F	41.0	2.780	Failure
T1-8	470	11.30	2170	1460	55°F	45.0	2.000	Statically broken at 1840 lb. (Broke at location equivalent to 1563 lb.)
T1-9	470	11.32	2160	-	90°F	61.0	0.453	Failure
T1-10	470	11.31	2160	-	*	50.0	0.024	*
T1-11	470	11.34	2170	-	70°F	-	-	Statically broken at 2200 lb.
T1-12	470	11.32	2170	-	70°F	-	-	" " " 2180 lb.
T1-13	470	11.30	2170	-	*	48.0	0.024	Failure*
T1-14	470	11.33	2180	-	55°F	34.1	6.185	Failure
T1-15	470	11.34	2170	-	55°F	45.0	1.985	Failure
T1-16	470	11.33	2170	2070	55°F	45.0	1.950	Statically broken at 2160 lb.

* : Temperature inconsistent or other consideration which rendered test results useless

TABLE 2. Series #2 Test Data

Beam Designation	Effective Prestress (Psi)	Weight (lbs.)	Initial Resonant Frequency	Final Resonant Frequency	Temperature of Test	Loading (In % of ultimate static)	No. of cycles of % (million)	Notes
T2-1	470	11.28	2200	-	73°F	45.0%	6.324	Failure
T2-2	470	11.30	2150	-	73°F	47.5%	4.228	Failure
T2-3	470	11.29	2160	2140	73°F	50%	10.000	(Test disregarded) Bending Fixture Broken
T2-4	470	11.32	2160	-	73°F	50.0%	2.661	Failure
T2-5	470	11.28	2150	1775	55°F	45.0%	1.992	Statically broken- 2010 lb. (Broke at location equivalent to 1310 lb)
T2-6	470	11.31	2170	1985	55°F	45.0%	1.980	Statically broken - 2100 lb.
T2-7	470	11.30	2170	2020	55°F	45.0%	1.976	Statically broken - 2140 lb.
T2-8	470	11.30	2170	2090	55°F	45.0%	1.900	Statically broken - 2200 lb.

TABLE 3. Series #3 Test Data

Beam Designation	Effective Prestress (psi)	Weight (lbs.)	Initial Resonant Frequency	Temperature of Test	Loading (in % ult. based on Series #1 & #2)	Loading (in % ult. based on Series #3)	No. of cycles to failure (millions)
T3-1	462	11.30	2150	90°F	47%	47.7%	6.817
T3-2	462	11.33	2170	90°F	45%	45.7%	10.564
T3-3	462	11.29	2150	90°F	49%	45.8%	4.602
T3-4	462	11.30	2170	90°F	43%	43.7%	15.161
T3-5	462	11.30	2170	70°F	Static 1/3 pt. load = 2200 lb.		
T3-6	462	11.31	2150	73°F	48%	48.7%	3.388
T3-7	462	11.35	2170	73°F	45%	45.7%	6.053
T3-8	462	11.33	2150	73°F	50%	50.8%	2.334
T3-9	462	11.32	2170	Varied	Temperature changed - Test no good		
T3-10	462	11.31	2150	70°F	Static 1/3 pt. load = 2140 lb.		

TABLE 4. Summary of Static Test Data (Members with 0 stress reversals)

Beam Designation	Beam Series	Static 1/3 pt. Loading Causing Failure	$p_{max.}$	Notes
T1-3	1	2220 lb.	990 Psi	
T1-11	1	2200 lb.	980	Ave. ult. 1/3 pt. load = 2200 lb. Ave. max. $\sigma = 980$
T1-12	1	2180 lb.	970	
T3-5	3	2200 lb.	980	
T3-10	3	2140 lb.	928	Ave. ult. 1/3 pt. load = 2170 lb. Ave. max $\sigma = 959$

TABLE 5. Summary of 550F Test Data

Beam Designation	Beam Series	Loading (in % of ult.)	No. of cycles to failure (millions)
Tl-6	1	46.8	1.485
Tl-7	1	41.0	2.780
Tl-14	1	34.1	6.185
Tl-15	1	45.0	1.985

TABLE 7. Summary of 90°F Test Data

Beam Designation	Beam Series	Loading (in % of ult. based on Series #1 & #2)	Loading (in % of ult. based on resp. series)	No. of cycles to failure (millions)
T1-9	1	61.0	61.0	0.453
T3-1	3	47.0	47.7	6.817
T3-2	3	45.0	45.7	10.564
T3-3	3	49.0	49.8	4.602
T3-4	3	43.0	43.7	15.161

Table 8. Summary of Data From Statically Destroyed Fatigued Specimens

Test Temperature = 55°F
Test Fatigue Load = 45% Static Ultimate

No. Fatigue cycles @ 45% ult. (millions)	Beam Designation	Beam Series	Initial Resonant Frequency	Final Resonant Frequency	Final Static Fail- ing Load	Notes
2.000	T1-8	1	2170	1460	1840 lb.	Broke in range of varying moment - equiva- lent load = 1563 lb. (see text)
1.950	T1-16	1	2170	2070	2160 lb.	
1.992	T2-5	2	2150	1775	2010 lb.	Broke in range of varying moment - equiva- lent load = 1310 lb. (see text)
1.980	T2-6	2	2170	1985	2100 lb.	
1.976	T2-7	2	2170	2020	2140 lb.	
1.900	T2-8	2	2170	2090	2200 lb.	

Table 9. Resonant Frequency Data - Specimens T3-1 & T3-4 (Series #3)

T3-1		T3-4	
No. cycles (millions)	Frequency (cps)	No. cycles (millions)	Frequency (cps)
0	2150	0	2170
0.444	2100	4.095	2020
0.901	2085	9.291	2000
1.434	2080	9.831	1995
2.090	2080	10.850	1990
2.690	2075	11.930	1955
3.422	2040	12.790	1885
4.130	1980	13.390	1850
4.600	1950	14.280	1770
5.100	1885	14.670	1700
5.520	1810	14.750	1655
6.250	1685	15.00	1535 (crack)
6.600	1580	15.160	1355
6.800	1500 (crack)	15.161	Failure
6.812	Failure		

TABLE 10. Results of Cylinder Tests (Loading Rate = 35 Psi/sec)

Series #	Cylinder Designation	Cylinder Age	Cylinder Size	Ultimate Load	Stress at Failure	
1	1-A	7 day	4"x8"	47,800	3820	Ave. 7 day Series #1 & #2 = 3925 PSI Ave. 28 day Series #1 & #2 = 5980 PSI
1	1-B	7 day	"	50,400	4030	
1	1-C	7 day	"	48,000	3830	
1	1-D	28 day	"	74,500	5935	
1	1-E	28 day	"	67,500	5380	
1	1-F	28 day	"	83,500	6650	
2	2-A	7 day	4"x8"	49,000	3920	Ave. 7 day Series #3 = 3850 PSI Ave. 28 day Series #3 = 5860 PSI
2	2-B	7 day	"	50,200	4010	
2	2-C	7 day	"	49,200	3930	
2	2-D	28 day	"	74,000	5900	
2	2-E	28 day	"	78,000	6220	
2	2-F	28 day	"	73,500	5870	
3	3-A	7 day	4"x8"	49,200	3930	Ave. 7 day Series #3 = 3850 PSI Ave. 28 day Series #3 = 5860 PSI
3	3-B	7 day	"	48,000	3830	
3	3-C	7 day	"	47,400	3790	
3	3-D	28 day	"	74,000	5900	
3	3-E	28 day	"	73,500	5870	
3	3-F	28 day	"	73,000	5810	

TABLE 11. Sieve Analysis of Concrete Aggregate

Sieve Size	% Coarser	% Held	% Coarser	% Held
1/2"	0.0	0.0	1.0	1.0
3/8"	0.3	0.3	15.0	14.0
#4	2.2	1.9	89.8	74.8
#8	18.6	16.4	98.0	8.2
#16	34.8	16.2	98.8	0.8
#30	52.8	18.0	99.0	0.2
#50	89.2	36.4	99.4	0.4
#100	99.3	10.1	99.8	0.4
Pan	100.0	0.7	100.0	0.2

Fine Agg. {

Coarse Agg. }

Fineness Modulus = 2.97

Fineness Modulus = 6.01

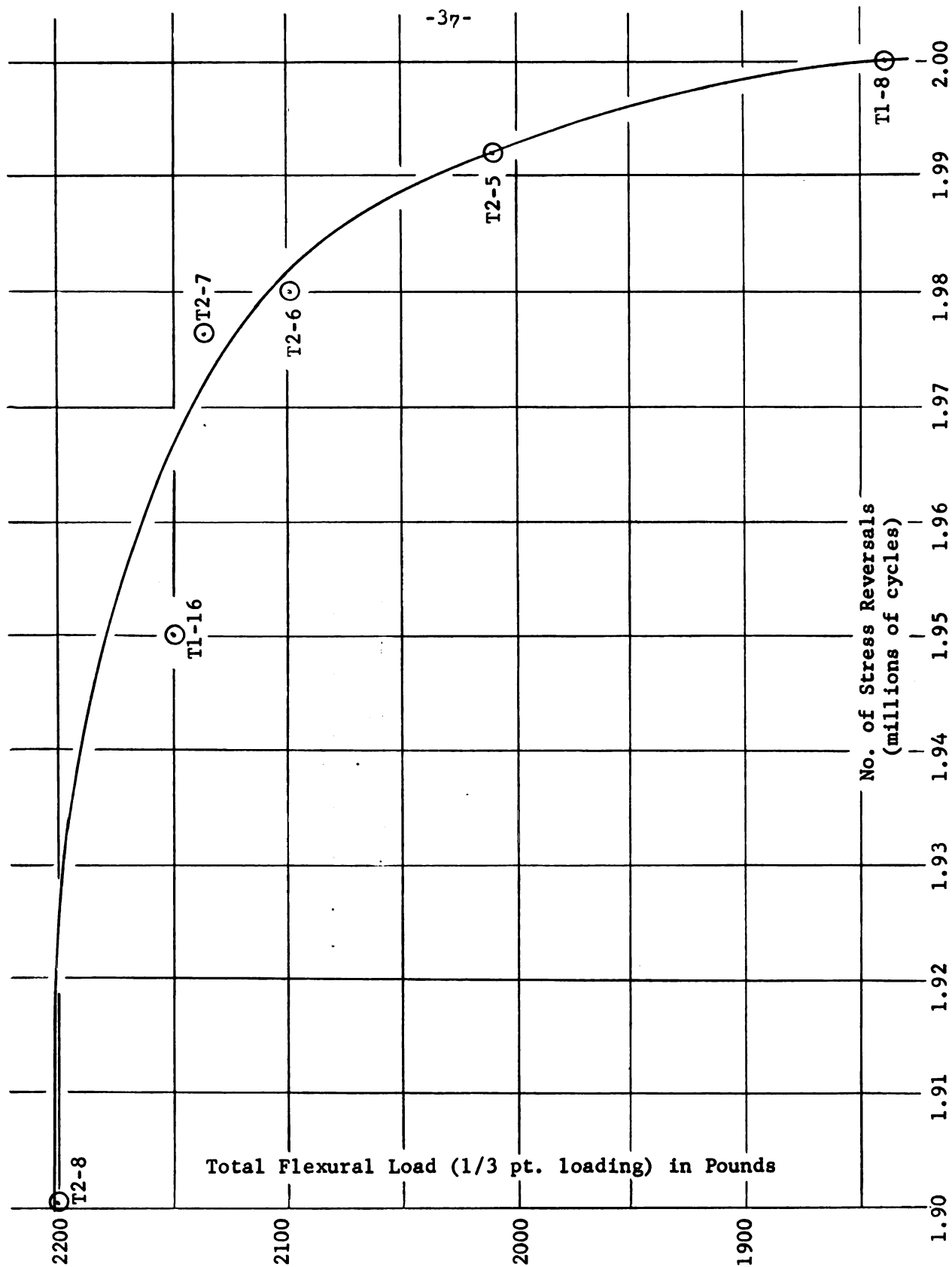


Fig. A. Ultimate Static Strength
vs.
No. Cycles @ 45% ult. $t = 55^{\circ}\text{F}$

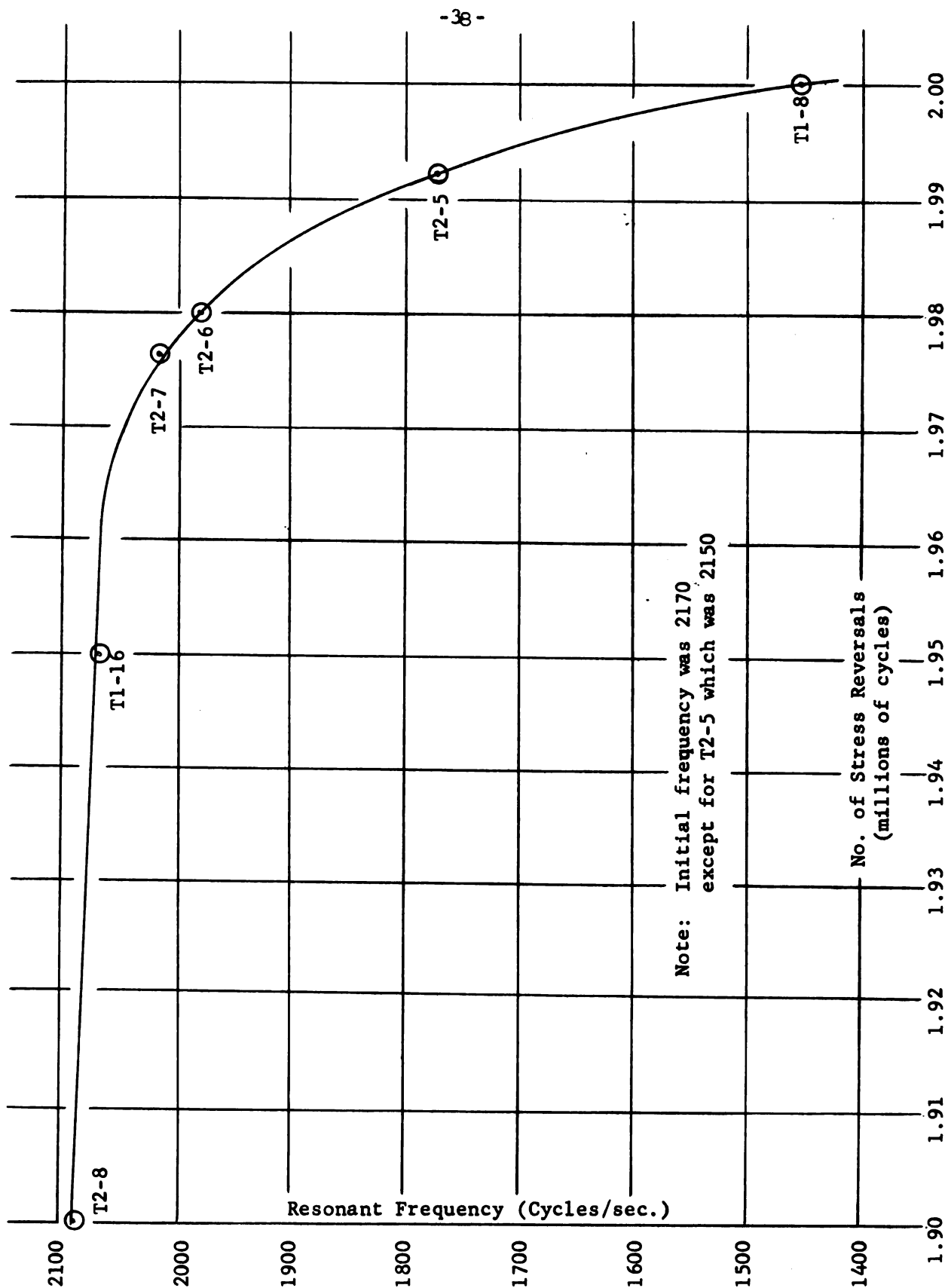


Fig. B. Resonant Frequency
vs.

No. of Cycles @ 45% ult. $T = 55^{\circ}\text{F}$

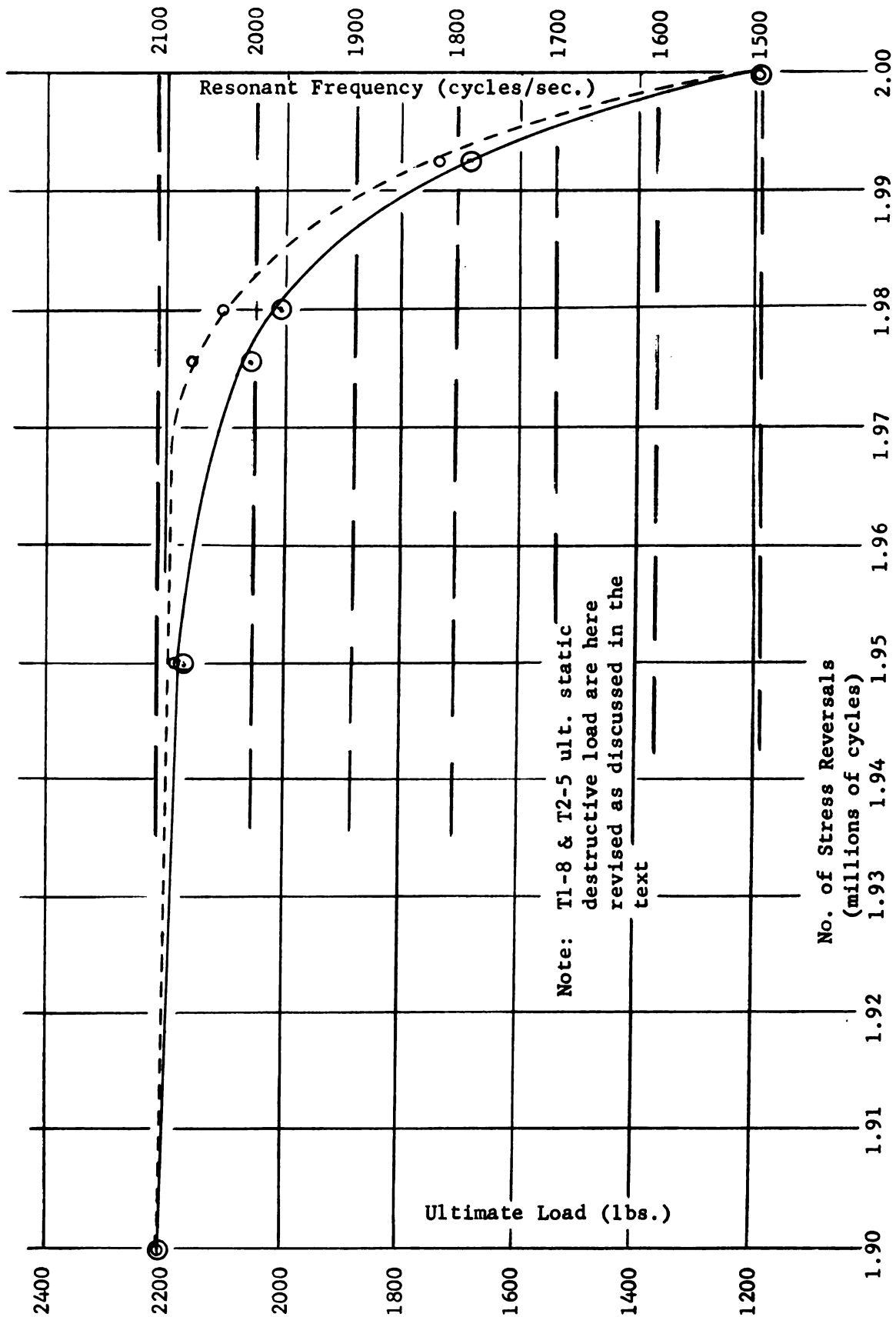


Fig. C. Comparison of:
Ultimate Static Destructive Load

vs.
No. cycles @ 45% ult. $t = 55^{\circ}\text{F}$
(-----)

Resonant Frequency
vs.
No. of cycles @ 45% ult. $t = 55^{\circ}\text{F}$
(-----)

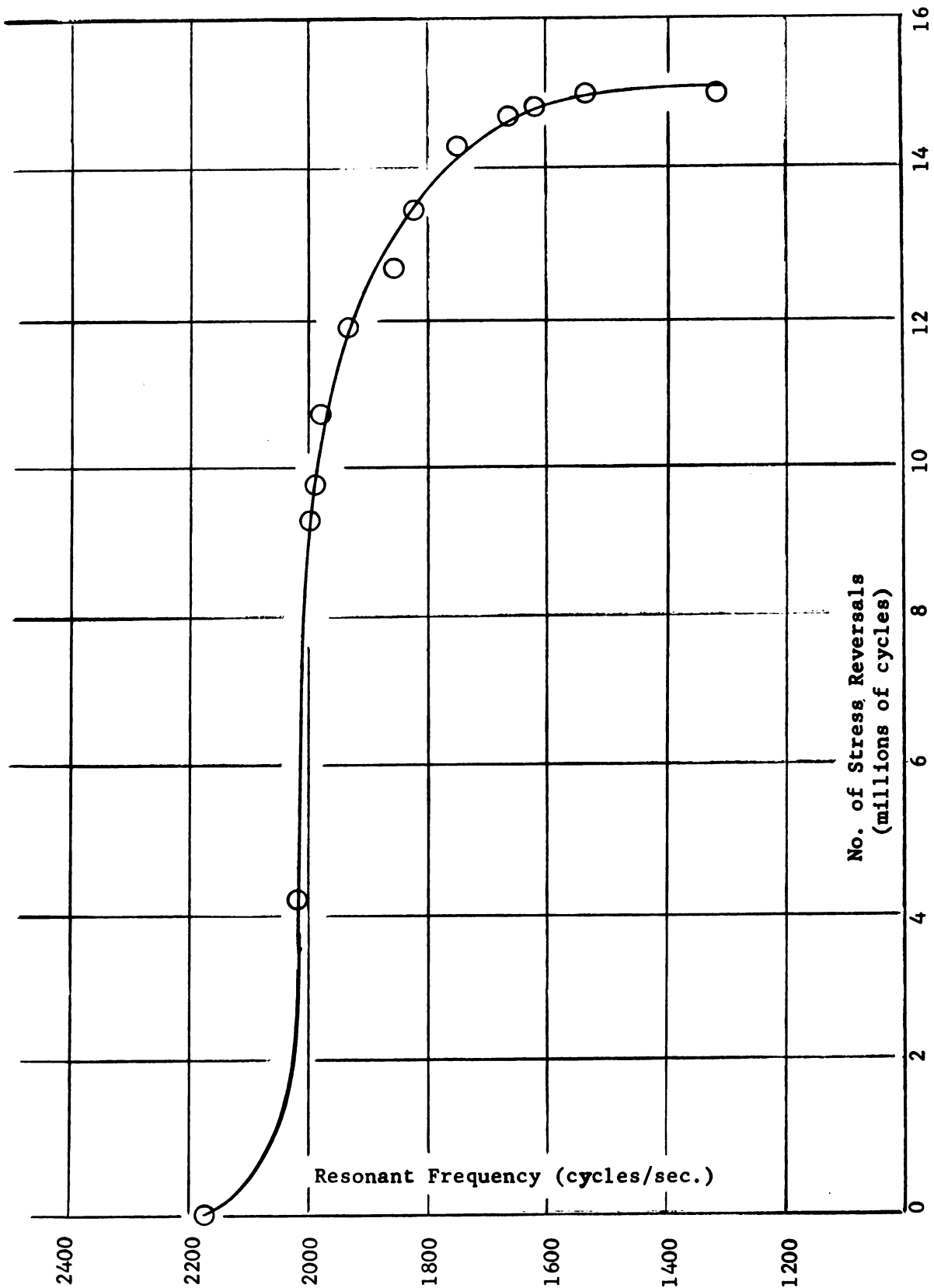


Fig. D. No. of Cycles
vs.
Sonic Frequency

Test Beam # T3-4 (Series #3)
Load = 43.68% ult. $t = 90^{\circ}\text{F}$

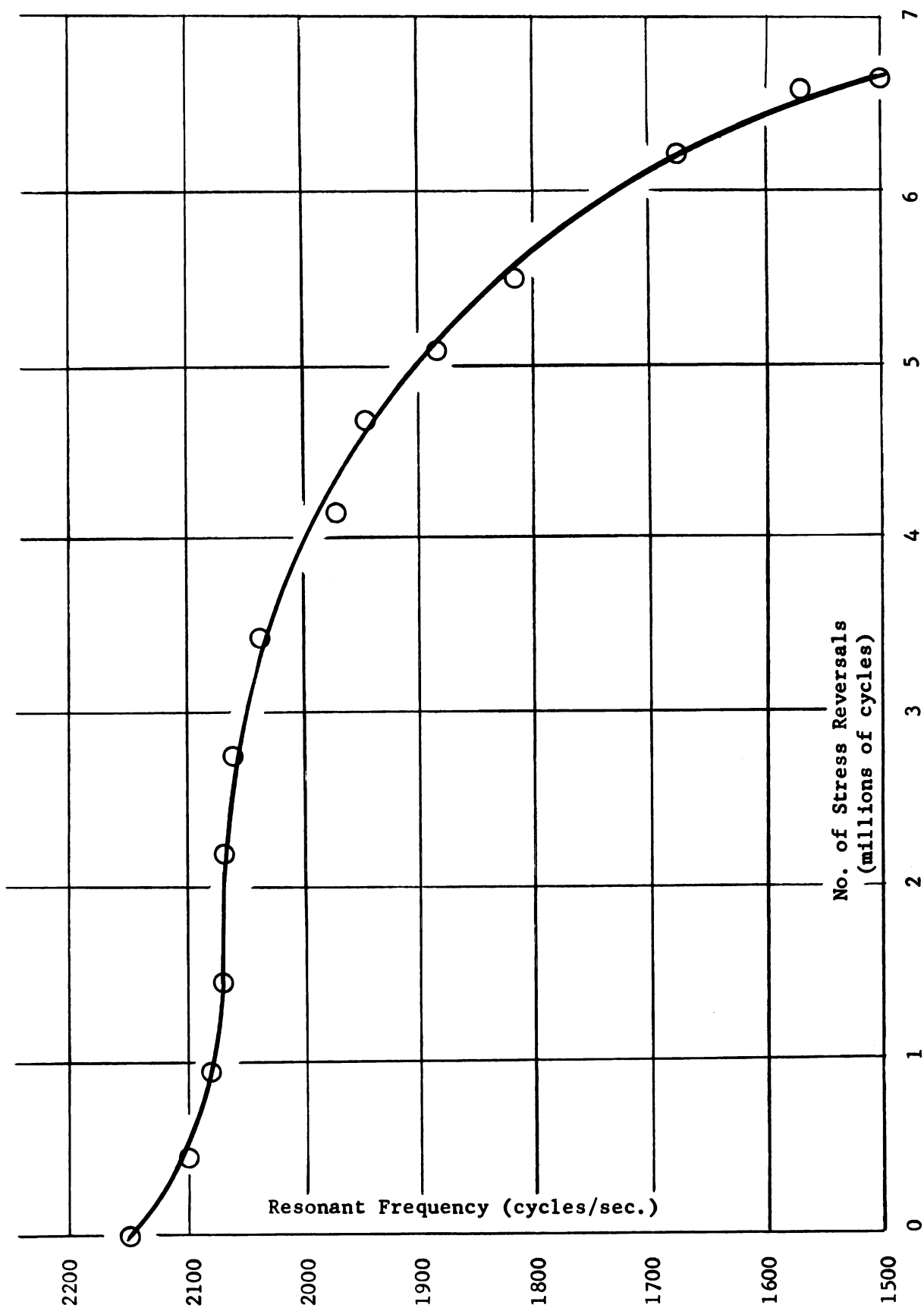


Fig. E. No. of Cycles
vs.

Test Beam # T3-1 (Series #3)
Load = 47.73% ult. Temp. = 90°F

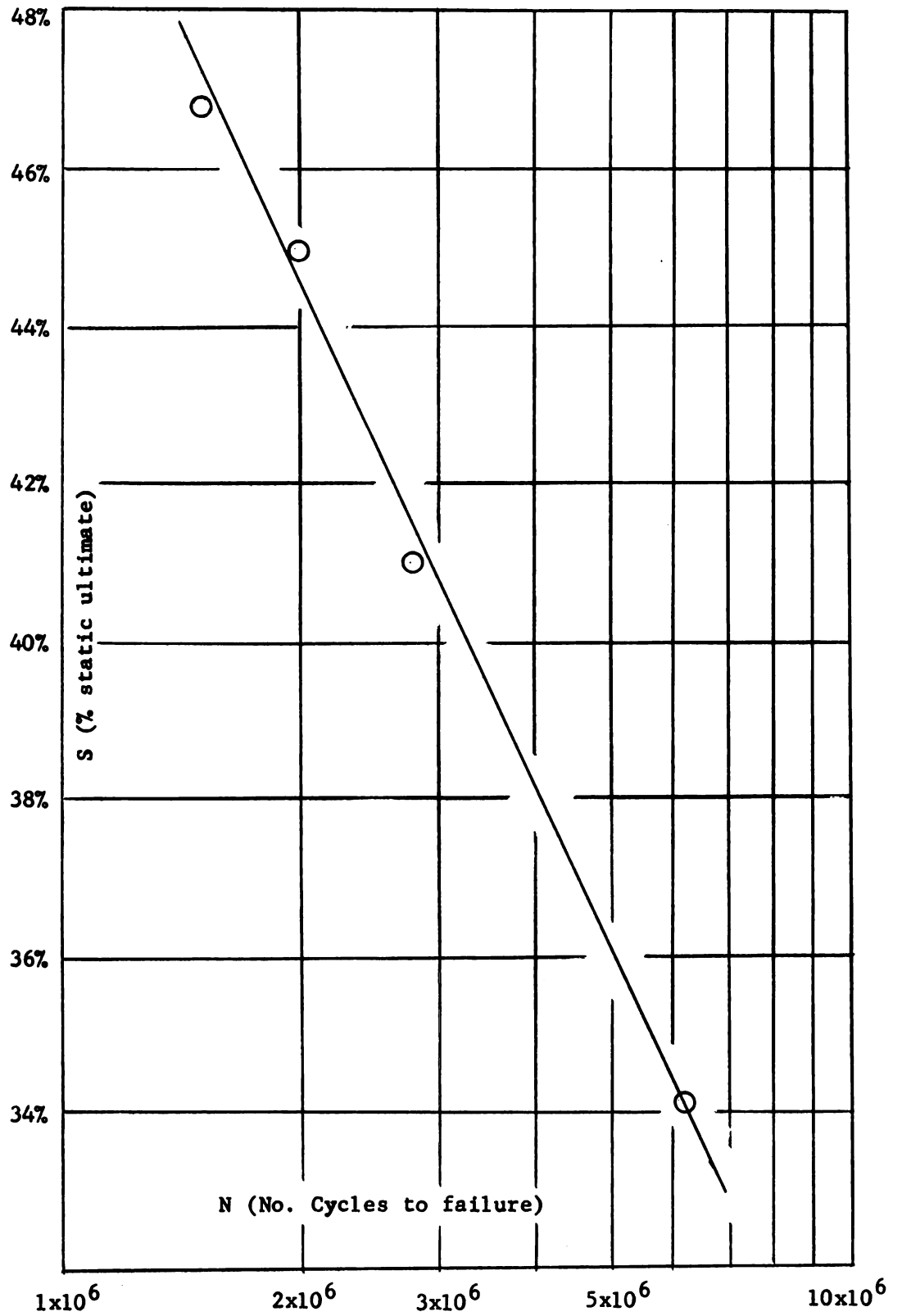


Fig. F. S vs. N
Temp. = 55°F
Test Series #1

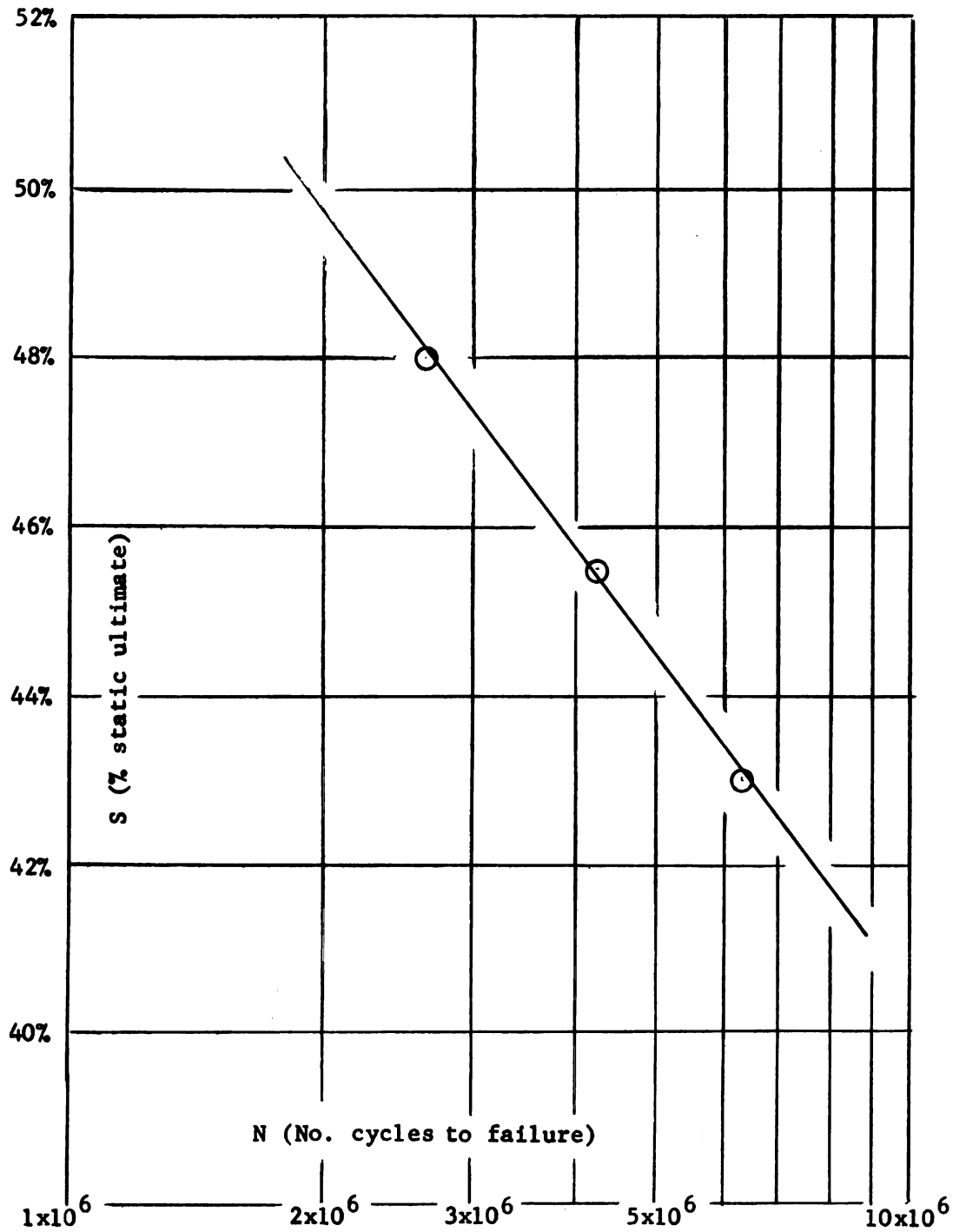


Fig. G. S vs. N
Temp. = 73°F
Test Series #2

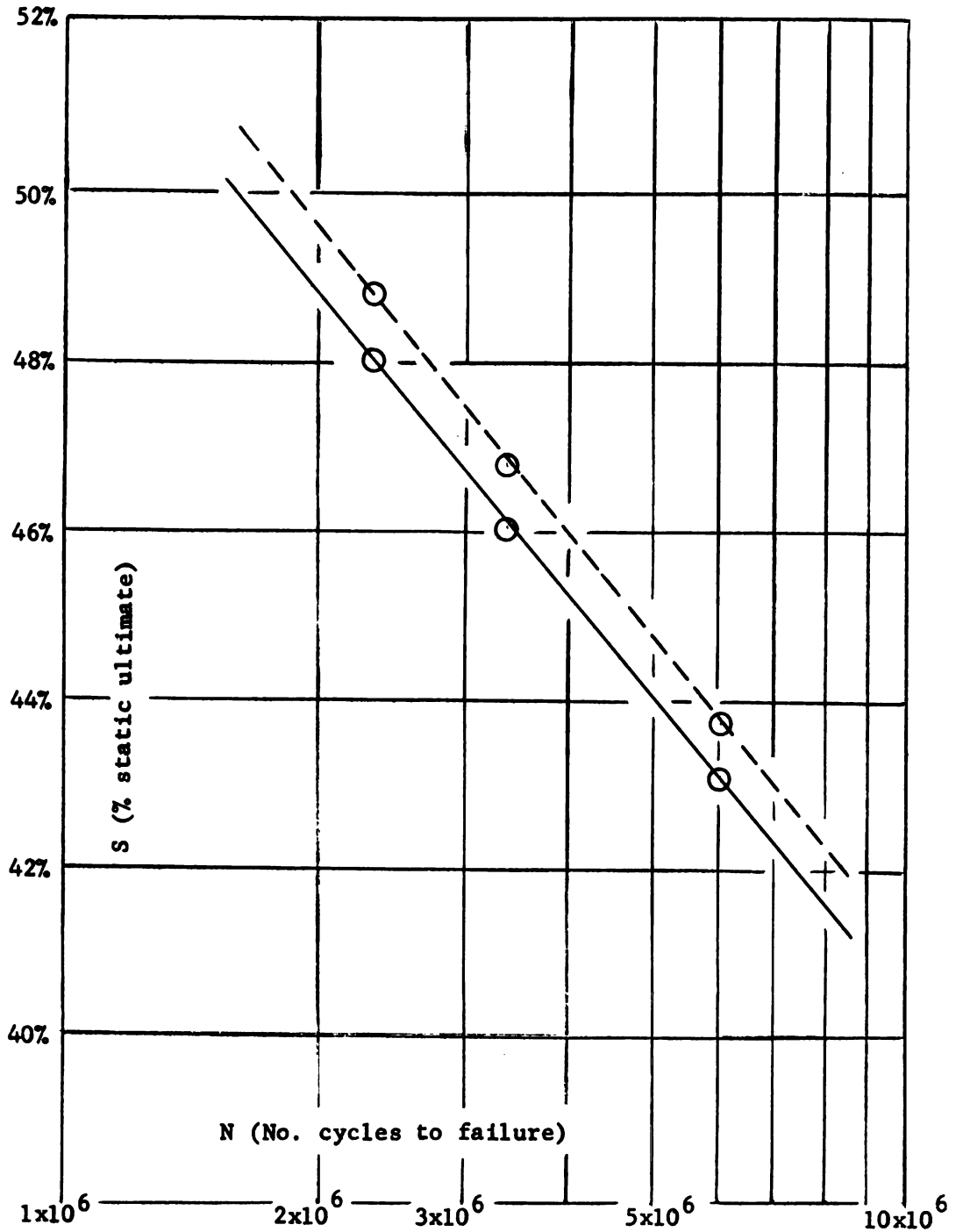


Fig. H. S vs. N
Temp. = 73°F
Test Series #3

———— = Based on Ult. for Series #1 & #2
----- = Based on Ult. for Series #3

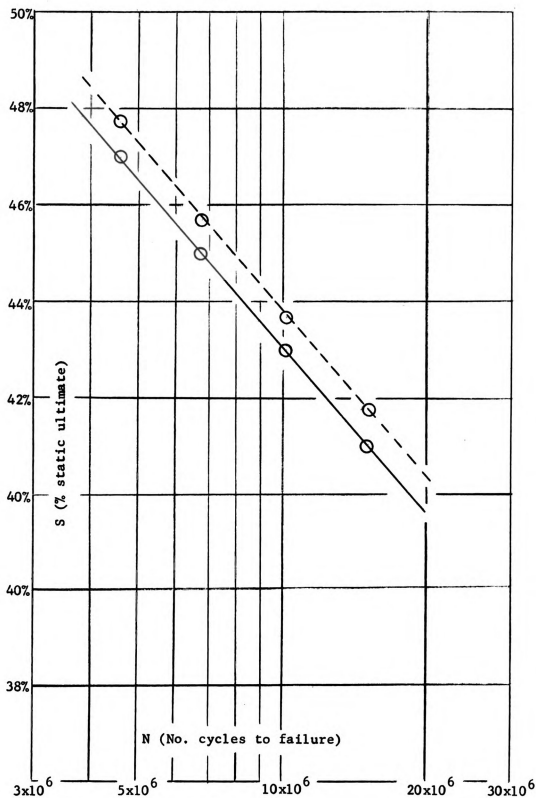


Fig. I. S vs. N
 Temp. = 90°F
 Test Series #3

_____ = Based on Ult. For Series #1 & #2

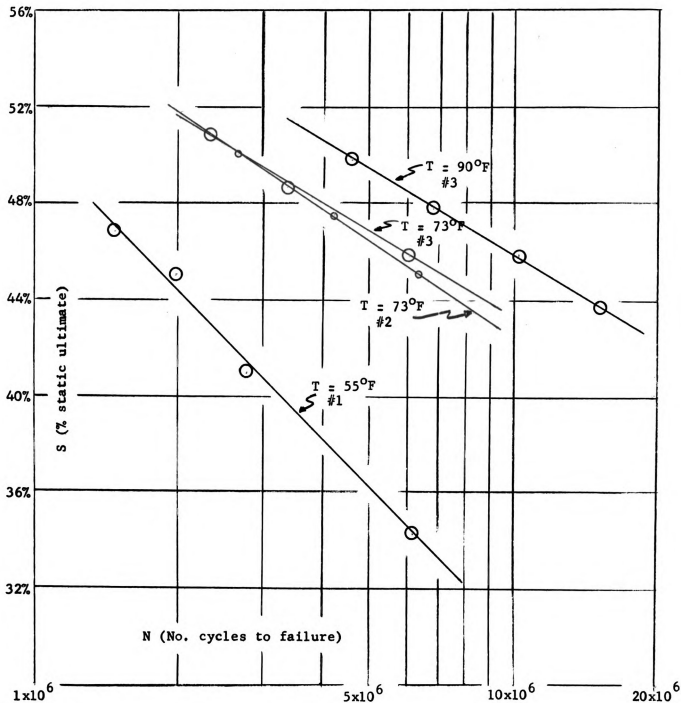
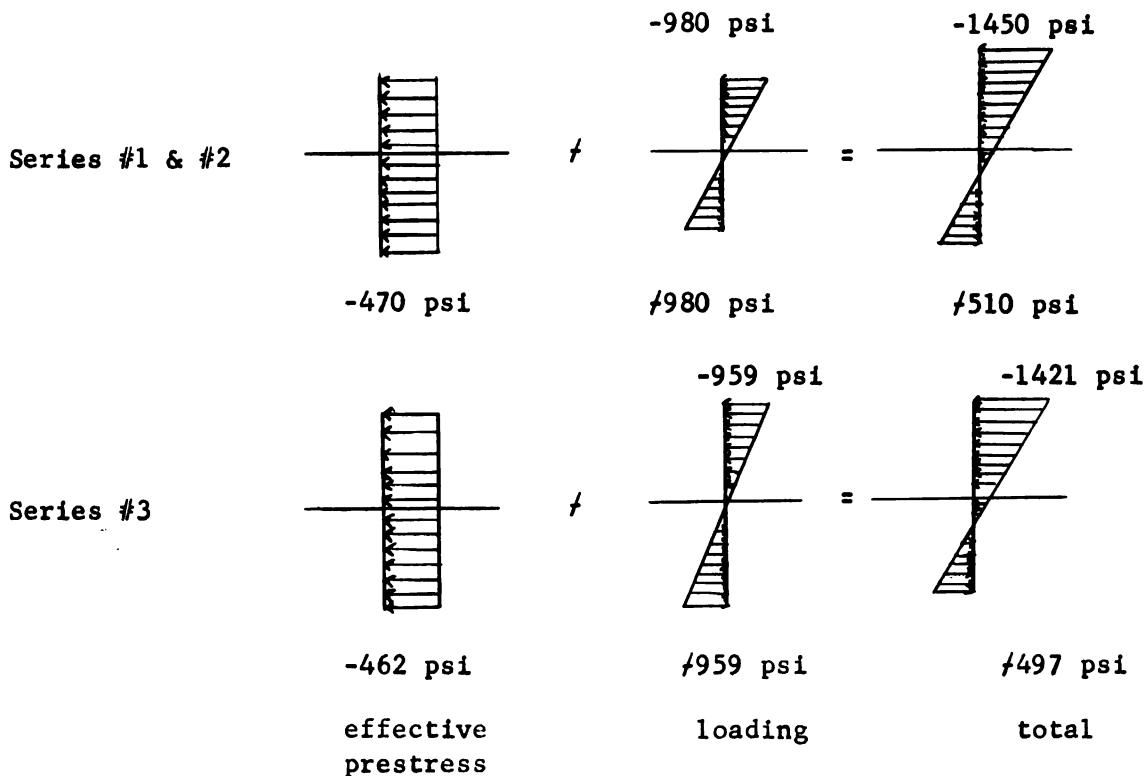


Fig. J. S vs. N
Temp. - Indicated
Based on Respective Series

VI. DISCUSSION OF EXPERIMENTAL RESULTS

As seen from the data, eight tests have been disregarded. This is due to the fact that for specimen T2-3, the SF-1-U bending fixture broke, and it was impossible to know the exact history of the specimen. For specimens T1-4, and T1-5, the preload equipment on the testing machine experienced a malfunction. For specimens T1-2, T1-1, T1-10, and T1-13, the temperature was not constant.

As is noted in Table Four, the average maximum stress for the specimens destroyed using the static third points loading was 980 psi for Series One and Series Two, while that for Series Three was 959 psi. Since the effective prestress was 470 psi and 462 psi respectively, the stress distribution at failure was as shown below.



The results of the tests conducted at 55°F are summarized in Table Five, and the corresponding S vs N plot shown in Figure F. The results of the 73°F tests are summarized in Table Six, and the corresponding results plotted in Figures G and H. Note that in Figure H the results are shown in two ways. One way with the stress level expressed as a percent of the static ultimate for Series One and Two, and the other way with the stress level expressed as a percent of the static ultimate for Series Three. The results of the 90°F test are summarized in Table Seven and the corresponding S vs N plot is shown in Figure I in a fashion similar to Figure H.

Figure J is a consolidation of Figures F, G, H, and I utilizing a smaller scale. Here it is noted that there is indeed a temperature dependence for fatigue life of prestressed concrete.

Table Eight summarizes the data collected from the portion of the tests in which members were subjected to a varying number of loadings at forty-five percent of the static ultimate stress, with the temperature held constant at 55°F. Here it is noted that when specimens T1-8 and T2-5 were statically broken using the third points loading method, the failure occurred outside the zone of maximum moment, as shown in Figure 10. Therefore, the loads used for computations concerning these members have been reduced to an equivalent load which would have produced a moment in the center portion of the beam equal to that which actually caused failure. Figure A presents the data of Table Eight in graphical form.



Figure Nine

Typical Static $1/3$ Point Break



Figure Ten

Break of Specimen T1-8 under Static $1/3$ Point Loading. (Typical of T2-5)

Table Eight also contains the resonant frequency data collected using these beams. This data is graphically presented in Figure 8.

A comparison of the 'Ultimate Static Strength vs Number of Cycles at 45% Static Ultimate' and the 'Resonant Sonic Frequency vs Number of Cycles at 45% Static Ultimate' is made in Figure C. Here, the resonant sonic frequency is reduced so that the beginning and ending points of this curve will coincide with the respective points on the other curve. From this Figure, it is apparent that there is some relationship between decrease in resonant frequency and decrease in static ultimate load. No attempt has been made to determine this relationship, since it is felt that the available data is not sufficient to obtain this relationship. The actual relationship should be determined by future investigations.

Table Nine presents resonant frequency data collected from specimens T3-1 and T3-4, for various numbers of cycles at 47% and 43% of the static ultimate load, respectively. Both tests were made at 90°F. Since Figure C shows there to be a relationship between resonant frequency and ultimate static strength, Figures D and E can also be interpreted to show decrease in static ultimate load.

Table Ten contains the data from which the strength of the concrete was determined. As noted, the loading of the 4" diameter 8" long cylinders was at the rate of 35 psi/second, which is within the range recommended by the American Society for Testing Materials.

Table Eleven contains the sieve analysis data from which the fineness moduli of the fine and coarse aggregates were determined.

From the data, it is apparent that a member loaded with sufficient load to eventually cause fatigue failure suffers eventual static load carrying damage. It does not appear, however, that this damage occurs until approximately 95% of the reversals required to cause failure by fatigue have been applied. It is also apparent that a reduction in resonant frequency corresponds to a reduction in ultimate static load-carrying capacity, and this fact has been used in the further data reduction. It is also apparent that the temperature of the fatigue tests affect the performance of the test beams.

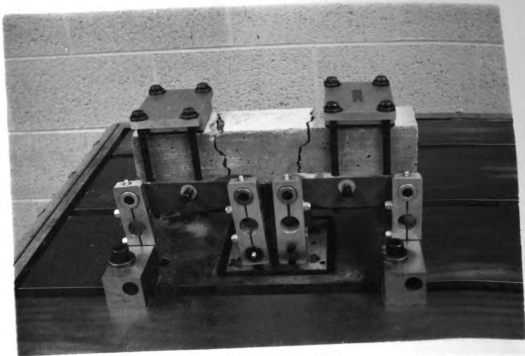


Figure Twelve
Typical Fatigue Fracture

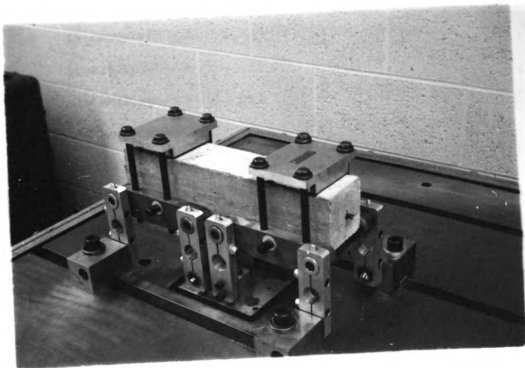


Figure Eleven
Bending Fixture and Test Beam

VII. CONCLUSIONS

From the observations made during the testing described, the following preliminary conclusions may be made:

1. The ultimate strength of prestressed concrete beams is adversely affected by a level of fatigue loading which would eventually cause failure. This phenomenon occurs only after approximately 95% of the total number of stress reversals to effect failure have been applied.
2. A fatigue loading of less than 45% of the static ultimate load will eventually cause failure of the member.
3. The temperature of the member must be considered when one is concerned with the fatigue performance of a prestressed concrete member. The lower the temperature, the more susceptible the member is to fatigue damage.
4. Limited measurements tend to indicate that a relationship exists between the reduction in static load-carrying capacity of a prestressed member and the transverse resonant frequency of the member.

VIII. RECOMMENDATIONS FOR FURTHER STUDY

It is recommended that further study be made in the following areas:

TEMPERATURE

It is suggested that tests be made at various temperatures and the data presented in a fashion similar to Figure J so that more exact fatigue considerations can be made with respect to temperature.

TRANSVERSE RESONANT FREQUENCY vs ULTIMATE STRENGTH

It is recommended that further investigations be made to determine the actual relationship between transverse resonant frequency, and ultimate static strength. Further consideration of the application of the sonic test to reinforced and prestressed members should be made.

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