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TO: Mr. B. E. Rossi, Executive Secretary
Pressure Vessel Research Committee
Room 503
29 West 39th Street
New York 18, N. Y.

Progress Report No. 7

PRESSURE VESSEL RESEARCH COMMITTEE
Fabrication Division

Lehigh University Project

October 1, 1950 to September 30, 1951

Introduction

The program carried out during the fiscal year 1950-1951 at Lehigh University consisted of two phases. The first was a study of the effect of plate edge conditions as produced by machining, flame-cutting, or shearing on the notch toughness of the pedigreed steels A201 and A285 used in previous investigations. The second phase covered the repeated load tests on cold worked and on welded specimens, in which the behavior of the steels was studied under repeated plastic straining.

The results of these investigations are reported in the form of the papers prepared for publication.

Respectfully submitted,

S. S. Tör

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Professor in Metallurgy

208.8

Part II

Repeated Load Tests on Strained and Welded Plates

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REPEATED LOAD TESTS ON WELDED AND PRESTRAINED STEELS

By

Sadun S. Tör*, Jan M. Ruzek*, and Robert D. Stout*

FOREWORD

This paper is one of a series resulting from a project at the Fritz Engineering Laboratory of Lehigh University sponsored by the Pressure Vessel Research Committee of the Welding Research Council. The project has as its object the study of the effects of fabrication operations on the mechanical properties of steels that are used in pressure vessels.

INTRODUCTION

Pressure vessels are generally subjected in service to some type of cyclic loading which may total during the lifetime of the vessel anywhere from several hundred cycles to 100,000 or more. This loading may be normal to the function of the vessel or it may occur accidentally by variations in the service conditions, thermal strains, or actual misuse (or abuse) of the vessel. If the loading is abnormal, it is apt to be higher than the design level

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and may produce plastic deformation in local areas containing stress concentrations. Eventually, such repeated overloading can result in failure of the vessel.

A study of the resistance of pressure vessel steels to repeated overloading does not involve fatigue testing of the usual type. No endurance limits are determined, since the levels of loading are in all cases above the yield strength of the material and produce failure in 100,000 cycles or less. The Fabrication Division of the Pressure Vessel Research Committee directed the project group at Lehigh University to study the effects of such fabrication operations as cold forming and welding on the resistance of pressure vessel steels to repeated overloading.

DEVELOPMENT OF THE TESTING METHOD

Specimen Design

There were two principal factors to be considered in the selection of a specimen design for repeated load testing. First, it was desirable to test the full plate thickness rather than some arbitrary portion of it. Second, the test section of the specimen had to be large enough to include a weld bead and the heated zone adjacent to it. This meant that the test section had to be 5/8 inches thick (the plate thickness) and at least one inch wide. Under these circumstances it was best to load the specimen in bending

in order to keep the magnitude of the loads required for plastic deformation within reasonable limits.

The specimen was designed as shown in Fig. 1. It was loaded as a cantilever beam with the reduced section near the stationary grip. The surface of the specimen was the original plate surface; and when weld beads were applied, they were machined flush with the surface before testing.

Machine Design

The repeated-load machine was designed and built at Fritz Laboratory. Figs. 2, 3 and 4 show different views of the machine. The design permits the application of either constant loads or constant deflections by the use of a coil spring or a solid link between the horizontal bars.

The machine was designed to the following specifications: loads up to 600 pounds and deflections up to 4 inches at the moveable end of the specimen, cycle speed between 100 and 400 cycles per minute, an automatic power cutoff at specimen failure, and a revolution counter.

Calibration of the machine was obtained by affixing strain gages to the loading link, as in Fig. 5, and a depth gage visible in Fig. 6. The loads and deflections applied to the specimen were correlated with the settings on the graduated eccentric of the crank arm.

TESTING PROCEDURE

Loading Method

It was first thought that constant loading would be preferable to constant deflection as a loading method, since it would better simulate service conditions. Other factors soon became apparent, however, to change this viewpoint, and constant deflection was used for the test program.

In Fig. 7 the chief factor in favor of constant deflection is made evident. The load on the specimen is plotted against the deflection of the specimen at the loading end. Note that the load rises linearly to about 300 pounds, corresponding to the yield point of the outer fibers of the specimen, then slopes off rapidly to about 400 pounds and thereafter remains virtually constant. Such behavior, which is characteristic of plastic bending, makes it impracticable to use the load as an index of the severity of deformation imposed on the outer fibers of the specimen. At least this is true for loading conditions which produce failure in the range of 2000-100,000 cycles significant to pressure vessel service.

A second factor is the work hardening that takes place in the test section. With constant load, the deflection of the specimen decreases noticeably as cycling continues. Decreased deflection corresponds to decreased strain in the test section. While this effect is probably present in service, it is so sensitive to

the geometry of the section that there is little likelihood that the specimen conditions match service conditions. With constant deflection it was possible to introduce a known, relatively constant plastic strain for the period of cycling preceding crack formation. In accordance with these factors, constant deflection was used throughout the investigation.

Calibration of Strains

In order to establish settings on the cam eccentric which would produce desired levels of strain in the test section it was necessary to calibrate the machine and the specimen. For this purpose $\frac{1}{4}$ inch SR-4 strain gages were cemented on both top and bottom surfaces at the throat of the specimen to measure the strain at the outer fibers as a function of the specimen deflection, which is indicated by the dial gage and regulated by the cam setting.

In Fig. 8 calibration curves are presented for as-received A-201 steel on the first loading cycle and also after 200 cycles and 1000 cycles. It will be noticed that the measured strain for the same load decreased after cycling. This was due to work hardening of the throat which forced unworked metal adjacent to the narrowest point to contribute a part of the total strain. The strain levels selected for the test program were in all cases defined as the strain produced on the initial cycle of testing.

Endpoint of Testing

Originally the machine was designed to shut off when the specimen broke into two and so fell on a microswitch feeding into the power relay switch. It was found that frequently the specimen would fail except for a paper-thin section which would hold together sometimes for a dozen, sometimes for several hundred cycles. This action contributed needless scatter to the results.

It was decided to define the endpoint of the test as that at which the load carrying capacity of the specimen dropped to a small fraction of the original value. This was accomplished by the device pictured in Fig. 9. A magnifying lever was rested on the end of the throat section nearest the stationary clamp. A small elastic movement in the specimen at this point actuated a flag between a light source and a photronic cell. The light reaching the cell varied directly as the amount of movement of the flag, and the voltage output of the cell was fed to a DC amplifier, the output of which was recorded on an Esterline-Angus voltmeter. When the throat of the specimen was cracked sufficiently, it no longer communicated load to the fixed end and the flag movement became small, as did the output voltage to the recorder. By this method, the end point of the test could be recorded without constant attendance of an operator.

Test Conditions

A pilot series of tests was made to determine the strain levels which would result in failure in the range of 1000 to 100,000 cycles of loading. These were found to be between the yield point and 1% total strain. Four levels of strain for testing were then established: 0.15%, 0.4%, 0.7% and 1.0%. Each test run was conducted with triplicate specimens. Reversed bending was imposed on all of the specimens.

Since loading in the plastic range produces measurable heating of the specimen, the cycling rates were limited to values which did not heat the specimens above 125°F. The speed ranged from 100 cycles per minute for 1.0% strain to 375 cycles per minute for 0.15% strain.

While most of the tests were conducted at room temperature, some of the test variables were investigated by cycling at 500°F. A furnace with an auxiliary heating unit was mounted on the machine to enclose the stationary clamp and the throat of the specimen. The temperature was controlled by fastening a thermo-couple to the throat of the specimen and by it controlling the auxiliary heater under the throat. The experimental setup is shown in Fig. 10.

THE VARIABLES STUDIED

The Steels

The steels used in this investigation were 5/8 inches thick

plates of two pedigreed heats obtained at the start of the project. One was aluminum-killed A-201 and the other was rimmed A-285 of the following analyses:

Steel Analyses

	C	Mn	Si	P	S	Cu	Ni	Cu
A-201	0.15	0.53	0.20	0.020	0.022	0.04	0.05	0.07
A-285	0.20	0.35	0.02	0.019	0.028	0.04	0.10	0.14

The steels were received in the as-rolled condition. All specimens were cut out with their long axis parallel to the rolling direction.

Treatments before Testing

Tests at Room Temperature:- The two steels received a series of treatments before testing which are listed below:

1. as-rolled plate, postheated at 75°, 500° or 1150°F
2. 10% tensile prestrain parallel to rolling, postheated at 75°, 500°, or 1150°F
3. 10% tensile prestrain transverse to rolling, postheated at 75°, 500° or 1150°F
4. longitudinally bead-welded on both sides with E6020 at 175 amperes and 10 inches per min., postheated 75°, 500° or 1150°F
5. transversely bead-welded on both sides with E6020 at 175 amperes and 10 inches per min., postheated 75° or 1150°F (A-201 steel only)

The longitudinal bead-welds were three inches in length and were deposited on the specimen before machining the throat section.

The transverse bead welds were deposited on an 8 x 18 inch plate before cutting out specimens.

Tests at 500°F:- The tests at 500°F were run on A-201 steel only with the following conditions:

1. as-rolled plate, postheated at 75° or 1150°F
2. 10% tensile prestrain parallel to rolling, postheated at 75° or 1150°F
3. longitudinally bead-welded on both sides with E6020 at 175 amperes and 10 inches per min., postheated at 75° or 1150°F

Special Tests

In addition to the program described above, a number of tests were conducted on A-201 steel to investigate (1) the origin of cracking in welded specimens, and (2) the effects of low temperature cooling rates following welding on the resistance to repeated loading.

The technique for determining initial cracking in the specimens consisted of polishing the flat throat section, etching it very lightly, and scanning the area with a microscope at 50 diameters at frequent intervals during testing.

The study of low temperature cooling rates was comprised of the following treatments before testing at room temperature:

1. E6020, 175 amps, 10 in per min., cooled to room temp.
2. E6020, 175 amps, 10 in per min., preheated to 200°F
3. E6020, 175 amps, 10 in per min., postheated 10 sec. after welding at 200°F for 1 hour
4. E6020, 175 amps, 10 in per min., preheated to 400°F
5. E6020, 175 amps, 10 in per min., postheated 10 sec. after welding at 400°F for 1 hour.
6. E6016, 210 amps, 10 in per min., cooled to room temp.

Straining was carried out in reverse bending for these special tests at one level of strain, 0.5%.

EXPERIMENTAL RESULTS

Room Temperature Tests

The cycles to fracture as a function of strain level are shown in a series of bar graphs in Figs. 11 to 16. The cycle data are plotted on a logarithmic scale because of the range of variation. For this reason, the differences developed among the test variables appear compressed at high cycle levels.

Tests at 500°F

The data obtained for the tests at 500°F are presented in the bar graph of Fig. 17. Note again the semi-logarithmic scale.

Special Tests

Photographs of the worked surfaces of polished specimens

comprise Figs. 18, 19, 20 and 21. ~~Figs. 18, 19 and 21 are photographs of unetched surfaces. Fig. 20 contains photographs of areas etched lightly before testing.~~

The data on low temperature cooling are shown in the bar graph of Fig. 20. A linear scale for the cycles to failure was satisfactory in this case, because only one strain level was involved.

DISCUSSION OF THE RESULTS

Tests at Room Temperature

The factors studied in this series of tests were (1) steel composition, (2) prestraining, (3) welding, and (4) postheating after prestraining or welding. From an examination of Figs. 11 to 15, the following observations can be made:

The A-201 steel was consistently 20 to 25% higher in cycles to failure than the A-285 at all strain levels except the lowest, 0.15%, where the two steels behaved virtually alike. These differences were present in the as-rolled, in the prestrained, and in the welded tests.

Prestraining had no effect on tests at higher strain levels. At 0.15% strain, however, failure was delayed noticeably by prestraining. The direction of prestraining was not significant. The

work-hardening effect of prestraining raises the yield and tensile strengths, and it thereby possibly increases the fraction of the deformation which is elastic, at the same time reducing the fraction of plastic deformation occurring in each cycle. At a low strain level, this elastic fraction becomes appreciable and can be expected to delay failure. At high strain levels the elastic portion remains too small to be important.

Longitudinal welds reduced the cycles to failure as much as 50% at high strain levels. Only at 0.15% strain was there an increase in cycles obtained from welding. As will be shown later, the cracks resulting in failure originated in the weld metal, indicating that the fused metal possessed lower ductility than the base plate. At the low strain level, the high yield strength of the weld acts to delay failure just as in the case of prestrained materials.

As shown in Fig. 16, the specimens containing transverse weld-beads were little affected by welding. Failure occurred in either weld metal or base metal at random. The higher yield strength of the weld metal can be expected to force deformation into the adjacent base metal.

Postheating produced some puzzling effects. The treatment at 500°F had little effect on prestrained material, but it provided unexpected improvement in most of the welded samples. Treatment at 1150°F was especially beneficial to the welded specimens tested at higher strain levels. Treatment of the prestrained material at

1150°F was mostly without effect, even at low strain levels where the loss in yield strength might be expected to lower the cycles to failure.

Tests at 500°F

The tests at 500°F are distinguished only by a general tendency to be higher in cycles to failure than the tests at room temperature, especially at low test strain levels. There is no tendency for strain-aging to lower the performance, despite the fact that 500°F is in the blue-brittle range.

Origin of Cracking

Microscopic examination of the polished surfaces of specimens at frequent intervals during testing revealed that the first phenomenon visible was the formation of numerous slipbands at roughly 45° to the direction of bending. As shown in Fig. 18, these bands were more numerous and marked in the weld metal than in the base plate. As testing continued some of the slipbands in the weld metal broadened and lengthened progressively until they became small cracks. This action is shown by the series of photographs in Fig. 19, in which an arrow indicates the growing crack. Note the forked ends of the crack which seem to maintain the 45° orientation of the slipbands. As the crack grows larger it can be seen to open and close, or "breathe", during cycling.

The tendency of the weld metal crack is to halt momentarily at the fusion line before propagating into the base plate. In some cases, the cracking proceeds by a merging to concurrently formed smaller cracks. Frequently there are numerous small cracks to either side of the main crack which are arrested when the load on them is relieved by the "breathing" of the large crack.

This brief study has shown that cracks apparently originate from slip-bands, and in the welded specimens, tend to initiate in the weld metal rather than in the base plate.

Effects of Low Temperature Cooling Rates

The work of Bland and of Flanigan has indicated that the rate of cooling from 400°F to room temperature after welding with high-hydrogen electrodes may influence the final properties of the weld. If the cooling rate is rapid, retained hydrogen may cause microfissures in the weld metal, the notch effect of which will lower the mechanical properties of the metal.

In Fig. 20, the results of a short study on this subject are summarized. Preheating or immediate postheating were used to retard the low temperature cooling. The level of the cycles to failure is raised about 20% by preheating and 50% by postheating. The specimens welded with E6016 show some 100% improvement over the E6020 welds. From this it appears that there is a noteworthy effect of the low temperature cooling rate when welding is performed with high-hydrogen electrodes.

SUMMARY

The results of the investigation can be summarized as follows:

1. A specimen and machine design has been developed to test the resistance of steel to repeated loads in the plastic range.
2. To produce failure in the range of 1000-100,000 cycles, such as may be experienced in pressure vessels, plastic strains between the yield strain and 1% were required.
3. The A-201 steel performed some 20% better than the heat of A-285 steel.
4. Cold work affected the cycles to failure only at low test strain levels, where it raised the level of resistance.
5. At all test strain levels over 0.15% longitudinal weld-beads lowered resistance to repeated loading.
6. Initial cracking originates from slipbands that form at 45° to the axis of bending. In welded specimens with longitudinal beads, cracking initiated in the weld metal. In transverse bead-welded specimens cracking occurred indiscriminately in weld or base metal.
7. Postheating at 1150°F did not improve cold worked (10% prestrain) specimens, but raised the cycles to failure of welded samples, especially at higher test strain levels.

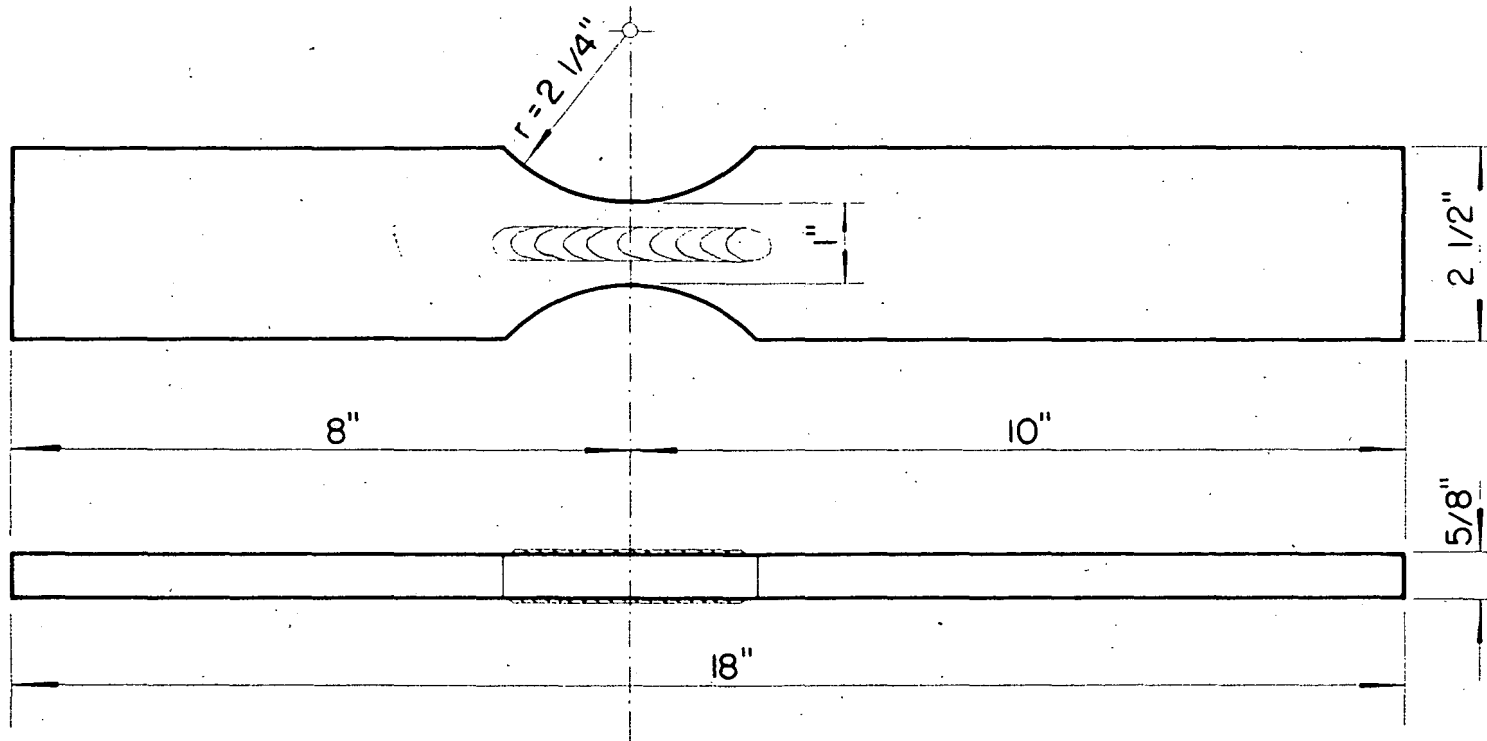
8. Reducing the low temperature cooling rate after welding with high-hydrogen electrodes was shown to be beneficial. Welds with low hydrogen electrodes outperformed those of high-hydrogen electrodes by about 100%.

ACKNOWLEDGMENTS

This work was sponsored by the Pressure Vessel Research Committee of the Welding Research Council, which is directed by William Spraragen. P. R. Cassidy is Chairman of the Pressure Vessel Research Committee and Boniface E. Rossi is Executive Secretary. F. L. Plummer is Chairman of the Fabrication Division of the Pressure Vessel Research Committee, which guided the project staff in this work.

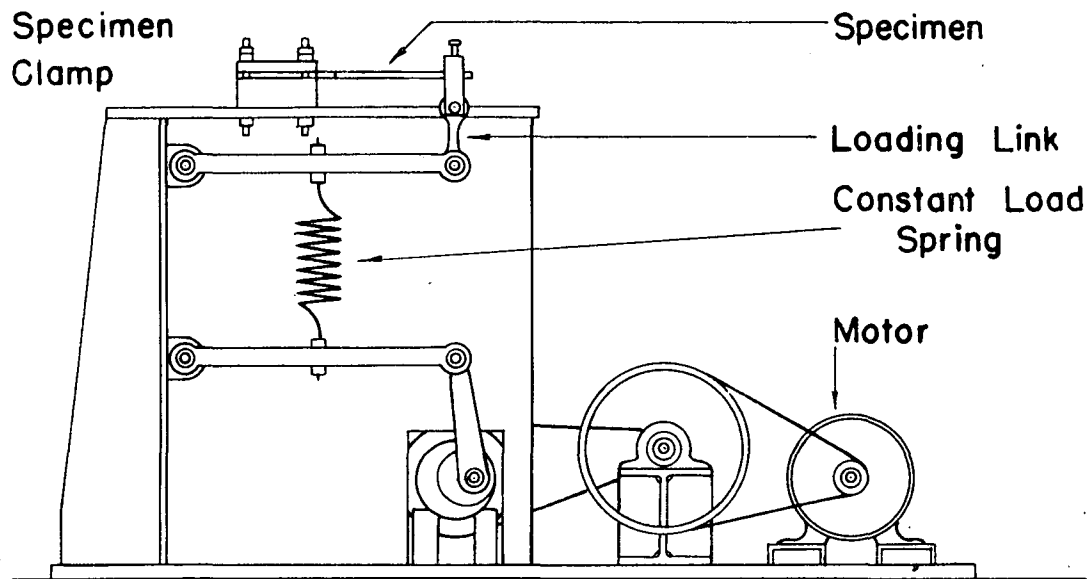
The project was carried on jointly by the Fritz Engineering Laboratory of the Civil Engineering Department, and the Metallurgy Department of Lehigh University.

The execution of work was made possible by the cooperation of Kenneth R. Harpel, laboratory foreman and the entire laboratory staff.

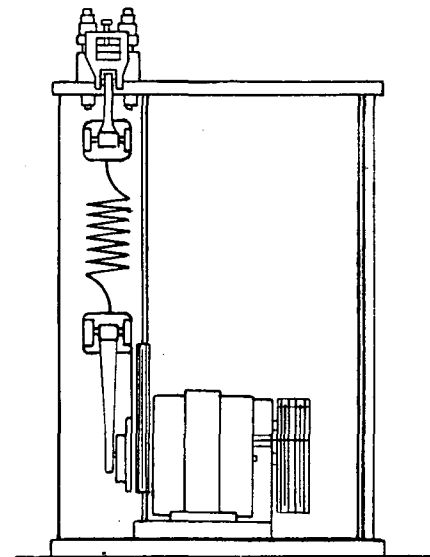


Note : Weld - beads were milled flush with the specimen surface before testing.

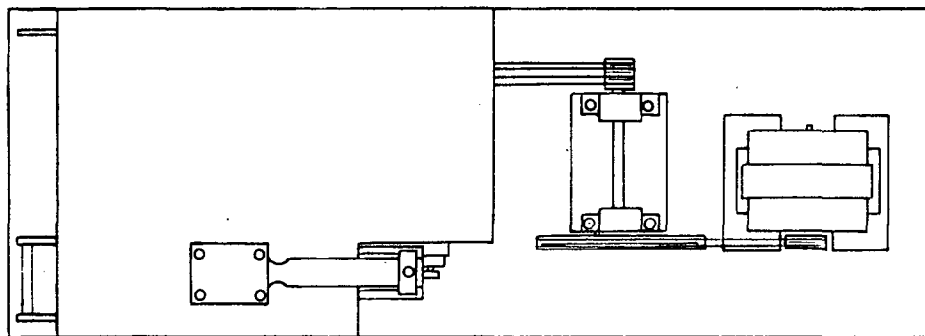
FIG. I. REPEATED LOAD TEST SPECIMEN.



Side view



End view



Top view

Fabrication Division
of the Pressure Vessel Research Committee
of the Welding Research Council

Fatigue Machine

Scale 1:20 FIG 2

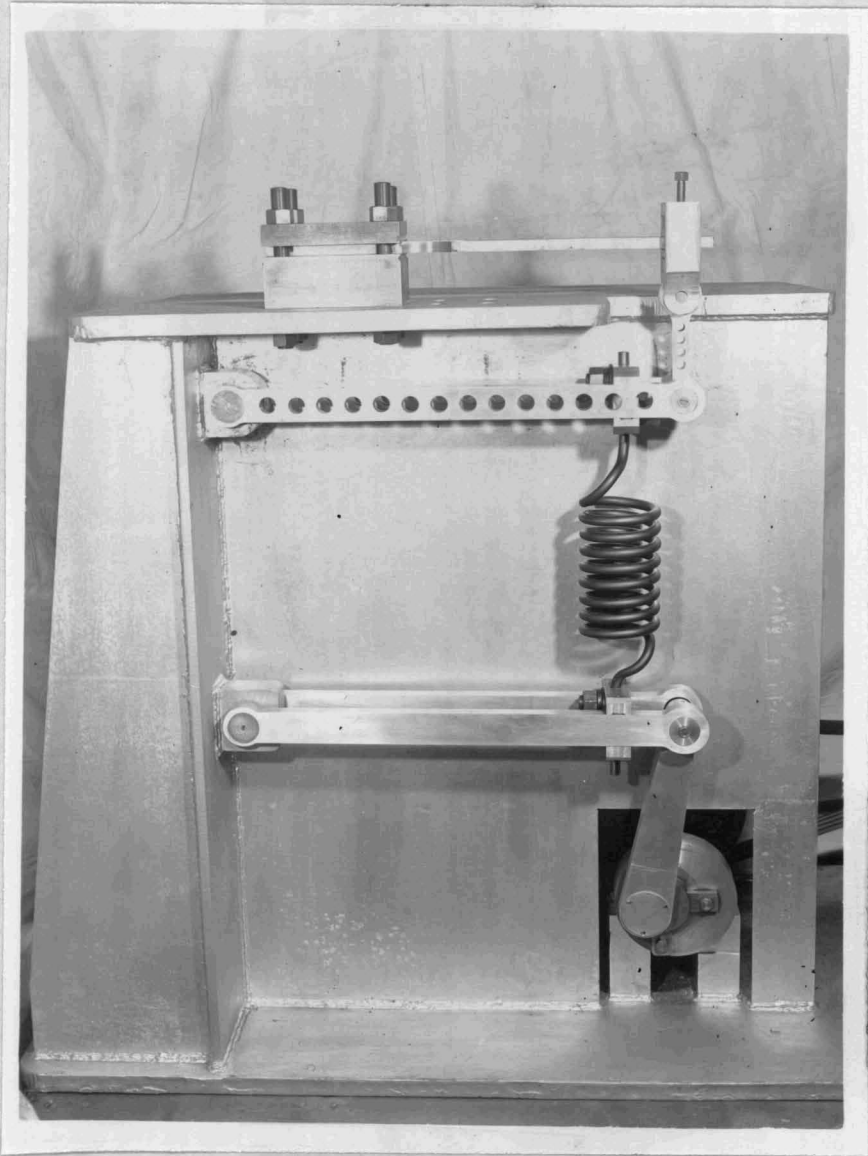


Fig. 3. View of repeated load machine showing constant-load spring link in position.

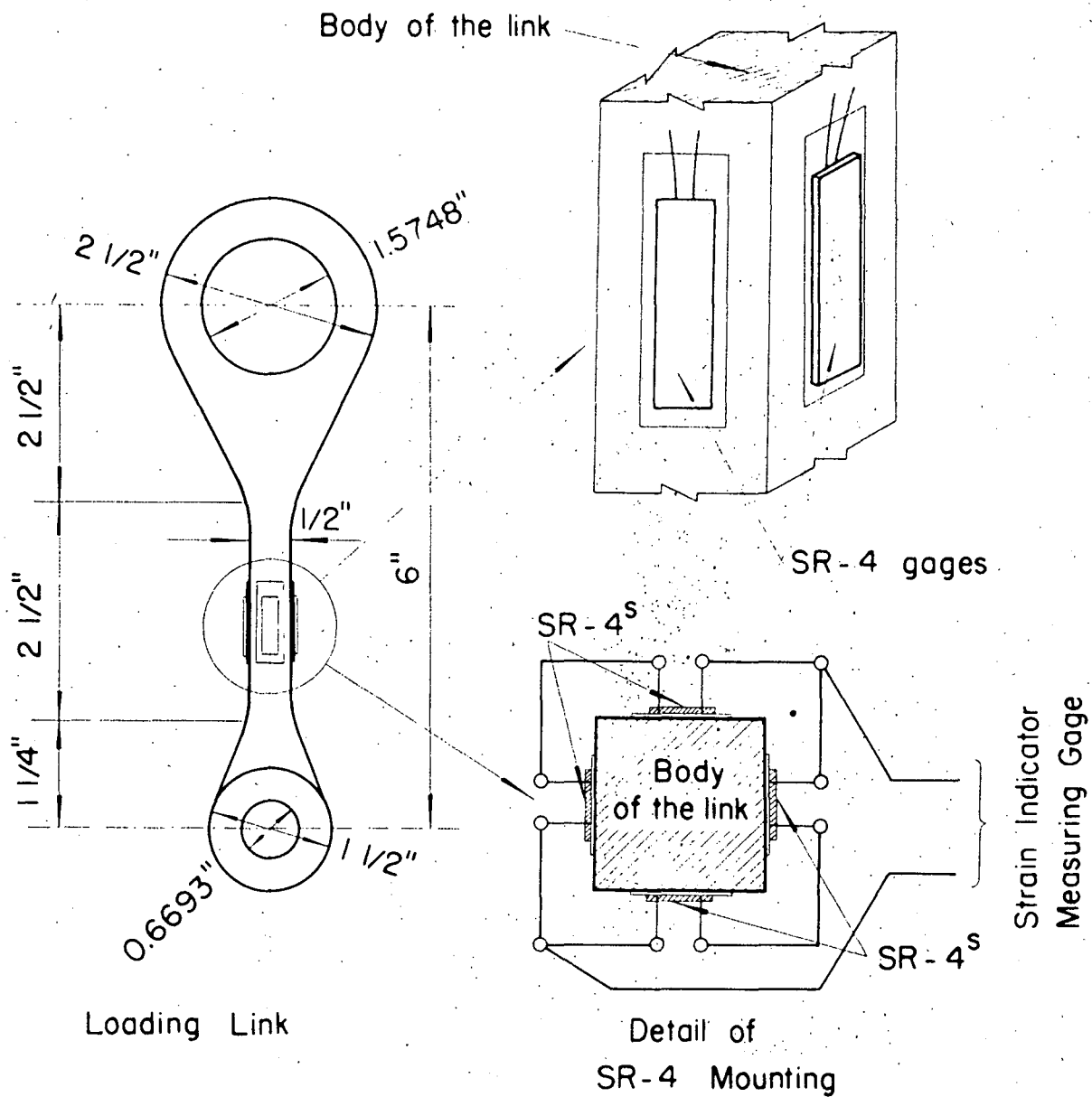


FIG. 5. SCHEMATIC CONNECTION OF SR-4 GAGES ON CALIBRATION LINK

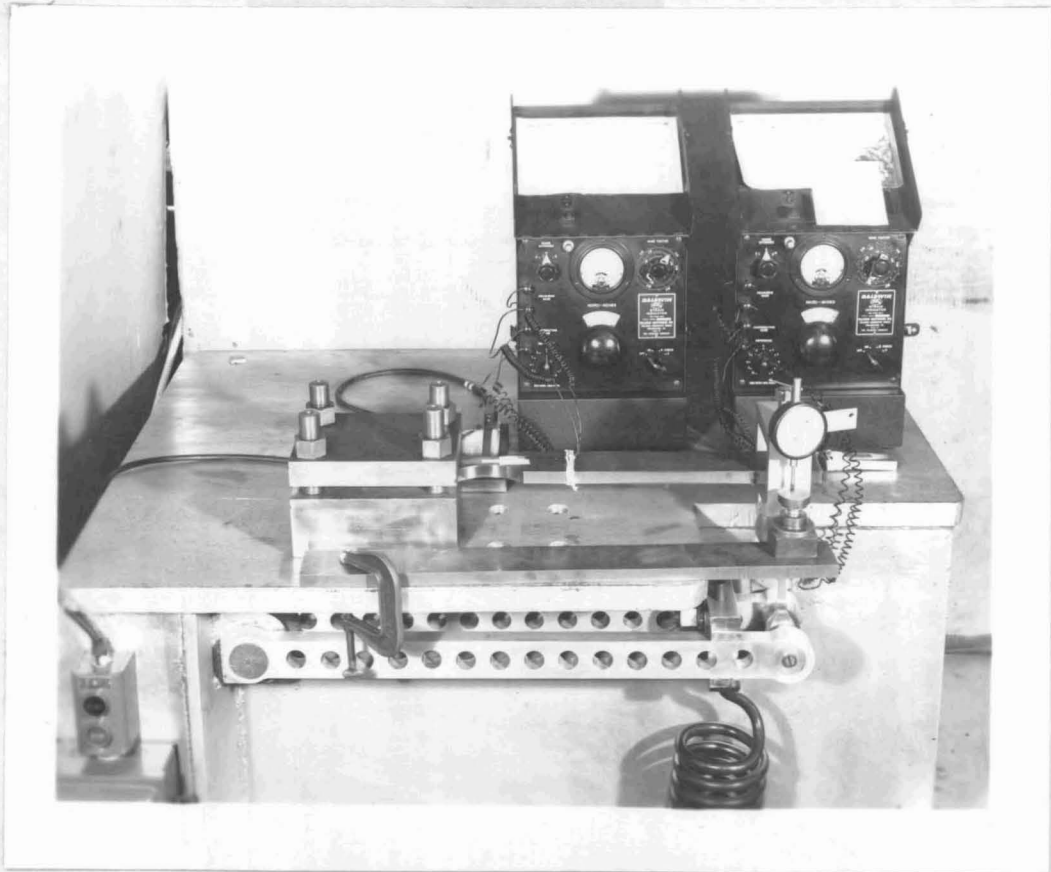


Fig. 6. Arrangement of SR-4 strain gages on the specimen and loading link, and the deflection dial gage for calibration of the machine.

center under plot

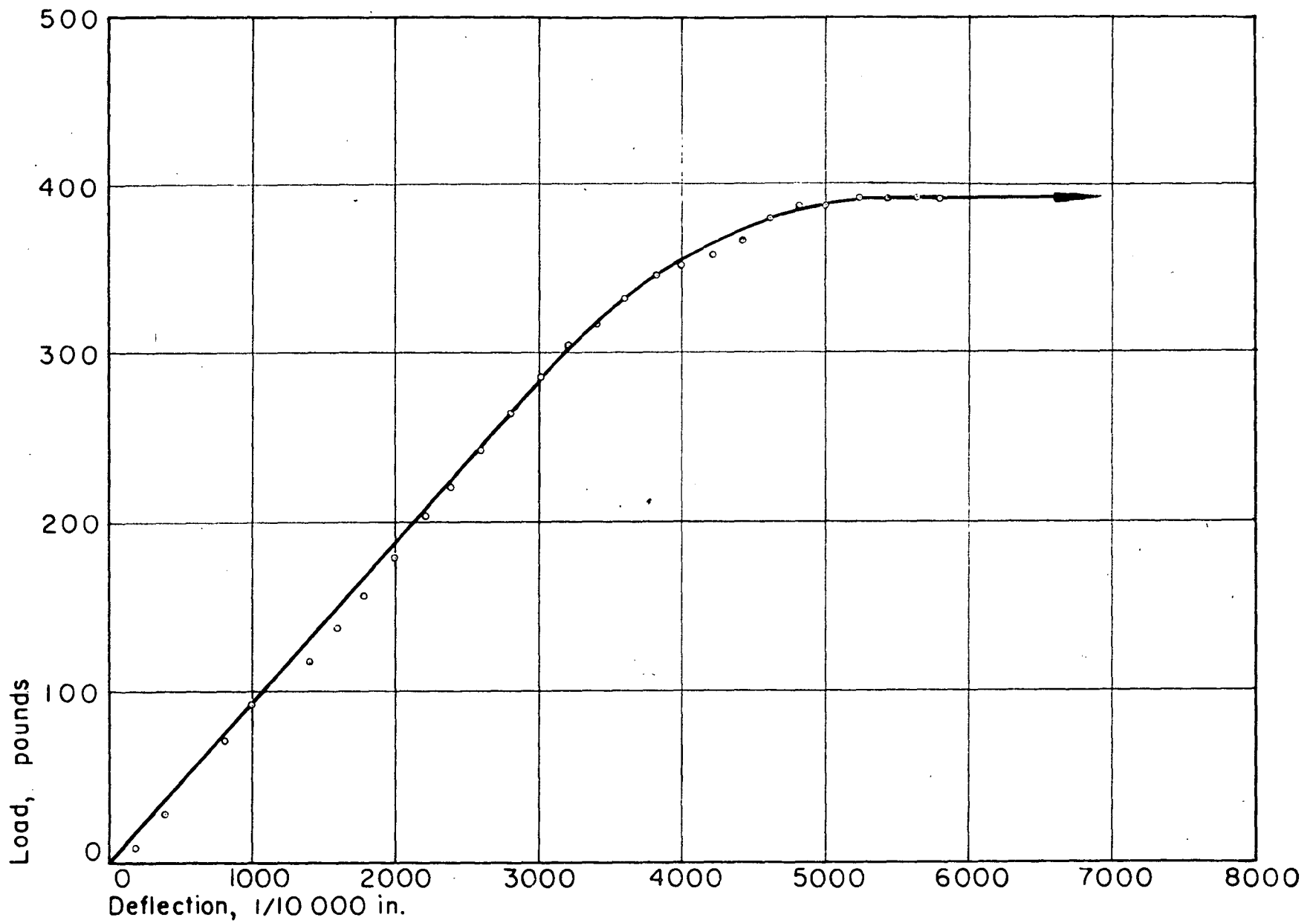


FIG. 7. RELATION OF THE DEFLECTION OF THE REPEATED LOAD SPECIMEN TO THE LOAD APPLIED

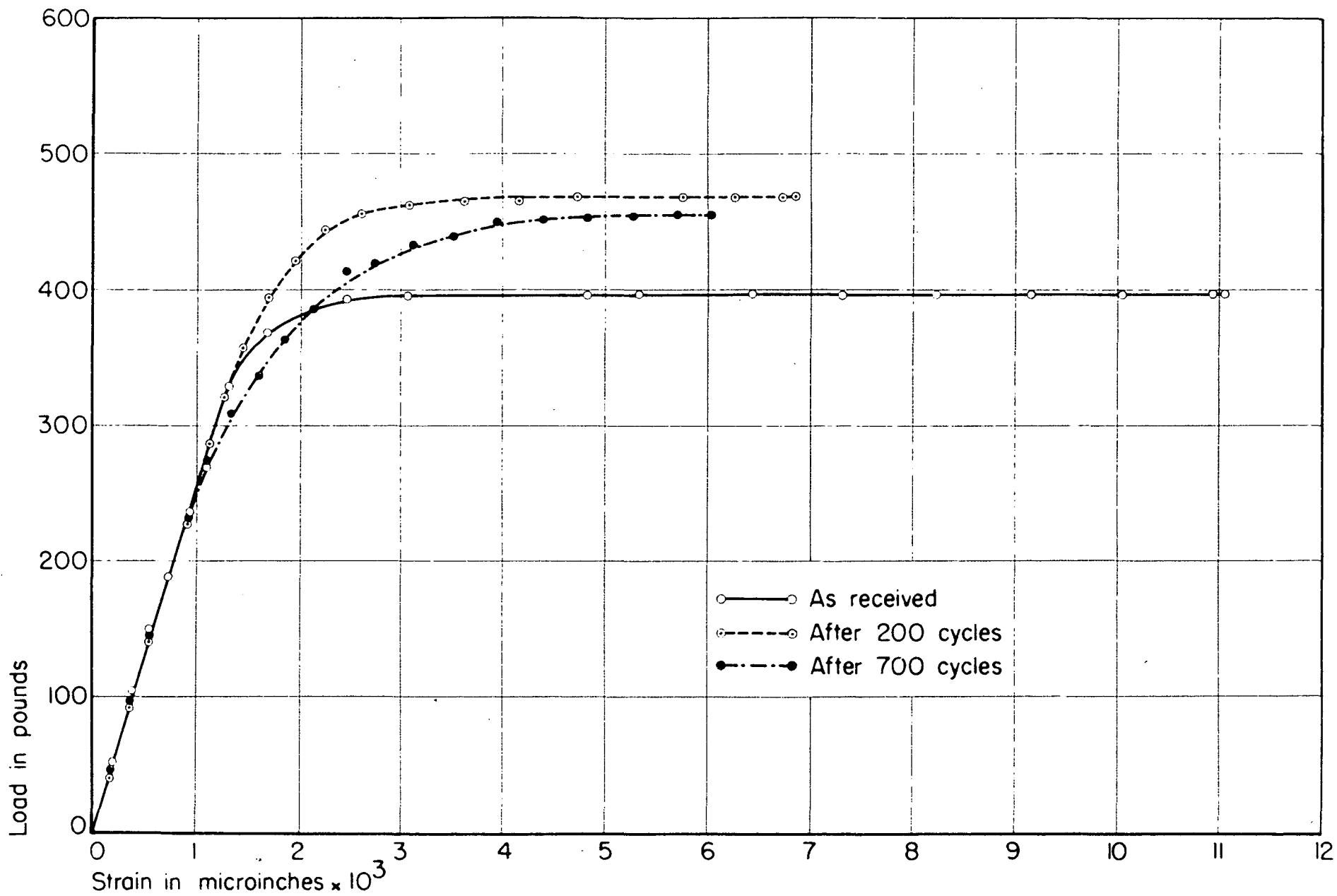


FIG. 8. THE RELATION OF LOAD TO THE STRAIN AT THE TEST SECTION OF THE REPEATED LOAD SPECIMEN

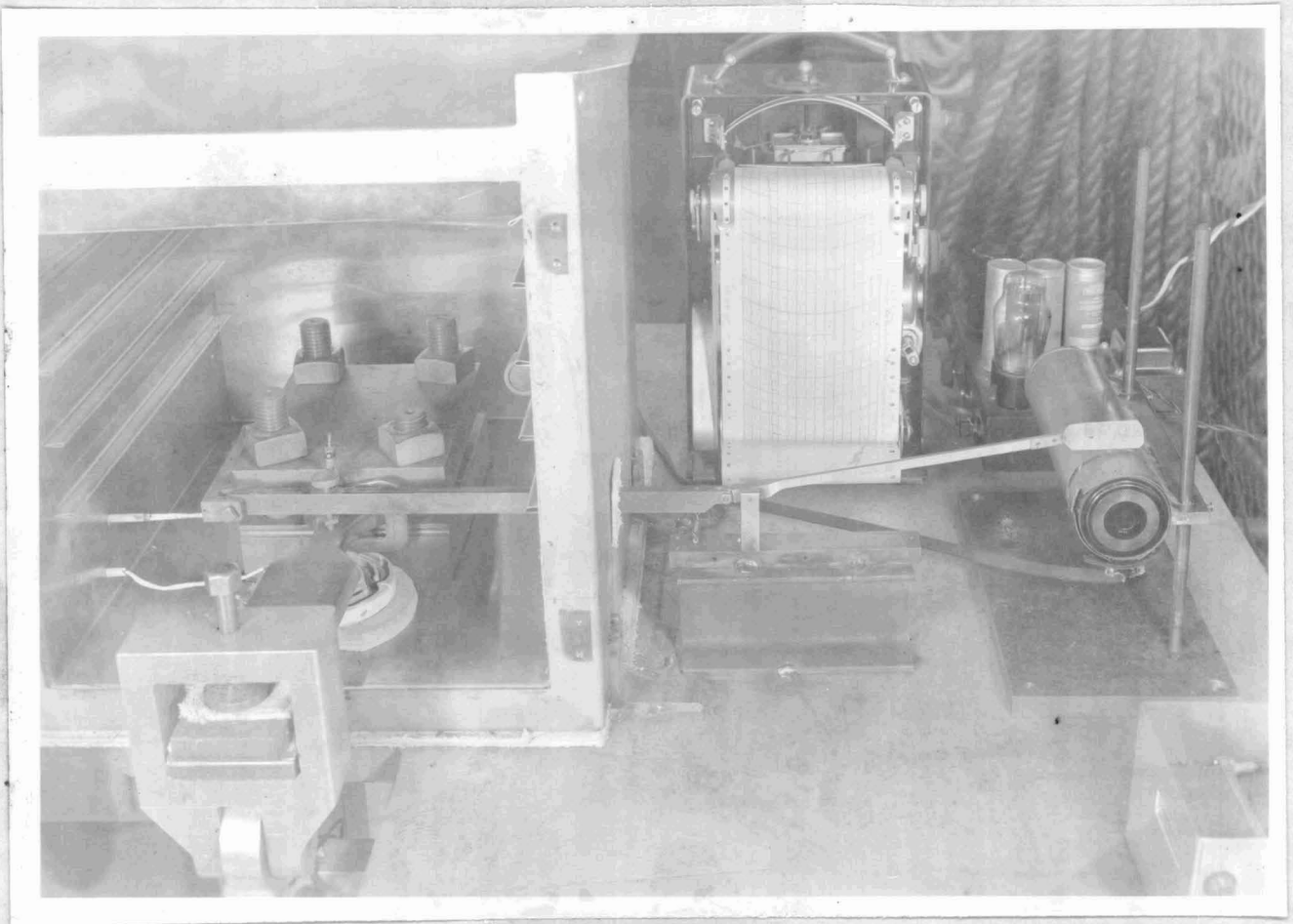
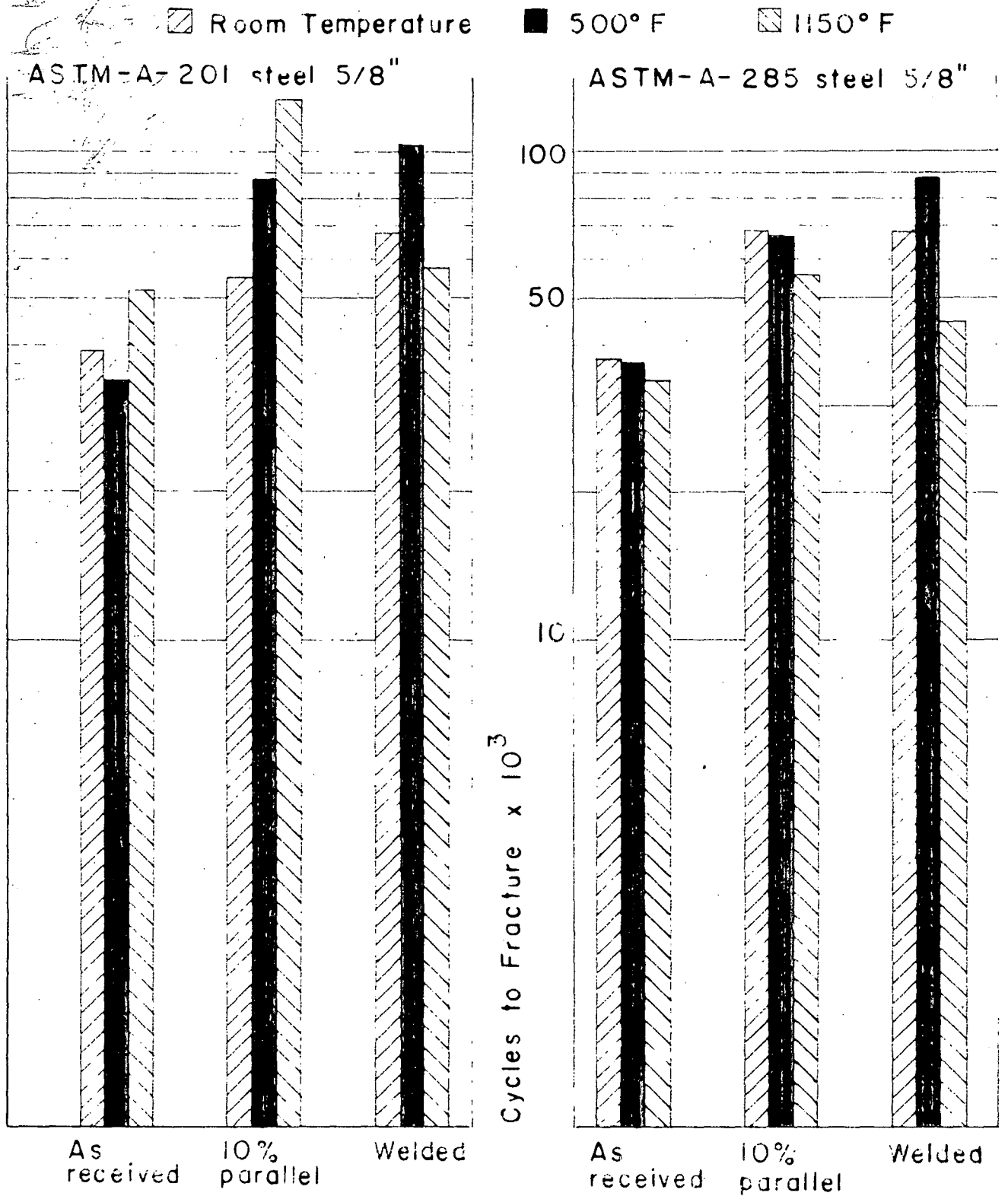


Fig. 9. Apparatus for detecting the endpoint of the repeated load tests.



Room Temperature Repeated Load Tests Above Yield Strain
 Strain Level: 0.15%

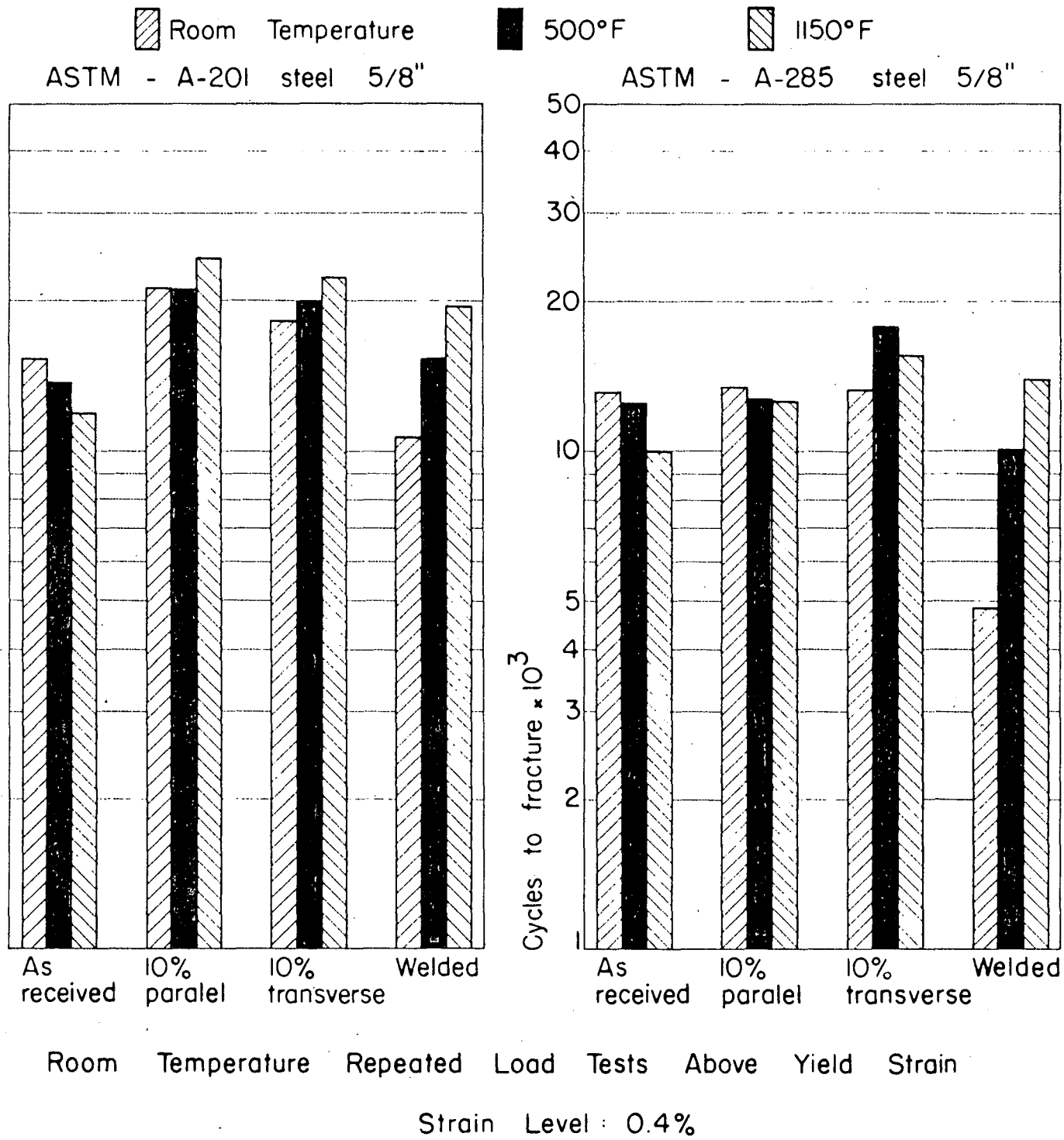
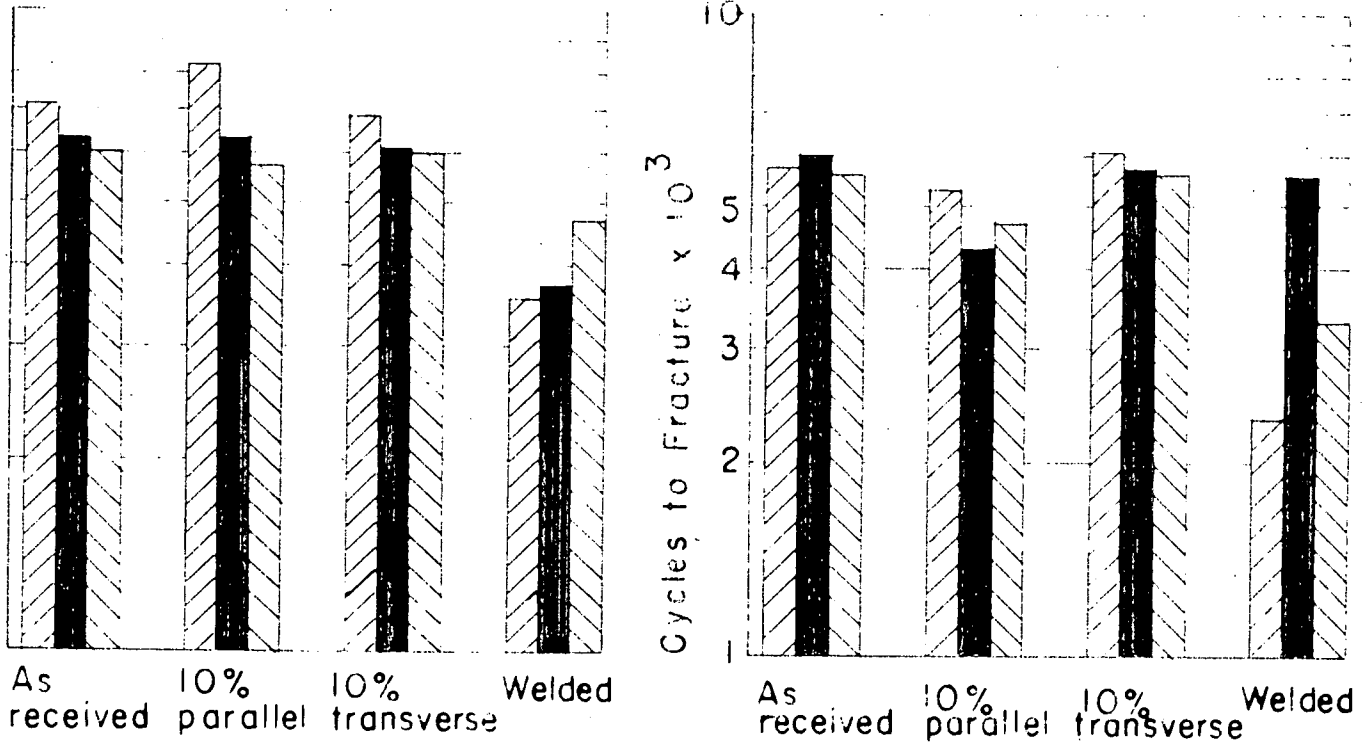


FIG.12.

Room Temperature
 500°F
 1150°F

ASTM-A-201 steel 5/8"

ASTM-A-285 steel 5/8"

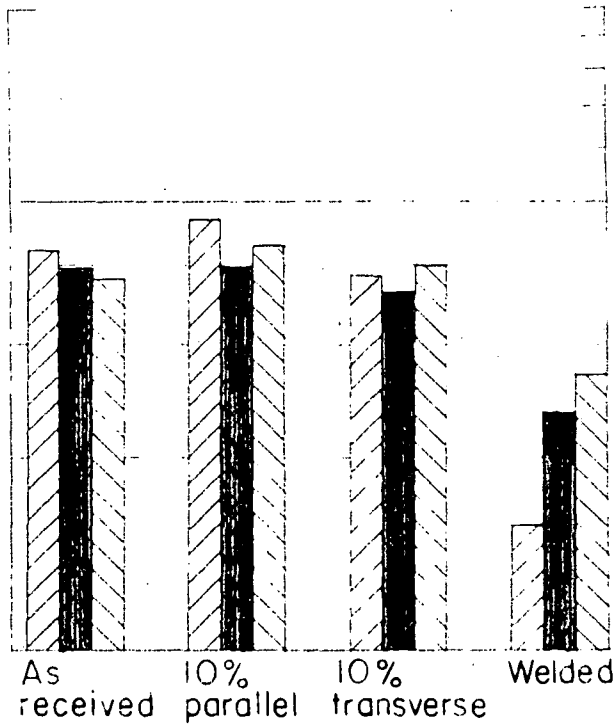


Room Temperature Repeated Load Tests Above Yield Strain
 Strain Level: 0.70%

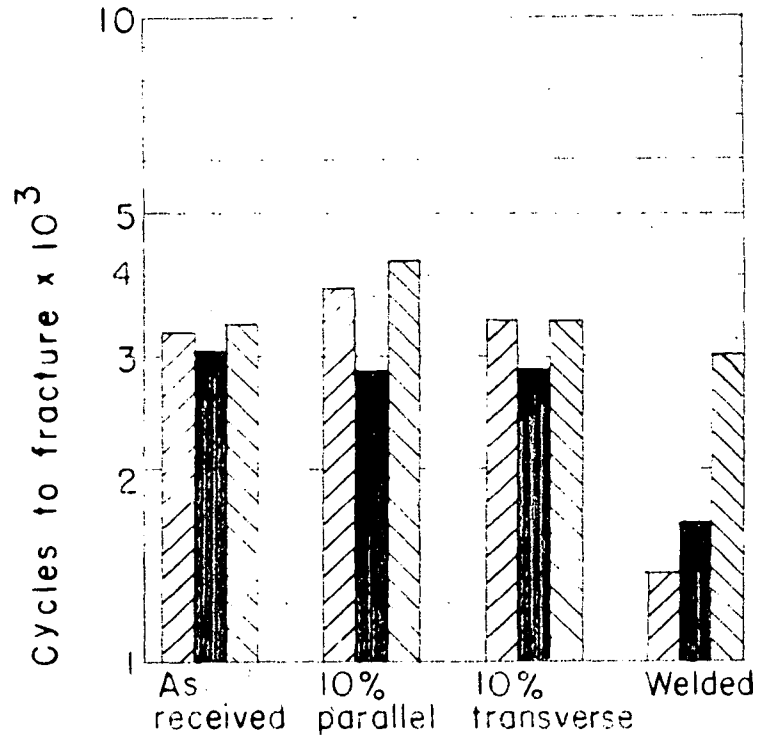
FIG.13.

Room Temperature
 500° F
 1150° F

ASTM-A-201 steel 5/8"



ASTM-A-285 steel 5/8"



Room Temperature Repeated Load Tests Above Yield Strain
Strain Level: 1.0%

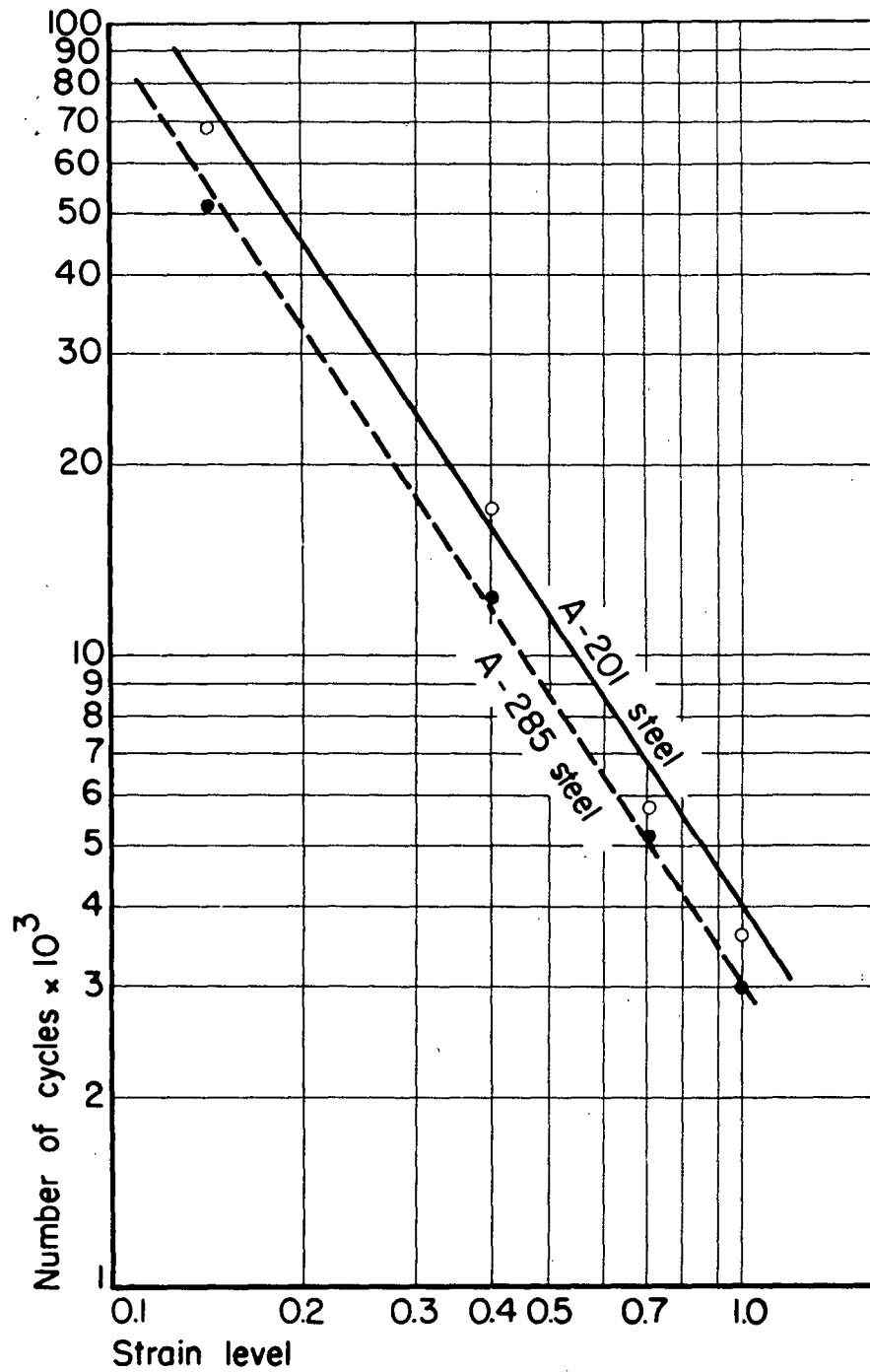
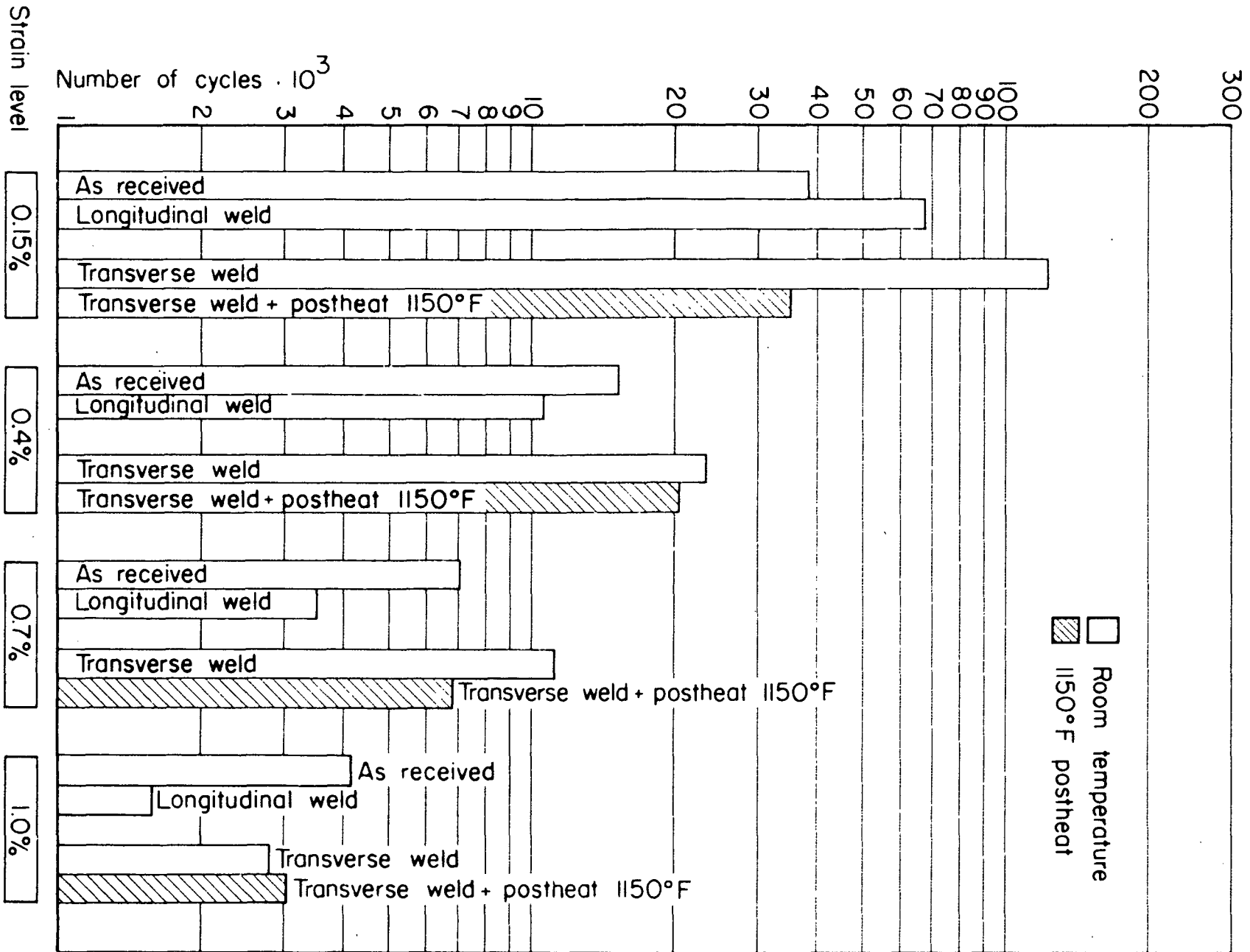


FIG. 15. GENERAL EFFECT OF THE STRAIN LEVEL ON THE NUMBER OF CYCLES TO FAILURE UNDER REPEATED LOAD. (AVERAGES OF ALL CONDITIONS FROM FIGURES 11-14.)

FIG. 16. COMPARISON OF LONGITUDINAL AND TRANSVERSE WELD BEADS



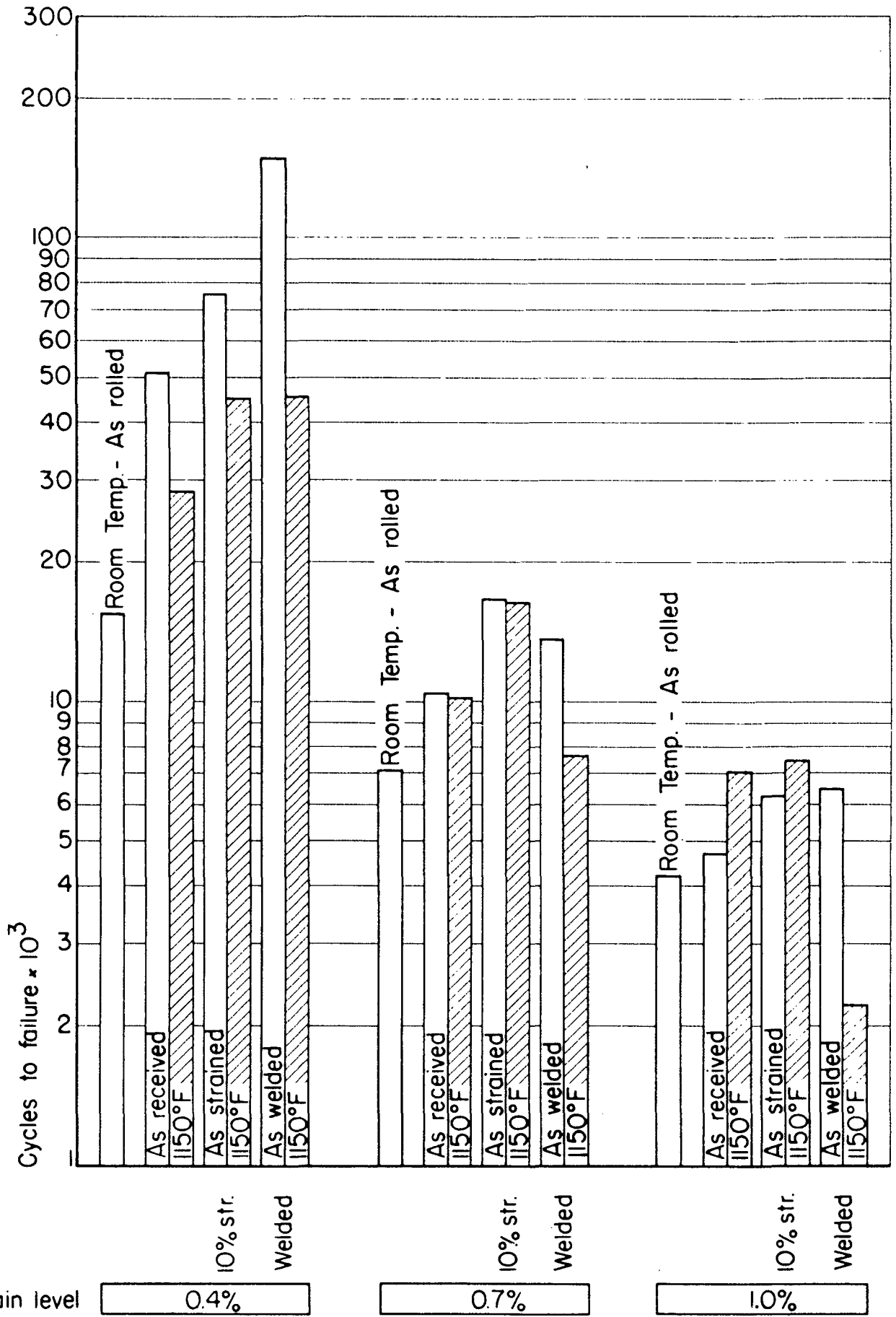


FIG. 17. REPEATED LOAD TESTS CONDUCTED AT 500°F

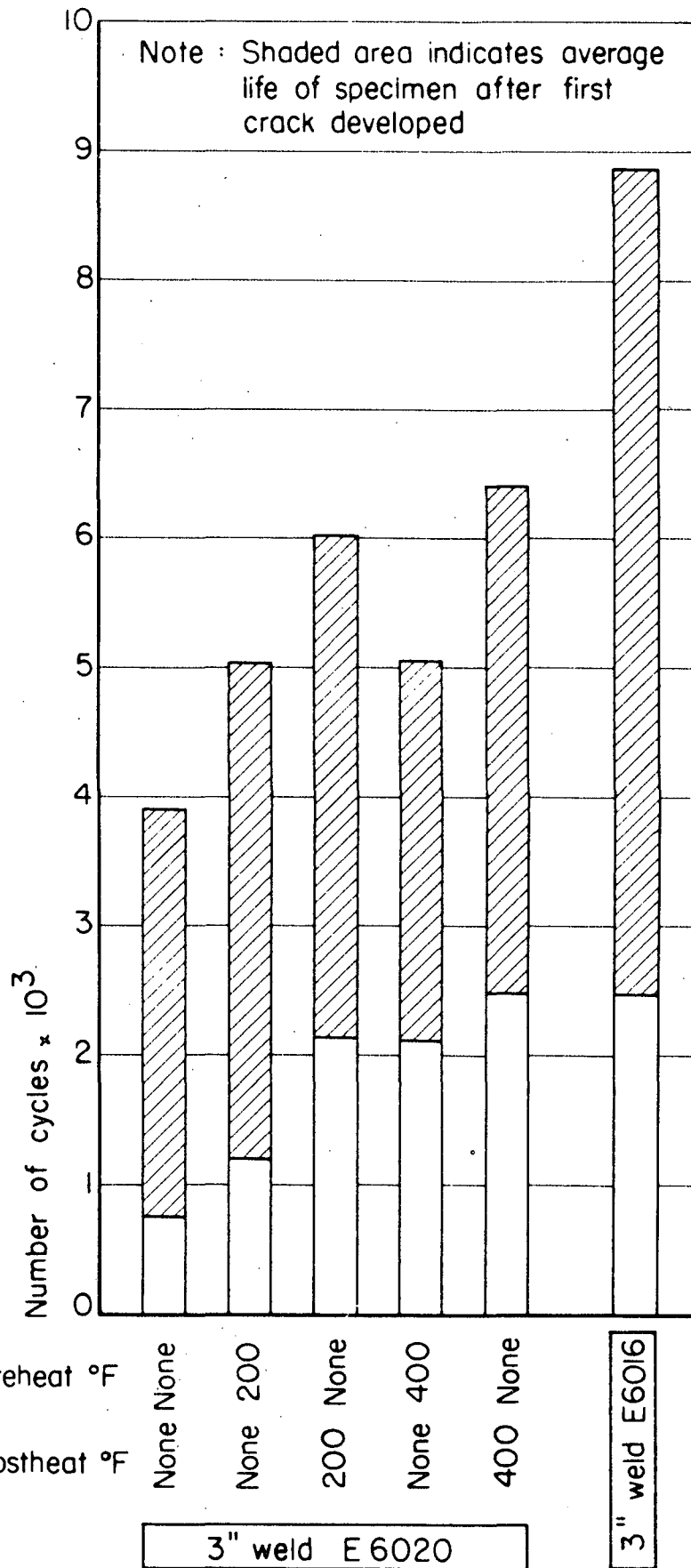


FIG. 20 EFFECT OF LOW TEMPERATURE COOLING RATE ON REPEATED LOAD RESISTANCE