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PRESSURE VESSEL RESEARCH COMMITTEE

FABRICATION DIVISION PROJECT REPORT

Factors Affecting Resistance of Pressure Vessel Steels to Overloading

by J. H. Gross, S. Tsang, and R. D. Stout

Report # 208.13

FACTORS AFFECTING RESISTANCE OF PRESSURE VESSEL STEELS TO OVERLOADING

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INTRODUCTION

In a previous report(1) the design of a specimen and a machine for testing the resistance of steels to repeated loads in the plastic range was described. With this testing method a survey was made of the effects of fabrication operations such as cold work, welding, and heat treatment on the resistance of two pressure vessel steels to repeated loading. Some phases for investigation suggested by the initial survey are reported here.

Relatively limited information is available on the behavior of steels under repeated overloading. Generally results of fatigue tests involving nominal stresses below the elastic limit cannot be extrapolated to the plastic range. Thus the effects of both geometrical and metallurgical variables in this field require further investigation. The following phases were studied:

a. direction of loading: zero to tension vs. reversed bending.

b. effect of surface stress raisers.

c. multibead welds with preheating or postheating.

d. effect of strength level.

An important phase of the investigation was the development of a specimen which would provide essentially 2:1 biaxial loading. Such a specimen may permit tests which can simulate conditions in a pressure vessel and thus allow the effects of fabrication operations to be evaluated without the use of expensive model vessels.

THE EXPERIMENTAL PROGRAM

Testing Method.

The testing machine is shown in Figure 1. The specimen was loaded as a cantilever beam, with a cam supplying a constant amount of deflection throughout the test. Usually four levels of strain were imposed (measured at the first cycle), equivalent to 0.15%, 0.4%, 0.7%, and 1% at the outer fibres of the test section. Loading was in equal reversed bending, except for the zero to tension tests. Triplicate specimens were tested at each level.

The original specimen design is shown in Figure 2. This specimen had been used for previous tests and was used for the zero to tension loading series to be described later. For subsequent tests a wider specimen providing 2:1 biaxial loading was developed and substituted for the original design.

The Steels.

The majority of tests was conducted on 5/8 inch thick plate of the pedigreed heat of A-201 steel employed in many previous tests for PVRC. A few tests were performed on a 5/8 inch plate of A-212 on hand in the laboratory. The analyses of the steels were as follows:

	C	Mn	P	S	Si	Cr	Ni	Cu
A-201	0.15	0.53	0.020	0.022	0.20	0.04	0.05	0.07
A-212	0.26	0.89	0.021	0.031	0.22	——	——	——

Tensile Properties

(.505" diam.; 2" gauge length)

	Lower Yield psi	Tensile Strength psi	Elongation %	Reduction of Area %
A-201	38,000	62,000	41	63
A-212	46,000	78,800	32.5	53.6

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

Zero to Tension Loading.

In previous tests, the loading of the specimen had been carried out in balanced tension and compression, obtained by bending the specimen equally in both directions. Since there are many instances in service where loading is in one direction only, a series of tests was undertaken to study the effects of zero to tension loading.

The A-201 5/8" plate was tested in the following conditions:

1. as received
2. 10% prestrain
3. bead welded on the tension side (175 amps, 10 in/min, E6020)
4. bead welded on the compression side (175 amps, 10 in/min, E6020)

Strain levels were chosen for these tests such that the total deformation per cycle in zero to tension was the same as the alternating load tests. This meant that the specimens were deflected twice as much from rest but in one direction only as compared to the alternating tests.

The results of the tests are shown in Figure 3. It will be noted that the performance of tests in zero to tension was very similar to alternating load tests for the same total strain per cycle. This would indicate that in the plastic range, the amount of strain imposed per cycle is much more important than its direction. Note also that the welded specimens with the bead on the compression side were essentially no more resistant to cycling than those welded on the tension side.

These results are not unexpected. When a specimen is bent appreciably beyond the yield strain in one direction, it cannot spring back to its original position but must be forced back by undergoing additional plastic flow. After the initial cycle, the stress and strain distribution at the outer fibres will be the same during cycling whether it is deflected one inch in a single direction or one-half inch in both directions. Moreover, the compression side will have no advantage over the tension side in resisting failure.

Specimen for Biaxial Loading.

It was suggested to the Lehigh staff by the Fabrication Division that attempts be made to test specimens of greater width than the one-inch throat previously used in order to introduce biaxial loading into the specimens. This was with the intent to parallel tests planned at the University of Illinois where a more elaborate testing procedure involving hydraulic-loaded diaphrams is to be utilized. It was suggested that a specimen having a width five times its thickness would develop essentially 2:1 biaxial strains.

When a narrow rectangular section of steel is bent into the plastic range, the section becomes roughly trapezoidal. At the outer fibres, the lateral movement is roughly 0.5 that of the longitudinal strain in obedience to Poisson's ratio. As the width is increased, a constraint to this lateral movement is developed and lateral stresses are created. A wide plate is capable of only negligible lateral flow and therefore the outer fibres will be placed under biaxial tension in which the effective tensile lateral strain bears the ratio of 1:2 to the longitudinal strain.

Since the A-201 plate is 5/8 inches thick, a specimen width of 3 inches was adopted for the initial tests for a 5:1 width to thickness ratio. Originally a side throat was introduced to control the locus of failure, but this design had a fatal defect. Because of stress concentration at the throat radius, the cracks originated at the corners of the section instead of the midsection where the biaxial loading should exist. Even with a large corner radius, this condition could not be eliminated. Therefore the throat section was abandoned.

After several other designs had been tried and discarded, the test specimen illustrated in Figure 4 was adopted. This specimen has a 2-inch radius surface notch cut 1/8 inch deep to localize the failure. The initial cracks formed consistently near the center of the test section rather than at the edges.

In order to obtain some measure of the biaxiality present in the specimen, SR-4 strain gages were affixed to the midsection in both lateral and longitudinal directions. Readings were obtained by loading the specimen slowly to maximum deflection. In Figure 5 the lateral strain is plotted as a function of the longitudinal strain. Ideally, the measured lateral strain should be zero. Actually it was about 2% that of the longitudinal strain and about 1% the amount that it should be if there were free lateral movement. Instead of a 2:1 ratio, the biaxiality was in the order of 2.1 to 1 at the maximum test strain, 1%. A similar calibration was made on a 1-inch wide specimen. The curve in Figure 5 indicates that the biaxiality in the narrow specimen was about 5.4 to 1.

Since the wide specimen more nearly approximates the loading encountered in pressure vessels, and in addition is cheaper to prepare and is free of corner cracking, it was decided to adopt it for all subsequent tests. In order to compare the characteristics of the new design with the original throated specimen, a series of tests were run (1) as-rolled plate, (2) plate prestrained 10% in tension, and (3) plate with a longitudinal bead-on-plate at 175 amperes and 6 inches per minute. As Figure 6 shows, the effects of prestraining and welding were consistent in the two specimen designs. However, the effect of welding is somewhat less marked in the wide specimen. This may be due to the reduced fraction of the cross section represented by the weld in the wider specimen.

Effect of Notches.

The influence of surface notches and discontinuities on the fatigue endurance limit is well known. The question may be raised whether notches will reduce the resistance to repeated loading in the plastic range to the same extent that they lower the endurance limit.

The effect of a notch was demonstrated by introducing a shallow transverse notch into the test section. A V-notch of 0.01 root radius was cut 0.010 inches deep at the midpoint of the 2-inch radius surface groove. In Figure 7 the performance of the notched and unnotched as-rolled A-201 steel is indicated. The influence of the relatively shallow notch was marked, resulting in a decrease of the cycles to failure of about 75% at all test strain levels.

It appears that the effect of a notch is as severe in repeated plastic loading as it is in elastic loading.

Tests on Multipass Welds.

The use of a single bead for assessing the influence of welding in these tests is open to the objection that the proportion of weld metal is low and no reheating is involved such as occurs in the production of a welded joint.

A deep longitudinal groove was cut into a series of specimens and filled with four beads of 3/16" E6020 electrode at 175 amperes and 6 inches per minute travel speed. Three welding conditions were included:

a. welded at room temperature with specimens half-immersed in a water bath.

b. welded with 300°F. preheat and interpass temperature.

c. welded as in (a) with 1150°F. postheat.

The results of these tests are presented in Figure 8. The multipass welds lowered the cycles to failure to the same degree as did single-pass welds. There was, however, no improvement obtained from preheating, and postheating was most effective for the low strain levels. Postheating had previously been shown(1) to improve single pass beads at the high strain levels but not at the 0.15% strain level.

In order to check the soundness of the deposits, radiographs were taken of two specimens from each welding condition. The welds appeared sound except for an occasional slog stringer.

Since the surface groove removed most of the final bead, the reheating of the under passes by the final bead may mask the effect of preheating or postheating.

Effect of Strength Level.

In order to understand the alterations in resistance to repeated overloading that can be produced by fabrication operations, it will be necessary to evaluate the part played by the mechanical and metallurgical characteristics of the steel. For example, the strong effect of a notch has already been demonstrated. Cold forming raises the resistance to repeated overloads just over the yield strength, probably because of the work-hardening accompanying cold work. The relative importance of the strength and ductility of the steel may shift as the testing strain level is changed.

The effect of the tensile strength of the steel on its behavior under repeated loading is of special interest. The strength may be raised by alloying, by heat treatment, or by cold work. How the repeated loading properties in turn are affected may possibly depend on metallurgical changes accompanying these treatments. More information is needed on this subject.

As a beginning a series of specimens was prepared in which the strength level of the A-201 steel was varied by cold work and by heat treatment. A second steel, A-212, was added to introduce the effect of composition.

The conditions studied were as follows:

a. A-201 steel, as-rolled.

b. A-201 steel, annealed at 1600°F.

c. A-201 steel, water-quenched from 1600°F., tempered 1150°F.

d. A-201 steel, prestrained 10% parallel to rolling.

e. A-212 steel, as-rolled.

f. A-212 steel, oil-quenched from 1600°F.

All treatments were performed on the steel cut to specimen size.

The results of these tests are summarized in Figure 9. In this same figure the tensile properties for each condition are also included. It will be noticed that for a test strain level of 0.15%, the yield or tensile level correlates with the cycles to failure. At higher strains, the order becomes mixed. The A-212 steel was consistently better than the A-201 steel, but the 10% prestrained A-201 which attained a tensile equal to that of the as-rolled A-212 likewise matched it in repeated load resistance.

The role of tensile strength is shown more clearly in Figure 10, in which the cycles to failure are plotted against the tensile strength of each of the six series of specimens. At a test strain level of 0.15%, there is a noticeable and consistent effect of tensile strength on the cycles to failure. At 1% strain, the slope of the curve becomes more nearly level, but still indicates an advantage for higher tensile levels.

In Figure 11, ductility values in the form of percent elongations are plotted against cycles to failure. The steels of higher ductility how reduced repeated load resistance. This does not mean, of course, that ductility in the steel is unfavorable for repeated loading, but rather that a gain in tensile strength at the sacrifice of some ductility is beneficial. This is true even at the relatively large plastic strain level of 1%. Such results are rather unexpected.

CONCLUSIONS and SUMMARY

The resistance of steel to repeated loading in the plastic range appears to be about as sensitive to design factors and the tensile strength level as is the endurance limit. Further work is required to establish the influence of variables such as yield strength, ductility, and metallurgical factors of microstructure and composition. Such information may be useful in connection with the proposed use of higher tensile steels in pressure vessels.

The testing machine for this investigation has been operated to impose a constant amplitude of deflection on the specimen. This means that a nominally constant amount of plastic strain was induced in the specimen during the test as opposed to the constant load generally employed in fatigue tests. There are advantages and disadvantages to both constant deflection and constant loading methods for testing in the plastic range.

In a pressure vessel the critical regions so far as potential failure is concerned are the changes in section, openings, and the unintentional notches introduced during forming and welding. Under loads which will cause only elastic strains in the body of the vessel, these critical regions, because of their stress-raising nature, may experience plastic flow. During loading and unloading the elastic movement of the vessel can force the local zones containing stress-raisers to flow plastically in alternate tension and compression. Thus there is just as much reason to select a testing method which uses a fixed amplitude of strain as to use a constant amplitude of load.

In future tests, particularly for studies involving loads just over the yield strength, both methods of testing will be included.

<u>Summary</u>.

1. In repeated overloading, the total amount of strain imposed per cycle appeared to have about the same effect whether it was applied in balanced reversed bending or in one direction only.

2. A specimen having a width to thickness ratio of 5 to 1 was found to be suitable for producing essentially 2 to 1 biaxial loading.

3. Multibead welds were found to lower the cycles to failure to about the same extent as single-bead welds.

4. The introduction of a relatively shallow notch lowered the resistance to repeated overloading 75% at all levels of strain.

5. The tensile strength as varied by cold work, heat treatment, or steel composition controlled the cycles to failure at all strain levels. At low strains the cycles rose markedly with tensile strength, while at high strains the increase was less marked. Since high tensile strengths resulted in a loss in ductility, the improvement at 1% test strain is rather unexpected.

ACKNOWLEDGEMENTS

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

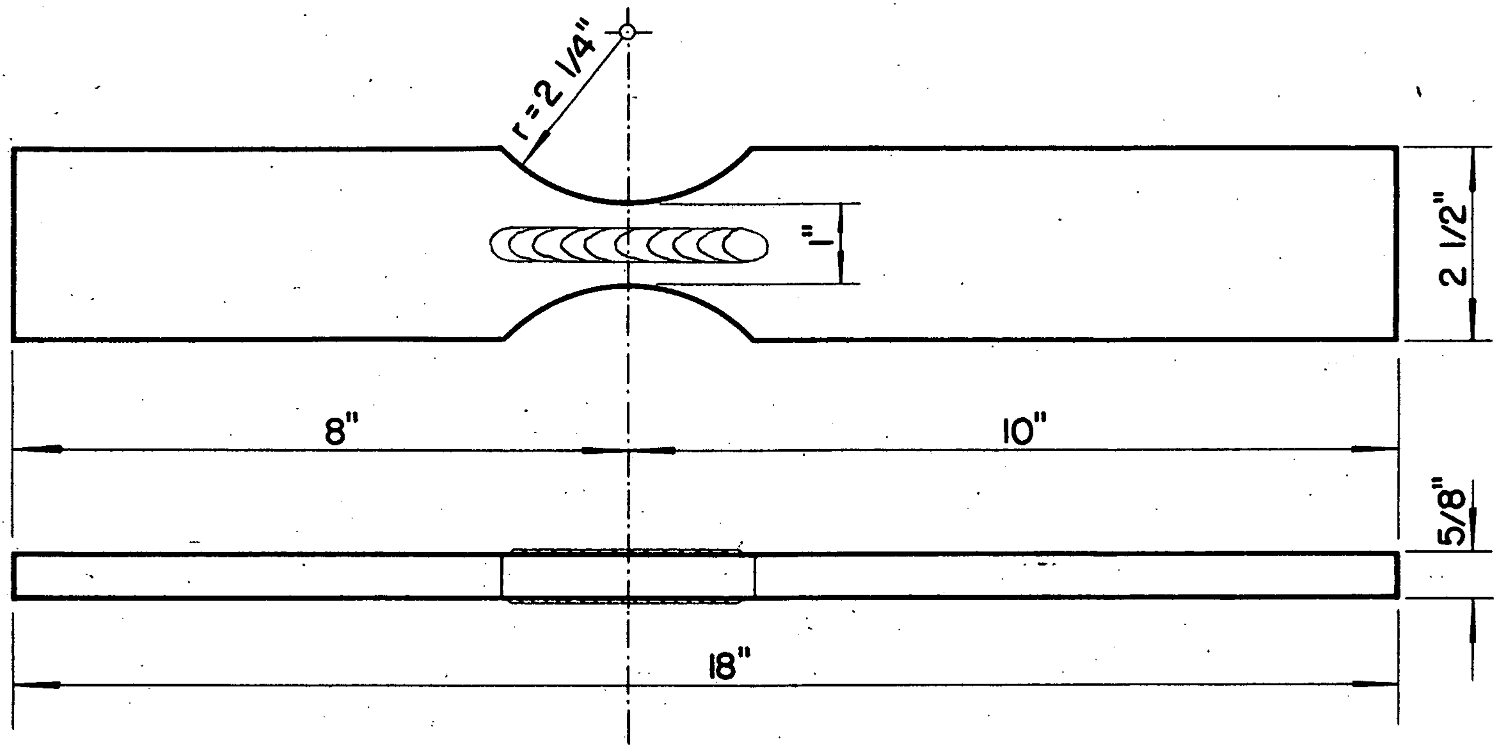
The execution of work was made possible by the cooperation of Kenneth R. Harpel, laboratory foreman and the entire laboratory staff.

REFERENCE

Repeated Load Tests on Welded and Prestrained Steels by S. S. Tor, J. M. Ruzek, and R. D. Stout Welding Journal Research Supplement Vol. 17, No. 5, pp. 238-246 (1952).

FIGURE 1

VIEW OF REPEATED LOAD TESTING MACHINE



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

FIG. 2 REPEATED LOAD TEST SPECIMEN. (THROATED)

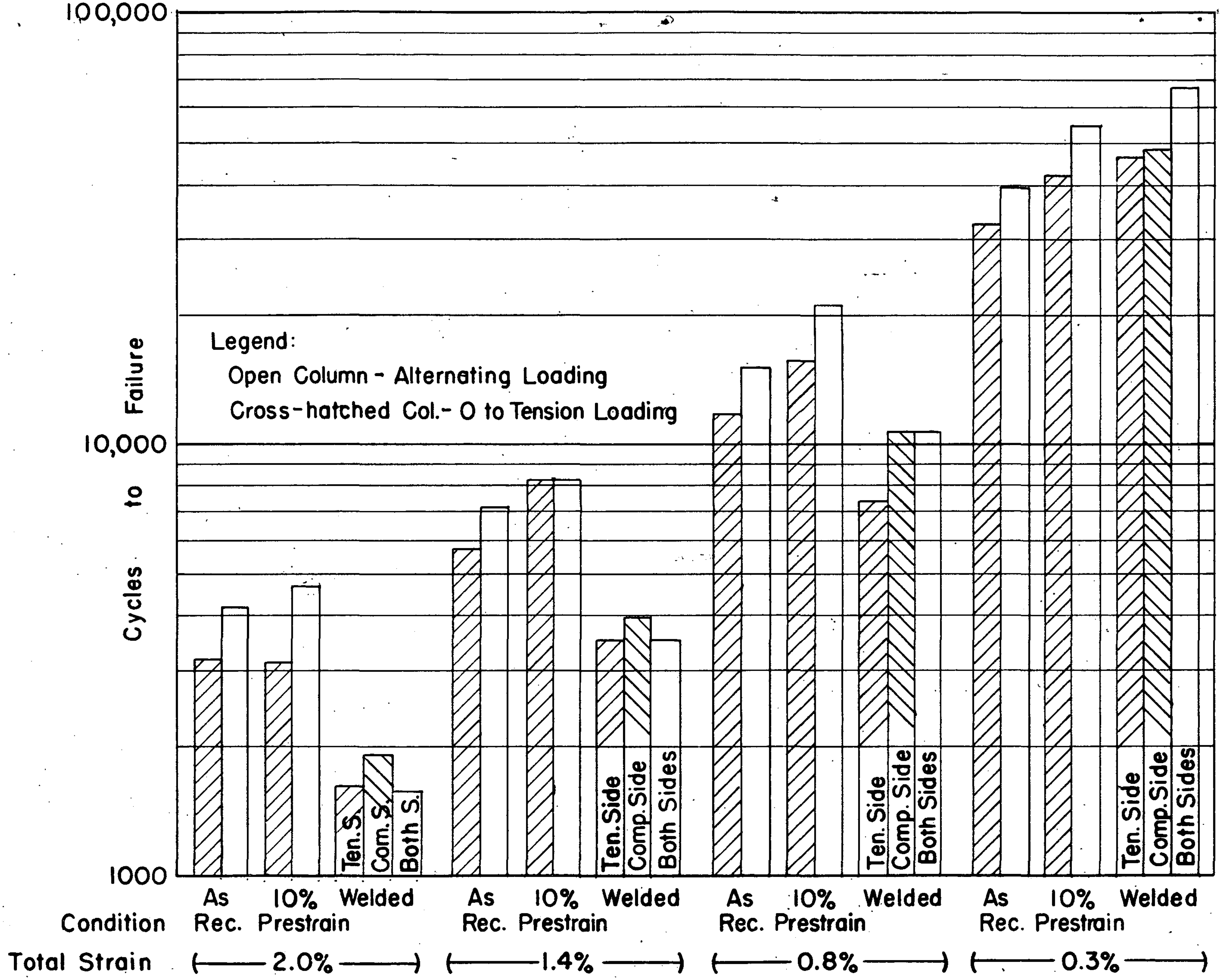


FIG. 3 Comparison of Repeated Load Tests Using Alternating and O to Tension Loading

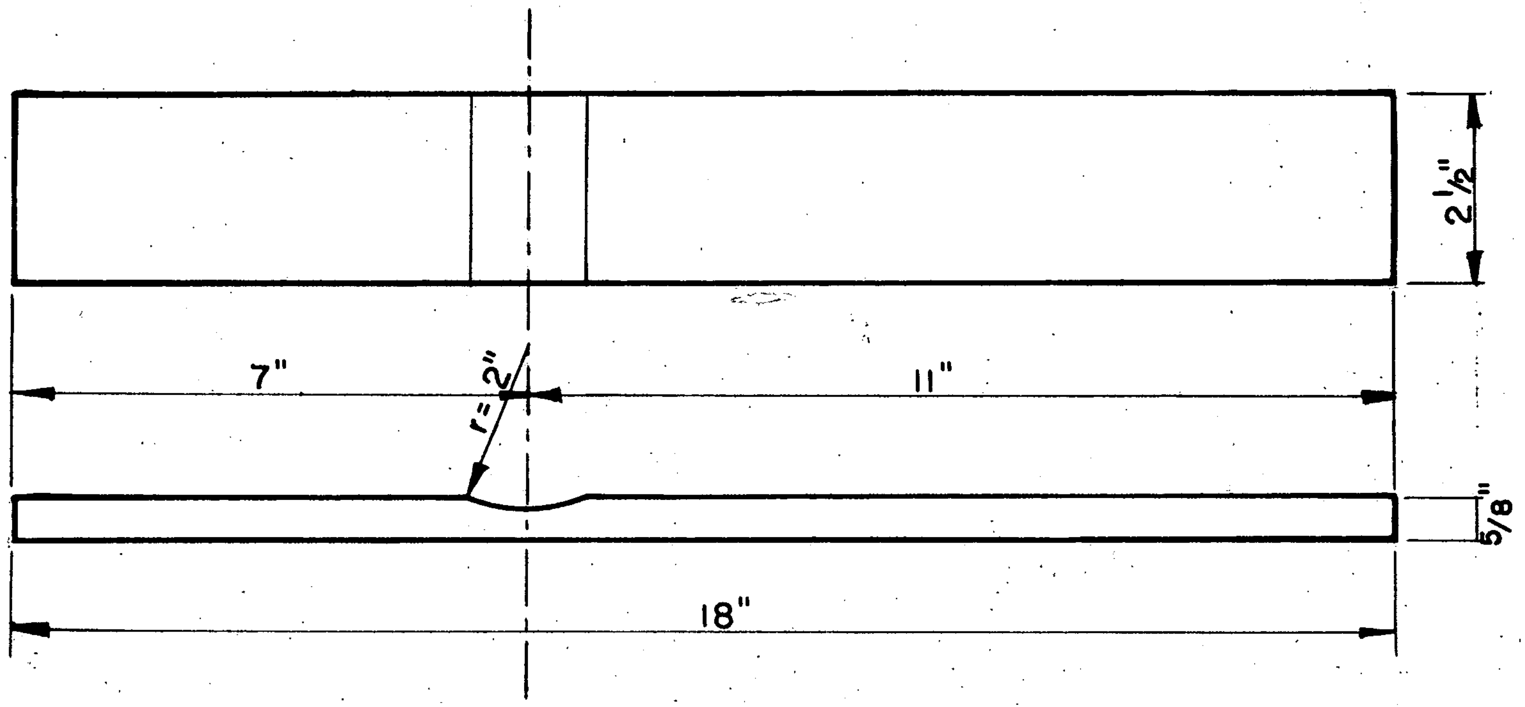


FIG. 4 MODIFIED REPEATED LOAD TEST SPECIMEN
(SURFACE NOTCHED)

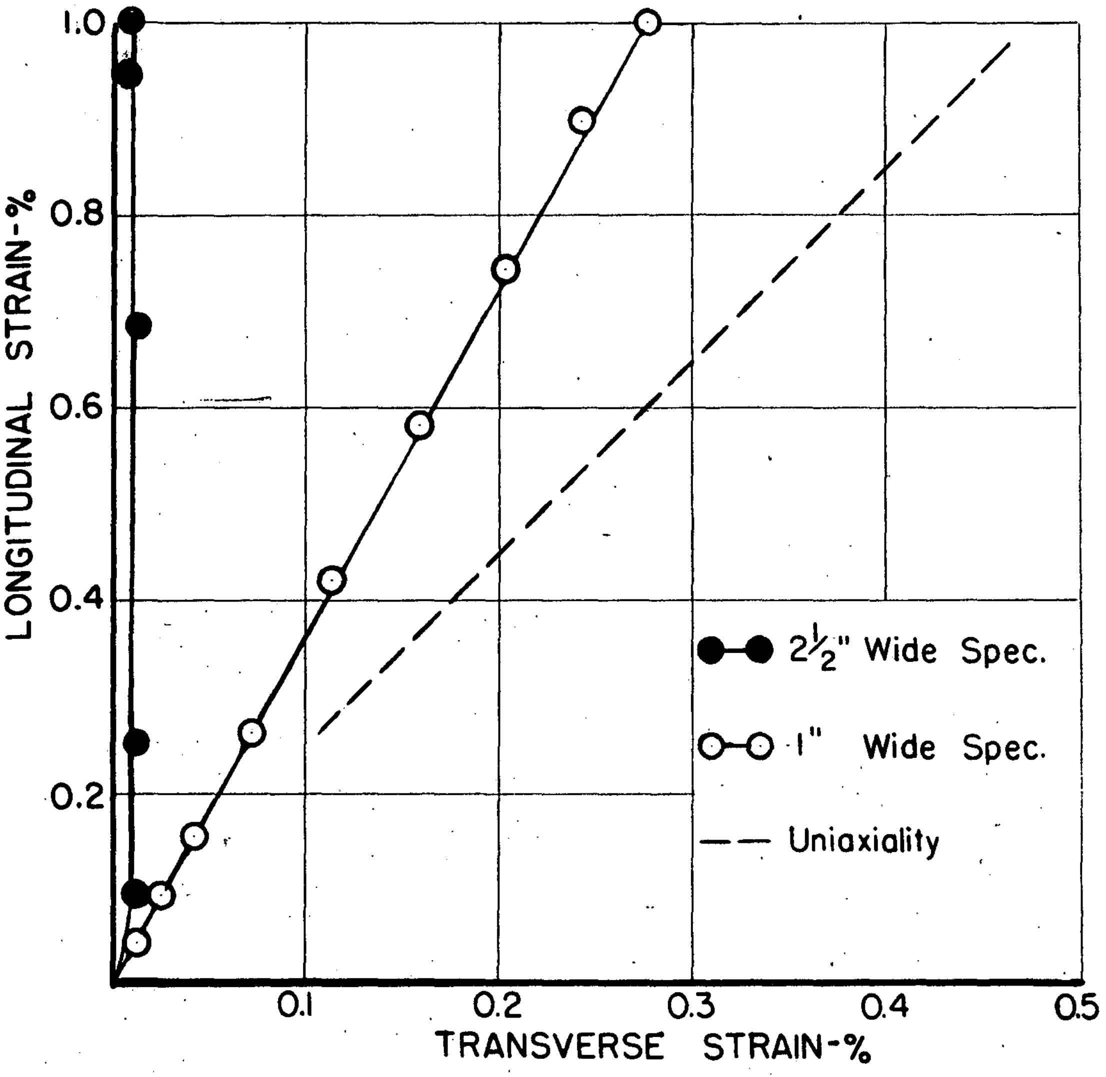


FIG. 5 EFFECT OF SPECIMEN WIDTH ON BIAXIALITY

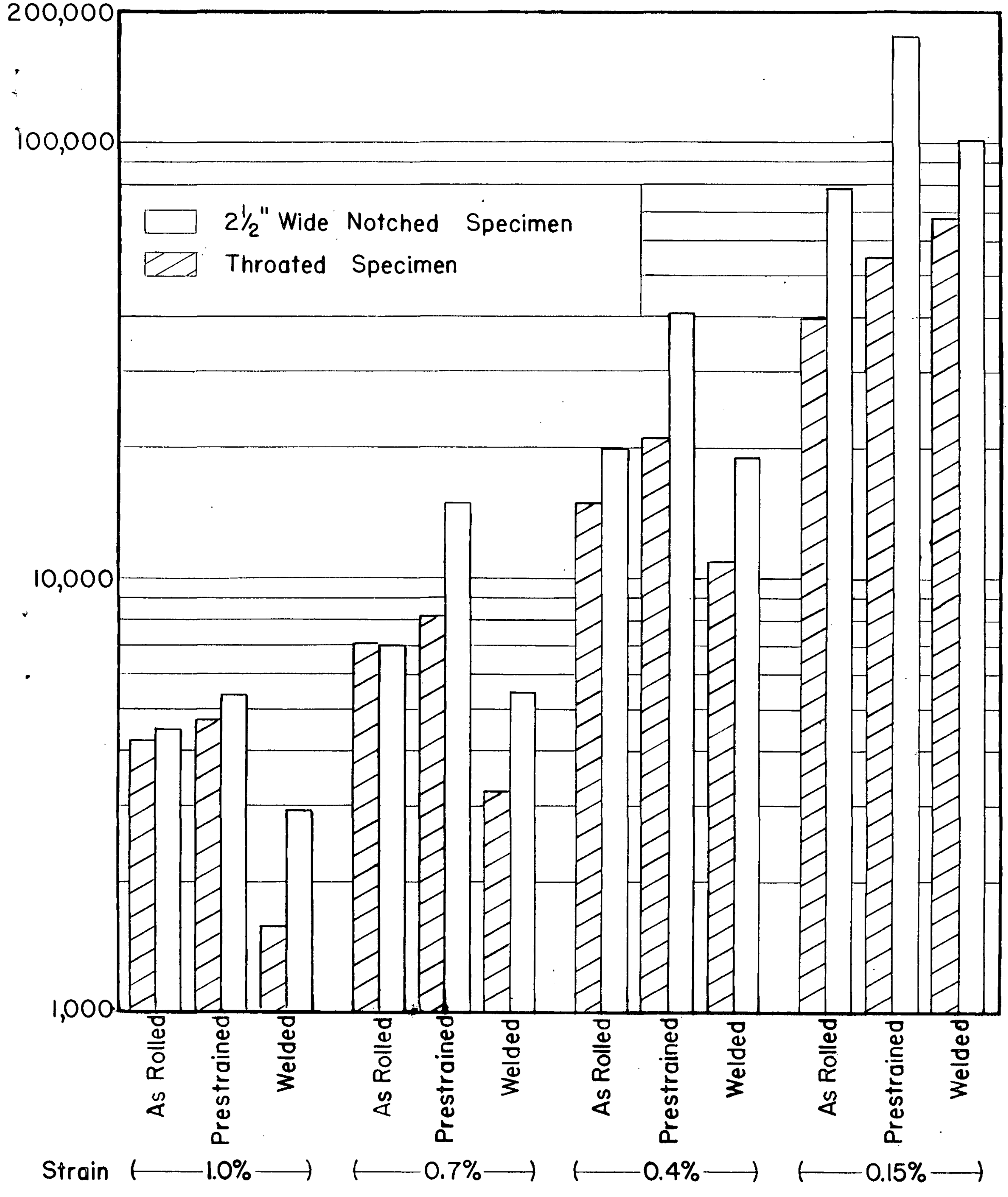


FIG. 6 EFFECT OF WELDING AND PRESTRAINING ON BEHAVIOR OF NOTCHED AND THROATED SPECIMENS

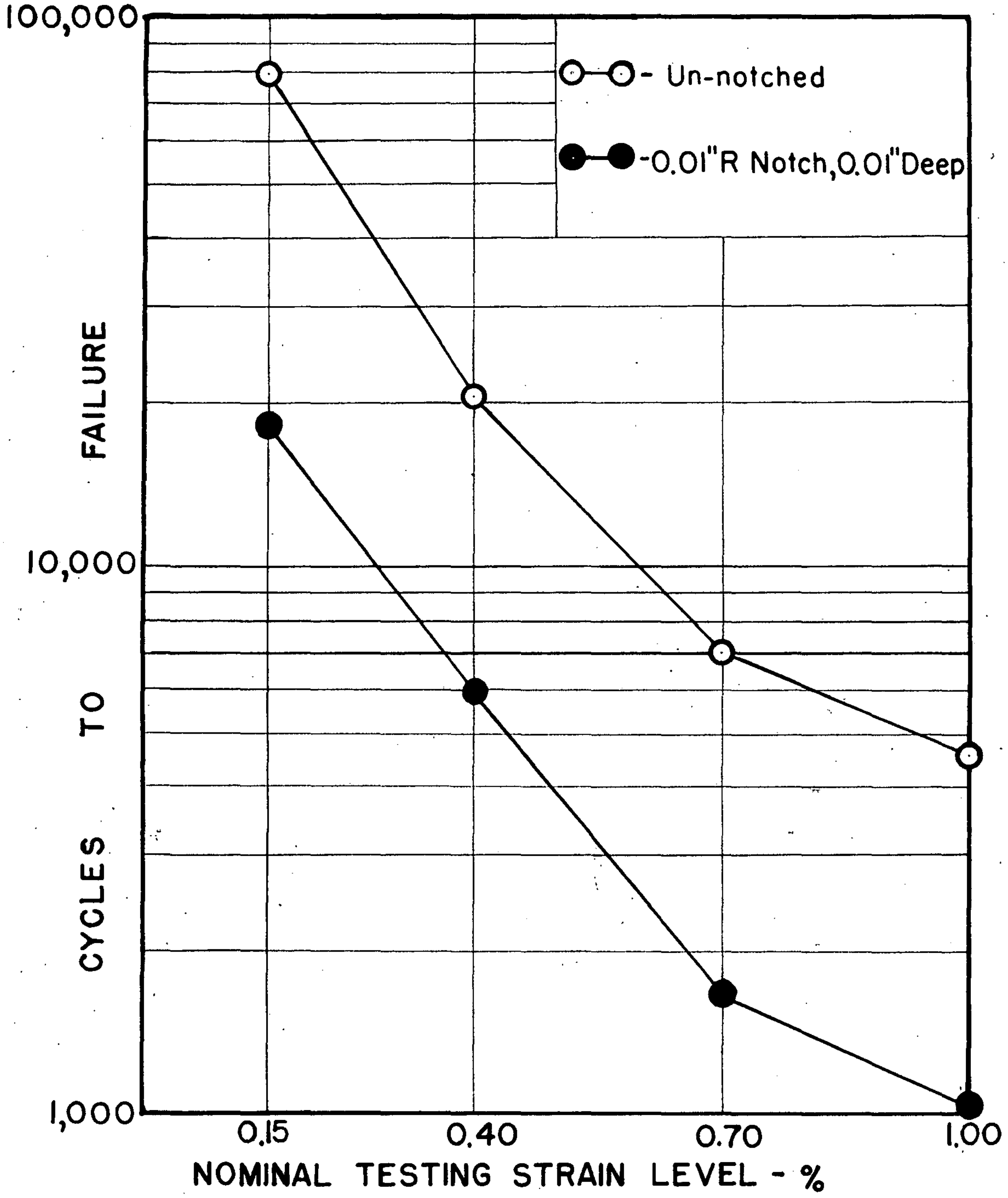


FIG. 7 EFFECT OF NOTCH ON RESISTANCE TO REPEATED OVERLOADING

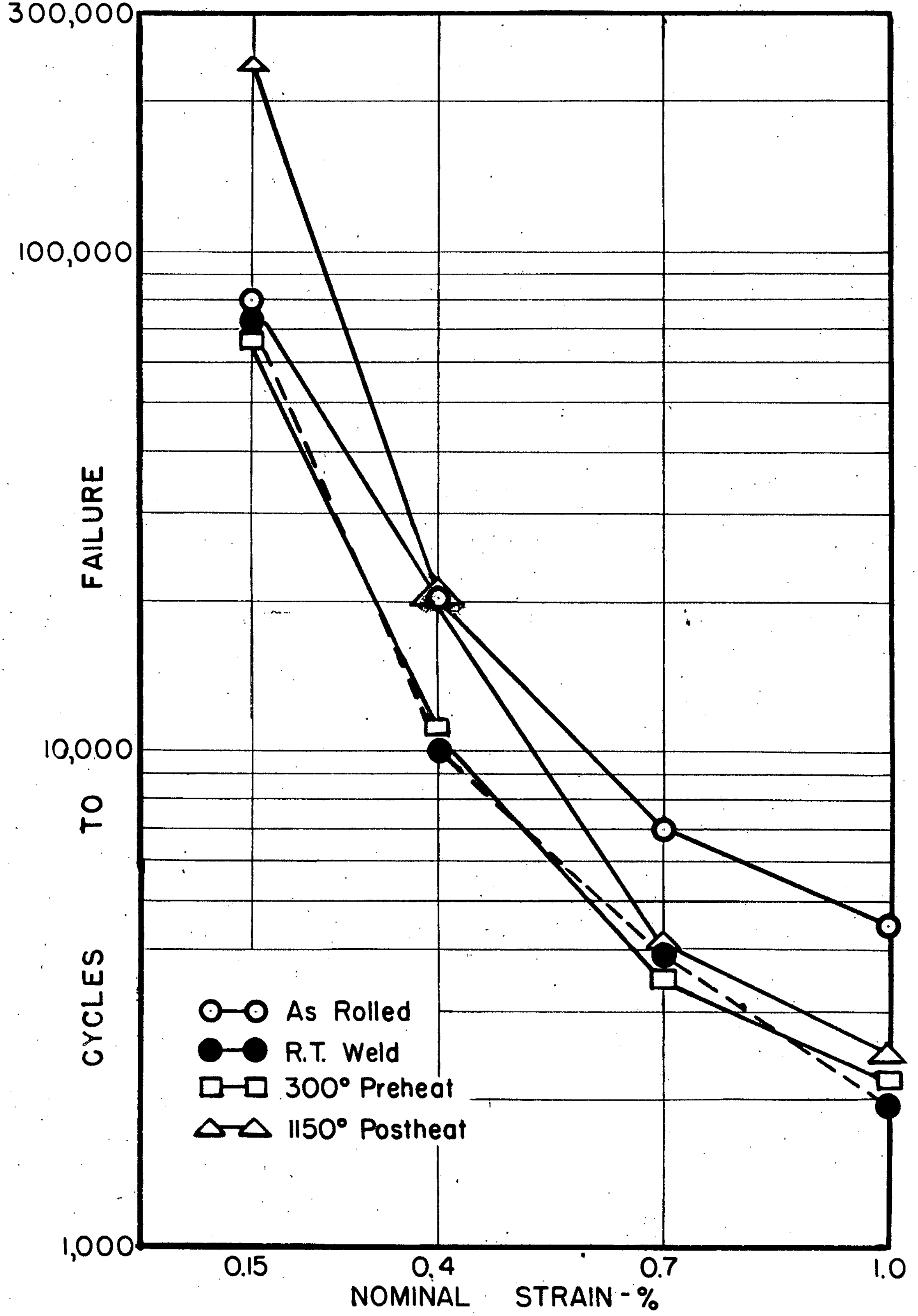
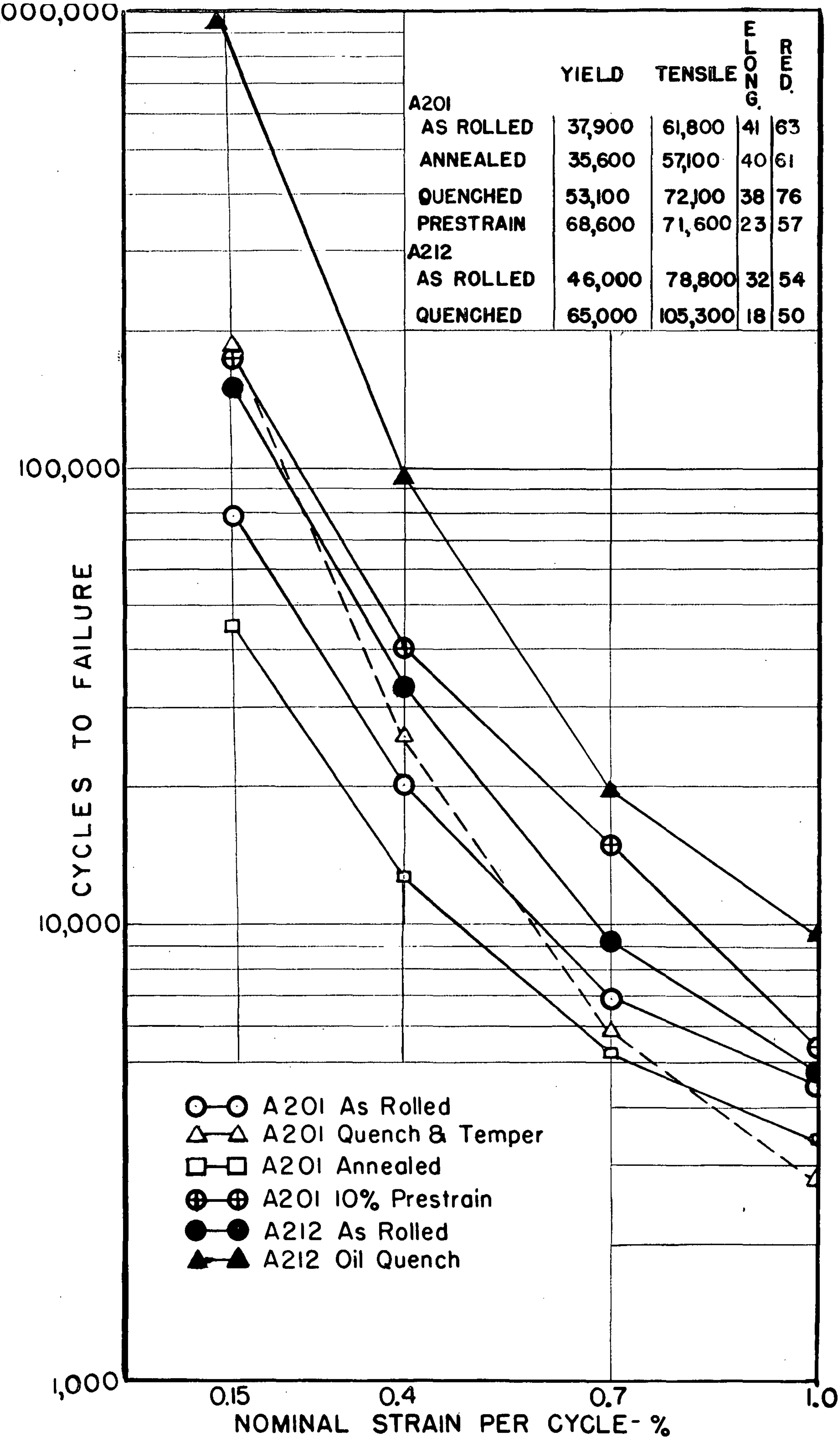


FIG. 8 BEHAVIOR OF MULTI-BEAD WELDED SPECIMENS IN REPEATED LOADING



	YIELD	TENSILE	ELONG.	RED.
A201				
AS ROLLED	37,900	61,800	41	63
ANNEALED	35,600	57,100	40	61
QUENCHED	53,100	72,100	38	76
PRESTRAIN	68,600	71,600	23	57
A212				
AS ROLLED	46,000	78,800	32	54
QUENCHED	65,000	105,300	18	50

FIG. 9 EFFECT OF TENSILE STRENGTH ON RESISTANCE TO REPEATED LOADING

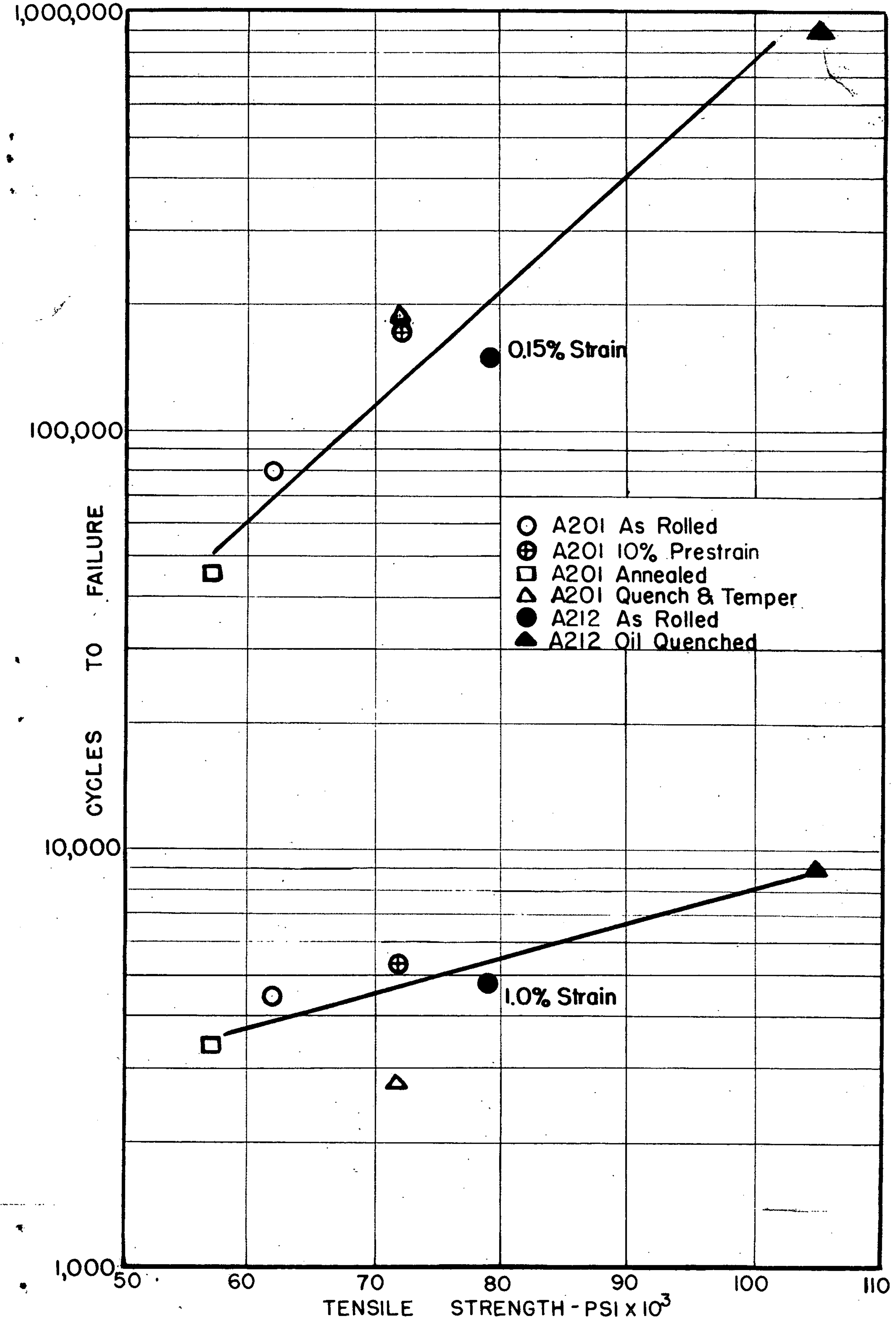


FIG. 10 CORRELATION OF TENSILE STRENGTH WITH RESISTANCE TO REPEATED LOADING

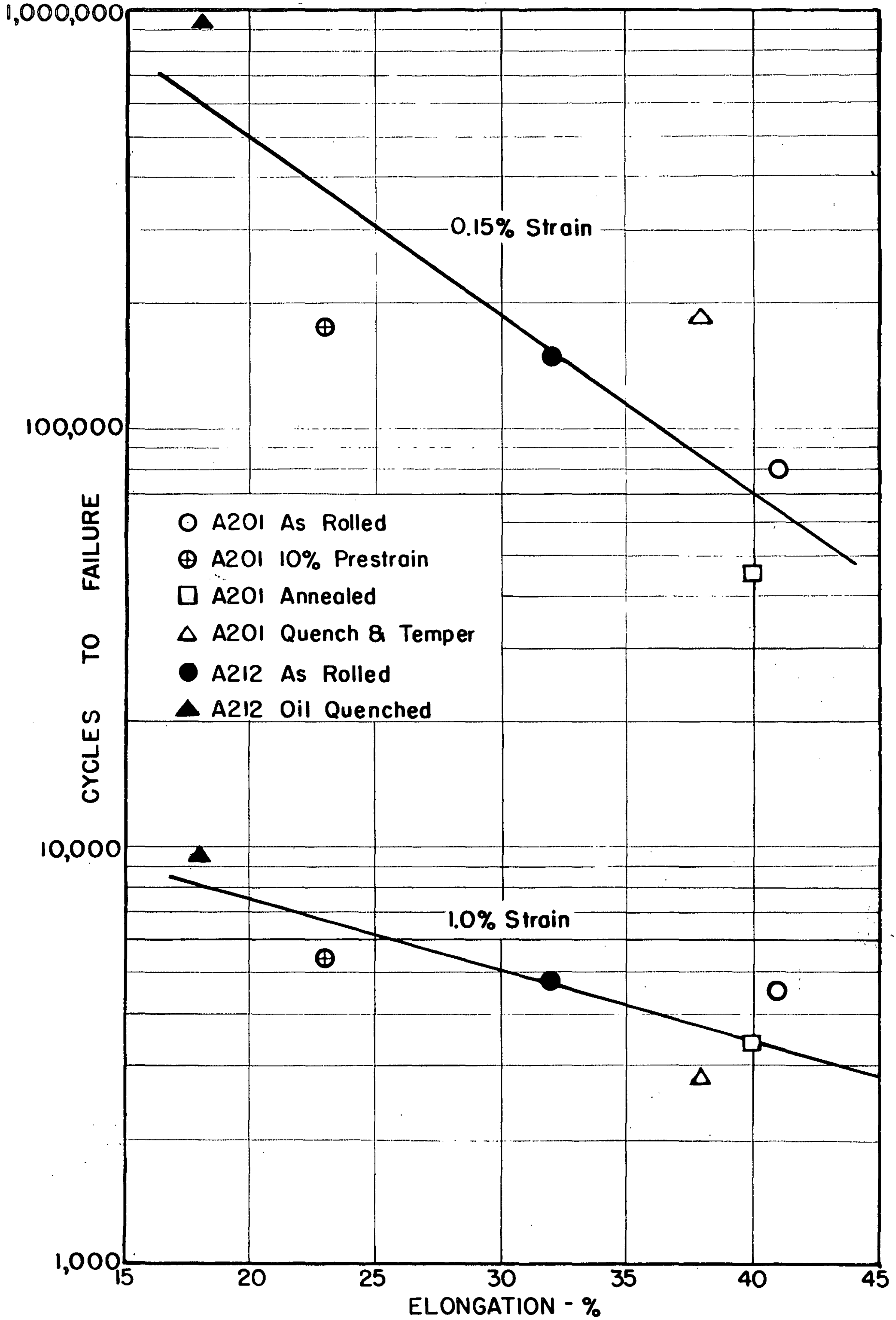


FIG. 11 CORRELATION OF DUCTILITY WITH RESISTANCE TO REPEATED LOADING