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FATIGUE BEHAVIOR OF WELDED JOINTS AND WELDMENTS IN HY-80 STEEL SUBJECTED TO AXIAL LOADINGS

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A REPORT OF AN INVESTIGATION CONDUCTED
by
THE CIVIL ENGINEERING DEPARTMENT
UNIVERSITY OF ILLINOIS
IN COOPERATION WITH
THE BUREAU OF SHIPS, U. S. NAVY
CONTRACT NObs 77137
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SYNOPSIS

Axial load fatigue tests on various types of welded joints and weldments in HY-80 steel are reported. The tests were carried out using three stress cycles; complete reversal, zero-to-tension, and half tension-to-tension. Most of the test lives lie between 2,000 and 600,000 cycles. These results have been used to develop Modified Goodman diagrams.

A preliminary series of fatigue tests was carried out to study the effects of interpass temperature, lack of penetration, type of electrode, and longitudinal fillet welded attachments.

When the specimens of a given test series failed due to an internal flaw, there was often a large amount of scatter in the test lives at a given stress level. Apparently internal weld flaws have a significant effect on the fatigue behavior of a welded joint.

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FATIGUE BEHAVIOR OF WELDED JOINTS AND WELDMENTS IN HY-80 STEEL SUBJECTED TO AXIAL LOADINGS

1. INTRODUCTION

1.1 Object and Scope of Program

In recent years there has been a marked increase in the use of high strength structural steels in welded structures. However, the usage of these materials in structures that are subjected to repeated loads has raised many questions concerning the fatigue behavior of the structures.

It is known that welded joints can have a great influence on the fatigue behavior of a structure. This effect is primarily a result of either an internal or external geometrical discontinuity at or in the weld, and possibly partly a result of the changes in the physical properties of the parent material due to welding. Furthermore, the high strength steels are much more sensitive than mild carbon steels to the effects of stress concentrations when subjected to cyclic loading.

The current research on the fatigue behavior of heavy chemistry HY-80 steel has been concerned principally with an evaluation of the fatigue behavior of certain selected welded joints and weldments subjected to stress cycles of complete reversal, zero-to-tension, and half tension-to-tension. Table 1 lists the tests that have been performed in this phase of the research program. The results of these tests and those reported in Ref. (1)* will be discussed in later sections of the report.

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* Numbers in parentheses refer to corresponding entries in the bibliography.

In addition, a series of exploratory tests was performed to obtain preliminary information concerning the effect of certain variables such as, interpass temperature, type of electrode, lack of penetration, combined welds, and longitudinal fillet welded attachments. The various tests that were performed are listed in Table 2.

The present report covers the work completed during the period from September 1960 to November 1961; the results of approximately 95 tests are reported. The individual results of all the tests are presented in tabular form in Appendix A and plotted in Appendix B.

1.2 Acknowledgements

The tests described in this report are the results of an investigation conducted in the Engineering Experiment Station of the University of Illinois. The program was carried out with funds provided by the Bureau of Ships, U. S. Navy, under contract NObs 77137, Index No. NS-021-200.

The investigation constitutes a part of the structural research program of the Civil Engineering Department of which N. M. Newmark is the Head. The research was carried out by A. J. Hartmann, Research Assistant in Civil Engineering, R. K. Sahgal, former Research Assistant in Civil Engineering, and J. E. Zimmerman, Research Assistant in Civil Engineering under the supervision of W. H. Munse, Professor of Civil Engineering.

The authors wish to express their appreciation to a number of persons on the University's staff who have assisted in the conduct of the investigation. These include J. E. Stallmeyer, Professor of Civil Engineering, who was responsible for the radiographic examinations of the specimens, W. Becker, former Research Assistant in Civil Engineering, who conducted the metallurgical studies of the specimens under the supervision of W. H. Bruckner, Professor of Metallurgical Engineering, and the Civil Engineering Shop staff who prepared the test specimens.

II. DESCRIPTION OF MATERIALS AND TESTS

2.1 Materials

The test specimens were fabricated from heavy chemistry (1-1/2 in. thick) HY-80 steel plates from four different heats of steel. The plates were in the as-rolled condition with the exception of the material bearing a "G" designation. This material had been ground on one surface. The specimens designated "G" tended to have a thickness in excess of 1.5 in. while the specimens fabricated from the other three heats had a thickness of 1.5 in. or less. The physical and chemical properties of the materials are listed in Tables 3 and 4.

MIL 11018 low hydrogen iron powder electrodes were used almost exclusively for the fabrication of test specimens; this electrode over matched the parent metal being welded. MIL 9018 grade electrodes which under match the parent metal were used to fabricate three specimens to study the effect of the electrode (strength) on the fatigue life of one type of welded joint.

All electrodes before being used were conditioned in a furnace at 800 deg. F for one hour. During this time, the maximum deviation in temperature was not more than 25 deg. F. The hot electrodes were then transferred to a holding oven; during the transfer, the temperature of the electrodes was maintained at not less than 300 deg. F. In the holding oven, the electrodes were held at a temperature of 200 to 300 deg. F. When the electrodes were required for welding, they were removed from the oven a few at a time. As a result the dried electrodes were never exposed to the laboratory atmosphere for a period of more than 30 minutes.

2.2 Test Specimens

The test specimens were fabricated using the full thickness of the plate material. The width of the specimen then was dictated by the stress level to which they were to be subjected. For this reason, the plain plate specimens had a test section width of 1.5 in. and the welded joints had a width of 2.5 in. The details of all specimens used in the current studies are shown in Fig. 1. The test section of the specimens is straight for a length of at least 5 inches. The transition radius was 4 in. for the plain plate specimens and 7 in. for the other specimens.

2.3 Fabrication of Specimens

The first step in the fabrication of the specimens was to flame cut 9 in. by 48 in. blanks from the large as-rolled plates. The edges that were to be welded were then machined to the required shape. Previously developed welding procedures were used but, in some cases, with slight modifications. The welding was done while the specimen was clamped in a welding jig. In all welding, a string or tempering bead technique was employed. In this technique, the first and second passes of each weld layer were placed against the base metal and each succeeding bead was laid against one that had been previously deposited. Thus the layer of weld metal was built up by working from the base metal inward; in this way, the weld beads tempered those which had previously been deposited. In welding, the rates of electrode travel were selected to assure that the heat input did not exceed fixed limits.

Upon completion of welding, the holes necessary to attach the specimen in the testing machine were drilled. Next the profile of the specimen was machined; in no case was any material near the test section removed by flame cutting. As a final step, the edges of the specimens were ground smooth using an electric disk sander and various grades of emery paper. Wherever necessary, a hand file was used for final finishing.

The welding procedures used in this test program were designated by the following notation:Pxx-xxxxx-Y. The letter "P" stands for procedure. The two numbers which immediately follow P give the nominal yield strength of the parent metal in kips per square inch. The set of four or five numbers between the dashed lines identifies the welding electrode which is to be used in fabricating the weld joint. The final letter is used to identify a particular procedure in the group. For example, P80-11018-D indicates that the welding procedure is used on 80 ksi yield strength steel plates, the electrode is of the 11018 class, and it is the fourth procedure that has been developed for this combination of base plate and electrode type. The details of all the procedures used to fabricate the specimens considered in this report are given in Appendix D.

2.3.1 Transverse Butt Welds

The profile of the transverse butt weld specimens is shown in Fig. 1b. Before welding, the blanks were sawed in half and the edges to be welded were beveled to form a double-V butt joint with an included angle of 60 degrees. The blanks were fastened to the welding jig and a 4 in. length of full penetration weld was placed. Then the specimen was machined to give a 2-1/2 in. wide test section. Typical macrographs for specimens prepared by this procedure can be found in Ref. (1).

2.3.2 Longitudinal Butt Welds

The details of the longitudinal butt weld specimens are shown in Fig. 1c. The 9 in. by 48 in. blanks were split longitudinally and the edges to be welded were beveled in the same way as stated above for transverse butt welds. The specimen was welded using procedure P80-11018-0.

In procedure P80-11018-0, the electrode change points, starting and stopping points for each weld pass, were fixed in the central 10 in. of the longitudinal butt weld. Outside this region, electrode change points were permitted to fall at random; the only requirement was that there be two or three electrode changes at each end of the specimens as shown in Fig. D-7.

2.3.3 Full Penetration Attachments and Tees

The details of the attachment and tee specimens are shown in Figs. 1d, 1e, and 1f. The only difference in fabrication procedure between the specimens fabricated in the present study and those fabricated under the previous one was the welding position. All of the latest specimens were welded in the horizontal position whereas the specimens previously tested(1) were welded in the flat position. Typical macrographs for the joints can be found in Ref. (1).

2.3.4 Special Tests

In addition to the tests referred to above, a series of preliminary tests were performed to investigate the effect of certain variables on the fatigue behavior of welded joints.

In order to determine the effect of under matching the electrode with the parent material in the case of plain plate specimens having a full penetration attachment on one side, three specimens, as shown in Fig. 1e, were fabricated using a MIL 9018 electrode. Welding procedure P80-9018-A was used in fabricating these specimens.

Another short series of tests was performed in which the interpass temperature for the full penetration transverse butt joints was made the variable. Interpass temperatures of room temperature, 300 deg. F., and 400 deg. F were employed.

Two specimens were tested to evaluate in a preliminary manner the effect of lack of penetration in 1-1/2 in. HY-80 steel. Welding procedure P80-11018-D was used with two changes; there was no root opening and the two edges which were butted had one-eighth inch lands in order to assure a lack of penetration.

A series of six specimens was fabricated to investigate the effect of combined longitudinal and transverse butt welds. Three specimens were prepared in which the transverse butt weld was deposited first. The blank then was split lengthwise and a longitudinal butt weld deposited. The second three specimens were prepared in the reverse order; the longitudinal weld was made first and then the transverse weld. Procedure P80-11018-D was used for the transverse butt weld while P80-11018-O was used for the longitudinal butt weld. The details of these specimens are shown in Figs. 1g and 1h.

Finally, one specimen was fabricated with fillet welded longitudinal attachments on two sides as shown in Fig. 1i. In this specimen, the fillet weld was feathered at each end of the attachment. The welding procedure, P80-11018-N, is listed in Appendix D.

2.4 Testing Equipment

The fatigue tests were carried out using the University of Illinois' 250,000 lb. lever-type fatigue machines such as that shown in Fig. 3. Figure 2 shows a schematic drawing of the machine and Fig. 4 shows a butt welded specimen ready for testing. The original operating speed for the machine was 180 cpm; but, during the early tests, this speed was reduced to 100 cpm to decrease the inertia effects and the amount of vibration in the machine while operating in complete reversal at the high loads required in the tests.

In the fatigue machine, a 15:1 force multiplication ratio is obtained between the dynamometer and the pullhead. The load is applied to the specimen by first setting a double throw eccentric to provide the desired load range; then a turnbuckle which is located below the dynamometer is turned so as to set the maximum load which is to be applied to the specimen. The magnitude of the load is obtained by measuring the deformation of the dynamometer as the specimen is subjected to a load cycle.

2.5 Testing Procedure

After a specimen had been installed in the machine and the load had been set, a microswitch was adjusted to shut the machine off when the fracture had propagated partially through the test section. As a rule, the machine was shut off when the fracture had passed through about one-half of the section; this was considered to be failure of the specimen. Since the criteria of failure was arbitrary and since from laboratory observations it appeared that the number of additional cycles needed for complete failure was small when compared with the total life, no attempt was made to convert "cycles to complete failure" to "cycles to the initiation of failure". However, it should be noted that the scatter induced by the method of defining failure would not be great.

In most instances the specimens were completely fractured before being removed from the machine. This was done by disconnnecting the microswitch at the end of the test and letting the fatigue crack propagate completely through the test section. This procedure had the advantage over pulling the test specimens apart statically in that it was faster and more convenient. Furthermore, the fracture surfaces resulting from the use of this procedure appeared to have undergone less plastic deformation than the surfaces of those specimens which had been pulled apart statically.

2.6 Inspection of Welds

All welds were given close visual inspection for cracks during the welding operation and any unusual conditions were noted on the fabrication data sheets.

Prior to testing, all transverse and longitudinal butt welded joints were subjected to radiographic inspection and were found, with the exception of two specimens, to be of excellent quality. In each case, the welds far exceeded the minimum radiographic requirements of the Bureau of Ships specifications for HY-80 welds[2].

2.7 Metallurgical Studies

In Ref. (1), two specimens were reported to have had very short fatigue lives for which no explanation was then available. Through subsequent metallographic studies, evidence was found of a small amount of slag between two of the weld passes. In addition, ferrite which could be due to a cooling rate too small to suppress proeutectoid ferrite formation was also found in the same general area. This ferrite indicates the presence of a higher interpass temperature than in the regular test series. It was to check the effect of this variable that a series of transverse butt weld specimens was fabricated using different interpass temperatures. The results of this study are given in Section 3.7.2.

III. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Evaluation of Fatigue Strength

In order to compare the results of the individual tests of a series the fatigue strengths of the specimens, corresponding to failure at a given life, were computed using Eq. 3.1.

$$F_n = S_N \left(\frac{N}{n}\right)^k \qquad (3.1)$$

where F_n is the stress that would cause failure at n cycles, S_N is the test stress that caused failure at N cycles, and k is the slope of the S-N curve. This empirical equation has been developed from many laboratory observations[3] and is based on the assumption that the S-N curve can be approximated by a straight line over any finite life range when the results are plotted on a log-log basis.

Previous investigations have indicated that k is a function of material properties, geometry of specimen, and stress cycles. In some cases, the S-N curves given in this report are based on only three test results, and the k value computed may therefore be very approximate. Nevertheless, the error associated with the value of the computed fatigue strength resulting from an error in k is generally relatively small. In order to control the error due to extrapolating the test data, the following limitations were set up giving the allowable range of extrapolation:[a]

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[a] There is one exception to this rule and it will be noted at the appropriate place in Section 3.4.

Fatigue Strength	Range of n
$F_{20,000}$	$4,000 \leq n \leq 100,000$
$F_{50,000}$	$10,000 \leq n \leq 300,000$
$F_{100,000}$	$20,000 \leq n \leq 600,000$
$F_{200,000}$	$40,000 \leq n \leq 1,000,000$
$F_{500,000}$	$100,000 \leq n \leq 3,000,000$
$F_{2,000,000}$	$300,000 \leq n$

A summary of the computed fatigue strengths, $F_{20,000}$, $F_{50,000}$, $F_{100,000}$, $F_{200,000}$, and $F_{2,000,000}$ is listed in Table 5 for the connections and weldments considered in this report. The results of each series of tests have been plotted and an S-N curve drawn through the data (these plots are contained in Appendix B). This average curve was obtained by a trial-and-error procedure using Eq. 3.1 and the above tabulation. An initial value of k was chosen that was a good visual approximation of the slope of the average curve. Having obtained the average fatigue strengths for two of the lives listed in the tabulation above, Eq. 3.1 was used to compute a new k value. This value of k was used for a new cycle of calculations from which an improved value of k was obtained. This cycle was repeated until the assumed value of k equaled the computed value. After the k value had been determined, the remaining fatigue strengths were computed using this value of k and the life range of the tabulation above.

3.2 Fatigue Tests of As-Rolled Plain Plate Specimens

Tests were conducted on plain plate specimens using two stress cycles: zero-to-tension and complete reversal. The data is tabulated in Tables A-1 and A-2 and plotted in Fig. B-1. These data were used to develop the Modified Goodman diagram for as-rolled plates shown in Fig. 5.

The S-N curve for complete reversal is based on 5 tests. A sixth test, V-55, was not considered in calculating the average curve since this specimen had been subjected to excessive bending at the start of testing; the bending was accompanied by flaking off of the mill scale on the surface of the specimen. This difficulty was remedied in later tests by providing lateral restraint at each end of the test section to prevent lateral movement of the pull heads.

The S-N curve for zero-to-tension also was based on five test results. A sixth specimen, HL-1, which was tested at 0 to +50.0 ksi, was not used in determining the average curve since the test section had been polished for instrumentation purposes. This test was stopped after the specimen had been subjected to 3,321,200 cycles of loading without failure. Thus, it is evident that the presence of mill scale or other surface irregularities is an important factor with regard to the initiation of failure in this control type of specimen. In all cases, failure in the plain plate specimens initiated in the transition curve of the specimen at one of the corners.

From the results of tests run on a zero-to-tension cycle, it can be seen that the fatigue life of the as-rolled material is about 35,000 cycles when subjected to a maximum stress equal to the nominal yield strength of the material. At this same life, the fatigue strength in complete reversal is about $\pm$ 60.0 ksi. We can see from the Modified Goodman diagram (Fig. 5) that an alternating stress in excess of $\pm$ 50.0 ksi is necessary to cause failure in less than 100,000 cycles when the specimen is subjected to complete reversal.

3.3 Fatigue Tests of Transverse Butt Welded Joints

Fatigue tests were conducted on transverse butt welded joints using three geometrical conditions and two stress cycles. The geometrical conditions were as-welded, reinforcement removed on one side, and reinforcement removed on two sides; the stress cycles were zero-to-tension and complete reversal. These tests are tabulated in Tables A-3 through A-5 and plotted in Figs. B-2 and B-3. The results have been used to develop the Modified Goodman diagrams shown in Figs. 6 and 7.

A second group of transverse butt welded joints, in the as-welded condition, was tested to study the effect of mean stress on the fatigue behavior of this type of joint. The results of these tests are tabulated in Tables A-6 and A-7 and are plotted in Fig. 19.

3.3.1 Zero-to-Tension

The results of the zero-to-tension tests on specimens in the as-welded condition have already been discussed[1]. For this reason, only the S-N curve has been reproduced in Fig. 17 to provide a comparison of the behavior of the as-welded joints with the other two geometrical conditions.

Of the nine specimens having reinforcement removed on one side, only two had failures which initiated at the edge of the weld reinforcement. Specimen V-16 failed at the edge of the weld reinforcement and had a life appreciably less than the average for the 0-to-35.0 ksi stress cycle. Three specimens, G-9, G-8, and G-5, were tested at 0-to-40.0 ksi. In the first two specimens, failure initiated near the edge of the weld reinforcement, seemingly due to external geometry; but, when the failure surfaces were inspected at the conclusion of the tests, slag appeared to be present at the point of fracture initiation under weld pass

No. 22. The failure of specimen G-5, which had the longest life of the three, initiated in the weld along a line which is believed to be the weld metal base metal interface. The S-N curve for these specimens has a flatter slope than the corresponding S-N curve for specimens in the as-welded condition.

Of the nine specimens tested with reinforcement removed on two sides, two had failures which initiated at the weld metal base metal interface (Fig. C-2b). In the remaining specimens, failure initiated at a defect in the weld. It is interesting to note that the specimens which had the longest lives for the 0-to-50.0 ksi and 0-to-70.0 ksi stress cycles were the two specimens in which failure initiated at the interface. The S-N curve for these tests had a flat slope and was located above the corresponding curve for specimens in the as-welded condition for n greater than 20,000 cycles.

The slopes of the S-N curves for specimens with the reinforcement removed on one side or on two sides are almost equal to the slope of the S-N curve for plain plate specimens tested on a zero-to-tension stress cycle. It can be seen in Fig. 17 that at short lives, n = 20,000 cycles, the curves for the three conditions are close together. However, at long lives, the effect of removing reinforcement on one side or on two sides becomes significant. In Fig. 18, we see that the reduction in fatigue strength of the base plate is about 20 percent for a weld with the reinforcement removed on one side and 7 percent for a weld with the reinforcement removed on two sides over the range $20,000 \leq n \leq 1,000,000$ cycles. The decrease in the reduction in fatigue strength with an increase in life for specimens having reinforcement removed on two sides is due to the fact that the experimentally determined value of k is slightly less than the value of k for plain plates tested on a zero-to-tension stress cycle. This low value for k is due to the rather short lives obtained from some of the specimens tested on a 0-to-70.0 ksi stress cycle.

3.3.2 Complete Reversal

The tests in complete reversal of specimens in the as-welded condition have been discussed previously[1] and only the S-N curve has been reproduced in Fig. 16 to provide a comparison for the specimens having reinforcement removed on two sides.

There was a large amount of scatter in the test results of specimens having reinforcement removed on two sides and tested at $\pm$ 40.0 ksi (see Table A-4); the results appeared to fall into two groups (Fig. B-3). One group had internal defects which were clearly visible on the fracture surface but not in the radiographs; the lives of these specimens were short. The group which had long lives also failed due to internal defects but these defects were almost impossible to locate. The S-N curve for the specimens was based on all of the test data; no consideration was given to the effect of the defects, their size or location. The curve has almost the same slope as the corresponding S-N curve for plain plates. One specimen tested at $\pm$ 25.0 ksi did not fail after being subjected to 2,725, 900 cycles of loading; the test was discontinued.

In Fig. 16 for $n < 25{,}000$ cycles, the S-N curve for transverse butt welds having the reinforcement removed on two sides lies below the S-N curve for specimens in the as-welded condition. In Fig. 18 over the range $20{,}000 \leq n \leq 2{,}000{,}000$ cycles, the reduction in fatigue strength is approximately 20 percent.

3.3.3 Fatigue Tests of Transverse Butt Welded Joints with Tensile or Compressive Mean Stresses.

Two series of tests were conducted using mean stress as the variable, one with a constant alternating stress of $\pm$ 30.0 ksi and the other with a constant alternating stress of $\pm$ 40.0 ksi. The specimens were transverse butt welded joints in the as-welded condition. The test results and the resulting curves showing mean stress vs. cycles to failure are shown in Fig. 19.

In the construction of the curves showing the effect of positive mean stresses, use was made of the S-N curves and scatter bands reported in Ref. (1) for stress cycles of zero-to-tension and complete reversal. It was considered necessary to use the scatter bands since the variability in life was large for negative mean stresses. From the S-N curves for zero-to-tension and complete reversal, the values of the scatter band and average curves which corresponded to alternating stresses of $\pm$ 30.0 ksi and $\pm$ 40.0 ksi were obtained. Curves were drawn through the points indicating the limits of scatter and were then extended through the exteme values of the test results for specimens tested with negative mean stresses. These scatter bands are shown in Fig. 19. Having defined the scatter bands, curves were drawn through the average values taken from Ref. (1) and extended through the negative mean stress region by making the curves bisect the scatter bands at each value of the mean stress. These curves are shown as heavy lines in Fig. 19; the solid line is the curve for $\pm$ 30.0 ksi and the dashed line is the curve for $\pm$ 40.0 ksi. These curves were then used to estimate the shape, at negative mean stresses, of the constant life contours shown in the Modified

Goodman diagram (Fig. 6) for transverse butt welds in HY-80 steel. Although it is only speculation, it is believed that further testing would show that in butt welded joints subjected to stress cycles having a negative mean stress the life is sensitive to the magnitude of the maximum tensile stress in the loading cycle and not so much to the total stress range.

For the two alternating stresses considered, the average curves discussed above are almost parallel to the mean stress axis for positive mean stress, life increasing only slightly with a decrease in mean stress. As the mean stress decreases and becomes negative, the slopes of the curves decrease rapidly. One might postulate that at a negative mean stress approaching the value of the alternating stress the life of a test specimen would be very long, providing failure is not precipitated by buckling. This neglects the possible effects of tensile residual stresses which could be present.

Specimen W-29 failed in the weld because of a serious weld flaw and therefore was not considered with the other test results. The fracture surface indicates that the specimen had a large internal defect (Fig. C-3) which did not show up on the radiograph of this specimen. The defect in this case was not a void; one side of the fracture surface showed a concave surface at the defect while the other surface showed a matching convex surface at this point, suggesting that there may have been a small internal crack in the weld.

3.4 Fatigue Tests of Longitudinal Butt Welded Joints

A series of fatigue tests was also conducted on longitudinal butt welded joints. The test results are tabulated in Tables A-8, A-9, and A-10 and plotted in Fig. B-4. Three stress cycles were used, zero-to-tension, complete reversal, and half tension-to-tension. These results were used to construct the Modified Goodman diagram shown in Fig. 8.

There was again a significant difference in the lives of specimens reported herein for a stress cycle of $\pm$ 30.0 ksi and those reported in Ref. (1). It was noted also that there was a difference in the effective defect diameter[b] in the specimens from the two sets of test results. Test specimen HL-17, a longitudinal butt weld specimen reported in Ref. (1), had an effective internal defect diameter d_e = 0.04 in. Test specimen G-43 which is reported herein had an internal defect diameter d_e = 0.018 in. However, specimen G-40 with an internal defect diameter of d_e = 0.03 in. had a long test life when tested at $\pm$ 40.0 ksi. Thus, it would appear that defect size is only one of the factors that influence the fatigue life of a longitudinal butt welded joint. Because of the scatter in the test results, the method for computing the S-N curve given in Section 3.1 was not used. Instead, all the test results were used without reference to the limits on n given in Section 3.1. A value of k = 0.12 was obtained; it is less than the value of k for the plain plate specimens tested in complete reversal.

Seven specimens have been tested on a cycle of zero-to-tension; three of these tests were originally reported in Ref. (1). The range in test life at a given stress level was also large in this series of tests. Specimen G-48 which appeared to have a small amount of slag in the root

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[b] Effective defect diameter $d_e = \sqrt{d_1 d_2}$, where d_1 = width of defect measured in direction of shortest width and d_2 = width of defect measured in a direction making an angle of 90 degrees with the direction of d_1.

pass had a life of 63,700 cycles while specimen G-42 which was tested at the same stress level, 0-to-60.0 ksi, and had porosity with an effective defect diameter d_e = 0.049 in. had a life of only 21,000 cycles. Another specimen G-41, tested at 0-to-40.0 ksi, had a long life and failure initiated at the edge of the weld reinforcement. The S-N curve for these specimens also provided a slope of approximately k = 0.12.

Three specimens were tested on a stress cycle of half tension-to-tension and there was little difference in lives for the three tests. For this reason, a slope of k = 0.12 was again assumed for the S-N curve.

Three general failure modes were obtained and these are shown in Fig. C-5. The most common was failure initiation in the weld at an internal defect; in this case the fracture spread radially from the internal defect. The second mode was failure initiation at an electrode change point and the third mode was failure initiation at the edge of the weld reinforcement.

Since the values of k for the S-N curves for longitudinal butt welded joints are less than the corresponding values of k for plain plate specimens, the percentage reduction in fatigue strength was found to decrease rather than increase with an increase in test life (Figs. 20 and 21). At 20,000 cycles, the maximum reduction in fatigue strength was about 40 percent for complete reversal and about 30 percent for zero-to-tension.

3.5 Fatigue Tests of Plates with Full Penetration Transverse Attachments

A series of tests was conducted to determine the effect that attachments placed on one side or on two sides would have on the fatigue behavior of a plain plate specimen. The results of these tests are tabulated in Tables A-11, A-12, A-13 and A-14 have been used to construct the Modified Goodman diagrams shown in Figs. 9 and 10.

3.5.1 Attachments on Two Sides

Five specimens were tested on a stress cycle of zero-to-tension and three on a stress cycle of half tension-to-tension. These results were used to construct S-N curves for these two stress cycles (Fig. B-6). The third curve on this figure is a reproduction of the S-N curve reported in Ref. (1) for specimens tested on a stress cycle of complete reversal. Basing an S-N curve on three tests may cause doubt as to the accuracy of the derived curve. Nevertheless, the slope of the S-N curve for half tension-to-tension is in reasonably good agreement with the slopes for the other two curves.

When we consider the reduction in fatigue strength for plates with attachments on two sides at n = 20,000 cycles, we see that there is a reduction of 42 percent for complete reversal and a reduction of 24 percent for zero-to-tension. At n = 200,000 cycles, the curves for the two stress cycles intersect at a reduction in fatigue strength of 65 percent. The reduction in fatigue strength for this type of member is greater than that reported in the previous sections for butt welds (see Figs. 20 and 21).

3.5.2 Attachments on One Side

Five specimens were tested on a stress cycle of zero-to-tension and three on a stress cycle of half tension-to-tension. In this case, the slope of the S-N curve for half tension-to-tension is less than the slope of the S-N curve for zero-to-tension. The results of these tests are shown in Fig. B-8 together with the S-N curve for specimens tested on a stress cycle of complete reversal. The latter curve was originally presented in Ref. (1).

When we consider, at n = 20,000 cycles, the reduction in fatigue strength for plates with attachments on one side, we find that there is a reduction of about 30 percent for complete reversal and a reduction of about 24 percent for zero-to-tension. At n = 200,000 cycles, both stress cycles have a reduction in fatigue strength of about 65 percent.

3.5.3 Discussion of Results

In all the tests, failure initiated at the toe of the weld reinforcement where the transverse attachment was welded to the plate. Since in this type of joint the discontinuity is relatively uniform from specimen to specimen, the scatter was not as large as that obtained for the butt welded joints. It is interesting to note that at n = 200,000 cycles, the reduction in fatigue strength was 65 percent for the two types of attachments reported above, irrespective of the stress cycle. In Fig. 21, it can be seen that the reduction in fatigue strength for specimens with attachments on one side and on two sides are almost identical for the zero-to-tension cycle.

3.6 Fatigue Tests of Full Penetration Transverse Tee Joints

Full penetration transverse tee joints were tested using three stress cycles; complete reversal, zero-to-tension, and half tension-to-tension. The results of these tests are tabulated in Tables A-15, A-16, and A-17 and plotted in Fig. B-10; they have been used to construct the Modified Goodman diagram shown in Fig. 11.

There was a large amount of scatter in the results of the tests in complete reversal. Two specimens G-30 and G-34 had short lives and appeared to have had large internal defects from which the failure cracks started to propagate early in the tests. Four specimens were tested at each of the two remaining stress cycles; for these specimens, the scatter in life was small.

In tee joints, the weld provides not only a geometrical discontinuity but must also serve to transmit the load through the joint. None of the specimens of this test series failed at internal defects while eight others had failures which initiated at the toe of the weld reinforcement.

At n = 20,000 cycles, the reduction in fatigue strength was 50 percent for complete reversal and 23 percent for zero-to-tension (see Figs. 20 and 21). At n = 200,000 cycles, the reduction in fatigue strength was 54 percent for complete reversal and 37 percent for zero-to-tension.

3.7 Special Tests

The special tests which are reported in this series are listed in Table 2. The tests were conducted to obtain an indication of the effects of selected variables.

3.7.1 Electrode Tests

Three specimens were tested to determine whether an electrode that under matches the strength of the parent metal would reduce the fatigue strength of plain plates with a full penetration attachment on one side. The results of these tests are tabulated in Table A-18. The electrode used for these tests was of the MIL 9018 class. The test lives of these three specimens, tested at $\pm$ 30.0 ksi, were less than the average life of specimens fabricated with MIL 11018 electrode. The average life for specimens fabricated with MIL 9018 was 36,200 cycles while that for specimens fabricated with MIL 11018 was 48,000 cycles. Although there is a difference in life, the difference is not large and is less than the scatter in some of the previously mentioned test series.

If we compare the fatigue strengths of the two series at n = 36,000 cycles, we find that the specimens fabricated with MIL 11018 electrodes had a fatigue strength of ± 35.0 ksi while the group fabricated with MIL 9018 electrodes had a fatigue strength of ± 30.0 ksi. This amounts to a reduction in fatigue strength of about 17 percent. Since there are only a limited number of tests, it is not known whether or not this reduction would be constant throughout the range in lives and for the other stress cycles considered in this study.

The difference in the mode of cracking for the two groups of specimens is worth noting. In both cases, the cracks started at the toe of the weld reinforcement; but the manner in which the cracks propagated was different. In the specimens fabricated with MIL 11018 electrodes, the cracks propagated into the plate material traveling normal to the direction of loading. But, in the specimens fabricated with MIL 9018 electrodes, the cracks initially traveled parallel to the direction of loading and then gradually changed direction so that it finally propagated normal to the direction of loading (Fig. C-7).

3.7.2 Variation of Interpass Temperature

A number of specimens were fabricated using interpass temperatures of room temperature, 300 deg. F., and 400 deg. F. These specimens were tested in the as-welded condition, using a stress cycle of ± 30.0 ksi. The test results are plotted in Fig. B-13. Although there is a large amount of scatter, the lives of the joints appear to increase with an increase in interpass temperature. Metallographic studies indicate an increase in hardness with an increase in interpass temperature; this increase in hardness may be due to tempering effects or to better mixing of the weld metal. If the increase is due to tempering effects, a maximum in hardness should occur as the tempering temperature is increased.

3.7.3 Combined Welds

Six specimens having combined longitudinal and transverse butt welds were fabricated to determine whether the order of welding has any effect on the fatigue behavior of this type of joint. The specimens were tested in complete reversal and may be compared also with specimens having either transverse or longitudinal butt welds.

All the failures occurred in the weld which was placed last. Of the six specimens tested, five failed due to weld defects; in the sixth specimen failure was initiated at the edge of the reinforcement of the weld which was placed last. Specimen HL-25 was first tested from + 23.3 ksi to - 25.5 ksi for 13,800 cycles. Then the specimen was tested at $\pm$ 41.4 ksi until failure at 16,000 cycles. The first 13,800 cycles were estimated to be equal to 5.5 percent of the expected life of the specimen at + 23.3 ksi to - 25.5 ksi. Form this, the life to failure at $\pm$ 41.4 ksi was estimated to be 16,900 cycles.

The slopes of the S-N curves shown in Fig. B-14 are about the same as that for plain plate specimens tested in complete reversal. In the life range $20{,}000 \leq n \leq 200{,}000$ cycles, the specimens which were fabricated with the transverse butt weld placed last had a reduction in fatigue strength of about 50 percent. In the same life range, specimens which were fabricated with the longitudinal butt weld placed last had a reduction in fatigue strength of about 40 percent.

Joint	$F_{20,000}$	$F_{200,000}$
Transverse Butt Weld	56.5 ksi	19.3 ksi
Longitudinal Butt Weld	39.3 ksi	29.6 ksi
Longitudinal Butt Weld Placed Last	39.2 ksi	27.1 ksi
Transverse Butt Weld Placed Last	34.0 ksi	21.0 ksi

From the table above it may be seen that the behavior of the members with combined welds under full reversal is very similar to that for longitudinal butt welded specimens for short lives. For short lives, the fatigue strength of transverse butt weld specimens is much higher than for specimens containing longitudinal butt welds. At n = 200,000 cycles, the combined weld specimens with the longitudinal weld placed last had a fatigue strength about equal to that of a specimen having only a longitudinal butt weld. At this same life, the combined weld specimens with the transverse butt weld placed last had a fatigue strength about equal to that for specimens having only a transverse butt weld. For $n > 200,000$, the S-N curves for combined welds lie between the S-N curves for specimens having either longitudinal or transverse butt welds.

3.7.4 Lack of Penetration

In order to explore in a preliminary manner the effect of lack of penetration on the fatigue behavior of transverse butt welded joints in the as-welded condition, two specimens were fabricated having a nominal lack of penetration of 8 percent[c]. Radiographs showed that

[c] Percent of cross sectional area that was not welded.

the lack of penetration was present, but the indication was somewhat blurred since the shrinkage of the weld had forced the landed surfaces into very close contact. In the specimen tested at $\pm$ 30.0 ksi, there was no observable movement of the gap; but in the specimen tested at 0-to-60.0 ksi, the gap opened and closed as the specimen was subjected to the load cycle. The specimen tested at $\pm$ 30.0 ksi had a life equal to that for full penetration transverse butt welds tested using the same stress cycle. In the case of the specimen tested at 0-to-60.0 ksi, the life was 26,700 cycles as compared to an average of 42,000 cycles for specimens having full penetration welds. The table below is for n = 26,700 cycles and a stress cycle of zero-to-tension.

Material	Source	Plate Thickness	% Lack of Penetration	% Reduction in F.S. [d]
HY-80	Present Study	1-1/2"	8%	14.3%
A-7	(5)	7/8"	43%	51.7%
A-7	(5)	7/8"	57%	59.3%

The results given in the table seem to indicate that as the amount of lack of penetration increases initially from zero there is a large decrease in fatigue strength. Since the materials are different and only one specimen was fabricated of HY-80 steel, no conclusions can be reached other than to observe that the lack of penetration can decrease the fatigue strength markedly.

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[d] This reduction is based on the life of a full penetration butt welded joint. Stresses are based on gross area.

3.7.5 Longitudinal Fillet Welded Attachments

One specimen having longitudinal fillet welded attachments on two sides was tested using a nominal stress of ± 20 ksi in the test section. This stress was computed on the assumption that no part of the load was carried by the attachments. At the ends of the attachments, where all the cracks initiated, the nominal stress on the net section was ± 9.5 ksi. Failure occurred after 696,400 cycles. The test results can only be considered qualitatively since the fillet weld returns at the ends of the attachments were situated in the transition region of the specimen. This region had stress raisers due both to the attachments and to the transition curve (Fig. 1i). The first crack appeared at point 2 (Fig. 22) in the fillet weld return after 170,000 cycles. After 242,000 cycles, cracks also appeared at points 1 and 3. After 450,000 cycles, the crack which had started at point 2 had propagated a distance of 1/2 in. along the plain plate surface on each side of the attachment. After 660,000 cycles, this crack propagated rapidly causing failure of the specimen. References (6) and (7) indicate that for specimens of this type failure almost always occurs at the end of the longitudinal attachment.

3.8 Comparison of Results

In this section, the fatigue behavior of welded joints discussed in Sections 3.3 through 3.6 are compared. The results of fatigue tests of plain plate specimens with an attachment on one side or with a transverse butt weld are also compared with test results reported in Refs. (8) and (9).

3.8.1 Comparison of the Behavior of Welded Joints

The constant life contours at n = 20,000 cycles for each type of joint tested are plotted on a Modified Goodman diagram in Fig. 12.

For a stress cycle of half tension-to-tension the curves for all types of joints fall within a range of maximum stress of approximately 85 ksi to 100 ksi. For a zero-to-tension stress cycle, the curves for tee joints, plates with attachments on one side or on two sides, and longitudinal butt welds are still grouped together but somewhat below the curves for plain plate and transverse butt weld specimens. As the mean stress approaches zero, the constant life contours spread out a great deal more. The highest curve is that for the plain plate specimens and the lowest curve is that for the tee joints; the alternating stress ranges from a maximum value of $\pm$ 66 ksi to $\pm$ 33 ksi, a reduction of 50 percent. The remaining curves lie between these two values. Thus, it is apparent that, for short lives, weld geometry becomes more important at the lower levels of mean stress.

The constant life contours at n = 200,000 cycles for each type of joint tested are plotted on a Modified Goodman diagram in Fig. 15. At this life, the effect of geometry, both external and internal, appears to be more important than at the shorter lives, especially in the case of complete reversal where the alternating stress for plain plate specimens is $\pm$ 44 ksi while that for plates having attachments on one side or on two sides is $\pm$ 15 ksi, a reduction of about 66 percent. For n = 200,000 cycles, we see also that the curves for transverse butt welds and tee joints are very similar.

In complete reversal (Fig. 20), the curves showing the reduction in fatigue strength of longitudinal butt welds and tee joints are almost constant over the life range $20{,}000 \leq n \leq 200{,}000$ cycles while the reduction in fatigue strength increases with life for transverse butt welds and plates with transverse attachments. For zero-to-tension loadings

(Fig. 21), this same situation is evident, except that the reduction in fatigue strength of the tee joints increases at a faster rate than in complete reversal. In the case of longitudinal butt welds and tee joint specimens, all failures at low fatigue lives were weld failures.

3.8.2 Comparison with Other Tests

Reference (8) gives the results of fatigue tests of two series of specimens, PB and LB, having full penetration attachments on one side which are referred to as "double fillet tees". The specimens were fabricated from HY-80 steel and were tested in flexure. The specimens were fabricated so that a trapezoidal stress distribution was produced through the thickness of the test section during loading; the loading cycle was such that the plate material at the toe of the weld was subjected to complete reversal. The results of these tests are plotted in Fig. 23, cycles to failure being taken as the number of cycles causing complete failure or tripping of a microswitch. The results reported in Ref. (1) for the same general type of joint subjected to an axial loading have also been plotted in this same figure and are found to be in good agreement with those given in Ref. (8). An interesting point is that for $n > 100,000$ cycles the results of the LB series indicate that the S-N curve tends to become flatter as the life increases.

Reference (9) gives the results of "double fillet tees" and butt weld specimens tested as simply supported plates subjected to a pulsating uniform pressure on their surface. The flexural stress at the surface of the specimens at the critical section varied from zero to tension. The results of the "double fillet tees" reported in Ref. (9) are plotted in Fig. 24 along with the data for the present studies. It should be remembered that the results reported in this report are for axially loaded members. Nevertheless, these results are also in good agreement with one another. For the tests reported in Ref. (9), cycles to failure was defined as the number of cycles necessary to produce an increase in deflection equal to 100 percent of the initial deflection.

A series of butt welds was fabricated from 1-11/16 in. material. Three of these were tested in the as-welded condition and five were tested with a reduced thickness of 1 in. This reduction in thickness was accomplished by removing material from the side of the plate that was in compression during the loading cycle. These results are given in Fig. 25 and again are in good agreement with previously reported results[1] for axially loaded butt welds in the as-welded condition.

The excellent correlation referred to above is most likely due to the fact that all failures initiated as a result of severe weld geometry. Figures 23, 24, and 25 are plotted using the nominal maximum stress at the surface at the critical section.

IV. SUMMARY

4.1 Summary of Results

The results of the tests are discussed in detail in Sections 3.2 through 3.6. Table 5 gives a summary of the results of these tests. Figure 5 contains a Modified Goodman diagram for as-rolled HY-80 plate. Figures 6 through 11 contain Modified Goodman diagrams for the various types of weldments and welded joints tested in this test program. The special tests have been listed in Table 2 and are discussed in Section 3.7.

The results of fatigue tests of plain plate specimens in complete reversal indicate that at n = 20,000 cycles the fatigue strength is about 67 percent of the static tensile strength of the material while at n = 200,000 cycles it is about 50 percent of the static strength.

The results of fatigue tests of transverse butt welded joints in the as-welded condition indicate that the importance of the mean stress, alternating stress, or maximum stress will vary, depending upon the test conditions. Where the positive mean stress is the variable, the stress range is generally the controlling factor in determining the fatigue life of the specimen. For negative mean stresses, the magnitude of the tensile component of the stress range has a great influence on the fatigue life of the test specimens.

For transverse butt welded joints tested in complete reversal, the removal of the reinforcement on two sides does not appear to increase the fatigue strength of the joint over that for a joint in the as-welded condition when the test life is short, n = 20,000 cycles. But, at longer lives, the improvement in fatigue strength due to removal of the reinforcement is quite evident (Fig. 16). For specimens tested in zero-to-tension (Fig. 17), there is little difference at n = 20,000 cycles in the fatigue strengths of the specimens tested in either of the geometrical conditions considered. However, the influence of improved geometry becomes quite evident at the longer fatigue lives. Thus, with the removal of the weld reinforcement, large improvements in the fatigue strength of welded joints can be expected at long lives if there are no serious internal flaws since removal of the weld reinforcement may make an internal flaw the nucleation point for fatigue failure.

The results of fatigue tests on longitudinal butt welded joints indicate that, at longer lives, the geometrical effect of the weld reinforcement is less than in the case of transverse welds in the as-welded condition. Since there was a large amount of scatter in the lives of the specimens tested in complete reversal, there may be some question as to the accuracy with which this S-N curve represents the behavior of longitudinal butt welded joints. Nevertheless, the test results indicate the destructive effects that internal defects may have on the fatigue life of welded joints. In the range $20{,}000 \leq n \leq 200{,}000$ cycles, the reduction in fatigue strength for specimens tested in complete reversal was about 40 percent and for specimens tested in zero-to-tension it was about 30 percent.

In the case of plain plate specimens with full penetration transverse attachments on one side or on two sides, all failures initiated at the toe of the weld and the scatter in cycles to failure was small in each series of tests. The slopes of the S-N curves for these types of joints were about the same as those for transverse butt welded joints in the as-welded condition. At $n = 200{,}000$ cycles, we can see in Fig. 20 and 21 that the reduction in fatigue strength is about 65 percent for specimens tested in zero-to-tension or complete reversal and having transverse attachments on one side or on two sides.

In a tee joint the weld not only provides a sharp discontinuity but also must transmit the load through the joint. This makes weld quality an important factor in determining the fatigue strength of the joint. The reduction in fatigue strength of this joint over the range, $20{,}000 \leq n \leq 200{,}000$ cycles, was 50 to 55 percent for complete reversal and 35 to 40 percent for zero-to-tension. In making this type of weld, care must be taken in order to obtain the necessary weld quality.

4.2 Closing Remarks

A great deal of information has been obtained for the various types of joints considered, but many of the S-N curves are based on a very limited number of tests. The Modified Goodman diagrams (Fig. 5 through 11) are based on the average values of fatigue strength tabulated in Table 5. Although the constant life contours in these figures appear to be uniformly distributed, it must be remembered that there is scatter in the fatigue strength for each fatigue life. The amount of scatter is generally a minimum when there are significant geometrical changes in the member since in this case the fatigue life depends primarily on the joint geometry.

Radiographs were taken of all transverse and longitudinal butt welded joints. They indicate that the weld quality of all the specimens exceeded by far the requirements of the current Navy specifications for HY-80 steel[2].

Due to the limited number of tests in any one series, it is dangerous to extrapolate the results of these tests to predict long life behavior. However, it is believed that in the range of lives for which test data is available herein, the values of fatigue strength reported are reasonable and interpolations can be made with confidence.

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TABLE 1

SUMMARY OF TESTS ON SPECIMENS OF 1 1/2" HY-80 PLATE

Specimen Type	Specimen Numbers	Heat No.	Welding Procedure (See Appendix D)
Plain Plate Fig. (1a)	V-55 to V-64	19595-1	-
Transverse Butt Welds Fig. (1b)	HL-30, HL-31 W-21 to W-23 W-27 to W-30 G-1 to G-21	20995 19165 19165 69S344	P80-11018-D P80-11018-D P80-11018-D P80-11018-D
Longitudinal Butt Weld Fig. (1c)	G-37 to G-48	69S344	P80-11018-O
Full Penetration Attachment Fig. (1d)	W-3 to W-10	19165	P80-11018-P
Full Penetration Attachment Fig. (1e)	W-11 to W-20	19165	P80-11018-Q
Full Penetration Tee Joint Fig. (1f)	G-22 to G-34	69S344	P80-11018-R

TABLE 2

SUMMARY OF SPECIAL TESTS ON SPECIMENS OF 1 1/2" HY-80 PLATE

Specimen Type	Specimen Numbers	Principal Variable	Heat No.	Welding Procedure (See Appendix D)
Transverse Butt Weld Fig. (1b)	HL-27 HL-28 HL-29 G-51 G-52 G-53	Interpass Temperature	20995 20995 20995 69S344 69S344 69S344	P80-11018-S P80-11018-E P80-11018-T P80-11018-S P80-11018-E P80-11018-T
Full Penetration Attachment Fig. (1e)	W-24 to W-26	Electrode	19165	P80-9018-A
Combined Transverse and Longitudinal Butt Welds	HL-20 to HL-22 Fig. (1g) HL-23 to HL-25 Fig. (1h)	Welding Sequence	20995 20995	P80-11018-0 & P80-11018-D P80-11018-D & P80-11018-0
Transverse Butt Weld Fig. (1b)	G-49, G-50	Lack of Penetration	69S344	P80-11018-D except no root opening
Longitudinal Fillet Welded Attachment Fig. (1i)	HL-26	Longitudinal Attachment	20995	P80-11018-N

TABLE 3

PHYSICAL CHARACTERISTICS OF BASE METAL

(Data Supplied by Manufacturer)

Heat Number	Designation	Properties in the Longitudinal Direction				
		Yield Strength* (ksi)	Tensile Strength (ksi)	Elongation in 2 in. (percent)	Reduction of Area (percent)	Charpy V Notch ft lbs @-120°F
20995	HL	87.3	105.0	25.0	69.4	138
19595-1	V	80.5	101.1	29.0	74.8	103
69S344	G	88.5	108.3	22.6	69.2	92
19165	W	82.6	102.5	26.0	--	112

* 0.2% offset.

TABLE 4

CHEMICAL CHARACTERISTICS OF BASE METAL

(From Mill Report)

Chemical Content (percent)	Heat Number and Designation			
	20995 HL	19595-1 V	69S344 G	19165 W
C	0.15	0.18	0.16	0.15
Mn	0.28	0.32	0.33	0.34
P	0.018	0.010	0.021	0.014
S	0.019	0.021	0.019	0.023
Si	0.25	0.20	0.26	0.25
Ni	2.95	3.01	2.86	3.00
Cr	1.40	1.47	1.61	1.57
Mo	0.41	0.48	0.48	0.42
Cu	0.16	0.20	--	--

TABLE 5

SUMMARY OF THE RESULTS OF THE FATIGUE TESTS

Specimen Type	Surface Condition	Source of Data	Stress Ratio*	k	Computed Fatigue Strengths, ksi				
					$F_{20,000}$	$F_{50,000}$	$F_{100,000}$	$F_{200,000}$	$F_{2,000,000}$
Plain Plate	As-Rolled	***	0	0.149	89.9	78.5	67.9	60.9	43.6
		***	-1	0.174	--	58.0	50.0	43.9	29.6
Transverse Butt Weld	As-Welded	**	0	0.340	77.3	56.3	44.6	35.0	--
		**	-1	0.465	56.5	36.4	26.6	19.3	--
	Reinforcement removed on one side	***	0	0.160	--	59.9	54.5	48.0	35.6
	Reinforcement removed on two sides	***	0	0.146	--	71.2	64.3	58.2	--
		***	-1	0.160	--	42.7	39.8	37.8	24.4
Longitudinal Butt Welds	As-Welded	***	1/2	0.12	--	--	80.9	74.3	56.0
		***	0	0.12	60.7	53.1	48.4	45.8	35.9
		***	-1	0.12	39.3	35.1	32.2	29.6	--
Full Penetration Attachments on Two Sides	As-Welded	***	1/2	0.580	--	82.5	55.2	36.9	--
		***	0	0.488	65.6	42.0	29.9	21.6	--
		**	-1	0.405	38.3	26.7	20.1	15.3	--
Full Penetration Attachment on One Side	As-Welded	***	1/2	0.331	--	76.3	60.7	48.2	--
		***	0	0.487	65.9	42.2	30.0	22.1	--
		**	-1	0.487	46.7	29.8	21.4	15.0	--
Tee Joints	As-Welded	***	1/2	0.225	--	82.9	71.2	60.9	36.5
		***	0	0.238	66.5	53.4	45.4	38.7	--
		***	-1	0.215	33.1	26.8	23.6	20.2	--

* Stress Ratio = $\frac{\text{Minimum Stress}}{\text{Maximum Stress}}$ ** Data reported in Ref. (1)

*** See Appendix A for detailed results (Tables A-1 to A-21 inclusive).

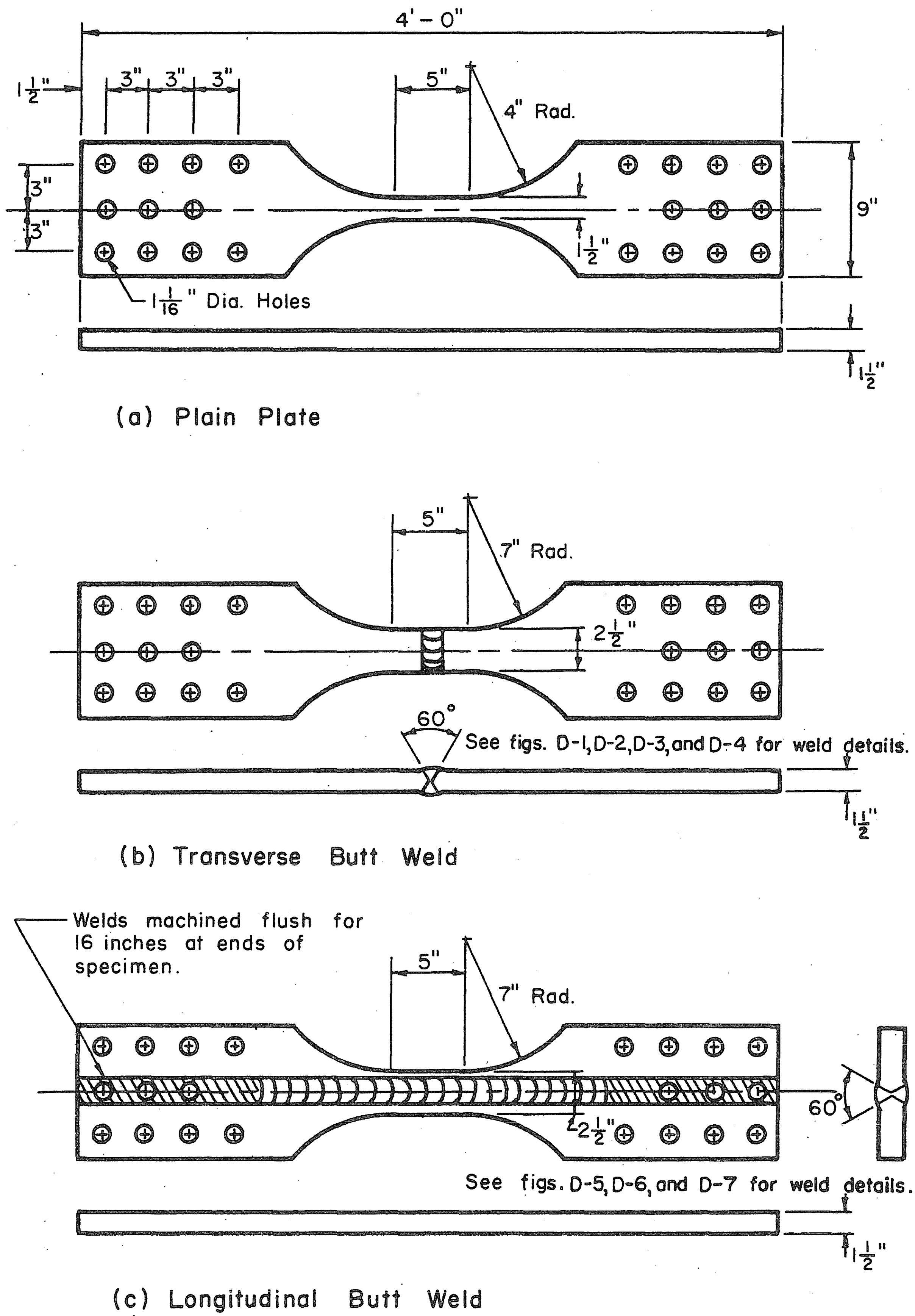
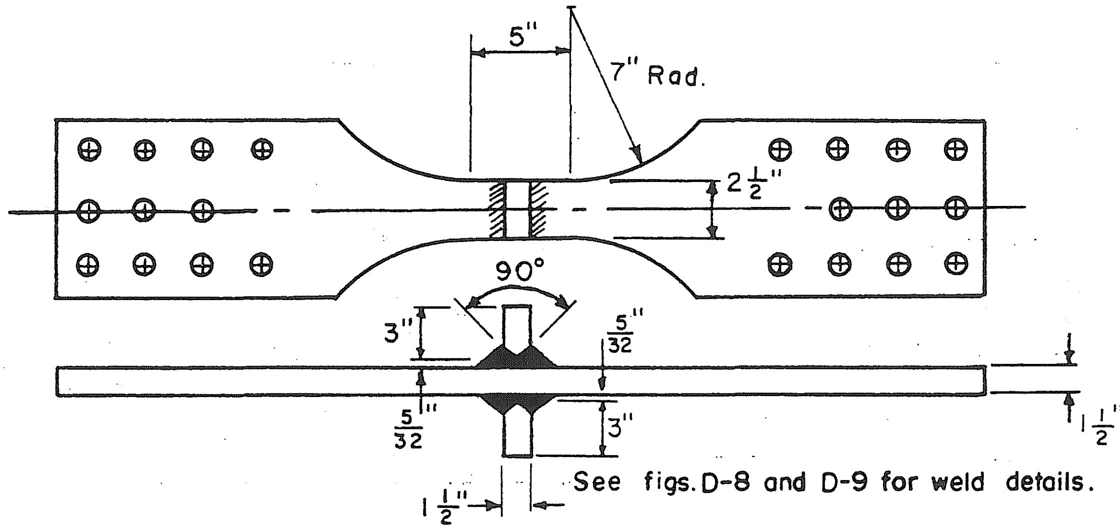
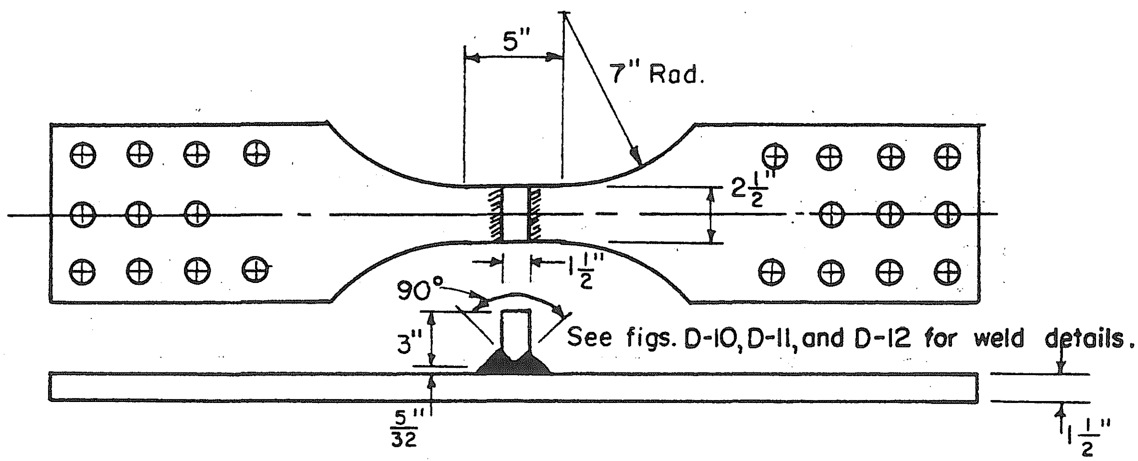


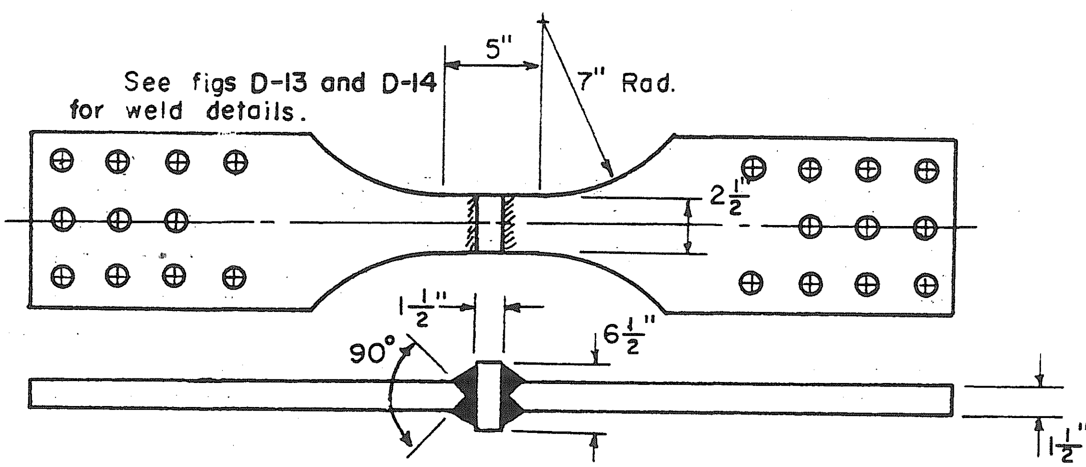
FIG. 1 DETAILS OF TEST SPECIMENS.



(d) Full Penetration Transverse Attachments

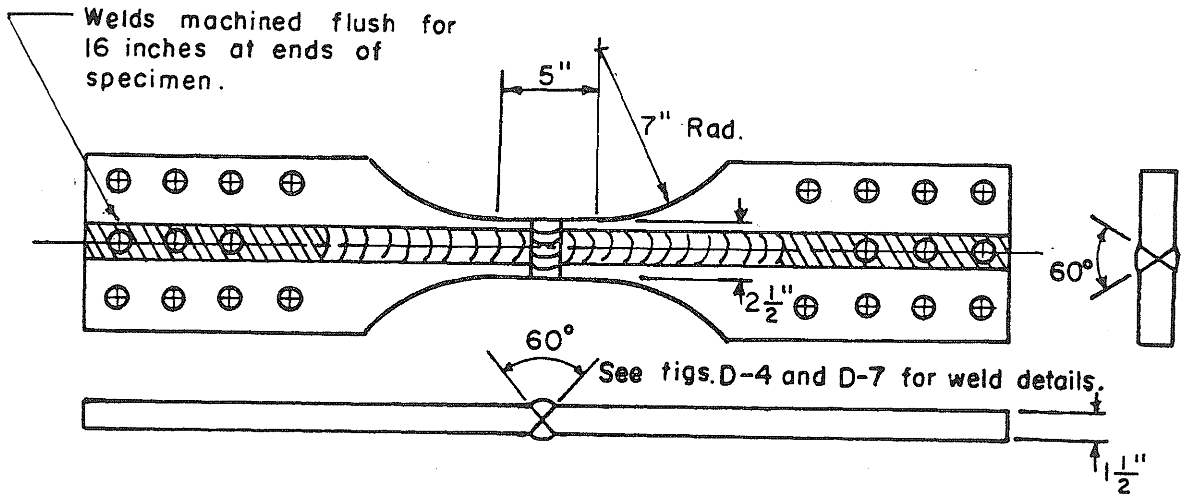


(e) Full Penetration Transverse Attachment

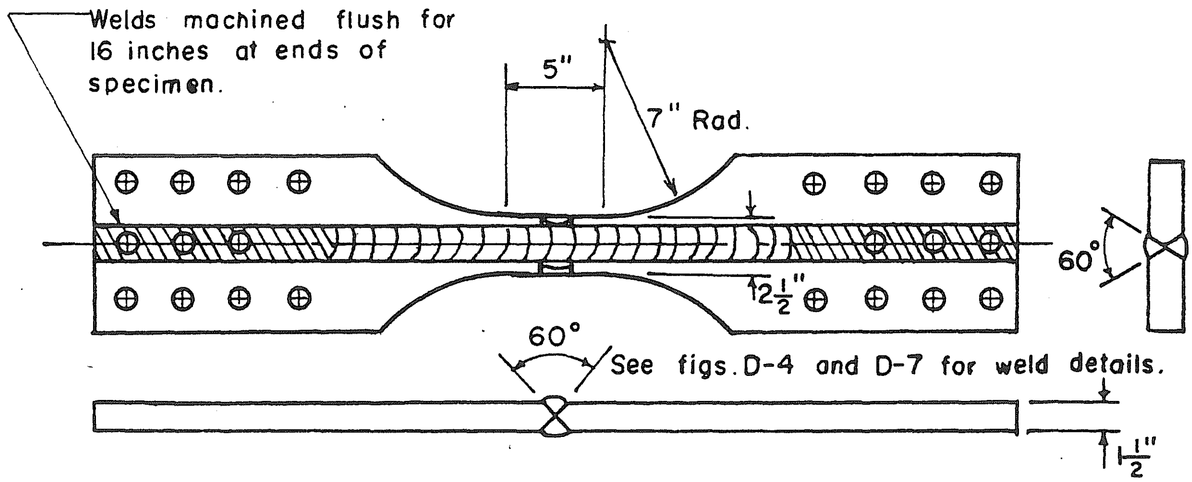


(f) Full Penetration Tee Joint

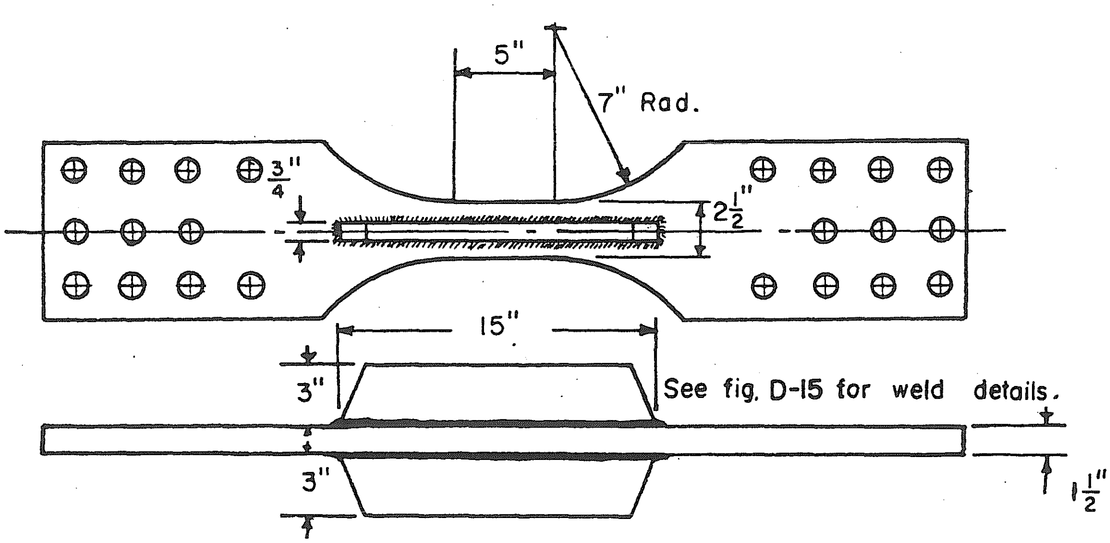
FIG. 1 (Contd.) DETAILS OF TEST SPECIMENS.



(g) Longitudinal Butt Weld Followed by Transverse Butt Weld



(h) Transverse Butt Weld Followed by Longitudinal Butt Weld



(i) Longitudinal Fillet Welded Attachments

FIG. 1 (Contd.) DETAILS OF TEST SPECIMENS.

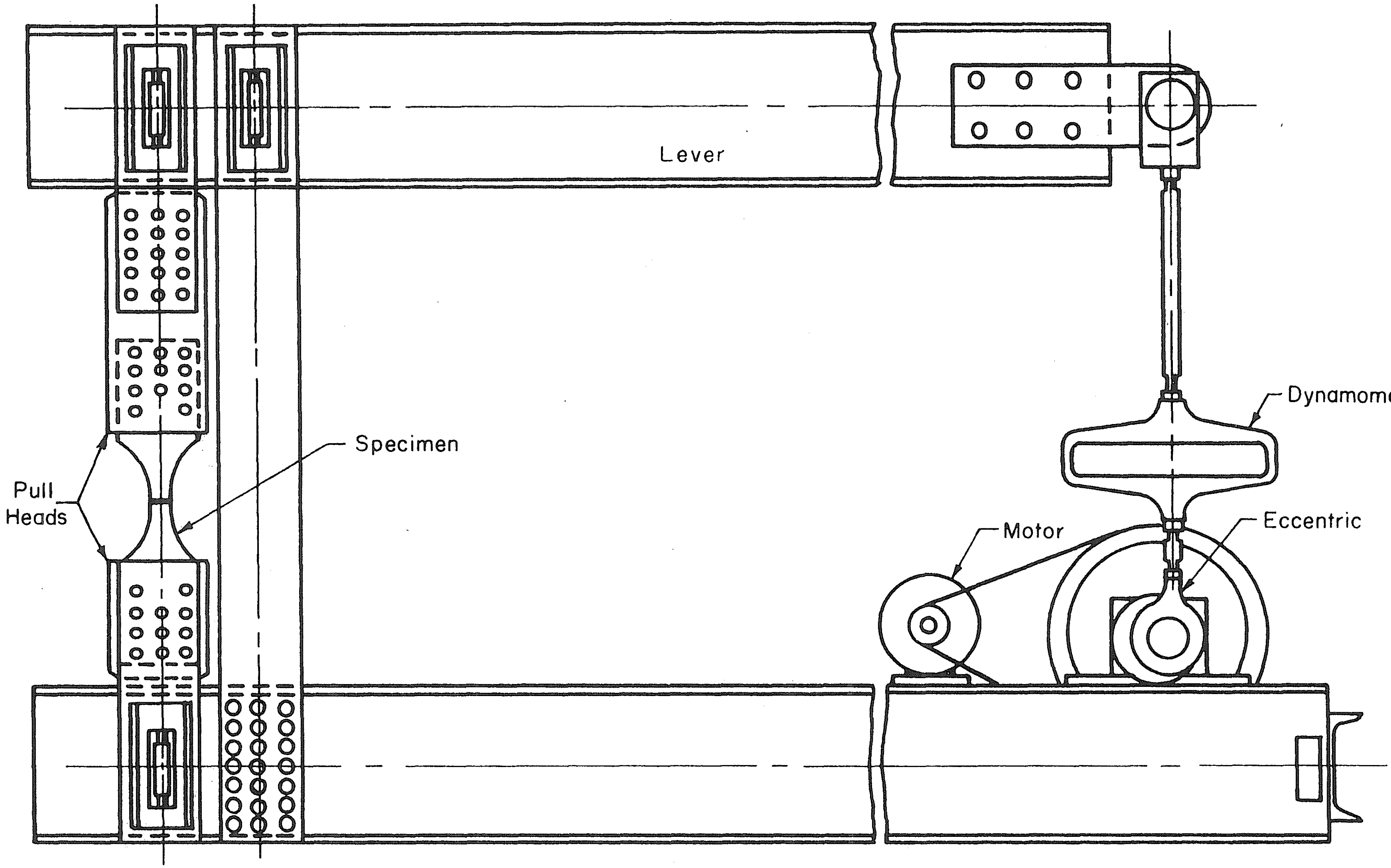


FIG. 2 ILLINOIS' FATIGUE TESTING MACHINE AS USED FOR AXIAL LOADING OF WELDED JOINTS.

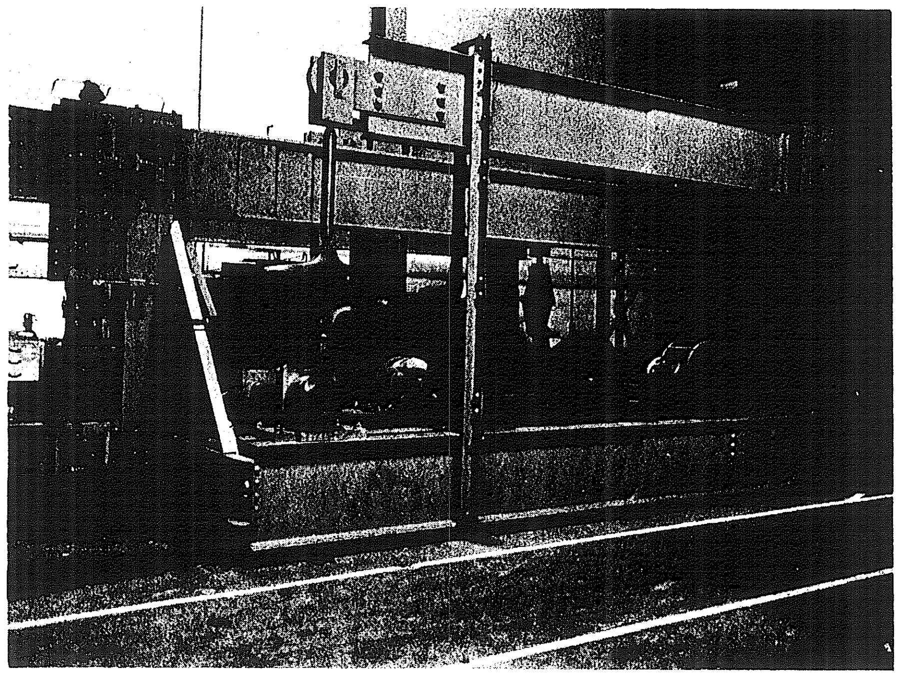


FIG.3 ILLINOIS' FATIGUE TESTING MACHINES.

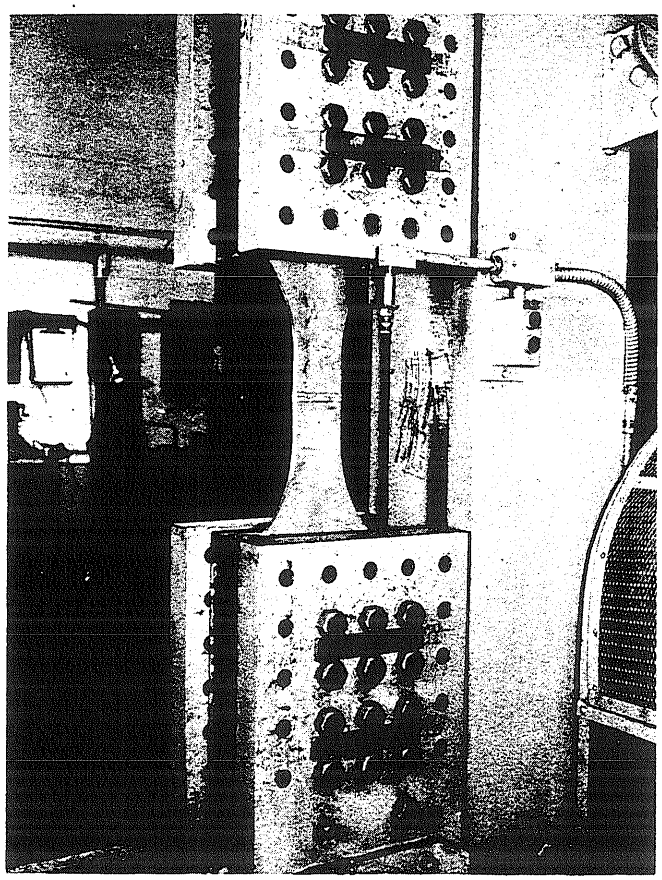


FIG. 4 TRANSVERSE BUTT WELDED JOINT IN FATIGUE MACHINE.

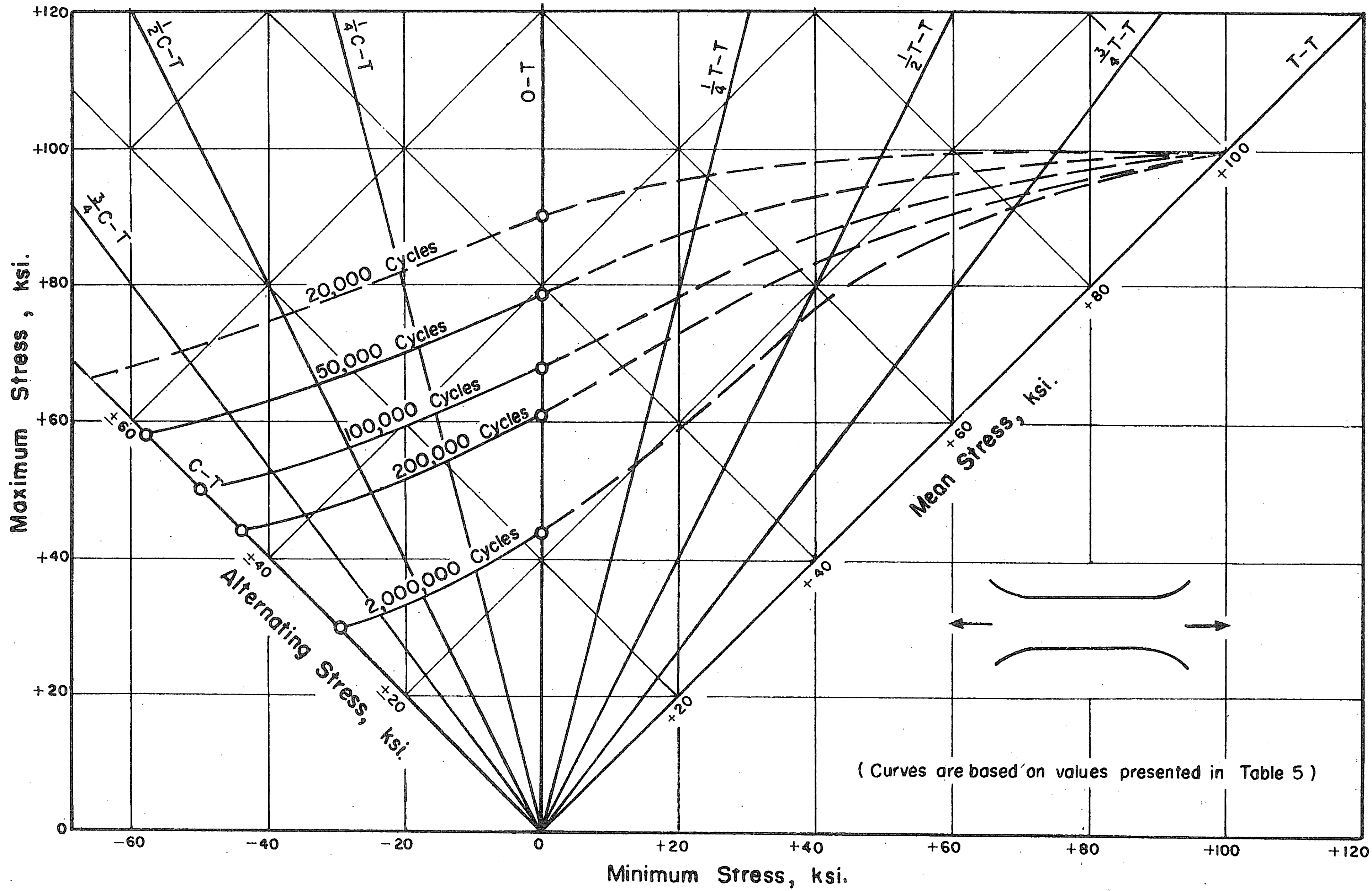


FIG. 5 MODIFIED GOODMAN DIAGRAM FOR AS-ROLLED HY-80 PLATE.

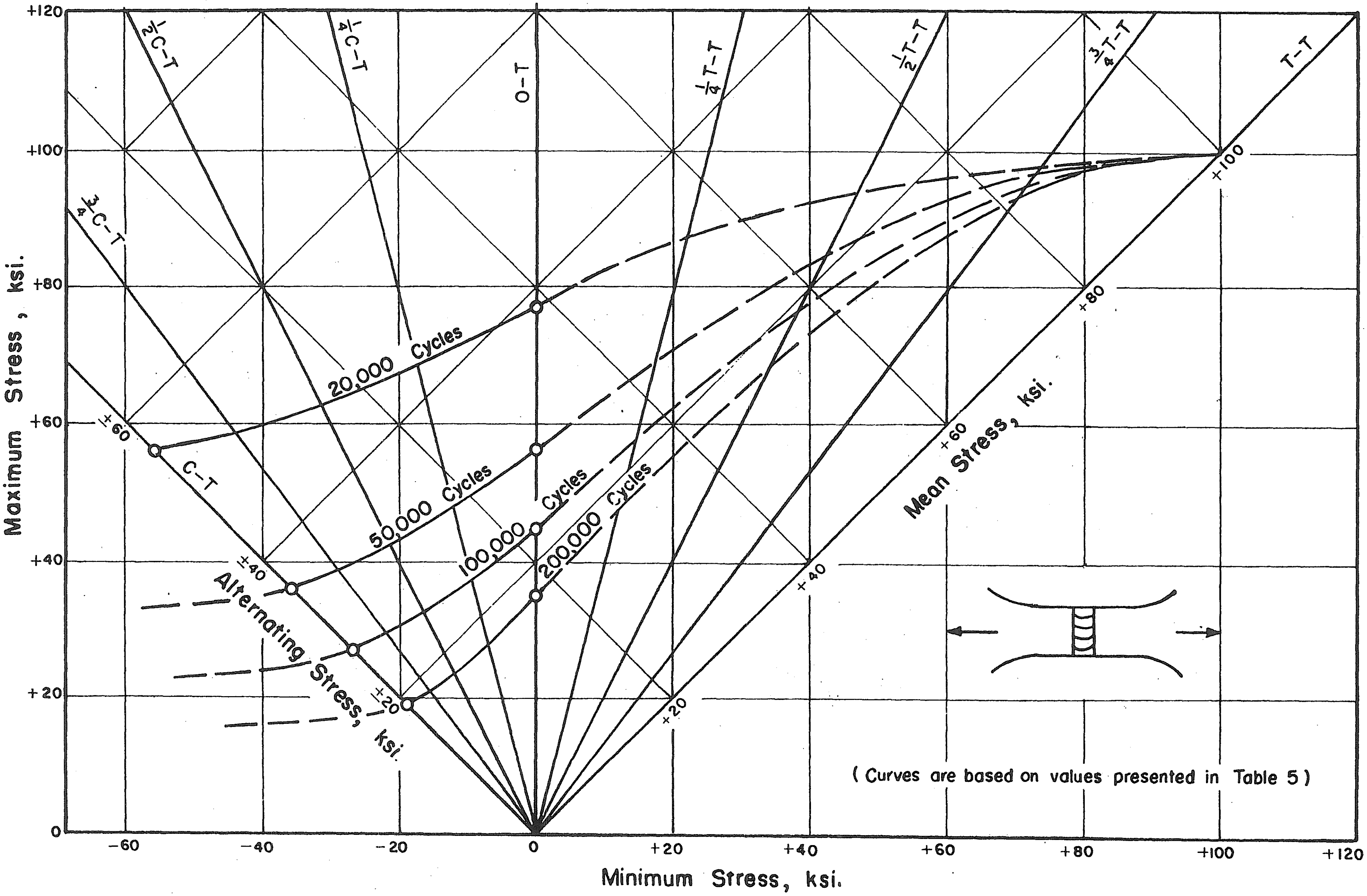


FIG. 6 MODIFIED GOODMAN DIAGRAM FOR TRANSVERSE BUTT WELDS IN HY-80 STEEL, IN THE AS-WELDED CONDITION.

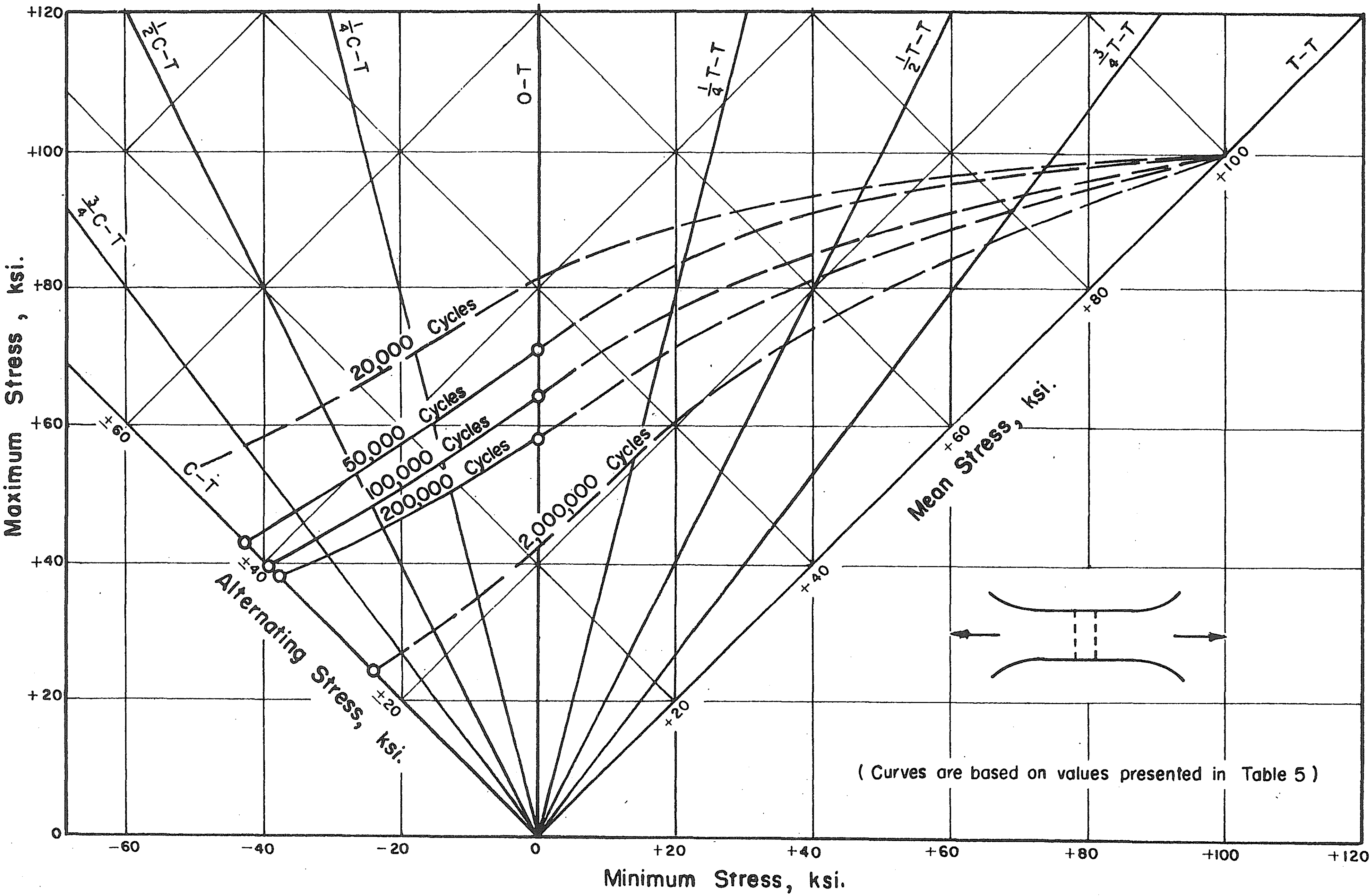


FIG. 7 MODIFIED GOODMAN DIAGRAM FOR TRANSVERSE BUTT WELDS IN HY-80 STEEL, HAVING REINFORCEMENT REMOVED ON TWO SIDES.

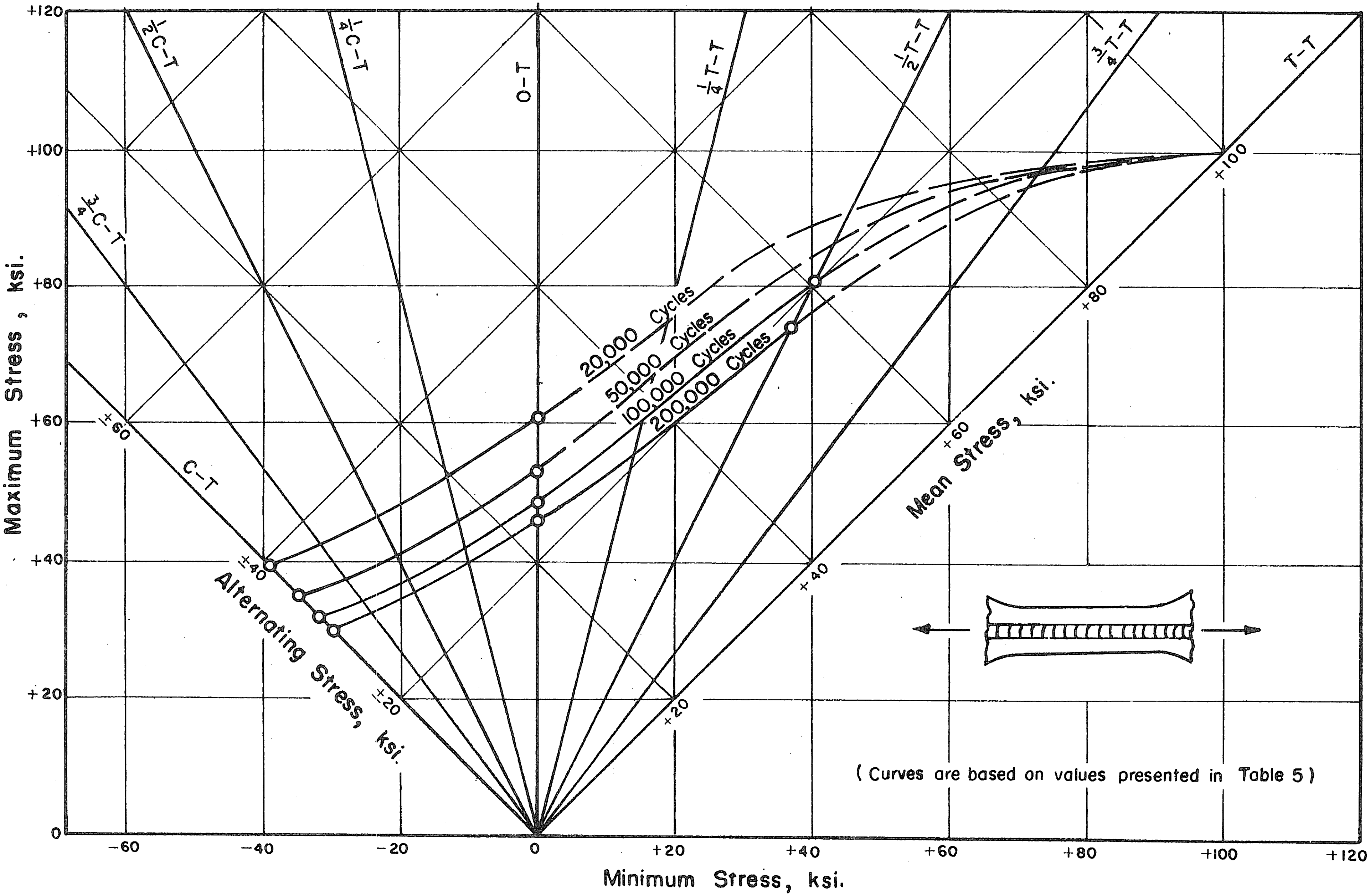


FIG. 8 MODIFIED GOODMAN DIAGRAM FOR LONGITUDINAL BUTT WELDS IN HY-80 STEEL, IN THE AS-WELDED CONDITION.

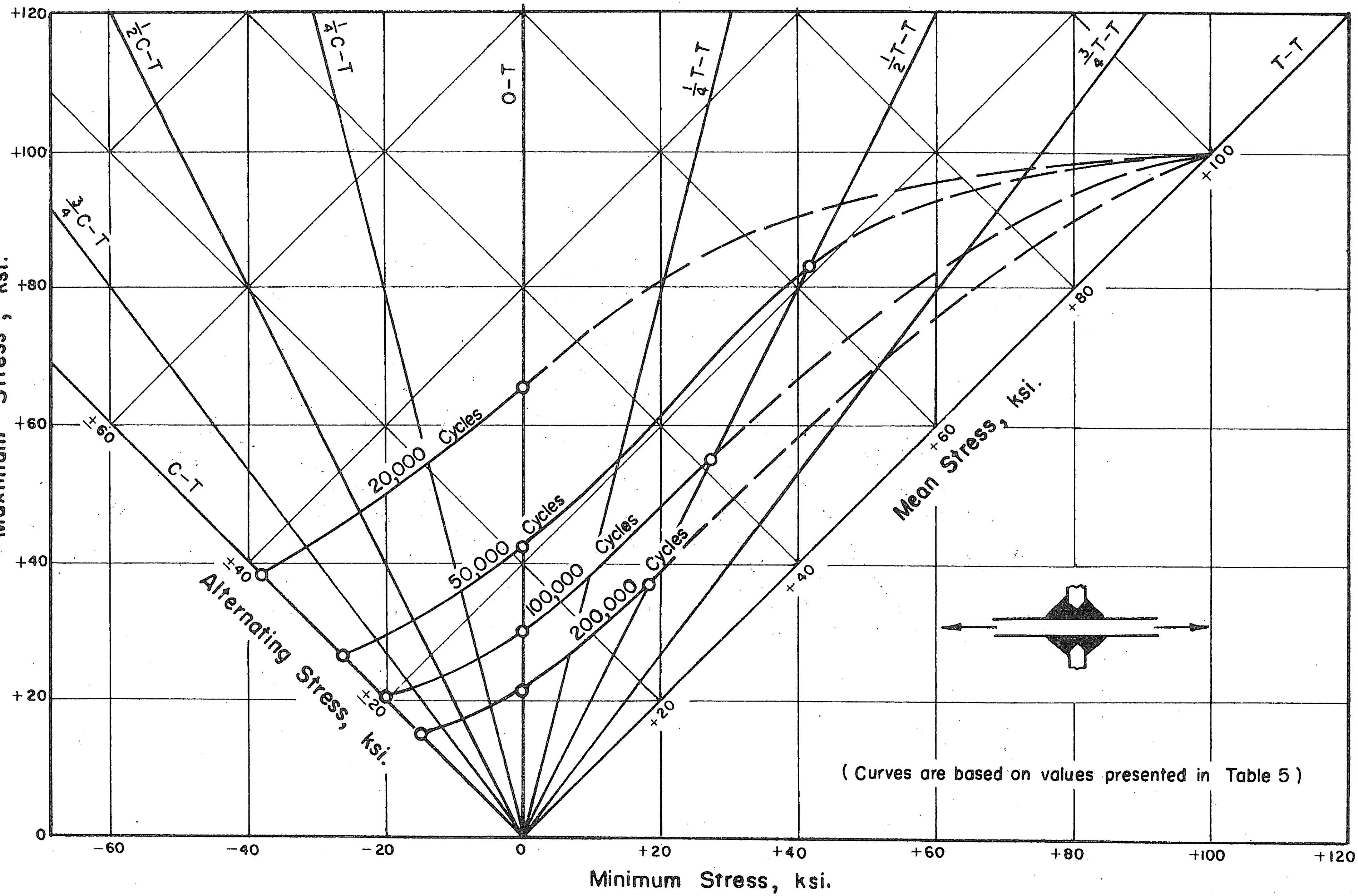


FIG. 9 MODIFIED GOODMAN DIAGRAM FOR AS-ROLLED HY-80 PLATE HAVING FULL PENETRATION ATTACHMENTS ON TWO SIDES.

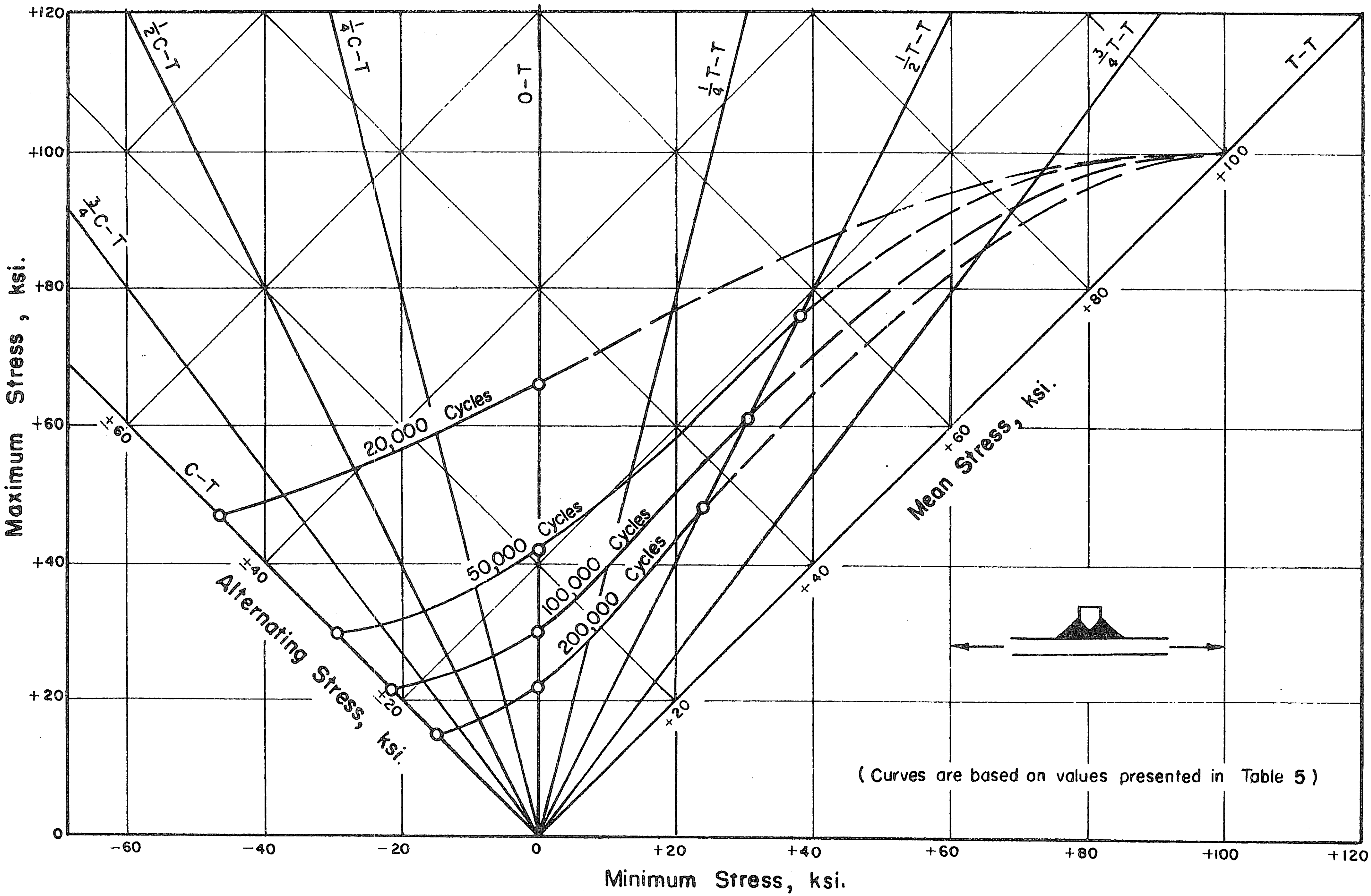


FIG. 10 MODIFIED GOODMAN DIAGRAM FOR AS-ROLLED HY-80 PLATE HAVING A FULL PENETRATION ATTACHMENT ON ONE SIDE.

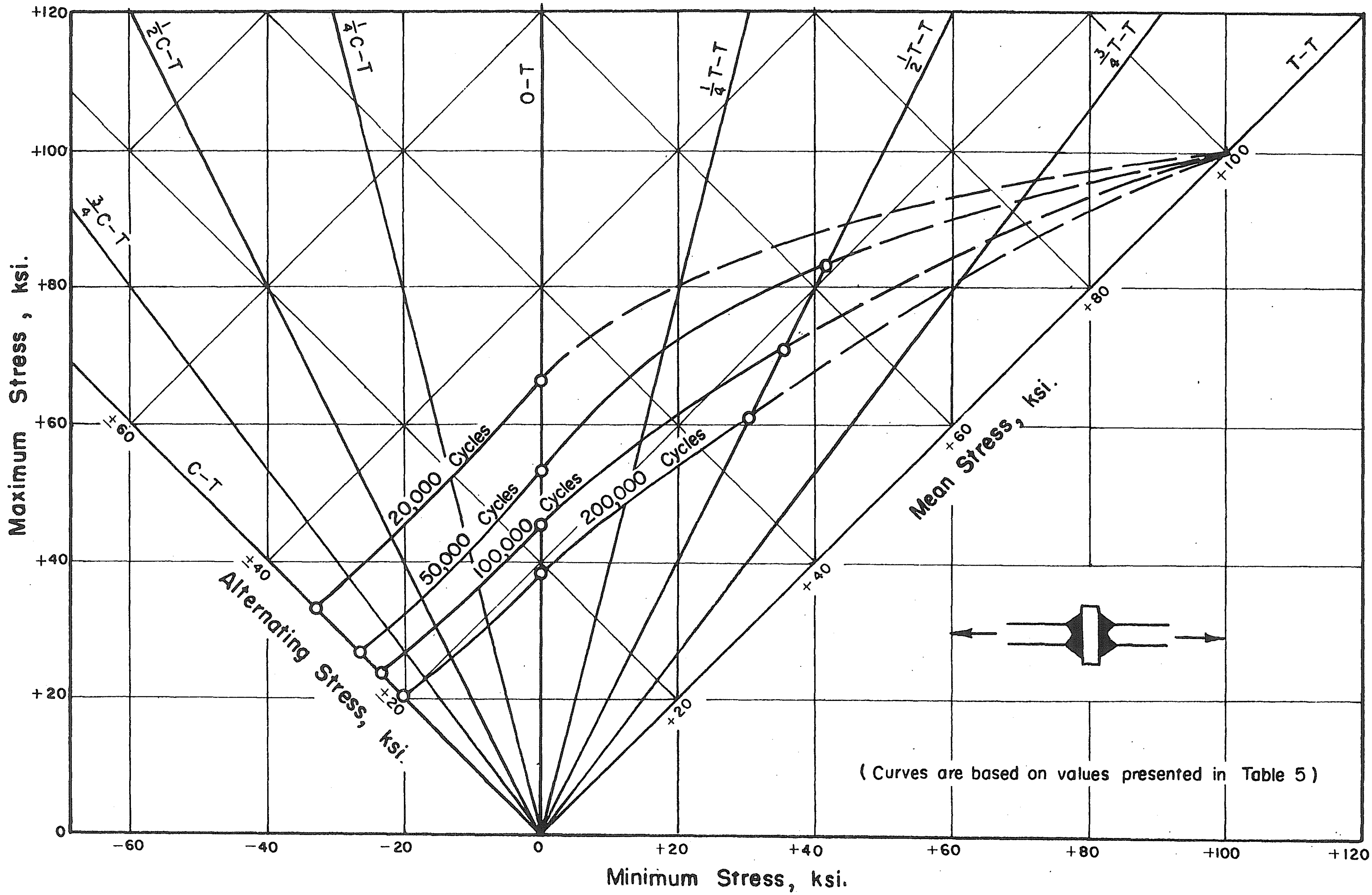


FIG. 11 MODIFIED GOODMAN DIAGRAM FOR TEE JOINTS IN HY-80 STEEL.

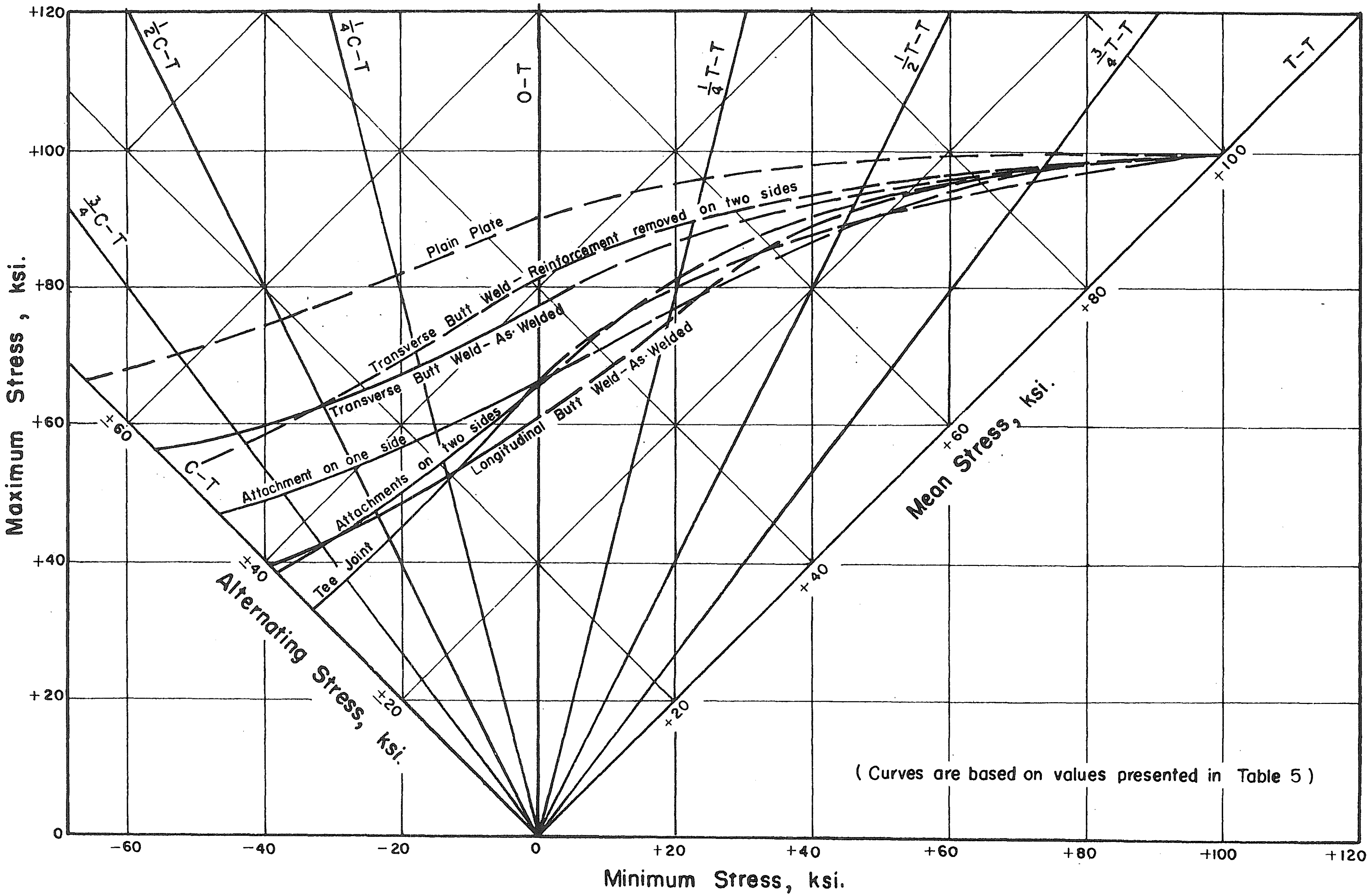


FIG. 12 MODIFIED GOODMAN DIAGRAM SHOWING $F_{20,000}$ CONTOURS FOR VARIOUS WELDMENTS IN HY-80 STEEL.

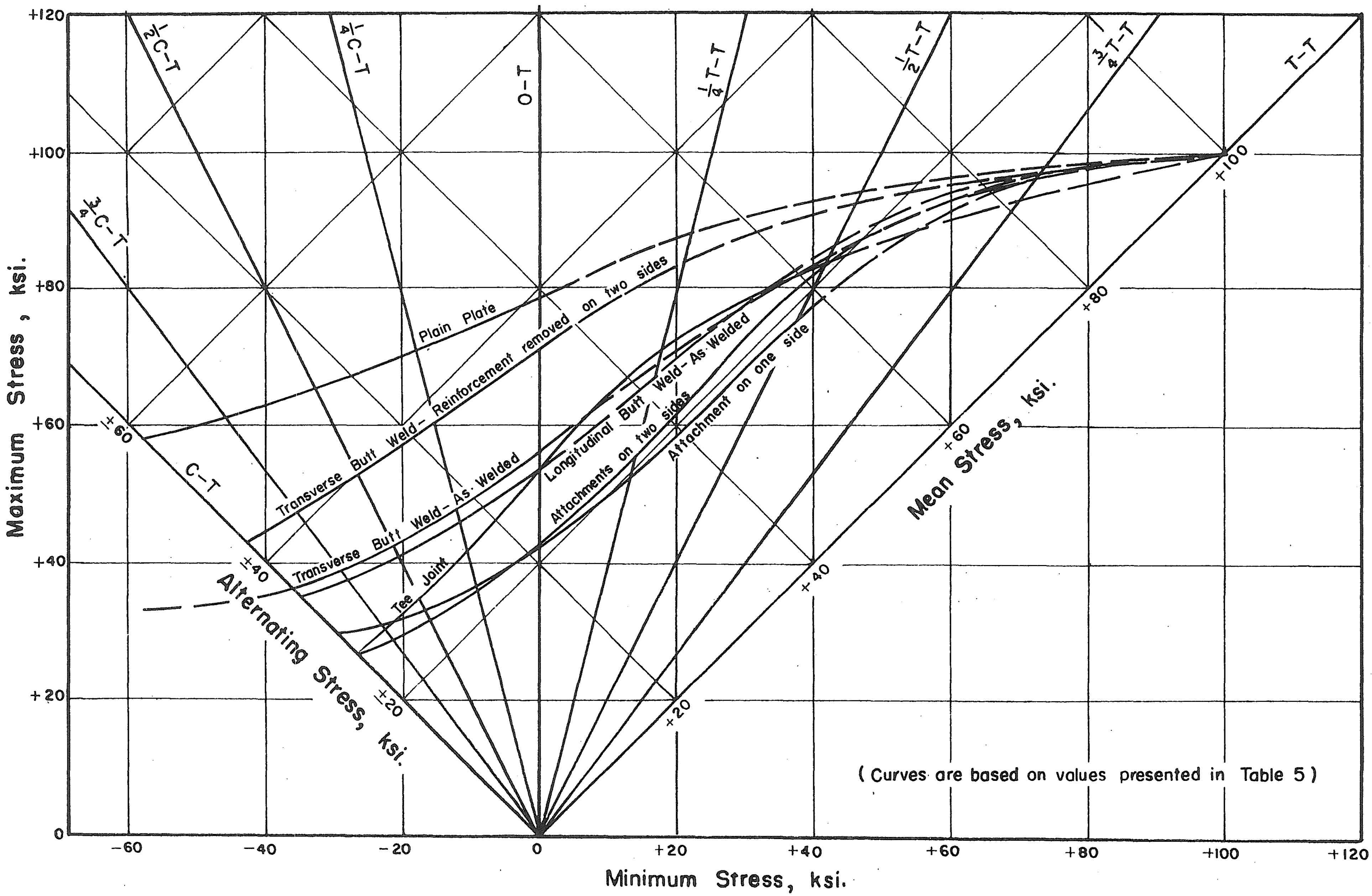


FIG. 13 MODIFIED GOODMAN DIAGRAM SHOWING $F_{50,000}$ CONTOURS FOR VARIOUS WELDMENTS IN HY-80 STEEL.

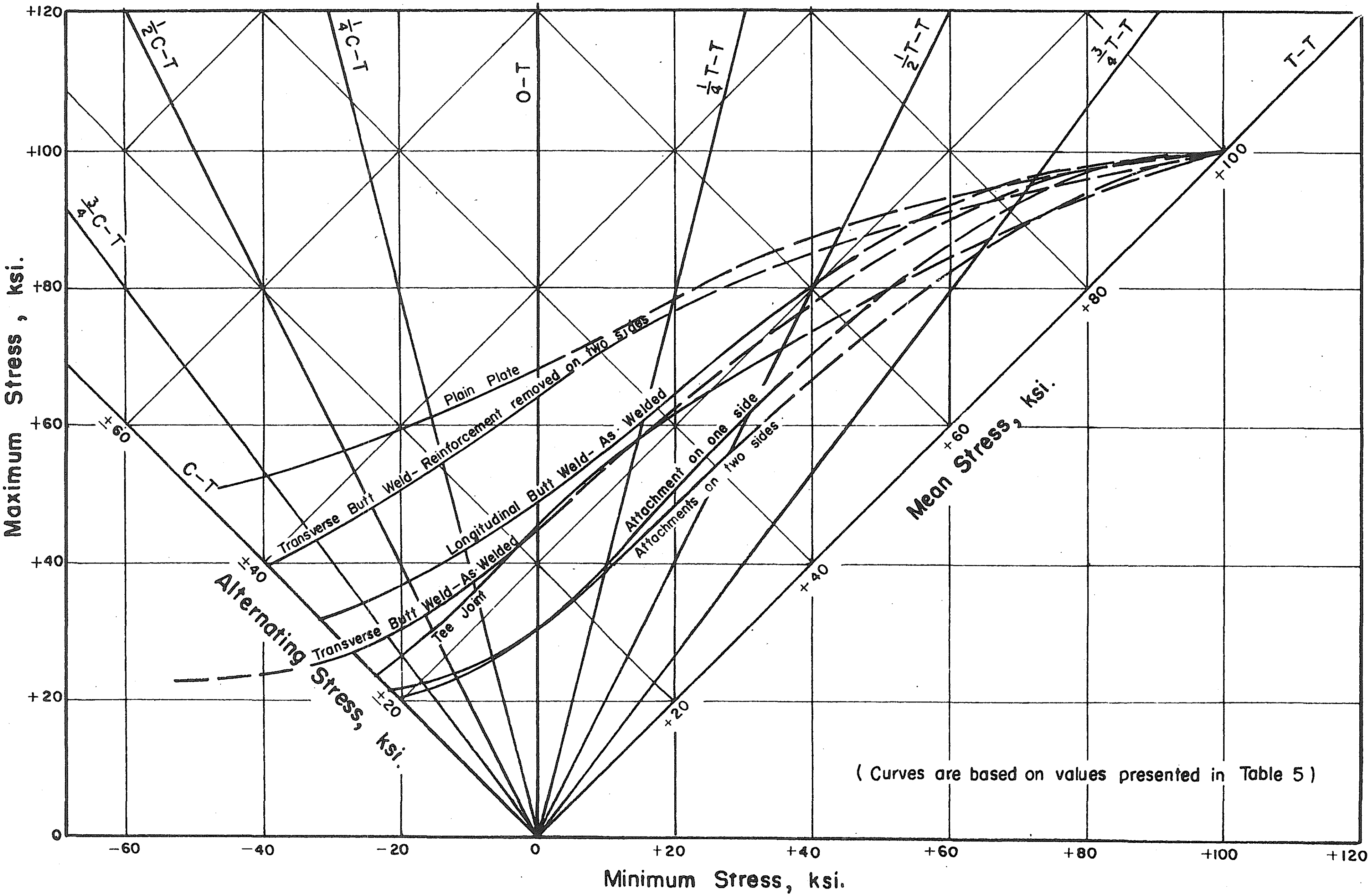


FIG. 14 MODIFIED GOODMAN DIAGRAM SHOWING $F_{100,000}$ CONTOURS FOR VARIOUS WELDMENTS IN HY-80 STEEL.

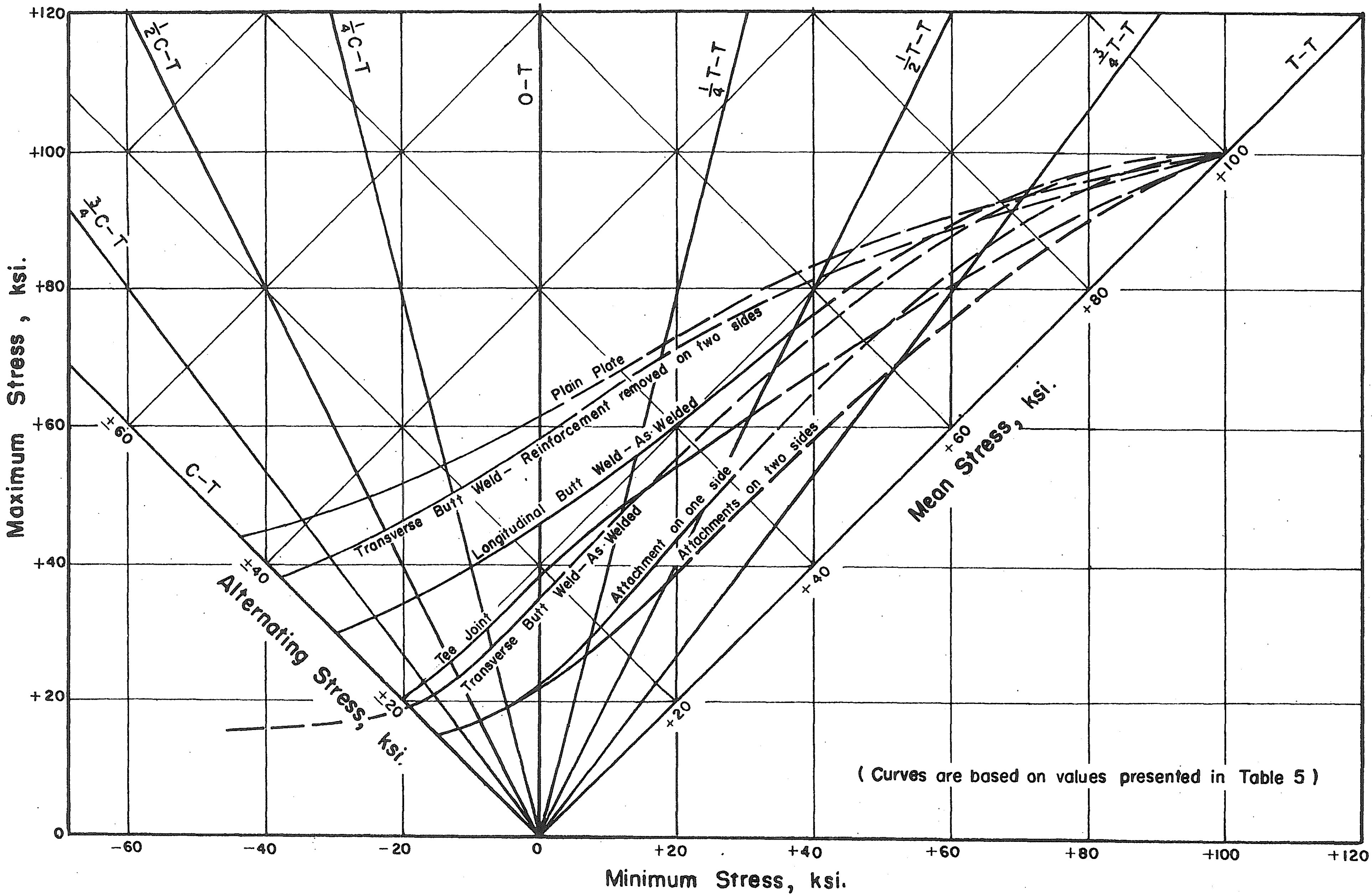


FIG. 15 MODIFIED GOODMAN DIAGRAM SHOWING $F_{200,000}$ CONTOURS FOR VARIOUS WELDMENTS IN HY-80 STEEL.

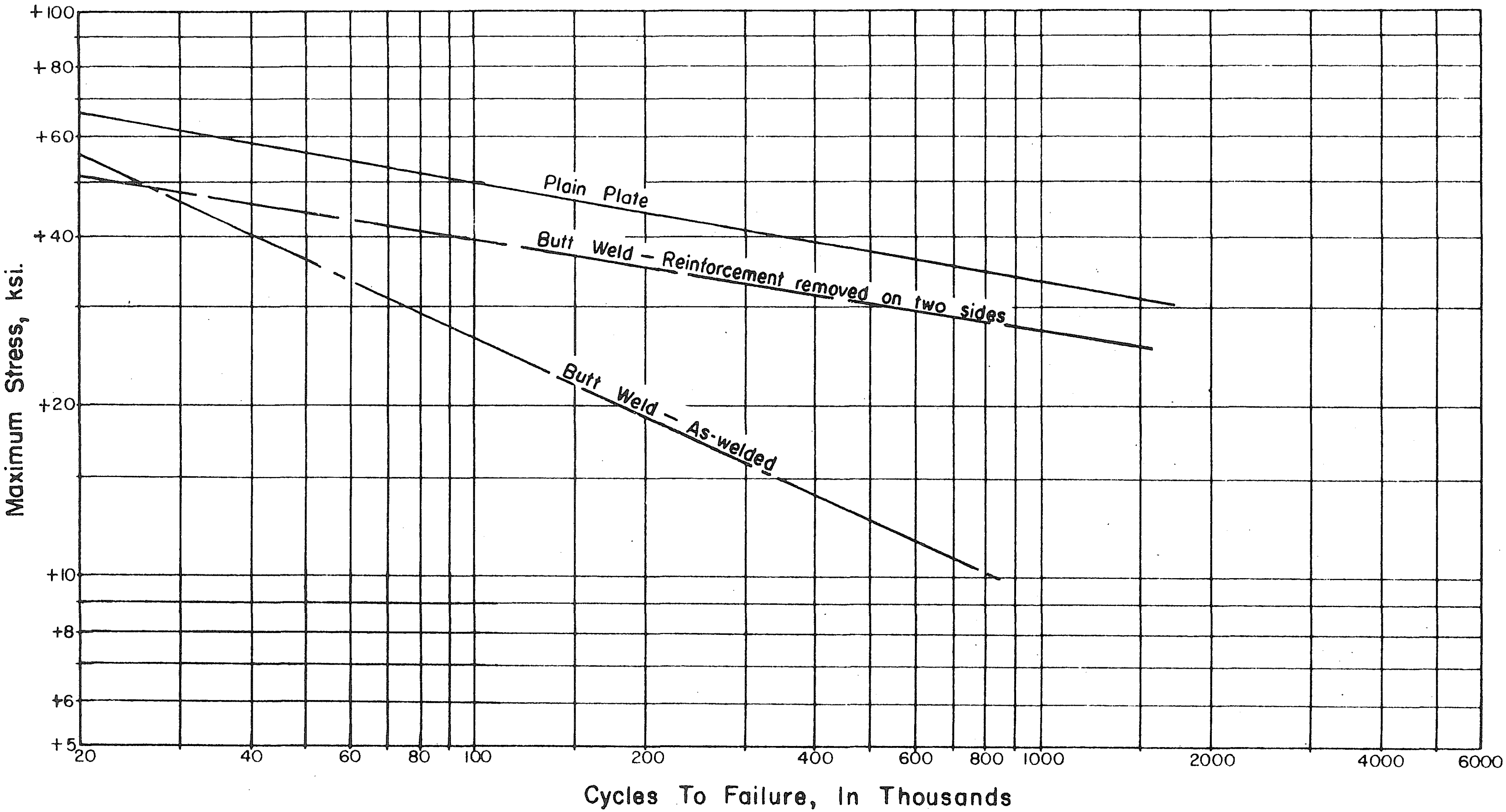


FIG. 16 SUMMARY DIAGRAM SHOWING THE EFFECT OF WELDING AND WELD GEOMETRY ON FATIGUE LIFE. (COMPLETE REVERSAL)

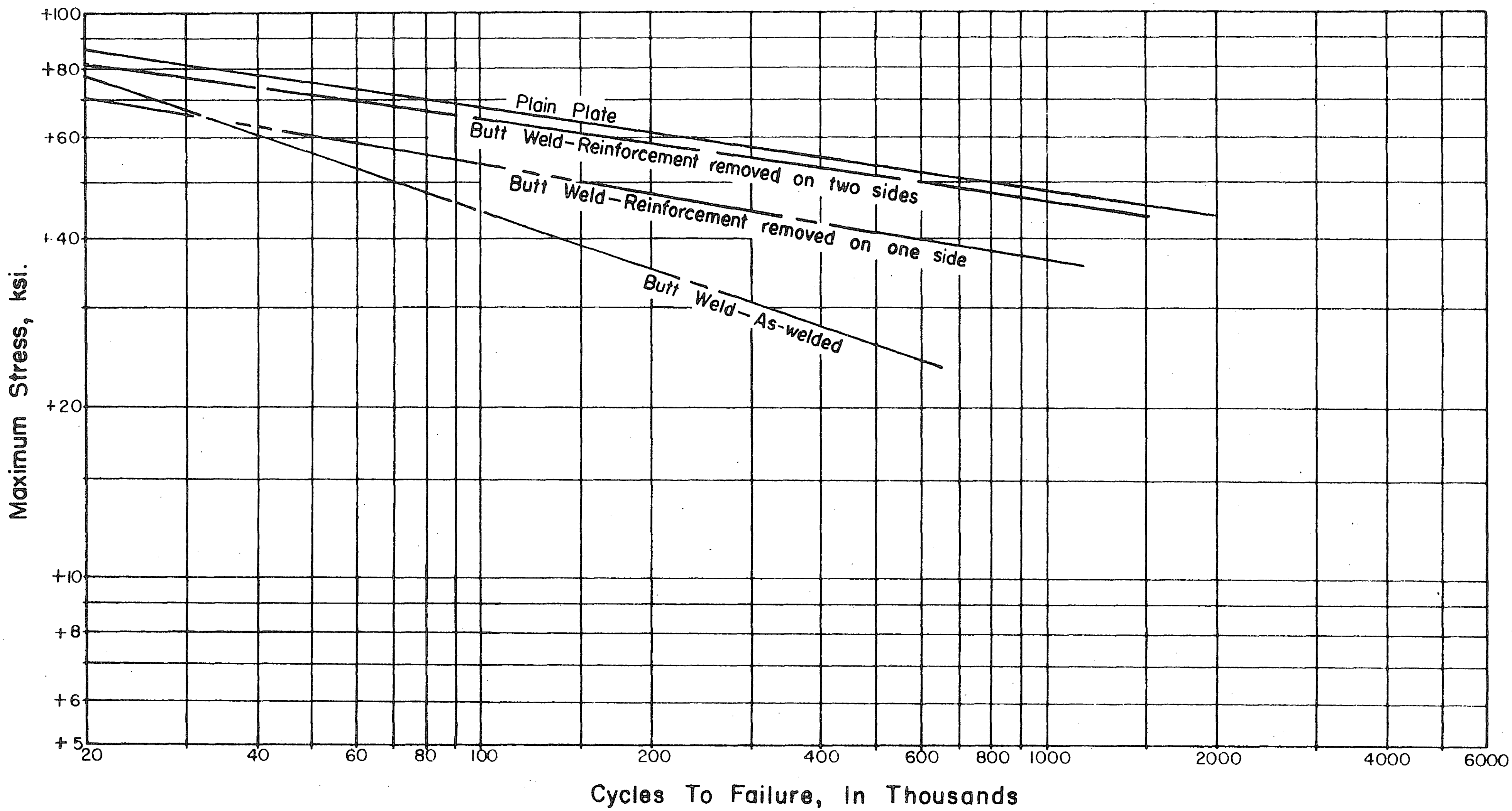


FIG. 17 SUMMARY DIAGRAM SHOWING THE EFFECT OF WELDING AND WELD GEOMETRY ON FATIGUE LIFE. (ZERO TO TENSION)

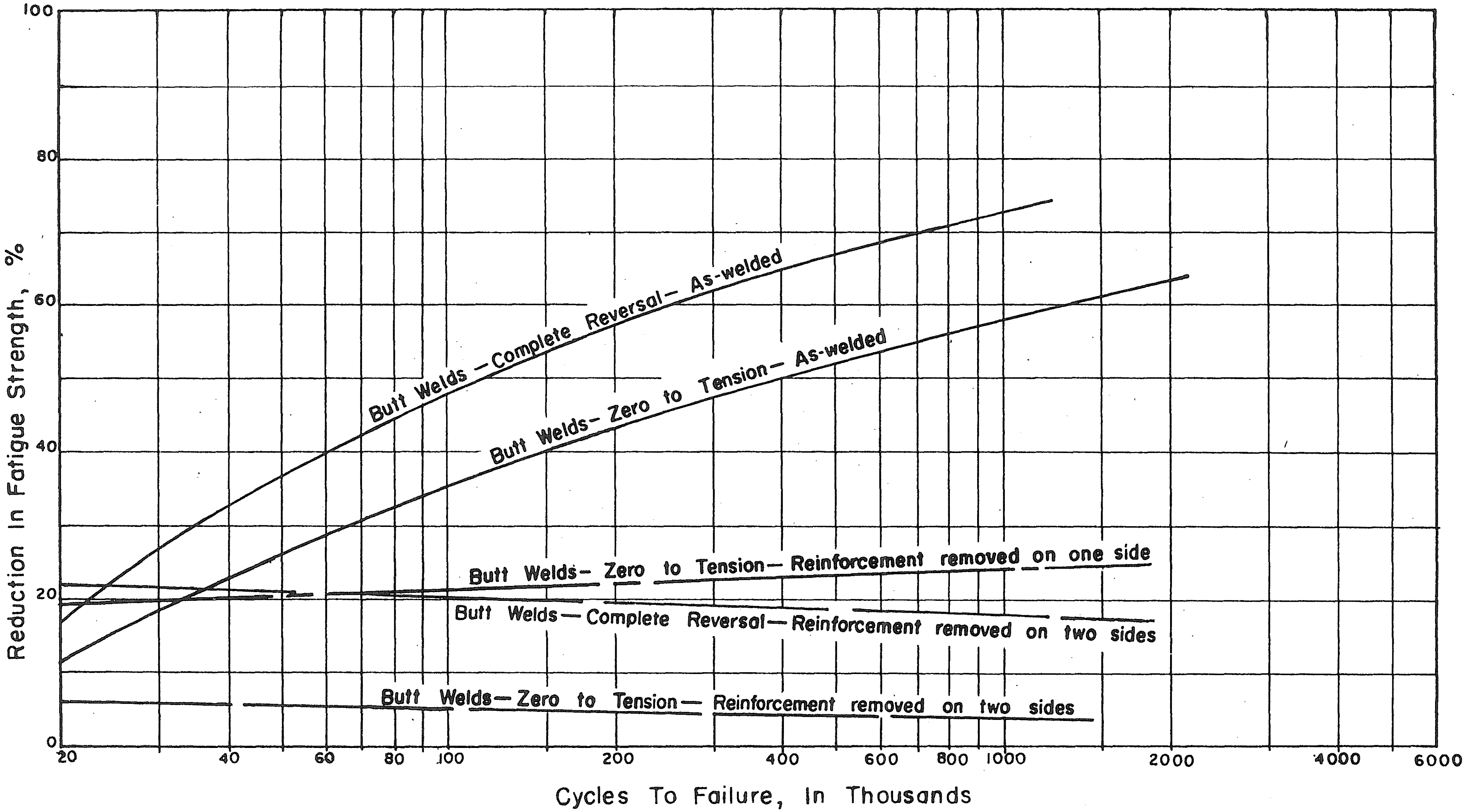


FIG. 18 REDUCTION IN FATIGUE STRENGTH OF AS-ROLLED PLAIN PLATES DUE TO A TRANSVERSE BUTT WELD.

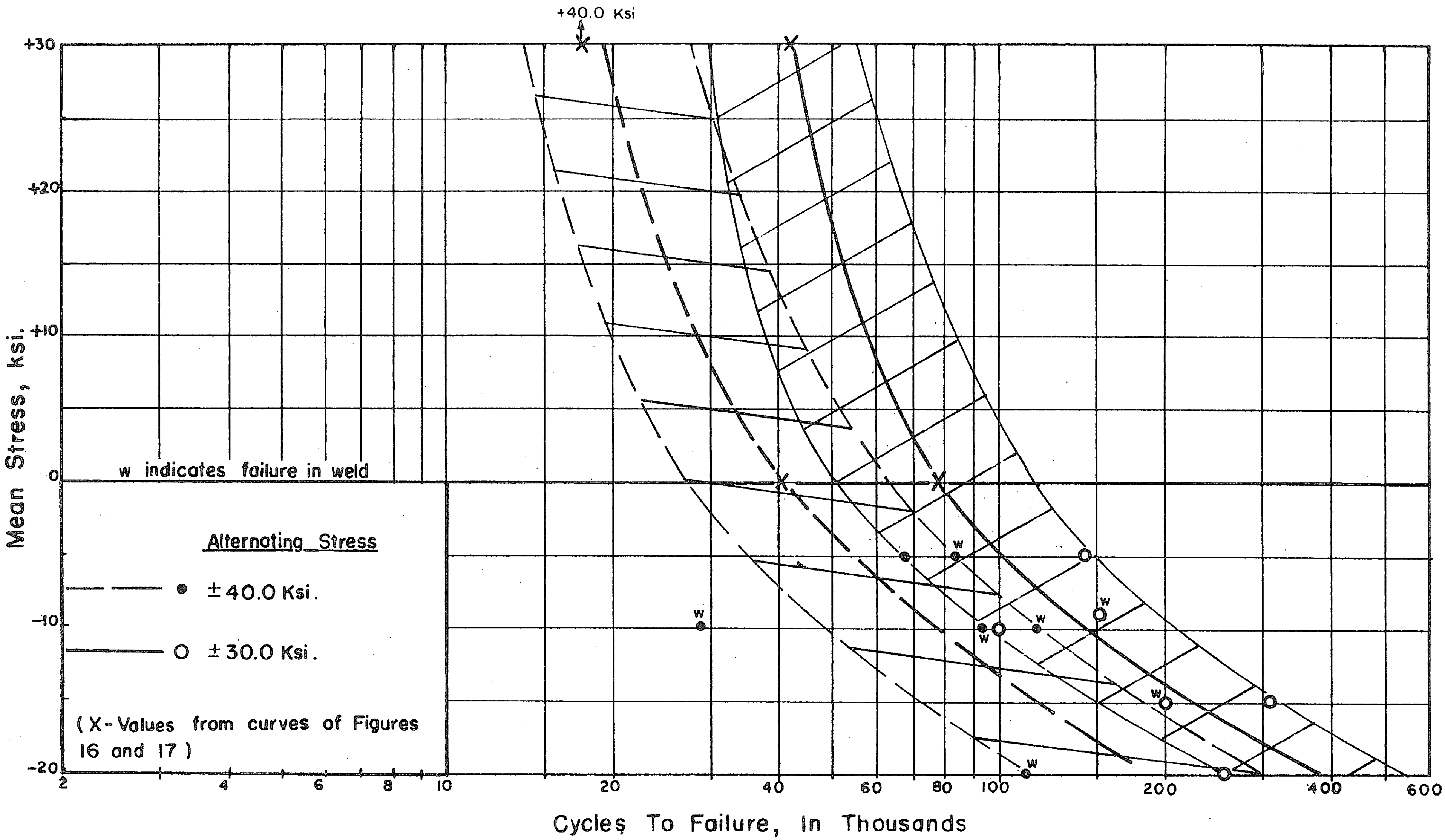


FIG. 19 EFFECT OF MEAN STRESS ON THE FATIGUE LIFE OF AS-WELDED TRANSVERSE BUTT WELDS.

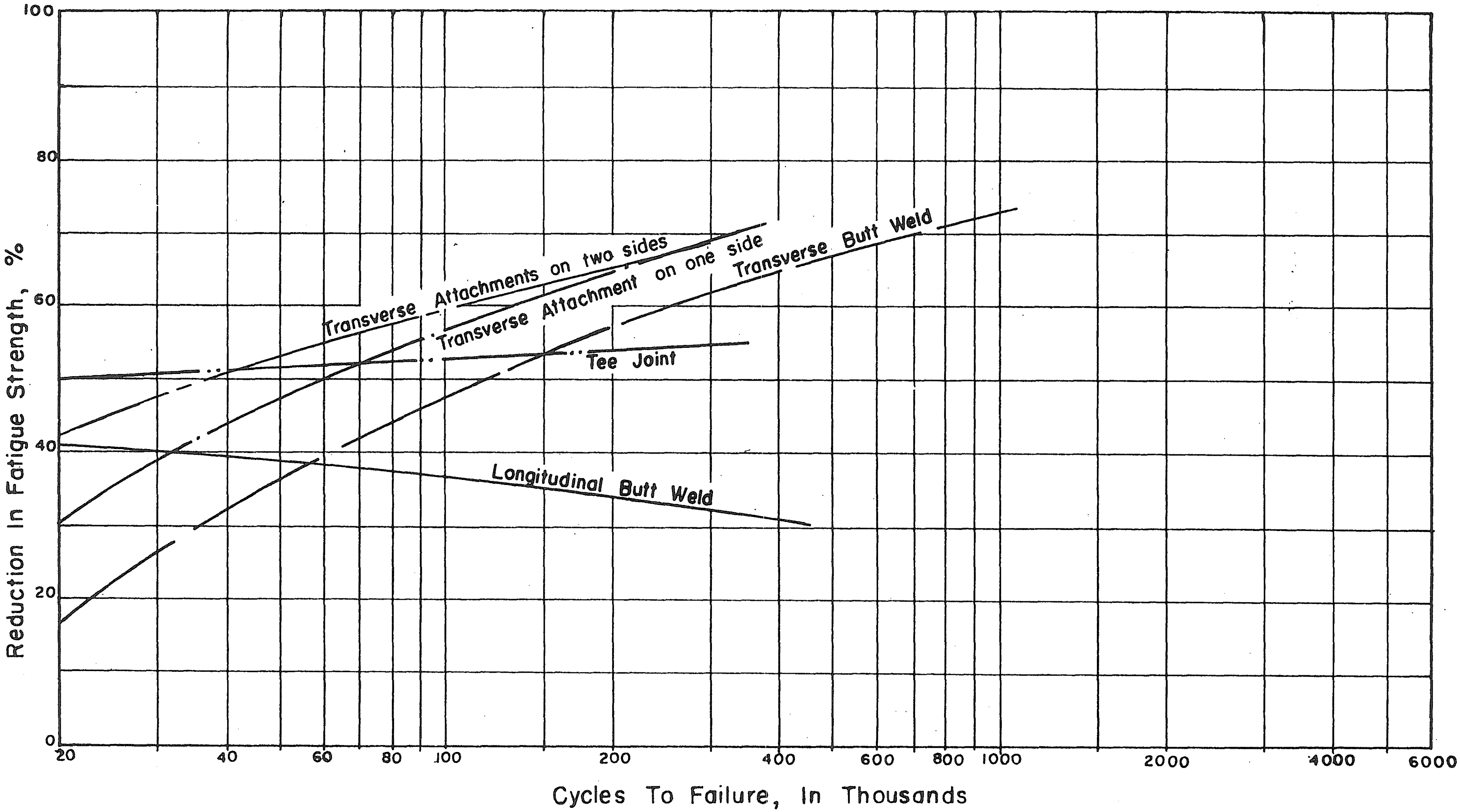


FIG. 20 REDUCTION IN FATIGUE STRENGTH OF AS-ROLLED PLAIN PLATES DUE TO VARIOUS WELDMENTS. (COMPLETE REVERSAL)

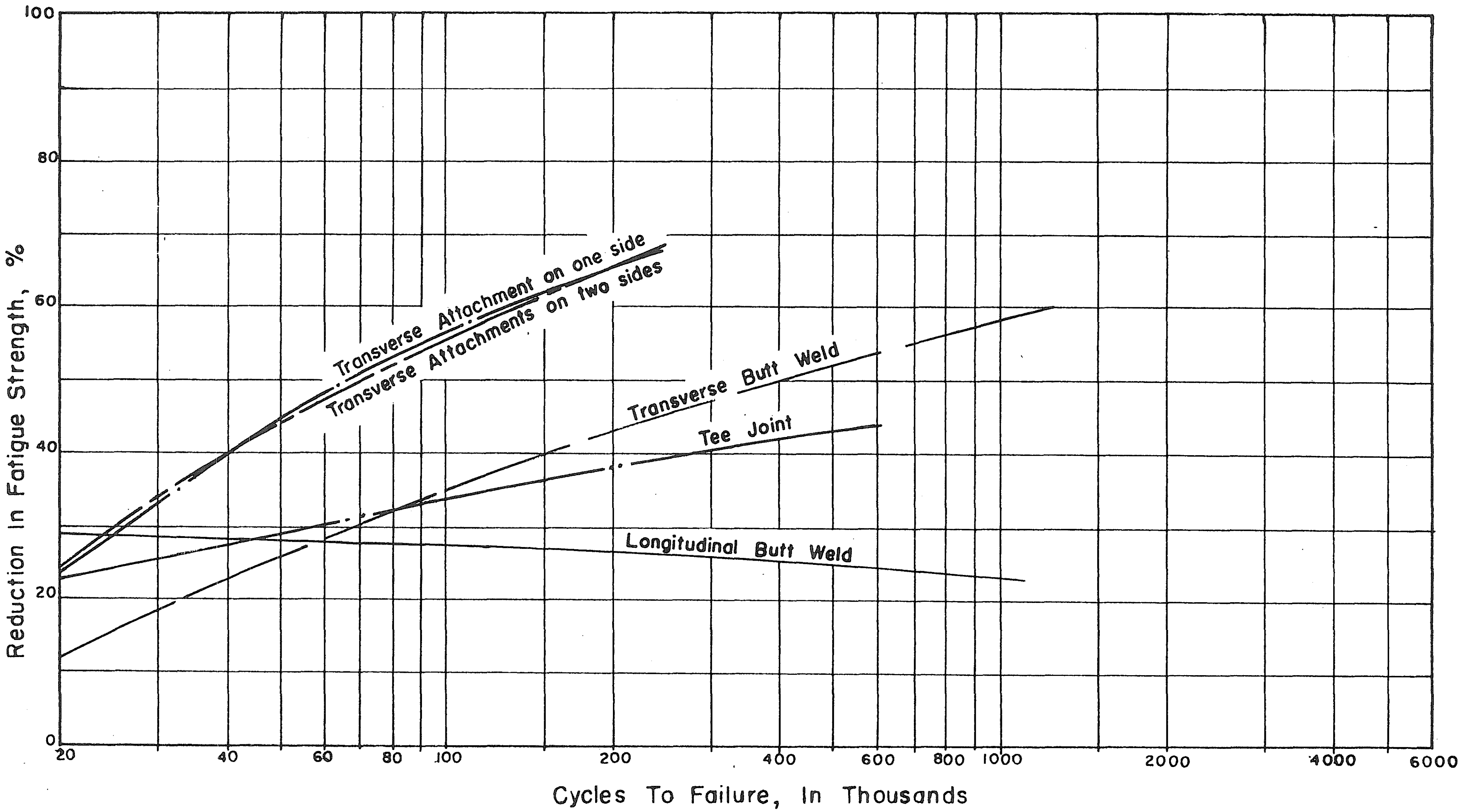


FIG. 21 REDUCTION IN FATIGUE STRENGTH OF AS-ROLLED PLAIN PLATES DUE TO VARIOUS WELDMENTS. (ZERO TO TENSION)

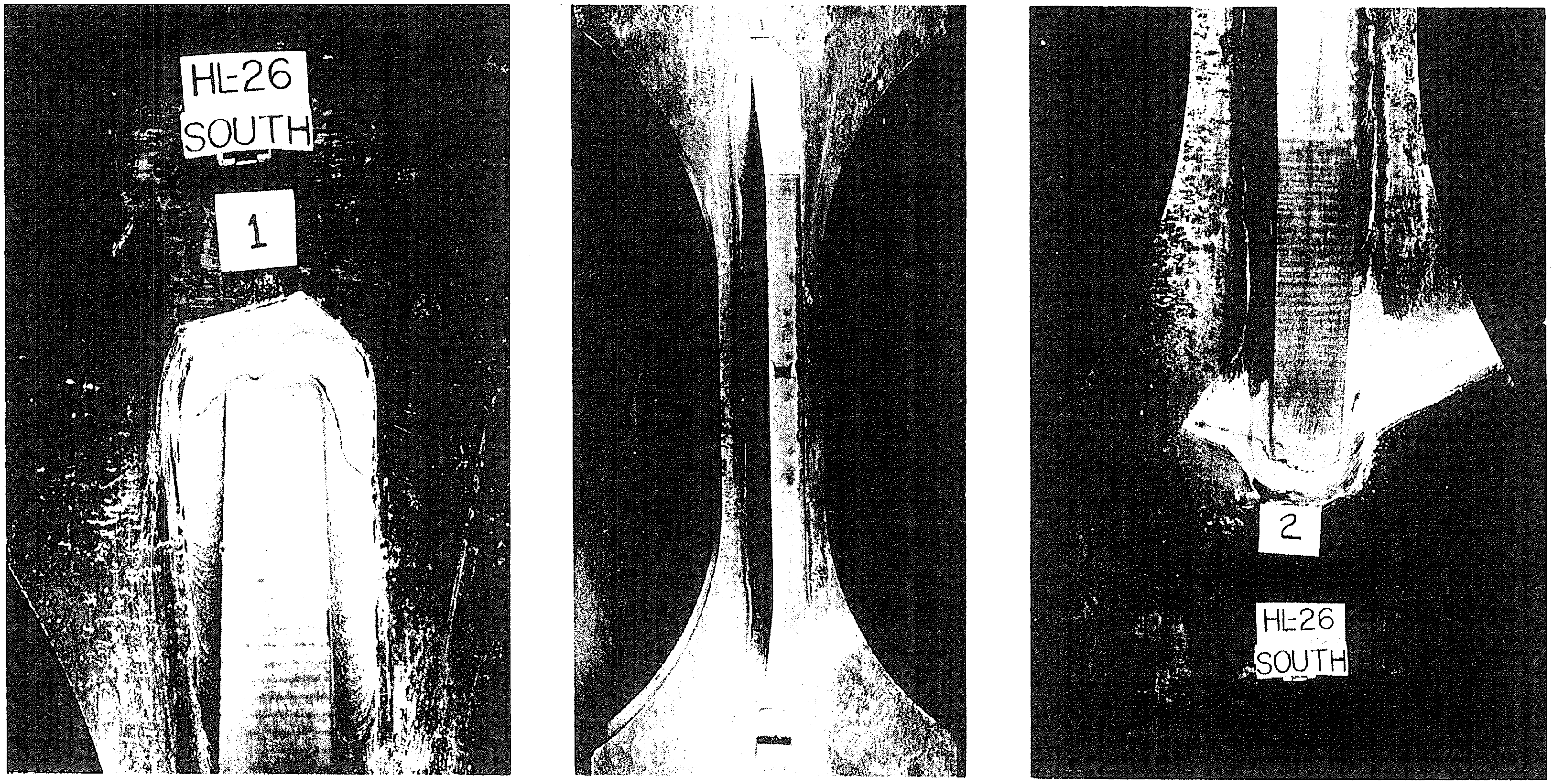


FIG. 22a FATIGUE CRACKS IN A SPECIMEN WITH LONGITUDINAL FILLET WELDED ATTACHMENTS ON TWO SIDES — SOUTH FACE.

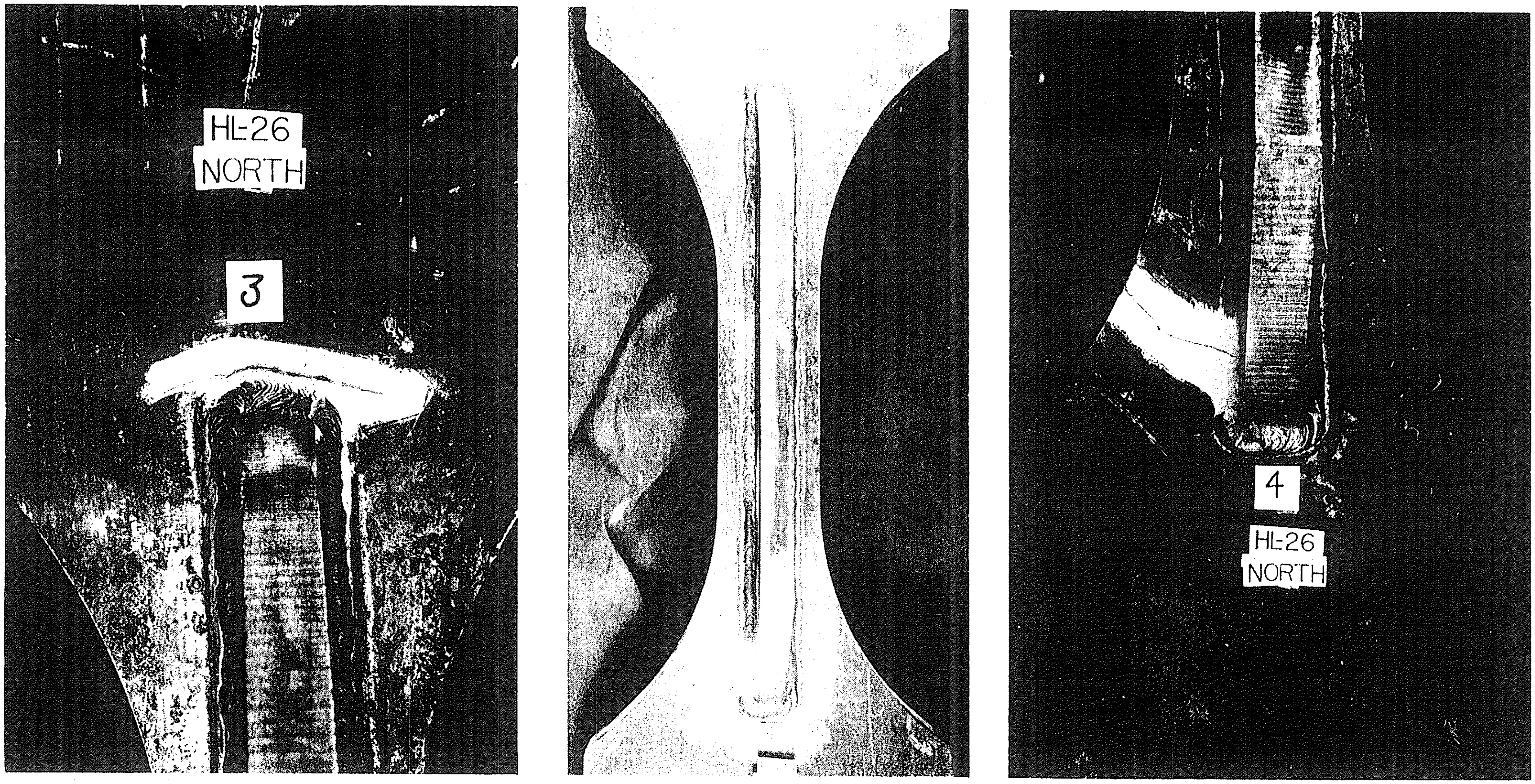


FIG. 22b FATIGUE CRACKS IN A SPECIMEN WITH LONGITUDINAL FILLET WELDED ATTACHMENTS ON TWO SIDES — NORTH FACE.

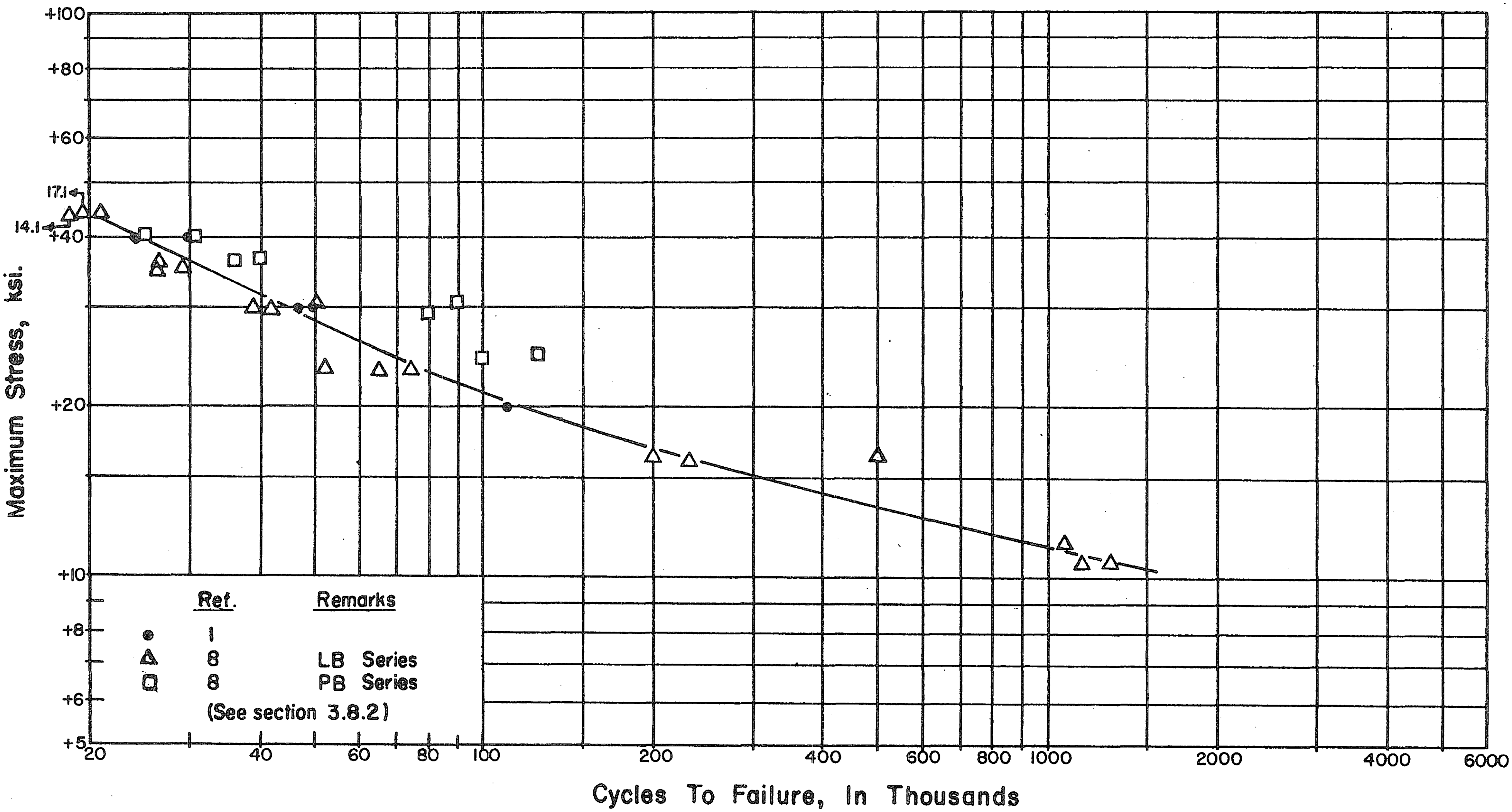


FIG. 23 COMPARISON OF RESULTS OF FLEXURAL AND AXIAL FATIGUE TESTS OF PLATES WITH A FULL PENETRATION TRANSVERSE ATTACHMENT ON ONE SIDE. (COMPLETE REVERSAL)

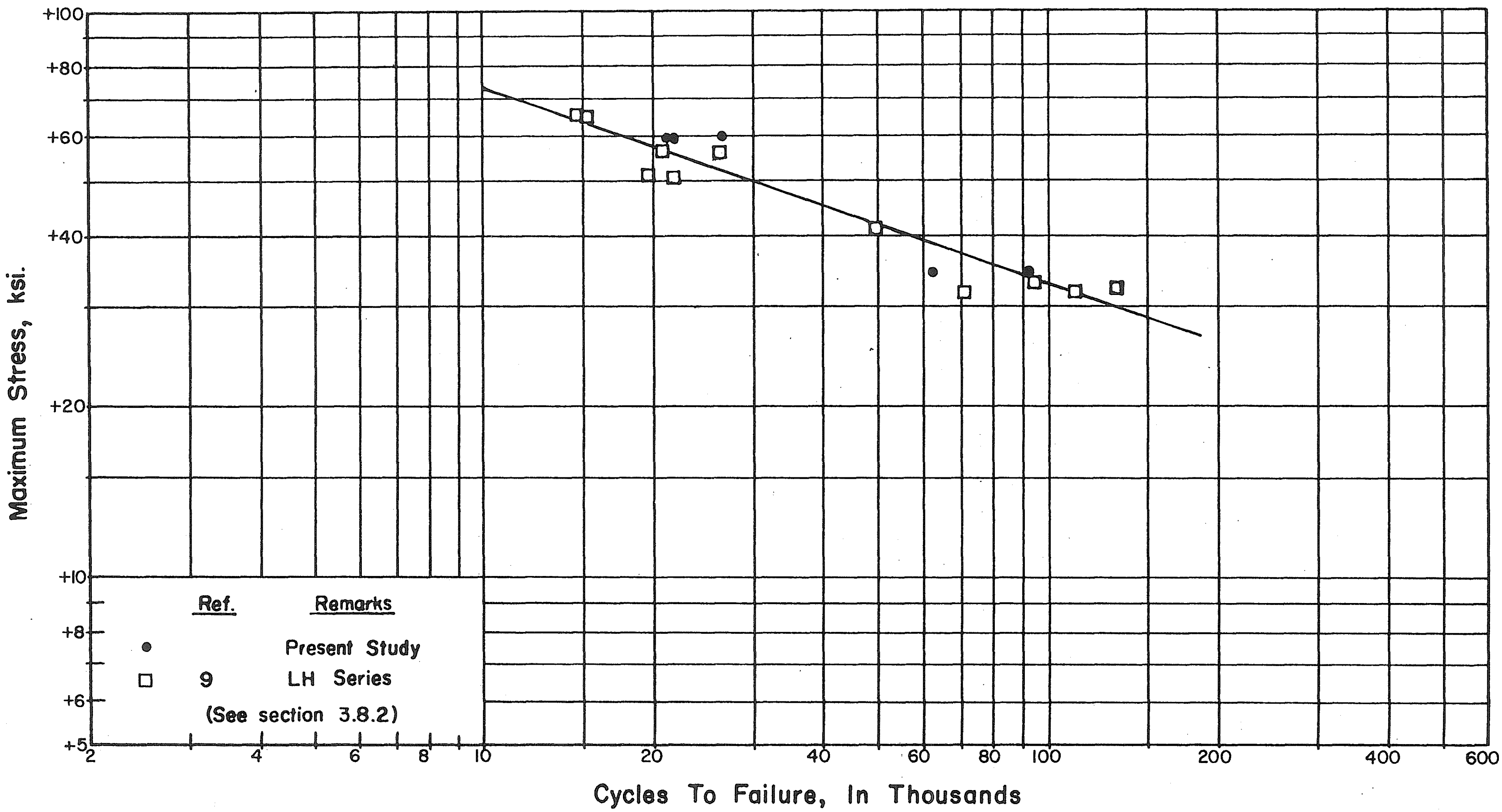


FIG. 24 COMPARISON OF RESULTS OF FLEXURAL AND AXIAL FATIGUE TESTS OF PLATES WITH A FULL PENETRATION TRANSVERSE ATTACHMENT ON ONE SIDE. (ZERO TO TENSION)

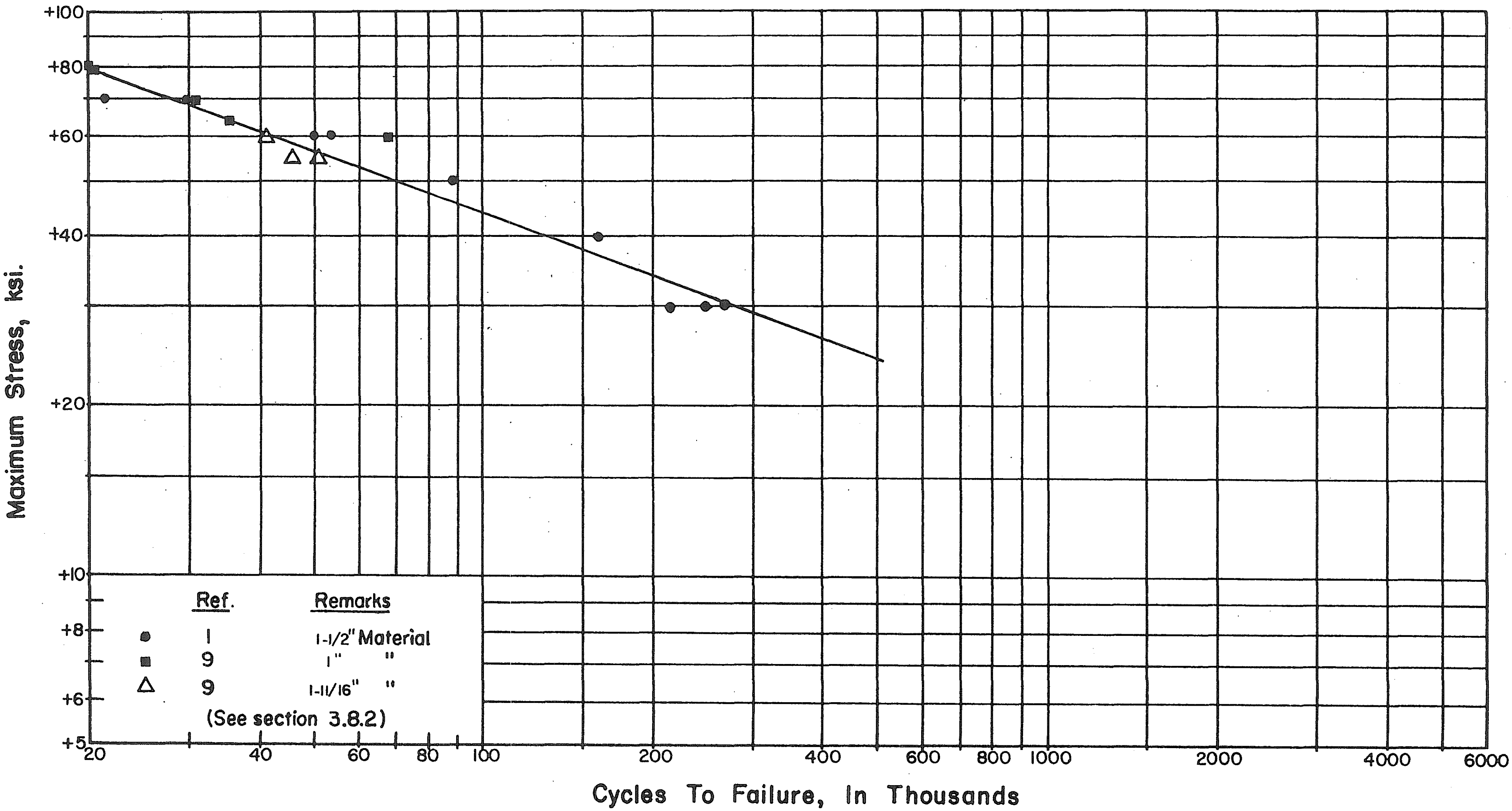


FIG. 25 COMPARISON OF RESULTS OF FLEXURAL AND AXIAL FATIGUE TESTS OF TRANSVERSE BUTT WELDS IN THE AS-WELDED CONDITION. (ZERO TO TENSION)

APPENDIX A - LIST OF TABLES

(Tabular Results of Fatigue Tests)

APPENDIX A - LIST OF TABLES (CONT'D)

TABLE A-1

RESULTS OF FATIGUE TESTS OF AS-ROLLED PLAIN PLATE SPECIMENS

(Complete Reversal)

Specimen Number	Stress Cycle (ksi)	Life** (cycles)	Computed Fatigue Strength,* ksi				
			$F_{20,000}$	$F_{50,000}$	$F_{100,000}$	$F_{200,000}$	$F_{2,000,000}$
V-55***	±50.0	53,700	--	--	--	--	--
V-60	±50.0	114,600	--	57.8	51.3	45.2	--
V-56	±50.0	118,600	--	58.1	51.5	45.7	--
V-57	±35.0	551,600	--	--	47.2	41.8	28.0
V-61	±35.0	628,900	--	--	--	42.7	28.6
V-62	±35.0	1,245,300	--	--	--	--	32.3
			Average	58.0	50.0	43.9	29.6

* k = 0.174

** All specimens failed at the radius of the test section.

*** Specimen subjected to prior bending damage.

TABLE A-2

RESULTS OF FATIGUE TESTS OF AS-ROLLED PLAIN PLATE SPECIMENS

(Zero to Tension)

Specimen Number	Stress Cycle (ksi)	Life** (cycles)	Computed Fatigue Strength,* ksi				
			$F_{20,000}$	$F_{50,000}$	$F_{100,000}$	$F_{200,000}$	$F_{2,000,000}$
V-63	0 to +70.0	88,400	87.4	76.2	68.7	61.9	--
V-58	0 to +70.0	129,100	92.3	80.7	72.7	65.5	--
V-59	0 to +50.0	1,536,700	--	--	--	--	48.1
HL-2	0 to +50.0	437,600	--	--	62.4	56.2	39.8
HL-3	0 to +50.0	701,900	--	--	--	60.2	42.8
HL-1***	0 to +50.0	3,321,200+	--	--	--	--	--
		Average	89.9	78.5	67.9	60.9	43.6

* k = 0.149

** All specimens failed at the radius, except as noted.

*** No failure, specimen was instrumented and had polished surfaces.

TABLE A-3

RESULTS OF FATIGUE TESTS ON TRANSVERSE BUTT WELDS WITH REINFORCEMENT REMOVED ON ONE SIDE

(Zero to Tension)

Specimen Number	Welding Procedure (See Appendix D)	Stress Cycle (ksi)	Life (cycles)	Location of Fracture**	Computed Fatigue Strength,* ksi			
					$F_{50,000}$	$F_{100,000}$	$F_{200,000}$	$F_{2,000,000}$
G-6	P80-11018-D	0 to +70.7	63,800	a	72.9	65.6	58.8	--
V-37	P80-11018-E	0 to +70.0	10,900	c	54.7	--	--	--
V-36	P80-11018-E	0 to +70.0	22,300	c	61.5	55.0	--	--
G-7	P80-11018-D	0 to +70.0	33,900	c	65.7	58.8	--	--
G-4	P80-11018-D	0 to +70.0	51,000	c	70.3	62.9	56.2	--
G-9	P80-11018-D	0 to +40.0	191,700	b	49.6	44.3	39.7	--
G-8	P80-11018-D	0 to +40.0	746,000	b	--	--	49.4	34.2
G-5	P80-11018-D	0 to +40.0	1,216,100	c	--	--	--	36.9
V-16	P80-11018-C	0 to +35.0	232,000	a	44.7	40.1	35.9	--
				Average	59.9	54.5	48.0	35.6

* k = 0.160

** a: failure initiated at edge of weld reinforcement.
b: failure initiated at edge of weld reinforcement in a slag inclusion.
c: failure initiated in weld.

TABLE A-4

RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS WITH REINFORCEMENT REMOVED ON TWO SIDES

(Complete Reversal)

Specimen Number	Welding Procedure (See Appendix D)	Stress Cycle (ksi)	Life (cycles)	Location of Fracture**	Computed Fatigue Strength,* ksi			
					$F_{50,000}$	$F_{100,000}$	$F_{200,000}$	$F_{2,000,000}$
V-30	P80-11018-E	±45.0	25,500	c	40.4	36.1	--	--
V-38	P80-11018-E	±40.0	12,000	c	31.8	--	--	--
V-31	P80-11018-E	±40.0	35,500	c	37.8	33.9	--	--
G-16	P80-11018-D	±40.0	44,600	c	39.2	35.2	31.4	--
G-21	P80-11018-D	±40.0	146,400	c	47.5	42.4	38.0	--
G-17	P80-11018-D	±40.0	179,200	c	49.1	43.9	39.3	--
G-18	P80-11018-D	±40.0	291,700	c	53.0	47.5	42.4	--
G-19	P80-11018-D	±25.0	1,729,300	d	--	--	--	24.4
G-20	P80-11018-D	±25.0	2,726,900+	no failure	--	--	--	--
				Average	42.7	39.8	37.8	24.4

* k = 0.160

** c: failure initiated in weld.
d: failure initiated in weld at base metal weld metal interface.

TABLE A-5

RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS WITH REINFORCEMENT REMOVED ON TWO SIDES

(Zero to Tension)

Specimen Number	Welding Procedure (See Appendix D)	Stress Cycle (ksi)	Life (cycles)	Location of Fracture**	Computed Fatigue Strength,* ksi			
					$F_{50,000}$	$F_{100,000}$	$F_{200,000}$	$F_{500,000}$
V-35	P80-11018-E	0 to +70.0	7,800	c	--	--	--	--
G-14	P80-11018-D	0 to +70.0	27,100	c	63.8	57.7	--	--
V-34	P80-11018-E	0 to +70.0	29,400	c	64.7	58.5	--	--
G-13	P80-11018-D	0 to +70.0	125,300	c	80.1	72.5	65.3	57.1
G-12	P80-11018-D	0 to +70.0	184,900	d	85.0	76.3	69.2	60.6
G-10	P80-11018-D	0 to +50.0	225,300	c	62.5	56.3	50.9	44.1
G-11	P80-11018-D	0 to +50.0	617,600	c	--	--	59.0	51.6
G-15	P80-11018-D	0 to +50.0	797,800	d	--	--	61.3	53.5
V-13	P80-11018-C	0 to +35.0	880,200	c	--	--	43.4	38.0
				Average	71.2	64.3	58.2	50.8

* k = 0.146

** c: failure initiated in weld.
d: failure initiated in weld at weld metal base metal interface.

TABLE A-6

RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS IN THE AS-WELDED CONDITION

(Variation in Compressive Mean Stress)

Specimen Number	Welding Procedure (See Appendix D)	Stress Cycle, ksi				Life (cycles)	Location of Fracture*
		Min. Stress	Max. Stress	Mean Stress	Alt. Stress		
HL-31	P80-11018-D	-35.0	+25.0	- 5.0	±30.0	145,500	a
G-1	P80-11018-D	-39.0	+21.0	- 9.0	±30.0	151,200	c
G-3	P80-11018-D	-40.0	+20.0	-10.0	±30.0	100,100	d
HL-30	P80-11018-D	-45.0	+15.0	-15.0	±30.0	200,400	c
G-2	P80-11018-D	-45.0	+15.0	-15.0	±30.0	316,800	d
W-28	P80-11018-D	-50.0	+10.0	-20.0	±30.0	261,700	a

*
a: failure initiated at edge of weld reinforcement.
b: failure initiated in weld.
c: failure initiated in weld at weld metal base metal interface.

TABLE A-7

RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS IN THE AS-WELDED CONDITION

(Variation in Compressive Mean Stress)

Specimen Number	Welding Procedure (See Appendix D)	Stress Cycle, ksi				Life (cycles)	Location of Fracture*
		Min. Stress	Max. Stress	Mean Stress	Alt. Stress		
W-23	P80-11018-D	-45.0	+35.0	- 5.0	±40.0	69,600	a(1)
W-21	P80-11018-D	-45.0	+35.0	- 5.0	±40.0	84,300	c
W-29	P80-11018-D	-50.0	+30.0	-10.0	±40.0	29,100	c
W-22	P80-11018-D	-50.0	+30.0	-10.0	±40.0	94,300	c
W-27	P80-11018-D	-50.0	+30.0	-10.0	±40.0	119,200	c
W-30	P80-11018-D	-60.0	+20.0	-20.0	±40.0	113,200	c

* a: failure initiated at edge of weld reinforcement.
b: failure initiated in weld.

(1) second crack started in weld.

TABLE A-8

RESULTS OF FATIGUE TESTS OF LONGITUDINAL BUTT WELDS IN THE AS-WELDED CONDITION

(Complete Reversal)

Specimen Number	Welding Procedure (See Appendix D)	Stress Cycle (ksi)	Life** (cycles)	Computed Fatigue Strength,* ksi			
				$F_{20,000}$	$F_{50,000}$	$F_{100,000}$	$F_{200,000}$
G-39	P80-11018-0	$\pm$40.0	64,900	46.3	41.3	37.9	34.9
G-40	P80-11018-0	$\pm$40.0	69,000	46.6	41.6	38.2	35.0
HL-16	P80-11018-G	$\pm$30.0	32,700	31.8	28.4	26.2	24.0
HL-17	P80-11018-G	$\pm$30.0	44,500	33.1	29.6	27.1	25.0
G-44	P80-11018-0	$\pm$30.0	148,200	38.3	34.2	31.5	28.9
G-43	P80-11018-0	$\pm$30.0	192,600	39.6	35.4	32.5	29.9
			Average	39.3	35.1	32.2	29.6

* k = 0.12

** All failures initiated in weld.

TABLE A-9

RESULTS OF FATIGUE TESTS OF LONGITUDINAL BUTT WELDS IN THE AS-WELDED CONDITION

(Zero to Tension)

Specimen Number	Welding Procedure (See Appendix D)	Stress Cycle (ksi)	Life (cycles)	Location of Fracture**	Computed Fatigue Strength,* ksi				
					$F_{20,000}$	$F_{50,000}$	$F_{100,000}$	$F_{200,000}$	$F_{2,000,000}$
G-42	P80-11018-0	0 to +60.0	21,000	c	60.3	54.0	49.6	--	--
G-48	P80-11018-0	0 to +60.0	63,700	c	69.3	61.8	56.8	52.1	--
HL-12	P80-11018-F	0 to +55.0	34,300	c	58.7	52.5	48.3	--	--
HL-10	P80-11018-F	0 to +50.0	39,900	c	54.4	48.6	44.7	--	--
HL-11	P80-11018-F	0 to +40.0	255,500	c	--	48.8	44.7	41.2	--
G-47	P80-11018-0	0 to +40.0	346,900	g	--	--	46.5	42.8	32.3
G-41	P80-11018-0	0 to +40.0	782,900	e	--	--	--	47.3	39.5
				Average	60.7	53.1	48.4	45.8	35.9

* k = 0.12

** c: failure initiated in weld.
e: failure initiated in test section at edge of weld.
g: failure initiated outside test section.

TABLE A-10

RESULTS OF FATIGUE TESTS OF LONGITUDINAL BUTT WELDS IN THE AS-WELDED CONDITION

(Half Tension to Tension)

Specimen Number	Welding Procedure (See Appendix D)	Stress Cycle (ksi)	Life (cycles)	Location of Fracture**	Computed Fatigue Strength,* ksi			
					$F_{100,000}$	$F_{200,000}$	$F_{500,000}$	$F_{2,000,000}$
G-45	P80-11018-0	+35.0 to +70.0	403,500	h(1)	83.0	76.2	68.2	57.6
G-37	P80-11018-0	+35.0 to +70.0	587,400	e	87.1	80.0	71.4	60.2
G-46	P80-11018-0	+30.0 to +60.0	466,400	h	72.5	66.6	59.4	50.2
				Average	80.9	74.3	66.3	56.0

* k = 0.12

** e: failure initiated in test section at edge of weld.
h: failure initiated at electrode change point.

(1) second crack initiated at electrode change point at transition radius.

TABLE A-11

RESULTS OF FATIGUE TESTS OF PLAIN PLATES WITH FULL PENETRATION TRANSVERSE ATTACHMENTS ON TWO SIDES

(Zero to Tension)

Specimen Number	Welding Procedure (See Appendix D)	Stress Cycle (ksi)	Life** (cycles)	Computed Fatigue Strength,* ksi			
				$F_{20,000}$	$F_{50,000}$	$F_{100,000}$	$F_{200,000}$
W-8	P80-11018-P	0 to +60.0	21,100	61.3	39.5	28.1	--
W-3	P80-11018-P	0 to +60.0	24,800	66.7	42.6	30.3	--
W-5	P80-11018-P	0 to +47.5	49,700	74.0	47.4	33.8	24.2
W-4	P80-11018-P	0 to +35.0	51,000	55.2	35.4	25.2	17.9
W-6	P80-11018-P	0 to +35.0	84,000	70.6	45.1	32.0	22.8
			Average	65.6	42.0	29.9	21.6

* k = 0.488

** All failures initiated at toe of weld.

TABLE A-12

RESULTS OF FATIGUE TESTS OF PLAIN PLATES WITH FULL PENETRATION TRANSVERSE ATTACHMENTS ON TWO SIDES

(Half Tension to Tension)

Specimen Number	Welding Procedure (See Appendix D)	Stress Cycle (ksi)	Life** (cycles)	Computed Fatigue Strength,* ksi		
				$F_{50,000}$	$F_{100,000}$	$F_{200,000}$
W-7	P80-11018-P	+35.0 to +70.0	60,600	78.2	52.2	35.0
W-10	P80-11018-P	+35.0 to +70.0	72,500	86.8	58.0	38.8
W-9	P80-11018-P	+25.0 to +50.0	119,200	82.6	55.3	37.0
			Average	82.5	55.2	36.9

* k = 0.580

** All failures initiated at toe of weld.

TABLE A-13

RESULTS OF FATIGUE TESTS OF PLAIN PLATES WITH A FULL PENETRATION TRANSVERSE ATTACHMENT ON ONE SIDE

(Zero to Tension)

Specimen Number	Welding Procedure (See Appendix D)	Stress Cycle (ksi)	Life** (cycles)	Computed Fatigue Strength,* ksi			
				$F_{20,000}$	$F_{50,000}$	$F_{100,000}$	$F_{200,000}$
W-20	P80-11018-Q	0 to +60.0	21,600	62.3	39.9	28.5	--
W-18	P80-11018-Q	0 to +60.0	21,600	62.3	39.9	28.5	--
W-11	P80-11018-Q	0 to +60.0	26,700	69.2	44.3	31.5	--
W-15	P80-11018-Q	0 to +35.0	63,500	61.3	39.4	28.0	20.0
W-19	P80-11018-Q	0 to +35.0	93,100	74.6	47.4	33.7	24.1
			Average	65.9	42.2	30.0	22.1

* k = 0.487

** All failures initiated at toe of weld.

TABLE A-14

RESULTS OF FATIGUE TESTS OF PLAIN PLATES WITH A FULL PENETRATION TRANSVERSE ATTACHMENT ON ONE SIDE

(Half Tension to Tension)

Specimen Number	Welding Procedure (See Appendix D)	Stress Cycle (ksi)	Life** (cycles)	Computed Fatigue Strength,* ksi		
				$F_{50,000}$	$F_{100,000}$	$F_{200,000}$
W-12	P80-11018-Q	+35.0 to +70.0	64,600	76.1	60.6	48.2
W-13	P80-11018-Q	+35.0 to +70.0	65,200	76.5	60.7	48.3
W-14	P80-11018-Q	+25.0 to +50.0	178,300	76.3	60.7	48.1
			Average	76.3	60.7	48.2

* k = 0.331

** All failures initiated at toe of weld.

TABLE A-15

RESULTS OF FATIGUE TESTS OF FULL PENETRATION TRANSVERSE TEE JOINTS

(Complete Reversal)

Specimen Number	Welding Procedure (See Appendix D)	Stress Cycle (ksi)	Life (cycles)	Location of Fracture**	Computed Fatigue Strength,* ksi			
					$F_{20,000}$	$F_{50,000}$	$F_{100,000}$	$F_{200,000}$
G-30	P80-11018-R	±40.0	2,400	c	--	--	--	--
G-34	P80-11018-R	±40.0	2,600	c	--	--	--	--
V-52	P80-11018-L	±40.0	11,400	c	35.5	29.0	--	--
V-53	P80-11018-L	±40.0	13,900	c	36.7	30.2	--	--
HL-18	P80-11018-L	±30.0	12,900	c(1)	27.3	22.4	--	--
V-51	P80-11018-L	±30.0	42,100	f	35.2	28.9	24.8	21.4
V-50	P80-11018-L	±30.0	55,000	f	37.2	30.6	26.4	22.7
G-32	P80-11018-R	±20.0	78,200	c	26.8	22.0	19.0	16.3
V-54	P80-11018-L	±20.0	132,400	f	--	24.6	21.2	18.3
G-27	P80-11018-R	±20.0	333,500	d	--	--	26.4	22.3
				Average	33.1	26.8	23.6	20.2

* k = 0.215

** c: failure initiated in weld.
d: failure initiated in weld at weld metal base metal interface.
e: failure initiated at toe of weld.

(1) second crack initiated in weld.

TABLE A-16

RESULTS OF FATIGUE TESTS OF FULL PENETRATION TRANSVERSE TEE JOINTS

(Zero to Tension)

Specimen Number	Welding Procedure (See Appendix D)	Stress Cycle (ksi)	Life (cycles)	Location of Fracture**	Computed Fatigue Strength,* ksi			
					$F_{20,000}$	$F_{50,000}$	$F_{100,000}$	$F_{200,000}$
G-31	P80-11018-R	0 to +70.0	15,400	c	65.8	52.7	--	--
G-26	P80-11018-R	0 to +70.0	17,000	c	67.2	54.0	--	--
G-29	P80-11018-R	0 to +40.0	151,900	c	--	52.0	44.3	37.5
G-25	P80-11018-R	0 to +40.0	187,800	f	--	54.8	46.5	39.9
				Average	66.5	53.4	45.4	38.7

* k = 0.238

** c: failure initiated in weld.
f: failure initiated at toe of weld.

TABLE A-17

RESULTS OF FATIGUE TESTS OF FULL PENETRATION TRANSVERSE TEE JOINTS

(Half Tension to Tension)

Specimen Number	Welding Procedure (See Appendix D)	Stress Cycle (ksi)	Life** (cycles)	Computed Fatigue Strength,* ksi				
				$F_{50,000}$	$F_{100,000}$	$F_{200,000}$	$F_{500,000}$	$F_{2,000,000}$
G-24	P80-11018-R	+30.0 to +60.0	171,100	79.2	67.8	58.0	47.0	--
G-28	P80-11018-R	+30.0 to +60.0	251,300	86.5	73.7	63.2	51.6	--
G-33	P80-11018-R	+25.0 to +50.0	451,200	--	70.4	60.0	49.0	35.7
G-23	P80-11018-R	+25.0 to +50.0	534,600	--	73.0	62.4	50.7	37.2
			Average	82.9	71.2	60.9	49.6	36.5

* k = 0.225

** All failures initiated at toe of weld.

TABLE A-18

RESULTS OF FATIGUE TESTS OF PLATES WITH A FULL PENETRATION ATTACHMENT ON ONE SIDE, WELDED WITH DIFFERENT ELECTRODES

(Complete Reversal)

Specimen Number	Welding Procedure (See Appendix D)	Electrode Type	Stress Cycle	Life* (cycles)
W-24	P80-9018-A	MIL 9018	±30.0	33,900
W-26	P80-9018-A	MIL 9018	±30.0	37,300
W-25	P80-9018-A	MIL 9018	±30.0	37,500
			Average	36,200
V-49	P80-11018-K	MIL 11018	±30.0	47,300
V-48	P80-11018-K	MIL 11018	±30.0	49,700
			Average	48,500

* All failures initiated at toe of weld.

TABLE A-19

RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS, FABRICATED USING DIFFERENT INTERPASS TEMPERATURES

(Complete Reversal)

Specimen Number	Welding Procedure (See Appendix D)	Preheat Temperature (°F)	Interpass Temperature (°F)	Stress Cycle (ksi)	Life (cycles)	Location of Fracture*
HL-27	P80-11018-S	Room	Room	± 30.0	24,300	c
G-51	P80-11018-S	Room	Room	± 30.0	51,100	c
V-9	P80-11018-B	150	300	± 30.0	55,300	c
G-52	P80-11018-E	200	300	± 30.0	63,700	c
V-21	P80-11018-C	150	300	± 30.0	72,700	a
V-20	P80-11018-C	150	300	± 30.0	75,900	a
HL-28	P80-11018-E	200	300	± 30.0	145,900	c
HL-29	P80-11018-T	200	400	± 30.0	161,800	a
G-53	P80-11018-T	200	400	± 30.0	324,900	d

* a: failure initiated at edge of weld reinforcement.
c: failure initiated in weld.
d: failure initiated in weld at weld metal base metal interface.

TABLE A-20

RESULTS OF FATIGUE TESTS OF SPECIMENS WITH LONGITUDINAL AND TRANSVERSE BUTT WELDS PLACED IN DIFFERENT ORDERS

(Complete Reversal)

Specimen Number	Welding Procedure (See Appendix D)	Stress Cycle (ksi)	Life (cycles)	Location of Fracture***	Computed Fatigue Strength, ksi $F_{20,000}$	$F_{50,000}$	$F_{100,000}$	$F_{200,000}$
(Longitudinal Weld followed by Transverse Weld)								
HL-21	P80-11018-0 & P80-11018-D	±35.0	22,000	c	35.6	30.0	26.1	--
HL-20	P80-11018-0 & P80-11018-D	±30.0	30,000	c	32.4	27.2	23.8	--
HL-22	P80-11018-0 & P80-11018-D	±20.0	256,500	a	--	27.4	24.0	21.0
				Average*	34.0	28.2	24.6	21.0
(Transverse Weld followed by Longitudinal Weld)								
HL-25	P80-11018-D & P80-11018-0	±41.4	16,900****	c	40.3	34.7	--	--
HL-24	P80-11018-D & P80-11018-0	±30.0	89,400	c	38.1	33.0	29.5	26.3
HL-23	P80-11018-D & P80-11018-0	±30.0	131,700	c	--	35.1	31.3	28.0
				Average**	39.2	34.3	30.4	27.1

* k = 0.193 ** k = 0.162

*** a: failure initiated at edge of weld.
c: failure initiated in weld.

**** Specimen ran 13,800 cycles at +23.3 to -25.5 ksi
16,000 cycles at ±41.4 ksi } Life given above was determined to the equivalent life at ±41.4 ksi

TABLE A-21

RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS IN THE AS-WELDED CONDITION, HAVING LACK OF PENETRATION

Specimen Number	Welding Procedure (See Appendix D)	Degree of Penetration	Stress Cycle (ksi)	Life (cycles)	Location of Fracture**
G-49	P80-11018-D*	92%	±30.0	75,000	i
V-9	P80-11018-B	100%	±30.0	55,300	c
V-21	P80-11018-C	100%	±30.0	72,700	a
V-20	P80-11018-C	100%	±30.0	75,900	a
V-19	P80-11018-C	100%	0 to +60.0	50,300	a
V-26	P80-11018-D	100%	0 to +60.0	54,000	a
G-50	P80-11018-D*	92%	0 to +60.0	26,700	i

* Same as procedure noted except no root opening was provided. The 1/8" lands of the groove were butted.

** a: failure initiated at edge of weld reinforcement.
c: failure initiated in weld.
i: failure initiated at lack of penetration.

APPENDIX B - LIST OF FIGURES
(Graphical Presentation of Test Data)

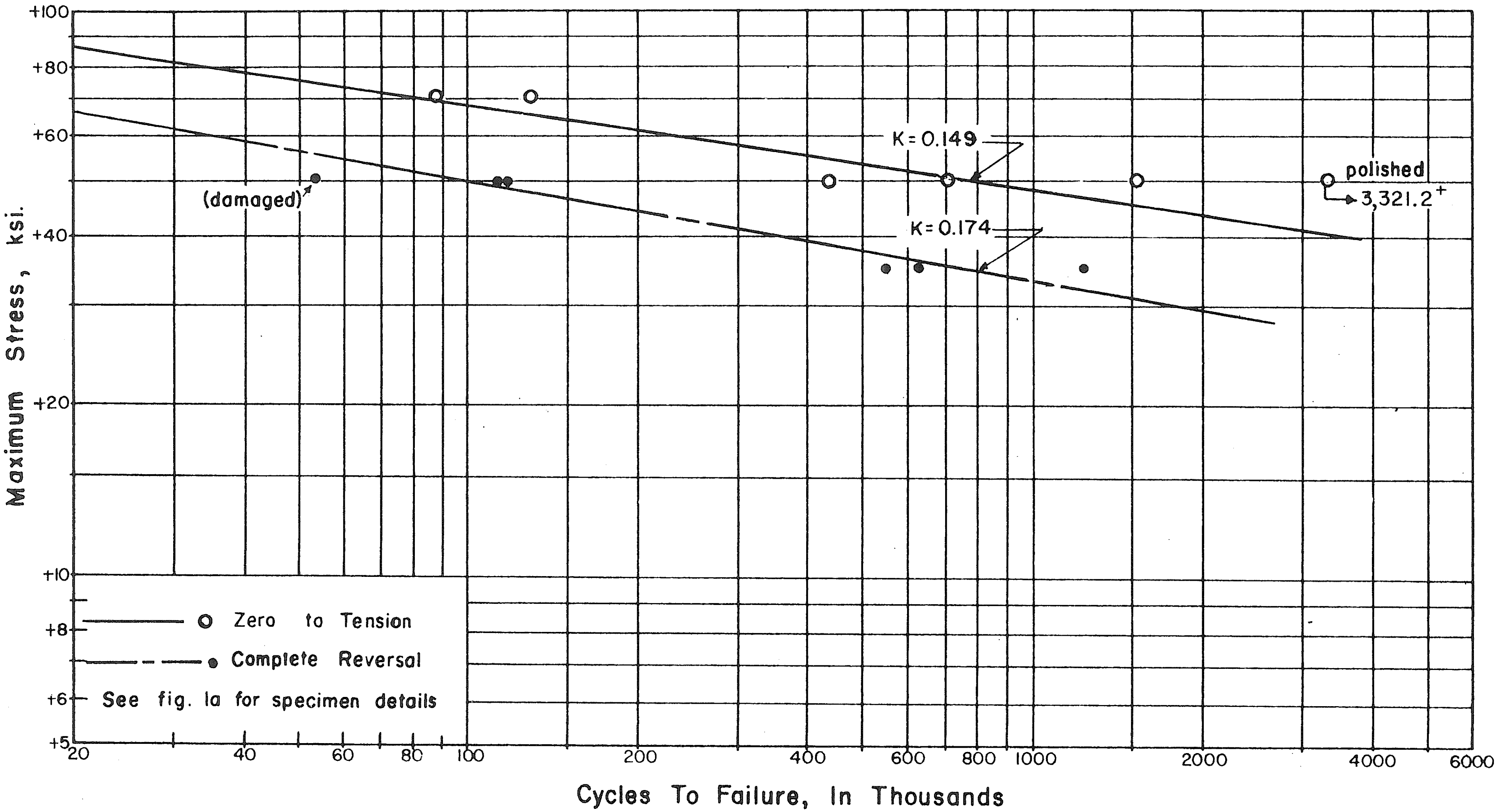


FIG. B-1 RESULTS OF FATIGUE TESTS OF AS-ROLLED PLAIN PLATE SPECIMENS

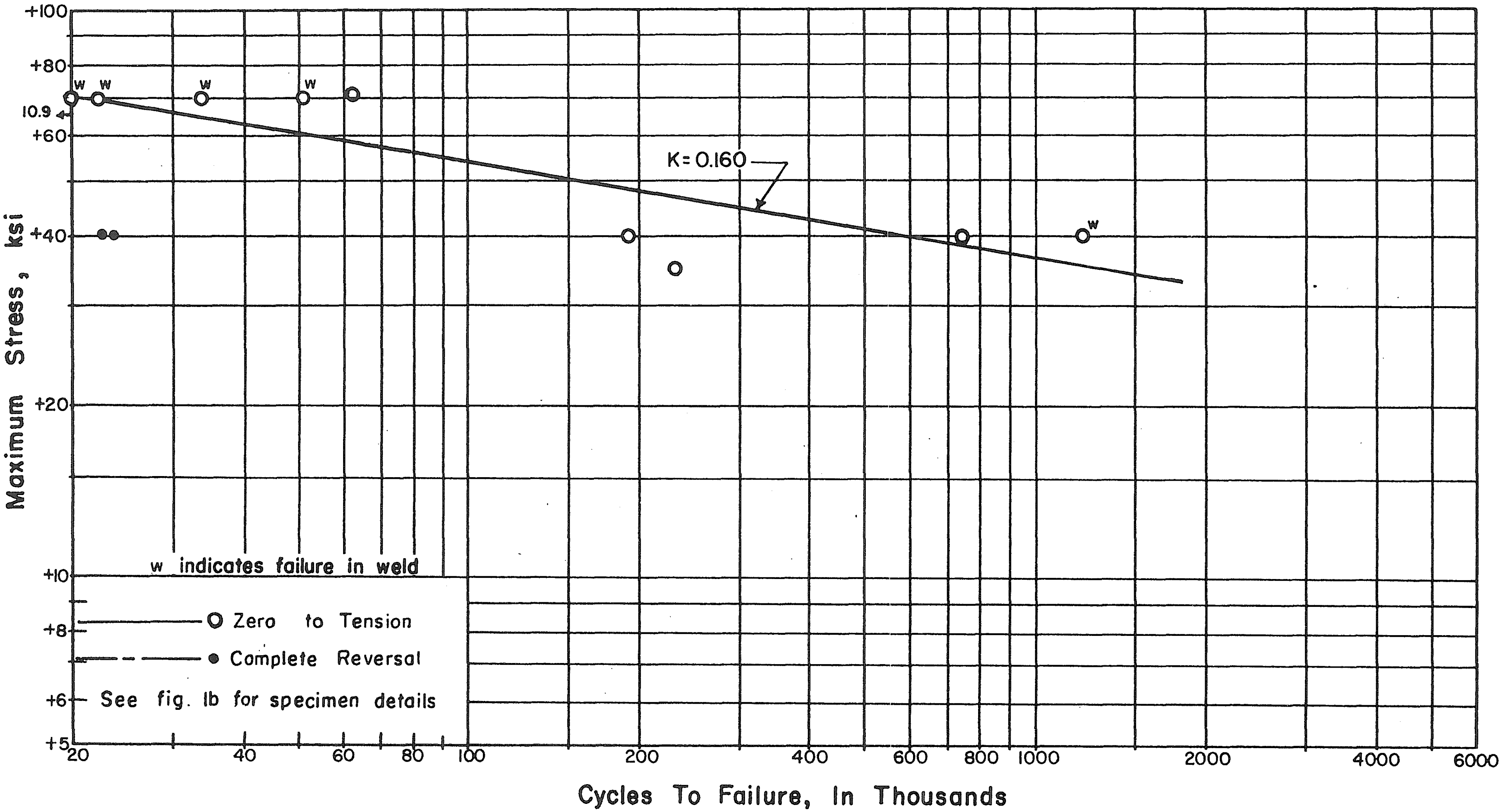


FIG. B-2 RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS WITH REINFORCEMENT REMOVED ON ONE SIDE.

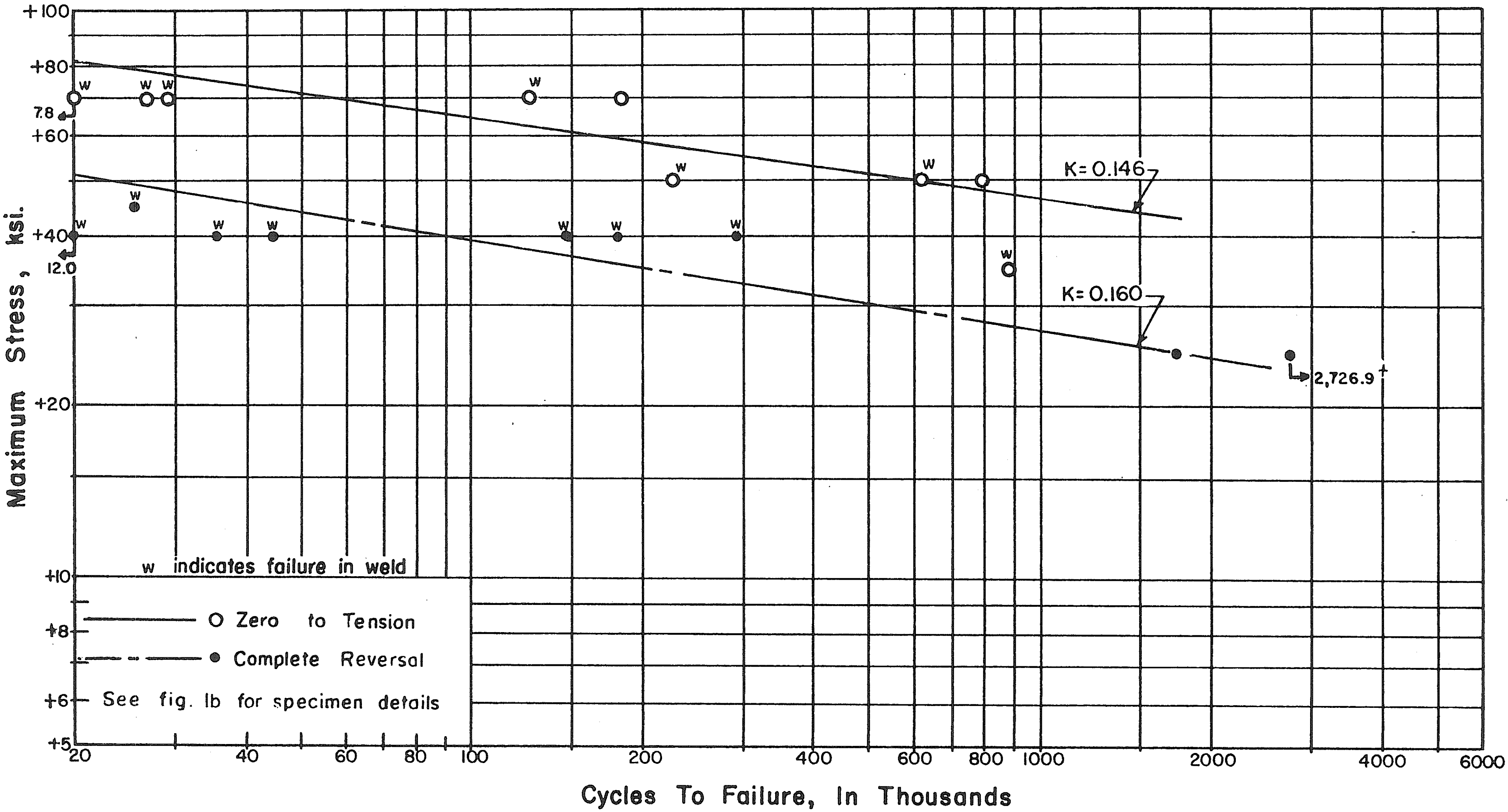


FIG. B-3 RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS WITH REINFORCEMENT REMOVED ON TWO SIDES.

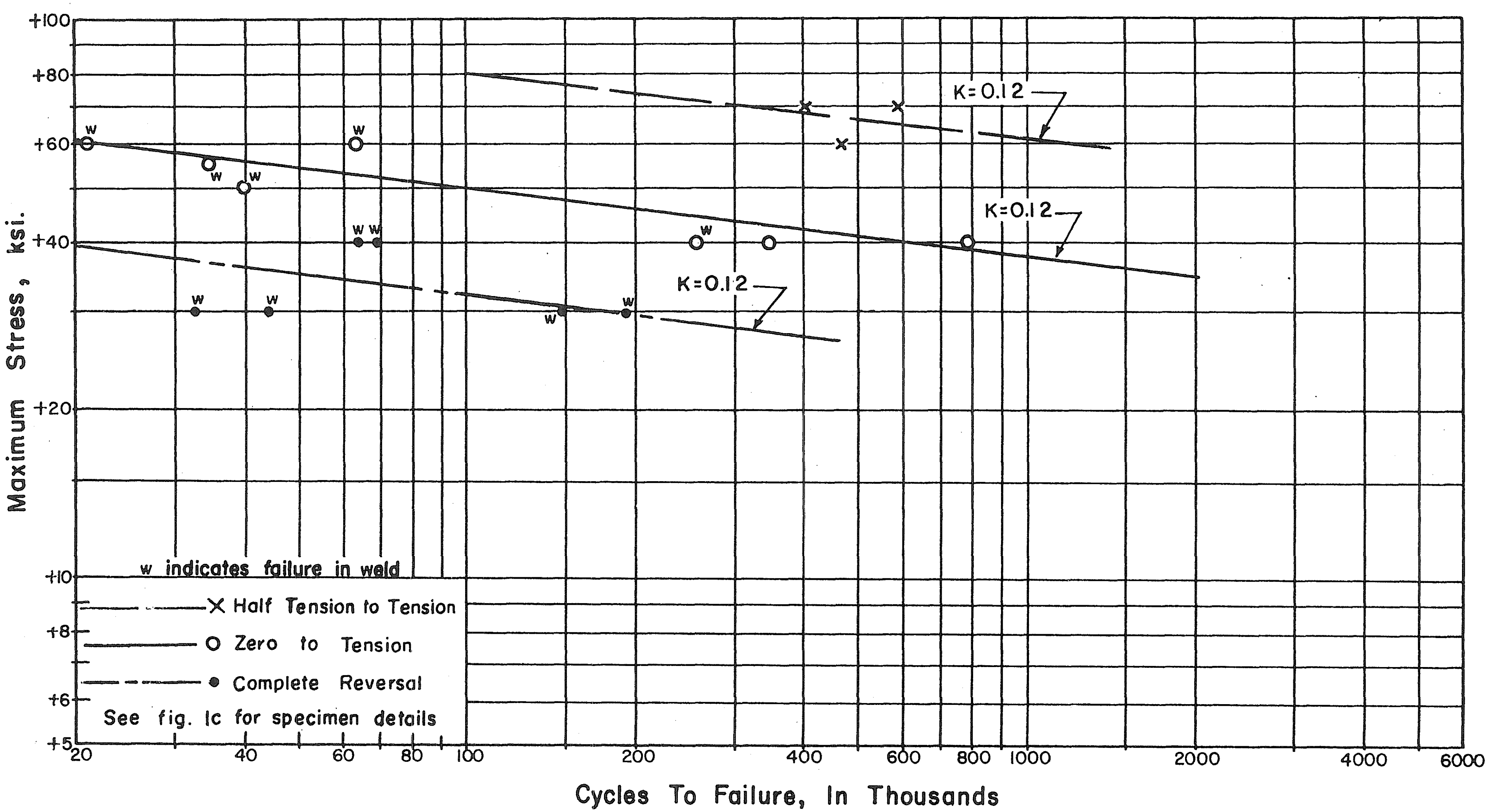


FIG. B-4 RESULTS OF FATIGUE TESTS OF LONGITUDINAL BUTT WELDS IN THE AS-WELDED CONDITION.

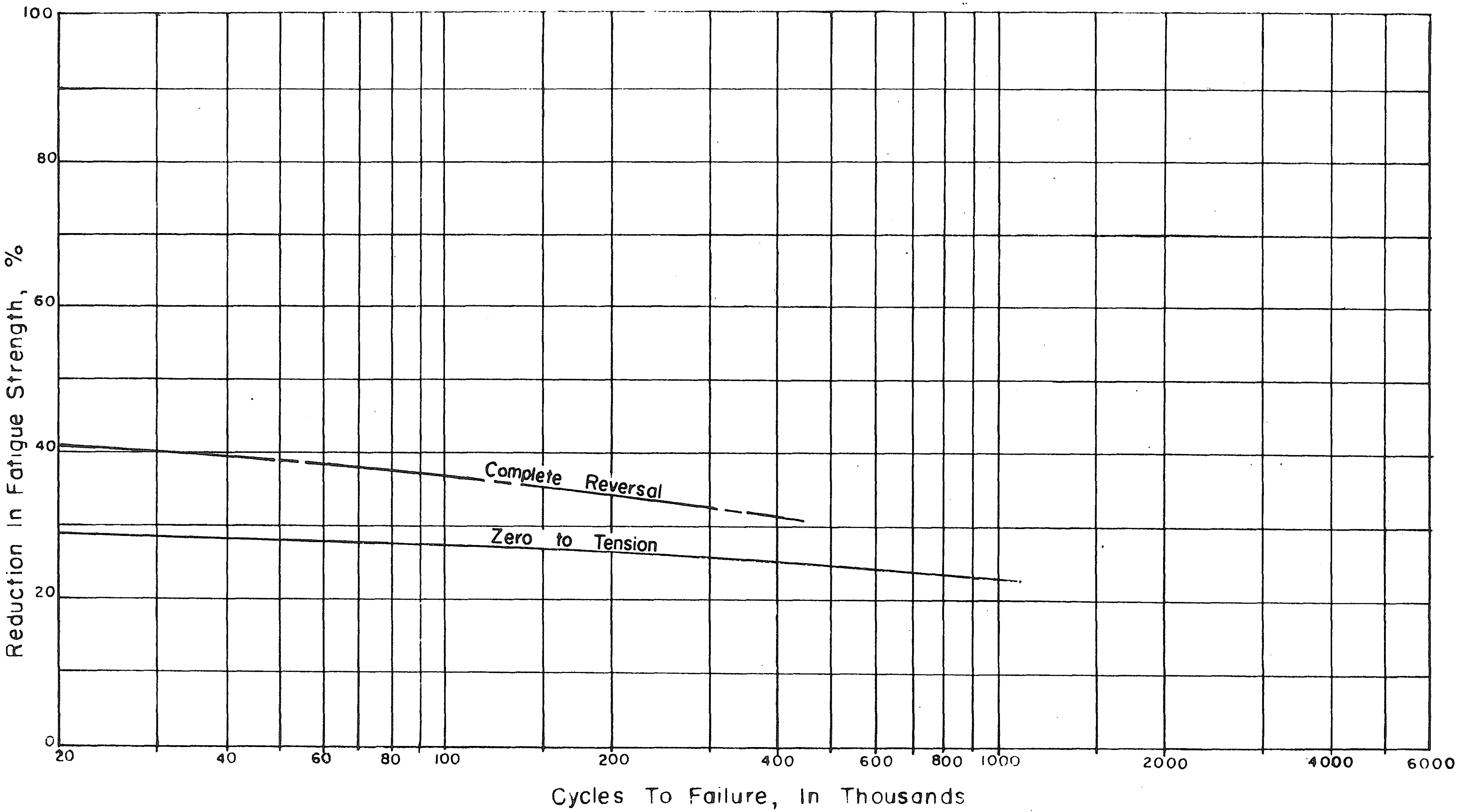


FIG. B-5 REDUCTION IN FATIGUE STRENGTH OF AS-ROLLED PLAIN PLATES DUE TO A LONGITUDINAL BUTT WELD.

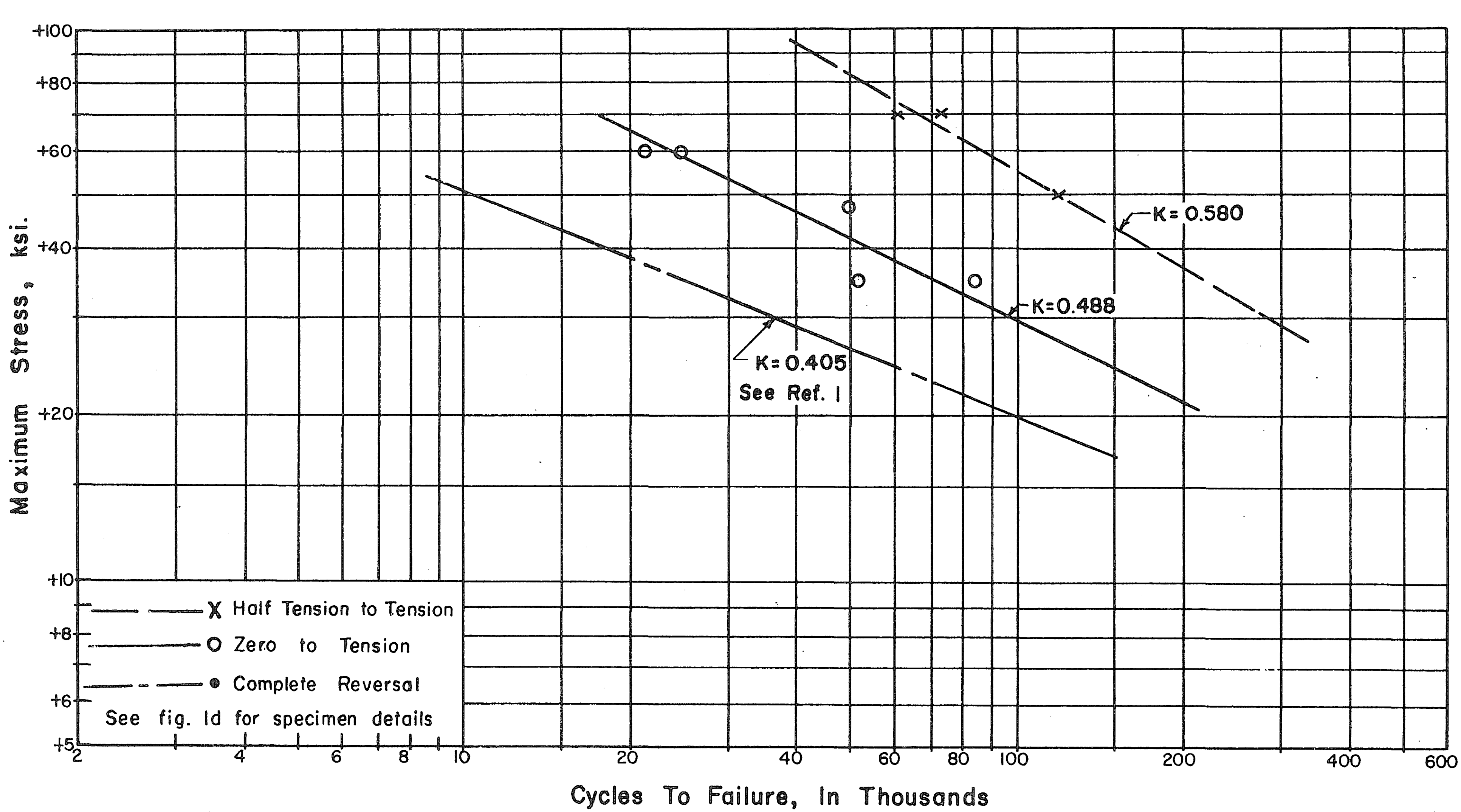


FIG. B-6 RESULTS OF FATIGUE TESTS OF PLATES WITH FULL PENETRATION TRANSVERSE ATTACHMENTS ON TWO SIDES.

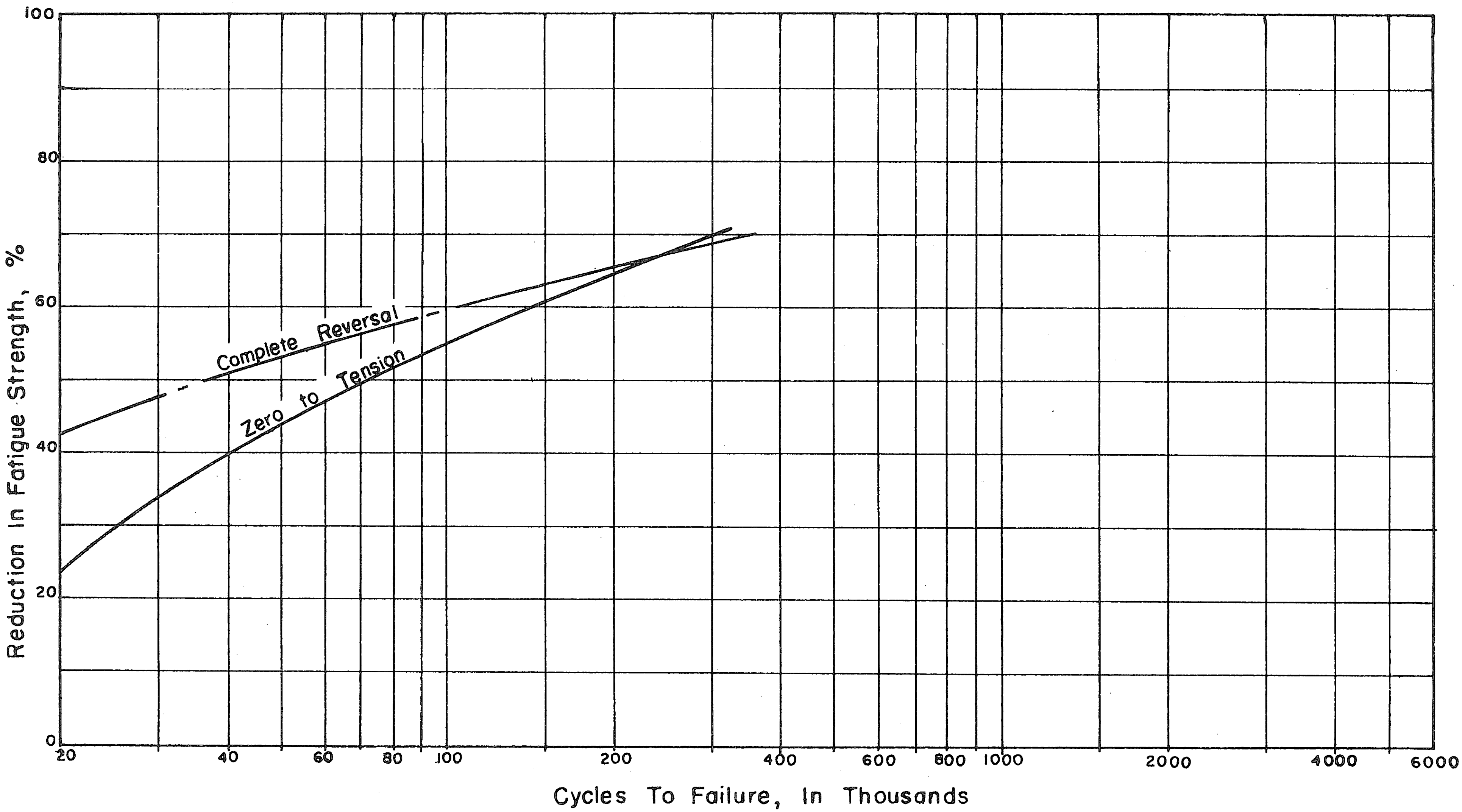


FIG.B-7 REDUCTION IN FATIGUE STRENGTH OF AS-ROLLED PLAIN PLATES DUE TO FULL PENETRATION ATTACHMENTS ON TWO SIDES.

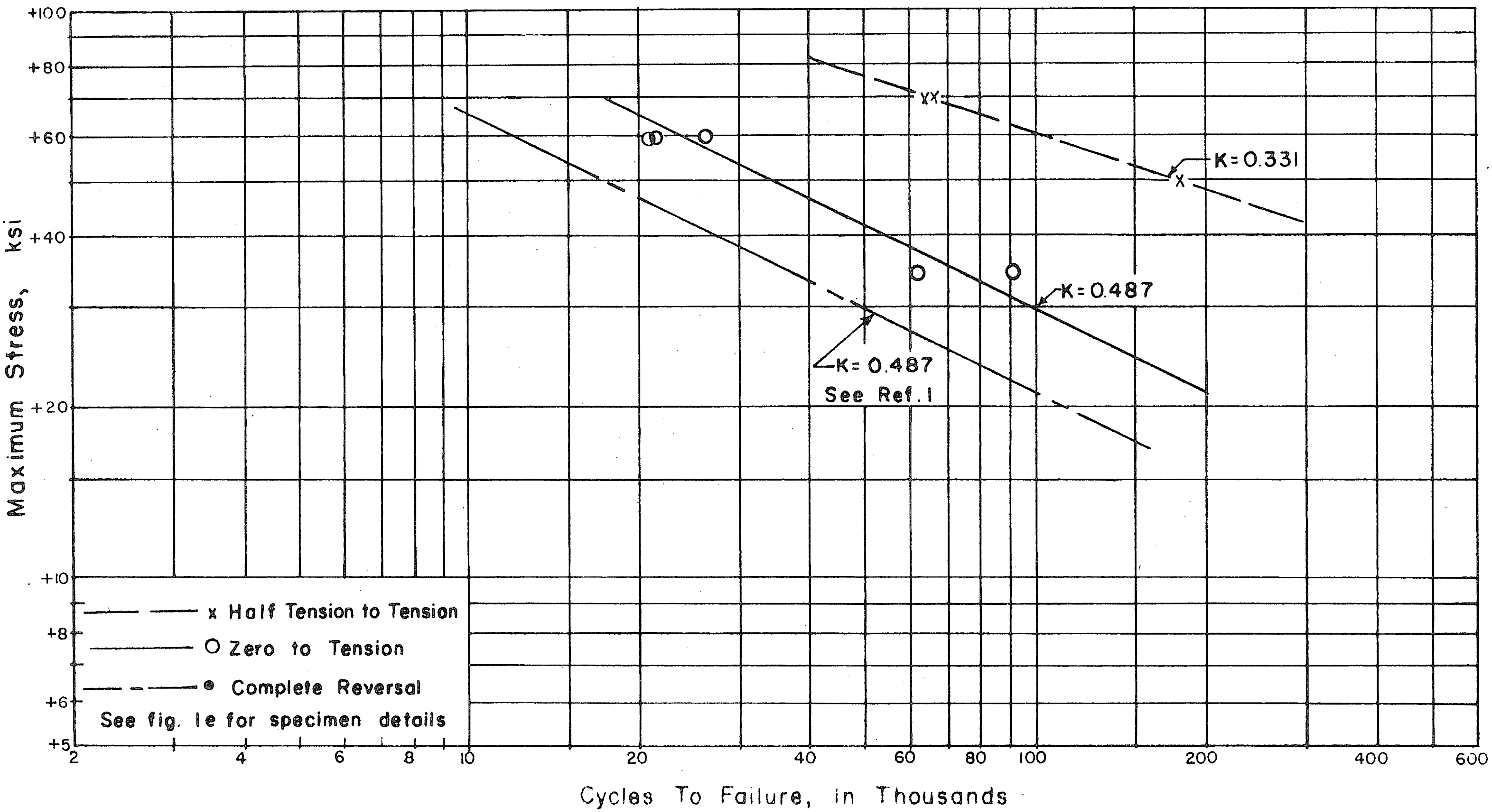


FIG. B-8 RESULTS OF FATIGUE TESTS OF PLATES WITH A FULL PENETRATION TRANSVERSE ATTACHMENT ON ONE SIDE.

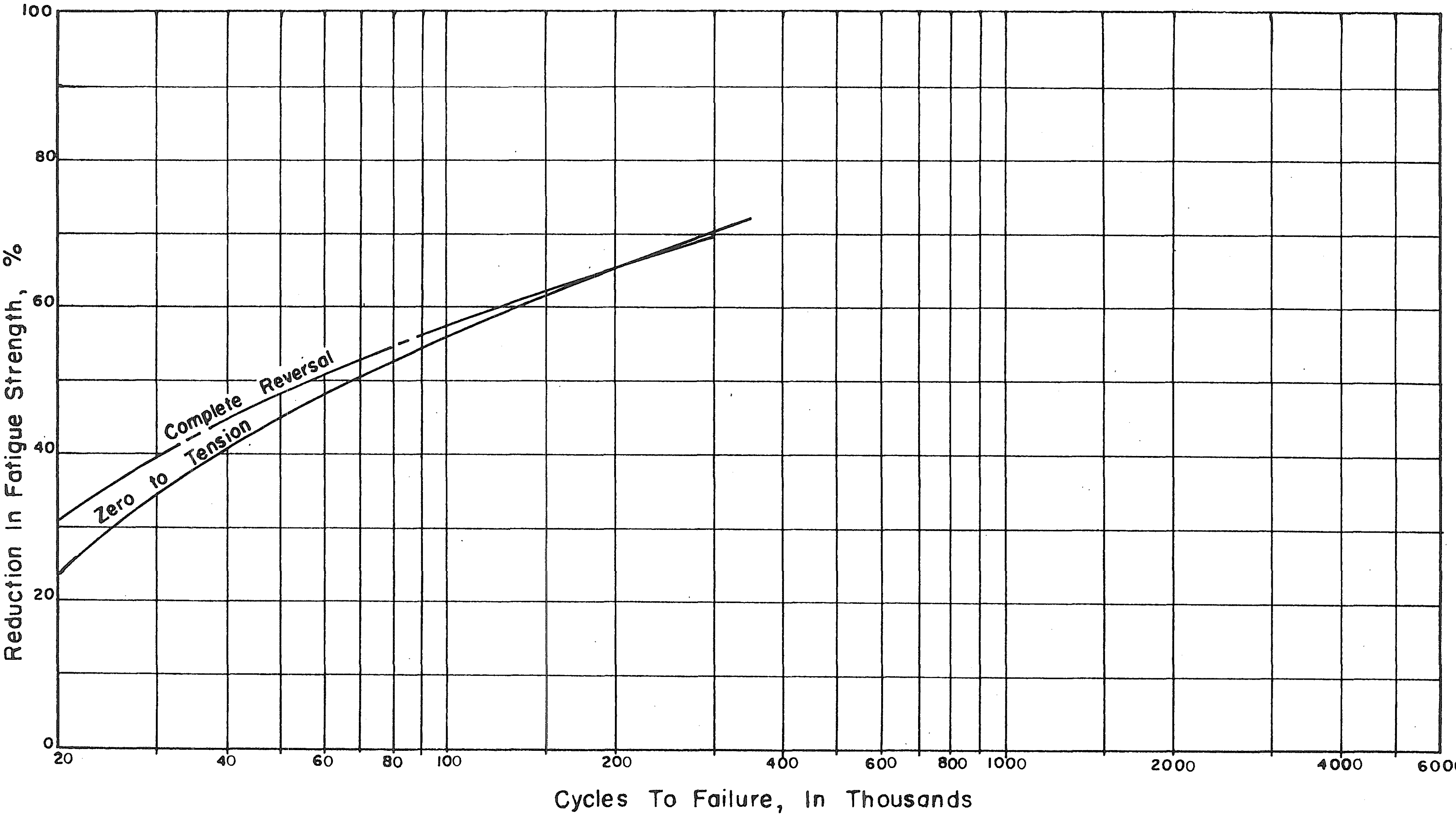


FIG. B-9 REDUCTION IN FATIGUE STRENGTH OF AS-ROLLED PLAIN PLATES DUE TO A FULL PENETRATION ATTACHMENT ON ONE SIDE.

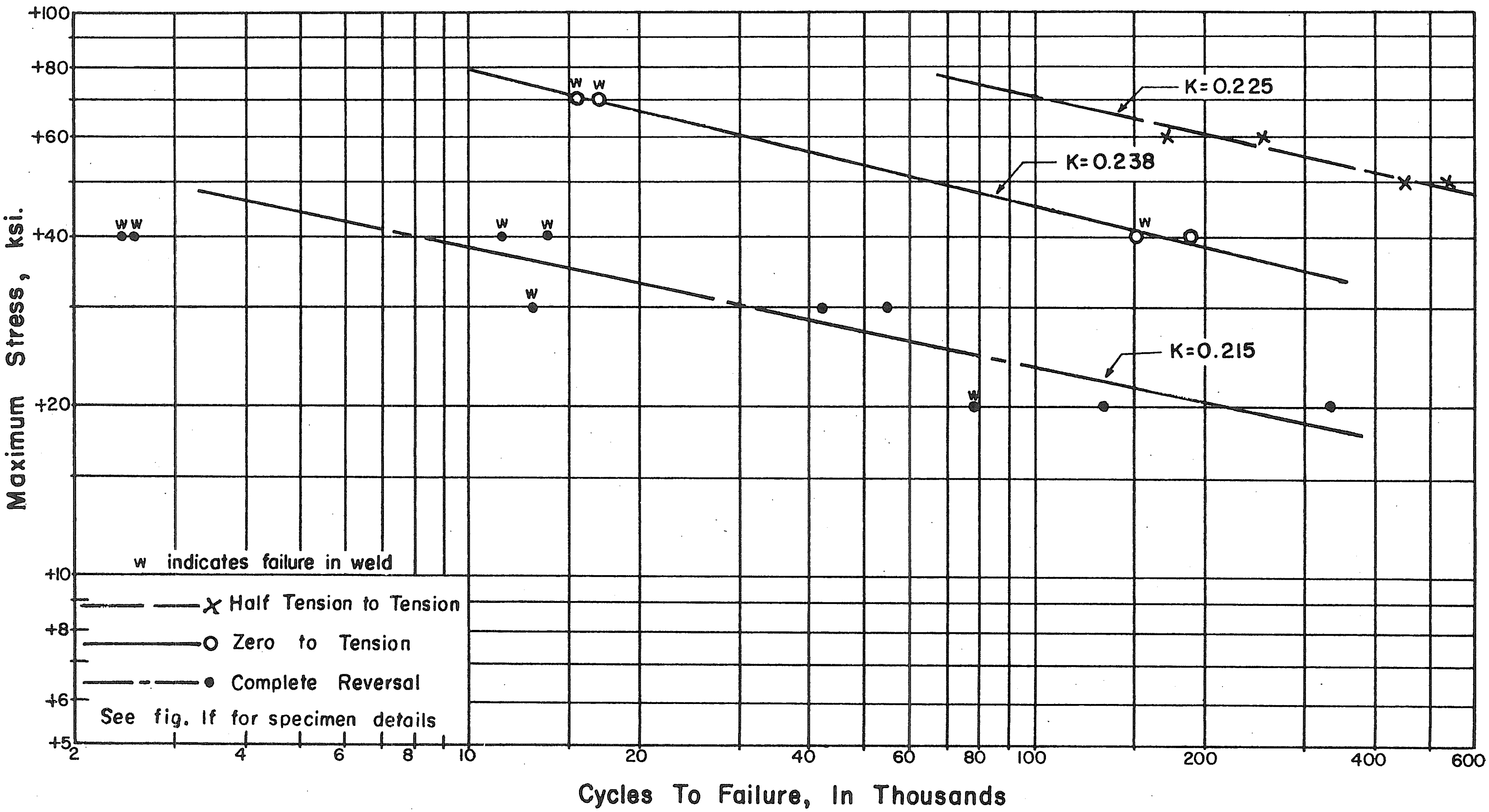


FIG. B-10 RESULTS OF FATIGUE TESTS OF FULL PENETRATION TRANSVERSE TEE JOINTS.

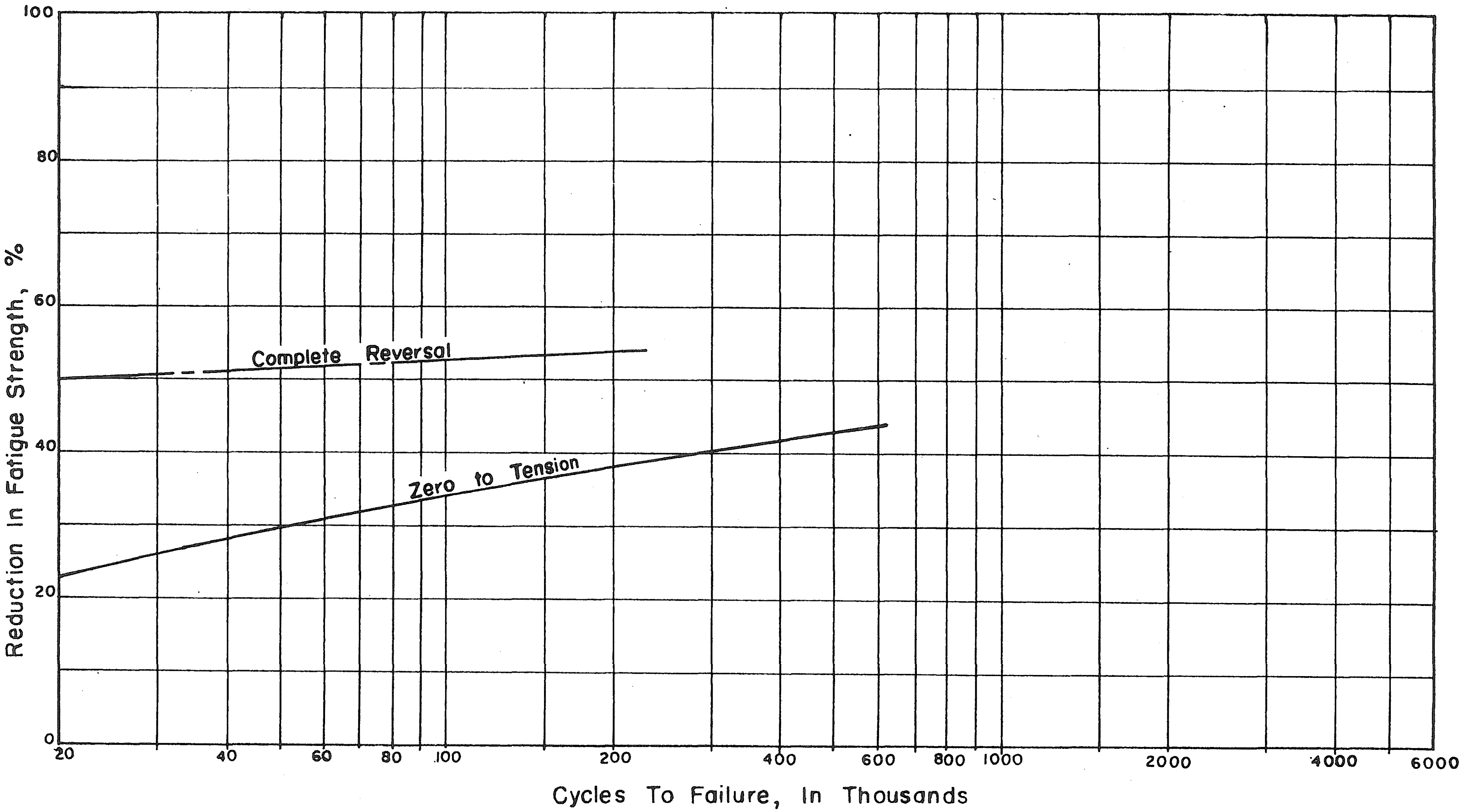


FIG. B-11 REDUCTION IN FATIGUE STRENGTH OF AS-ROLLED PLAIN PLATES DUE TO A FULL PENETRATION TRANSVERSE TEE JOINT.

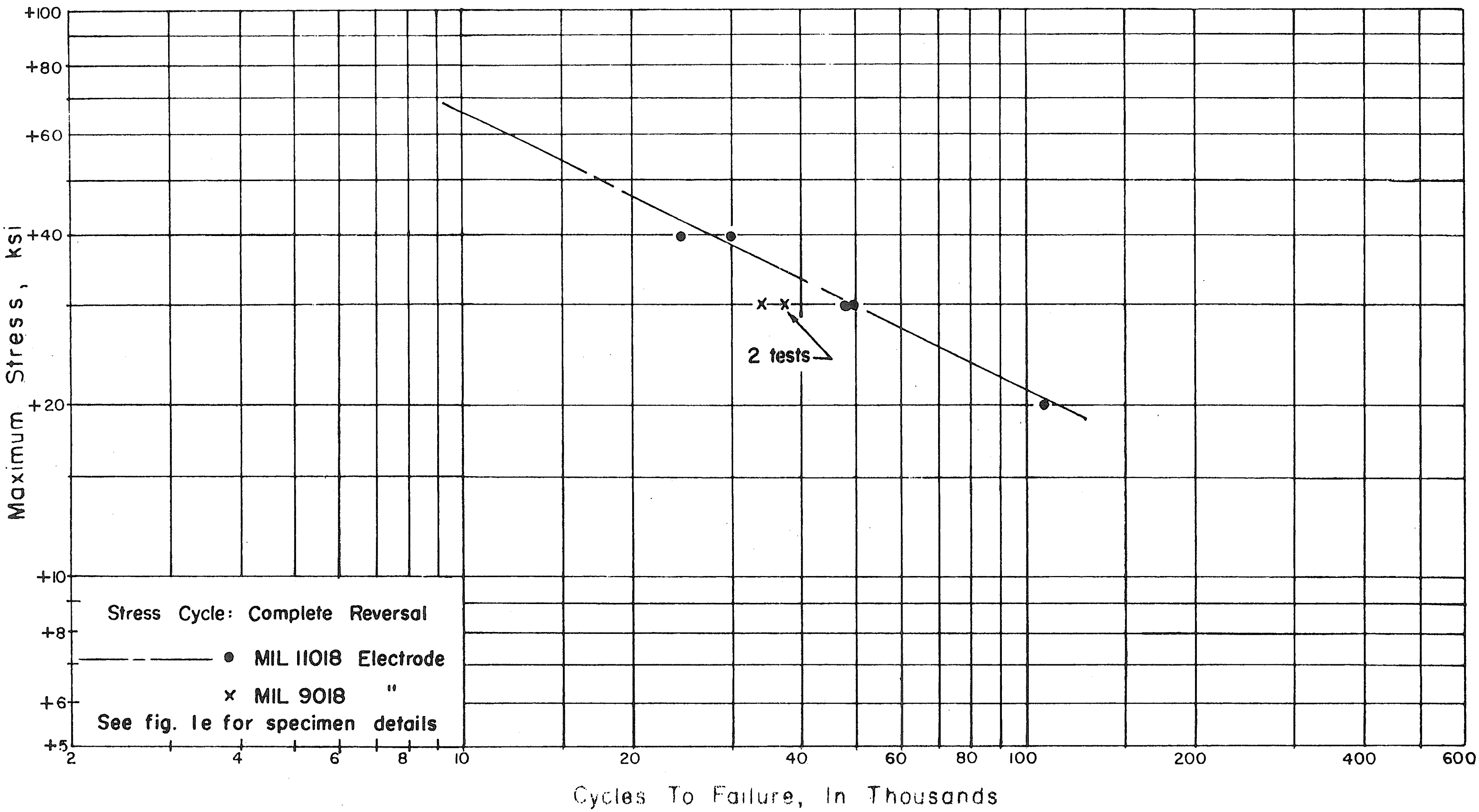


FIG. B-12 RESULTS OF FATIGUE TESTS OF PLATES WITH A FULL PENETRATION TRANSVERSE ATTACHMENT ON ONE SIDE, WELDED WITH DIFFERENT ELECTRODES.

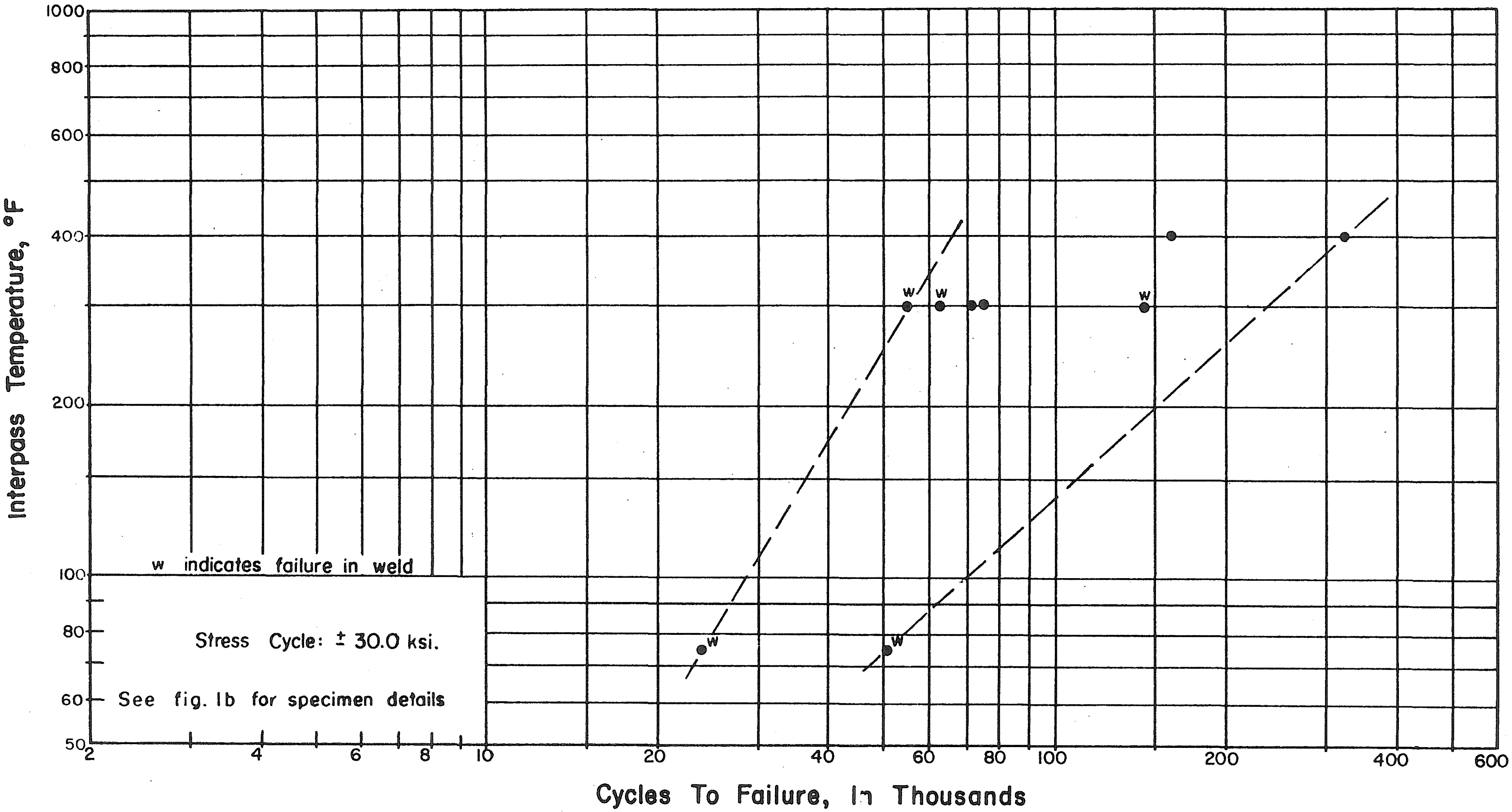


FIG. B-13 RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS FABRICATED USING DIFFERENT INTERPASS TEMPERATURES.

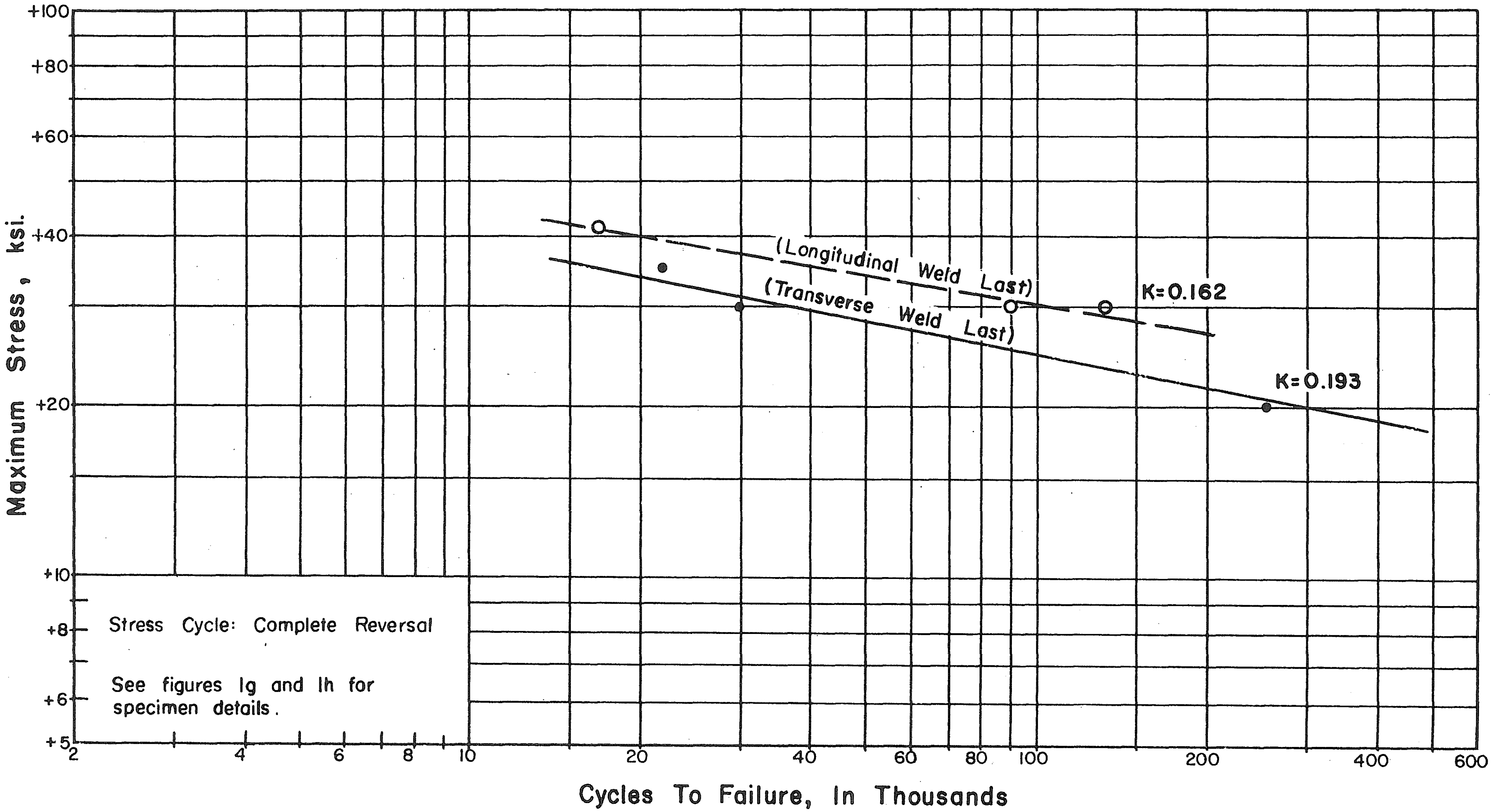


FIG. B-14 RESULTS OF FATIGUE TESTS OF PLATES WITH LONGITUDINAL AND TRANSVERSE BUTT WELDS PLACED IN DIFFERENT ORDERS.

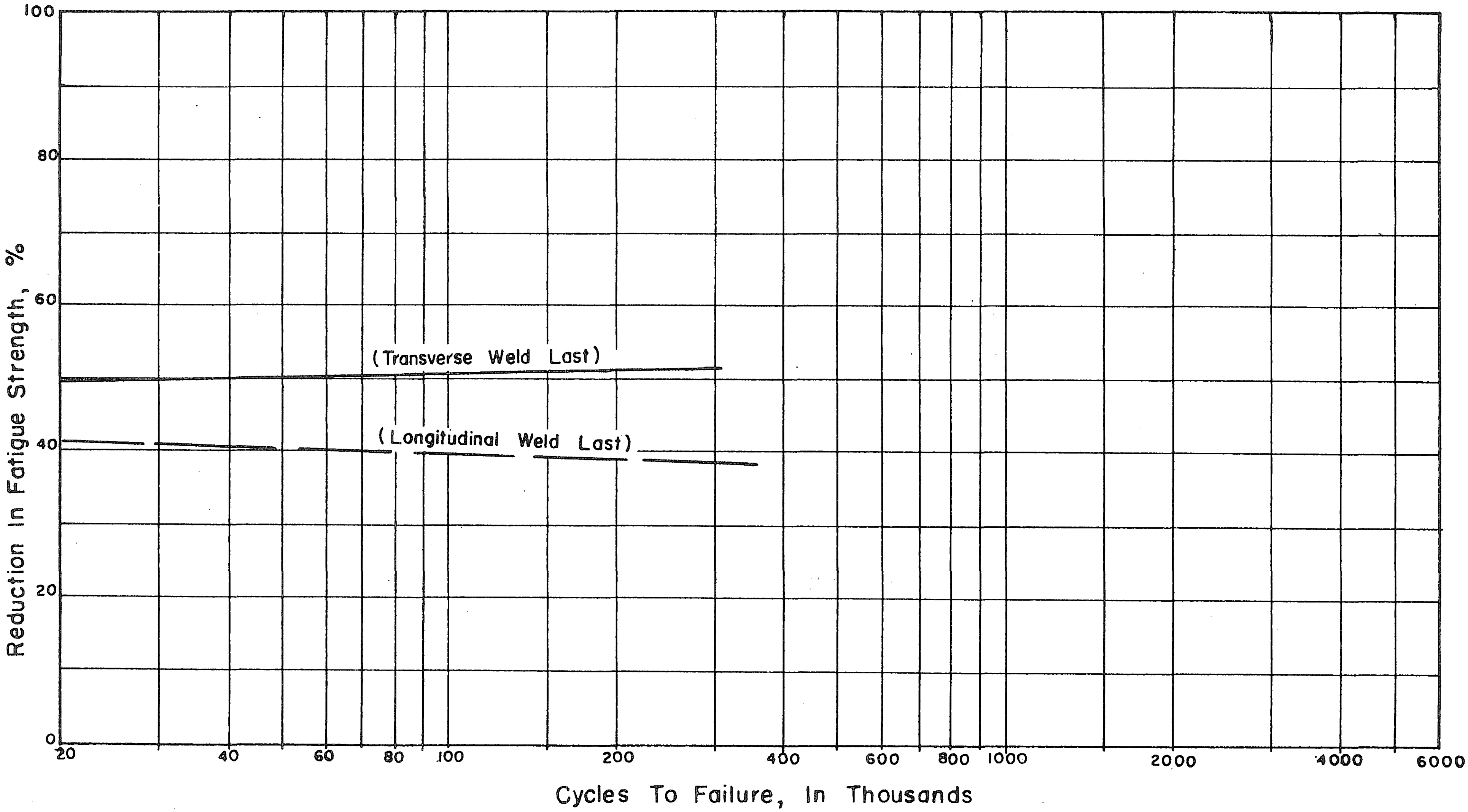


FIG. B-15 REDUCTION IN FATIGUE STRENGTH OF AS-ROLLED PLAIN PLATES DUE TO COMBINED LONGITUDINAL AND TRANSVERSE BUTT WELDS.

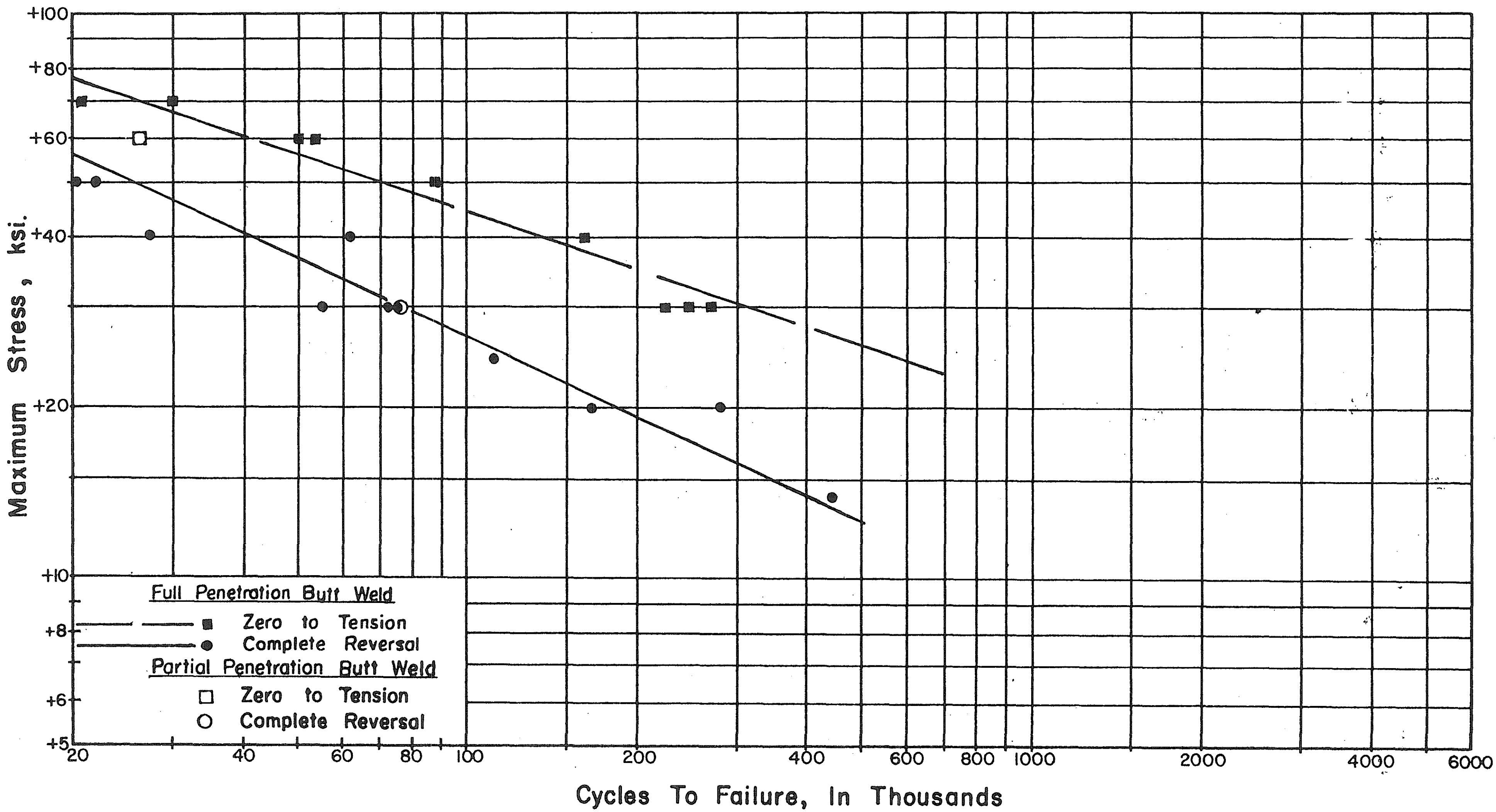


FIG. B-16 RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT WELDS IN THE AS-WELDED CONDITION HAVING LACK OF PENETRATION.

APPENDIX C - LIST OF FIGURES

(Test Specimen Fractures)

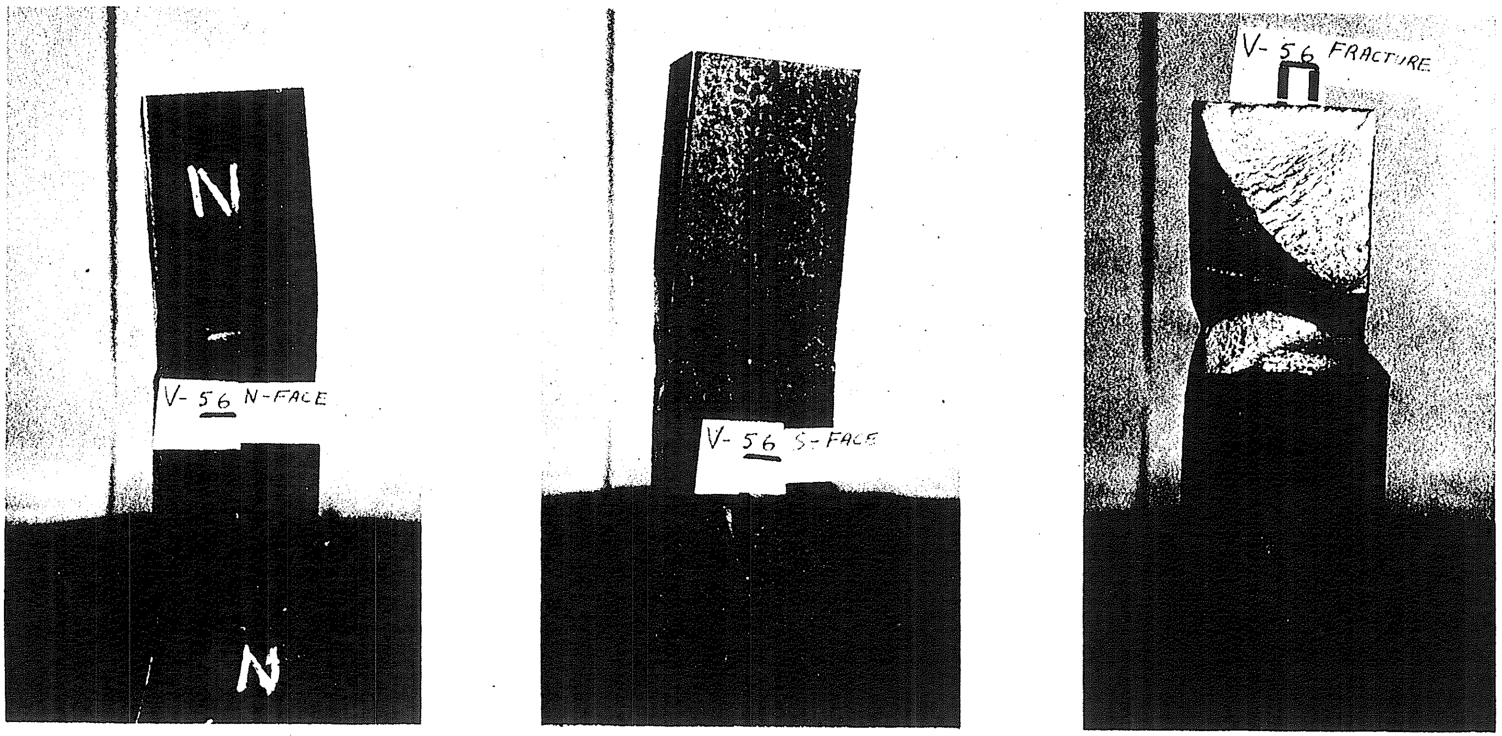
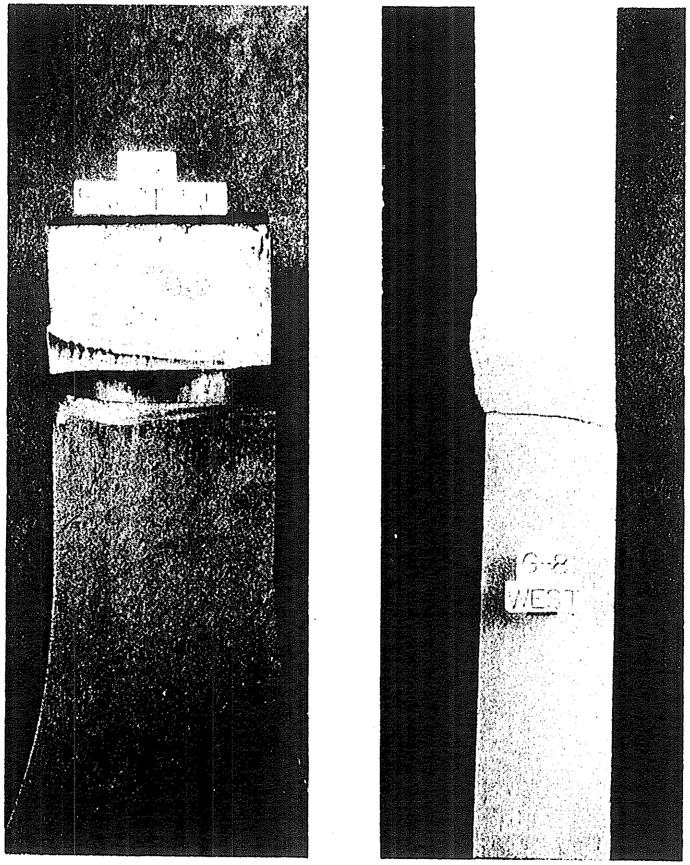
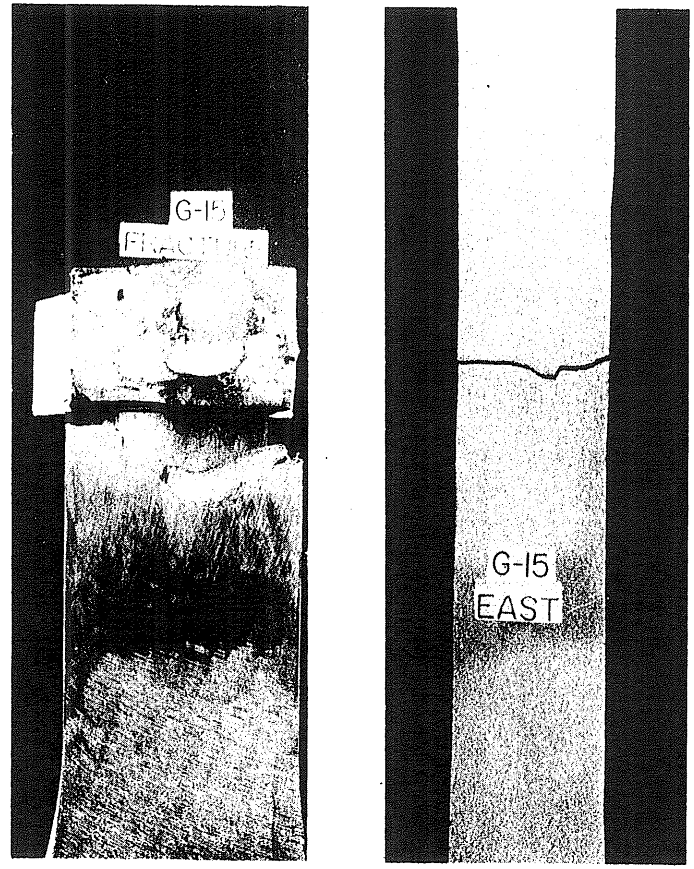


FIG. C-1 TYPICAL FRACTURE FOR AS-ROLLED PLAIN PLATE SPECIMENS.

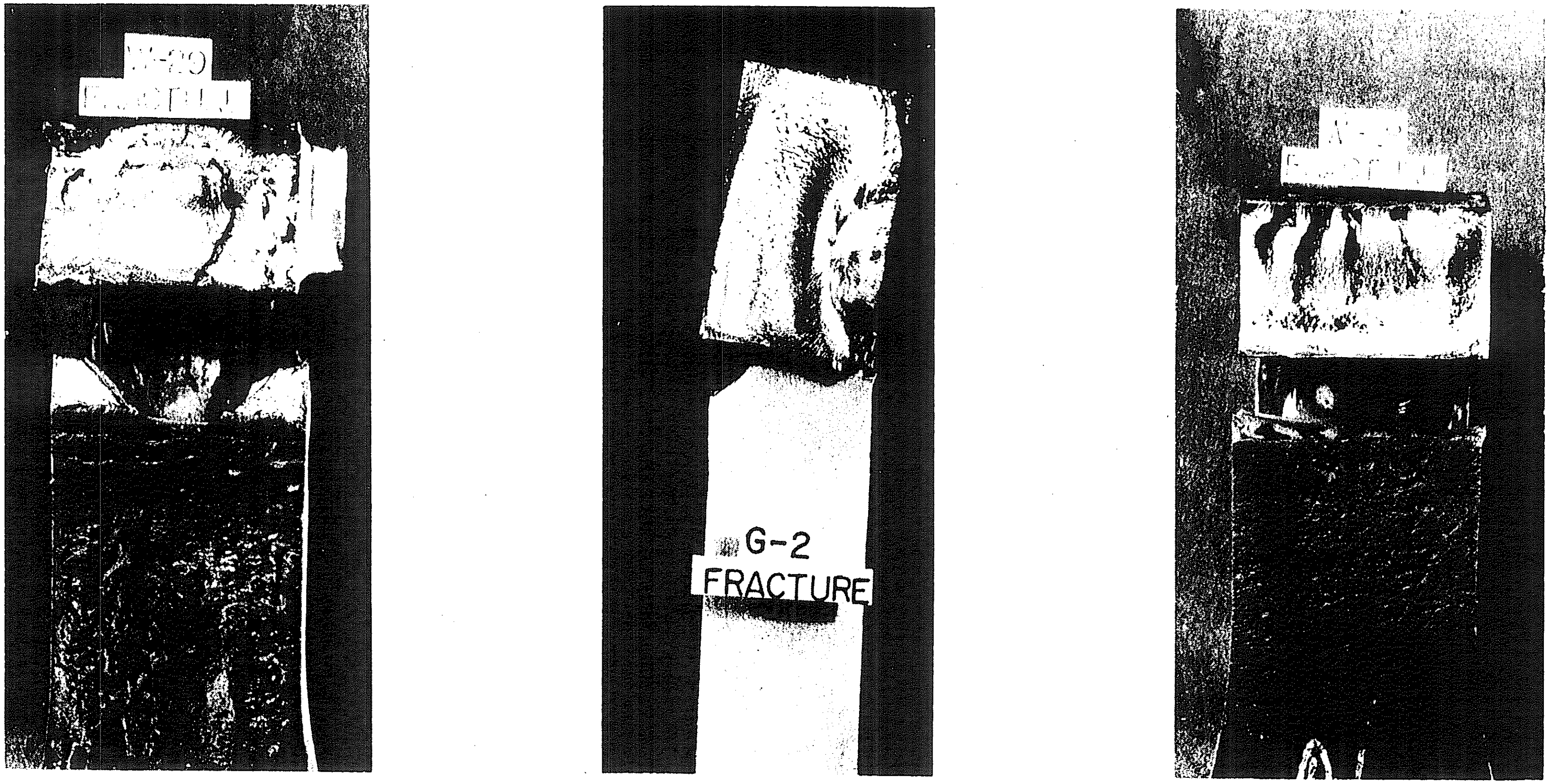


a) Reinforcement removed on one side.



b) Reinforcement removed on two sides.

FIG. C-2 TYPICAL FRACTURES FOR TRANSVERSE BUTT WELDS WITH REINFORCEMENT REMOVED.

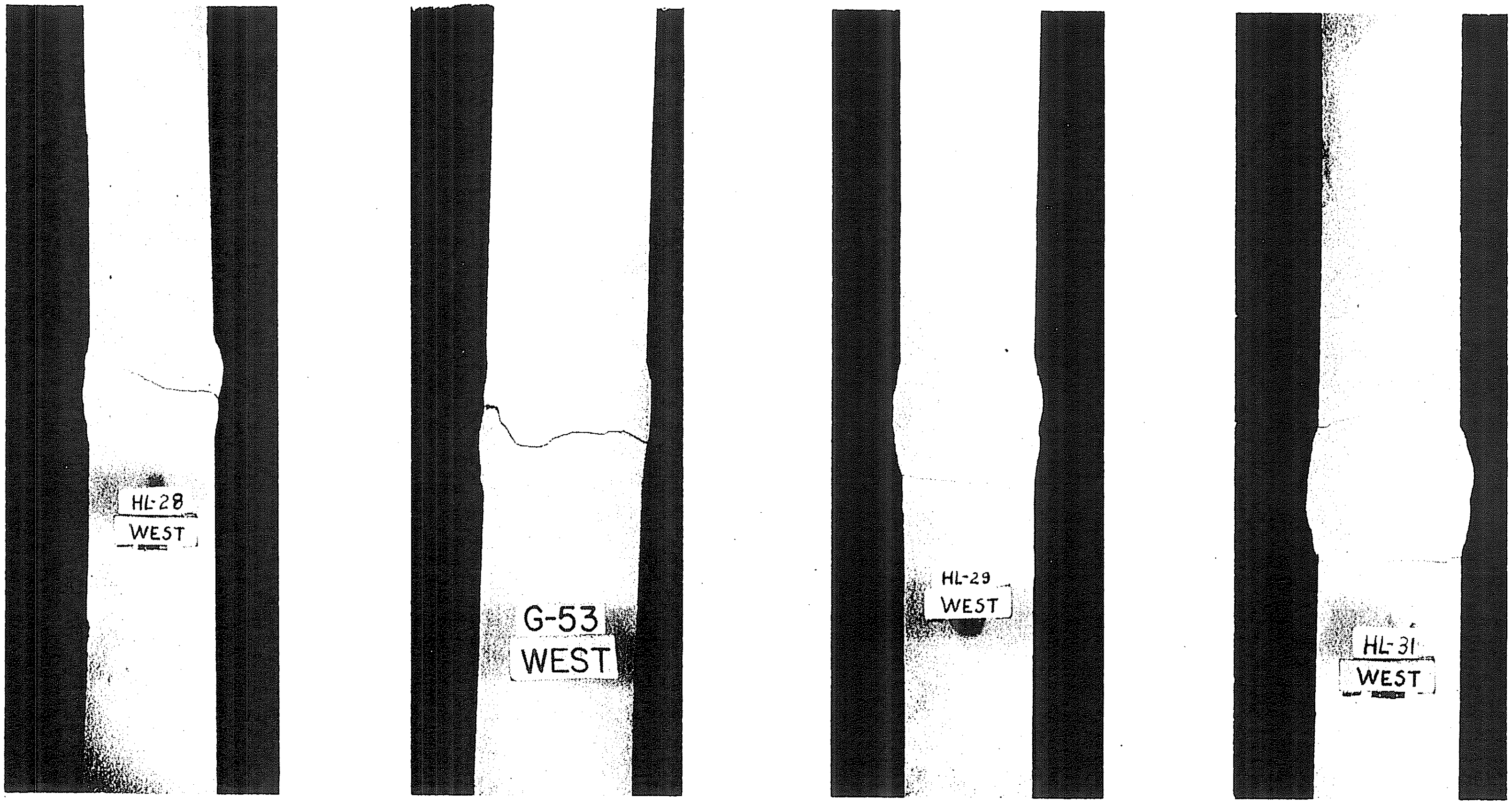


a) Failure initiated at defect in weld.

b) Failure initiated at base metal weld metal interface.

c) Failure initiated at edge of weld reinforcement.

FIG. C-3 VARIOUS TYPES OF FAILURES OBTAINED WITH TRANSVERSE BUTT WELDS.



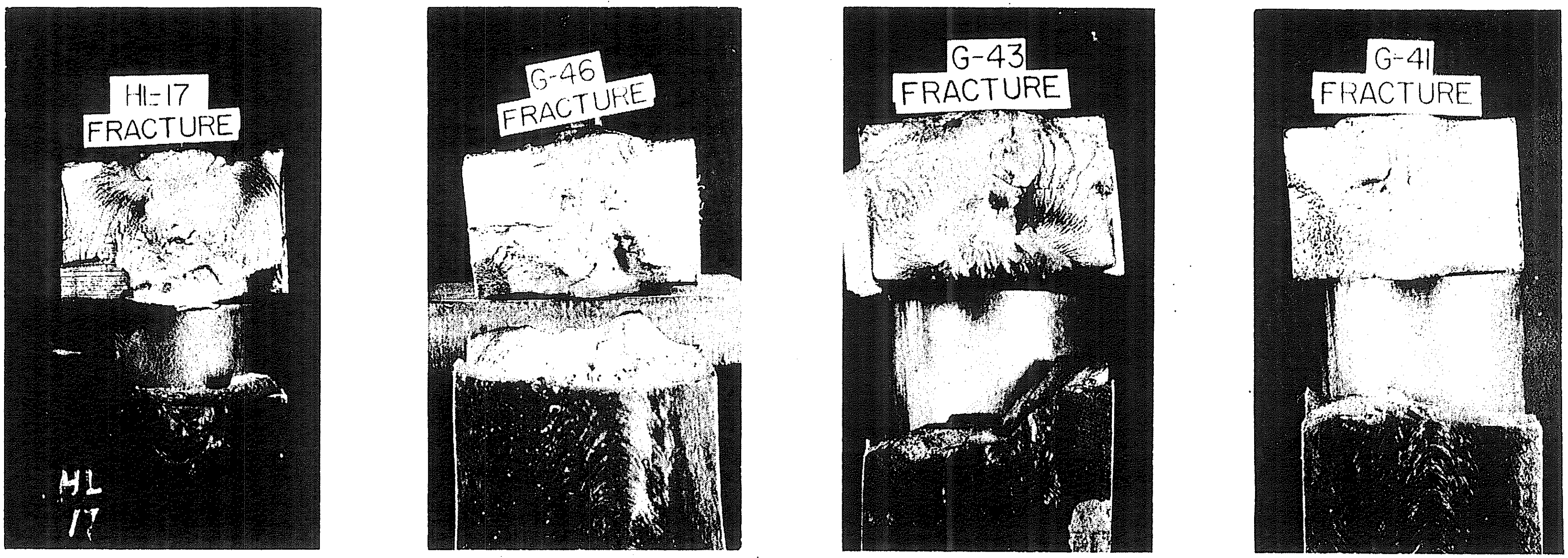
a) At junction of two weld beads.

b) Initiated at weld metal base metal interface.

c) At toe of weld.

d) Simultaneous cracks at toe of weld.

FIG. C-4 VARIOUS FRACTURE MODES FOR TRANSVERSE BUTT WELDS IN THE AS-WELDED CONDITION.



(a) (b) Failure initiated at porosity in weld.

(c) Failure initiated at electrode change pt.

(d) Failure initiated at edge of weld.

FIG. C-5 TYPICAL FRACTURES FOR LONGITUDINAL BUTT WELDS IN THE AS-WELDED CONDITION.

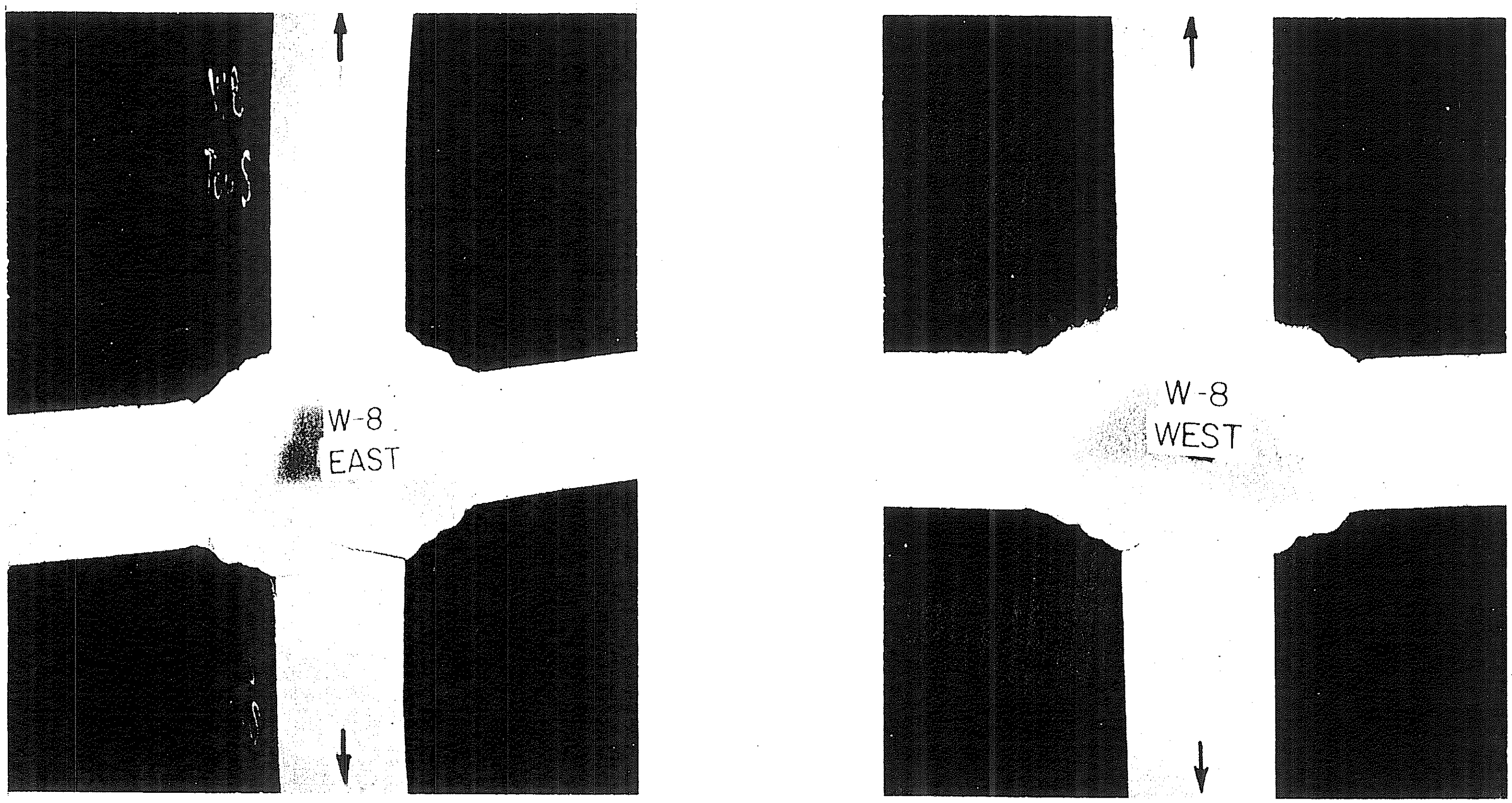
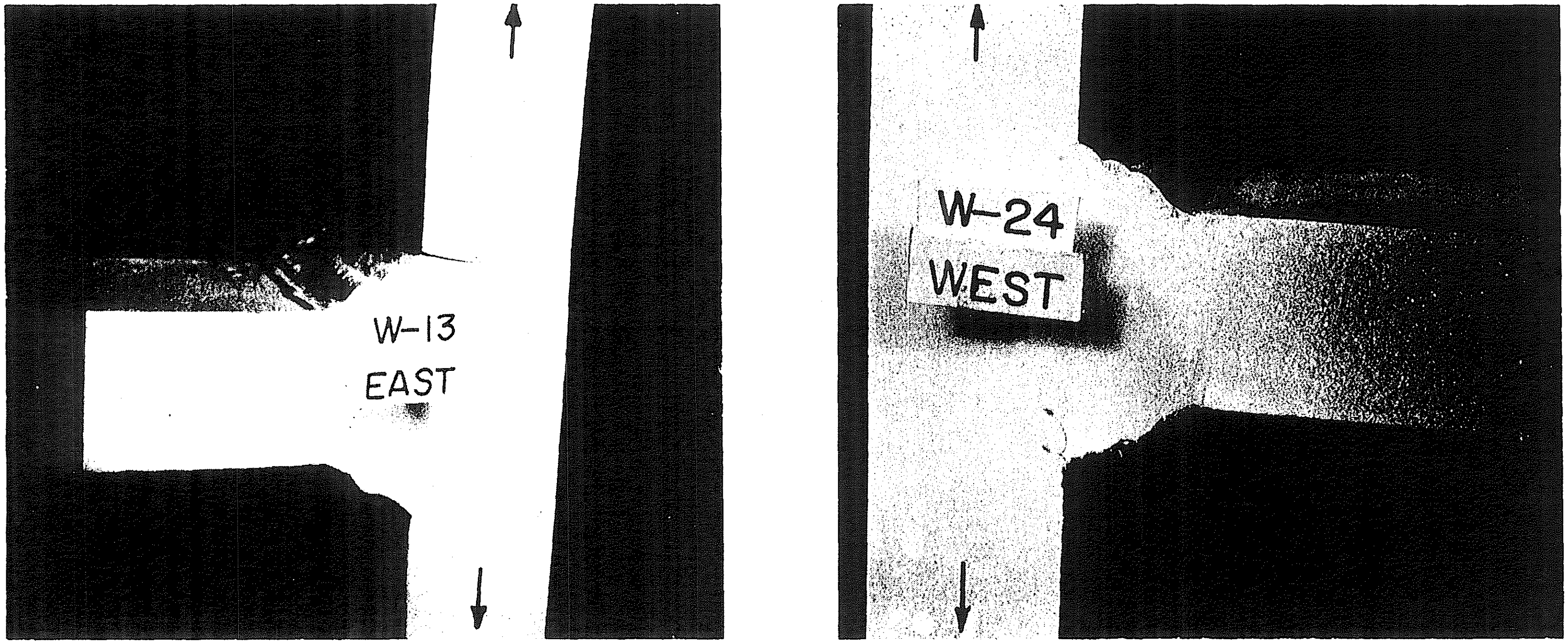


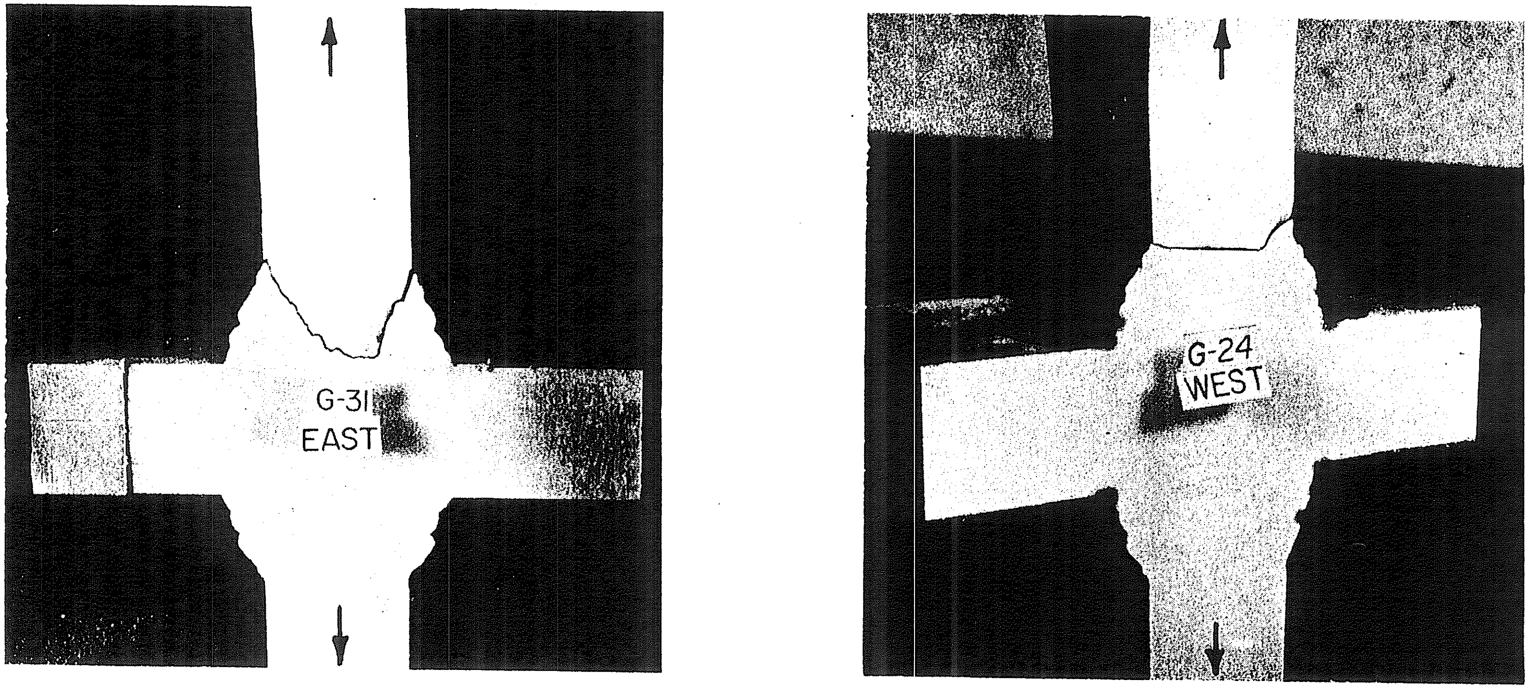
FIG. C-6 TYPICAL FRACTURE FOR AS-ROLLED PLAIN PLATE WITH FULL PENETRATION ATTACHMENTS ON TWO SIDES.



a) Welded with MIL 11018 electrode.

b) Welded with MIL 9018 electrode.

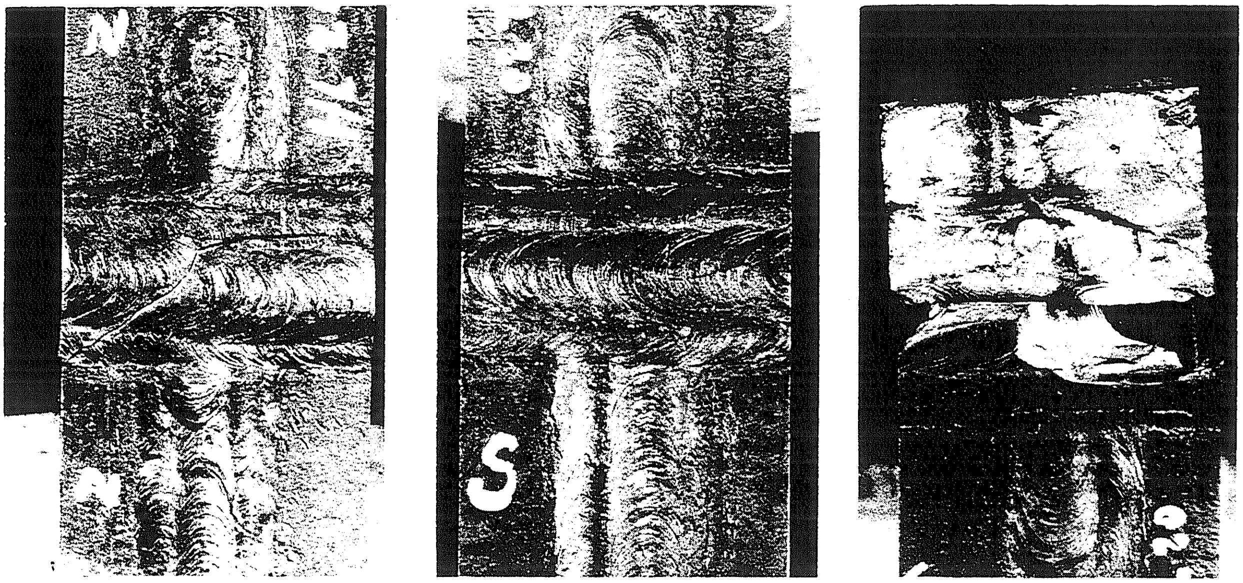
FIG. C-7 TYPICAL FRACTURES FOR AS-ROLLED PLAIN PLATES WITH A FULL PENETRATION ATTACHMENT ON ONE SIDE.



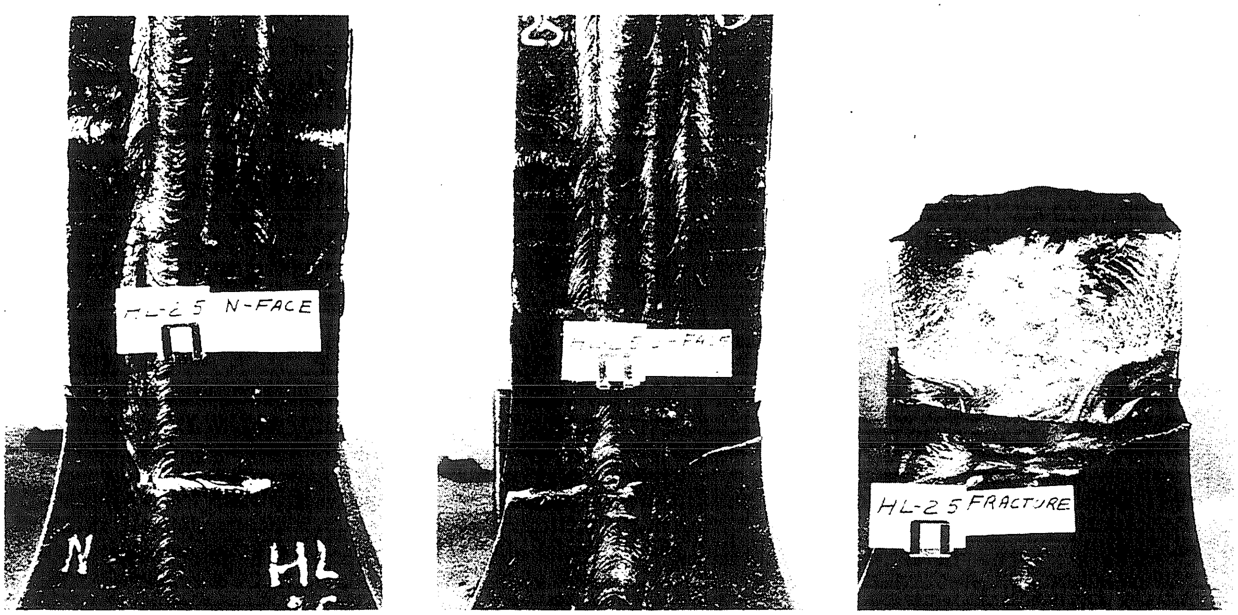
a) Failure initiated in weld.

b) Failure initiated at toe of weld.

FIG. C-8 TYPICAL FRACTURES FOR FULL PENETRATION TEE JOINTS.



a) Transverse butt weld placed last.



b) Longitudinal butt weld placed last.

FIG. C-9 TYPICAL FRACTURES FOR SPECIMENS WITH COMBINED TRANSVERSE AND LONGITUDINAL BUTT WELDS.

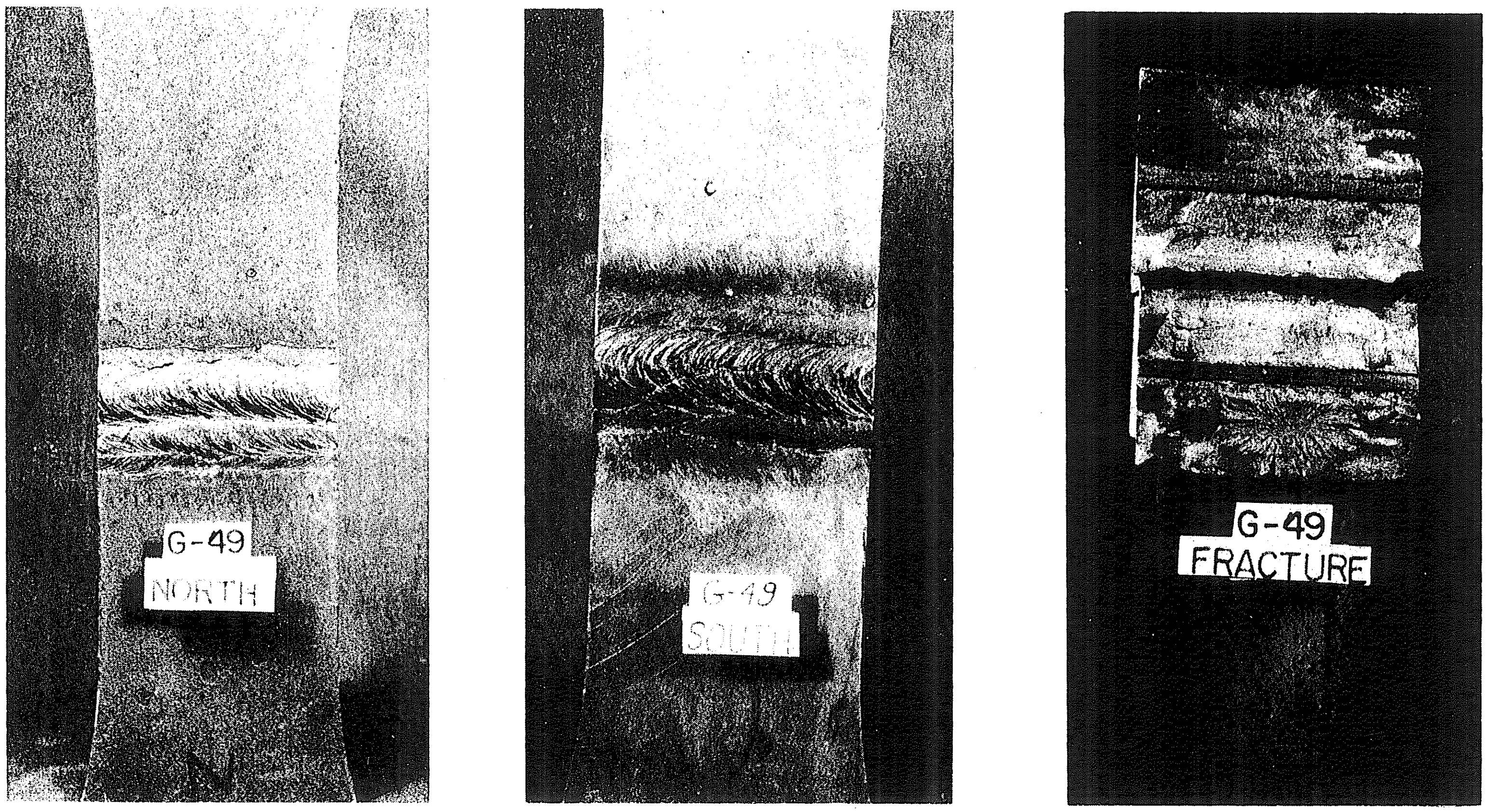
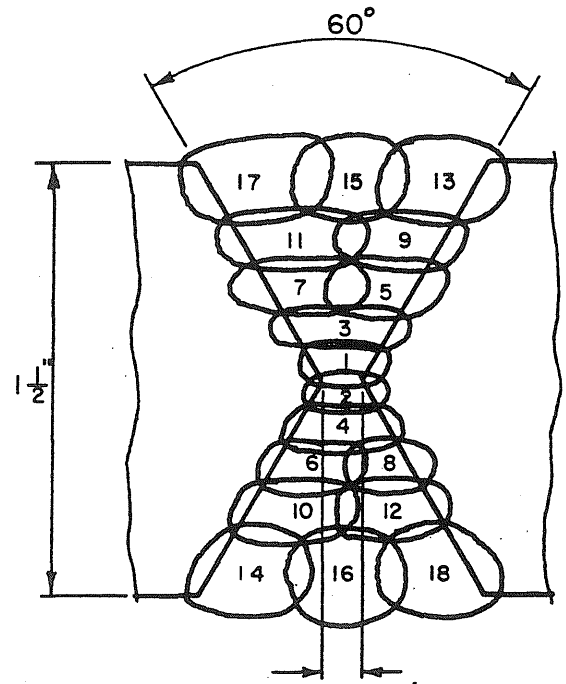
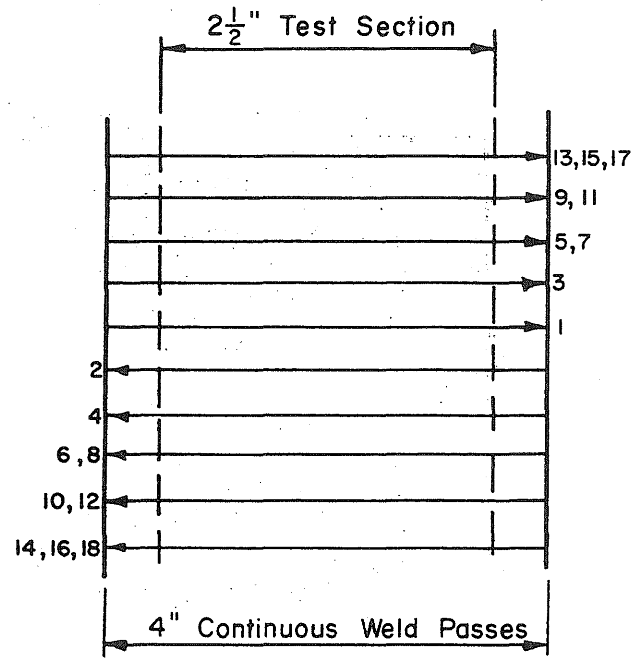


FIG. C-10 TYPICAL FRACTURE FOR TRANSVERSE BUTT WELDS WITH A LACK OF PENETRATION.

APPENDIX D - LIST OF FIGURES
(Welding Procedures)



Root opening $\frac{1}{8}$ in.



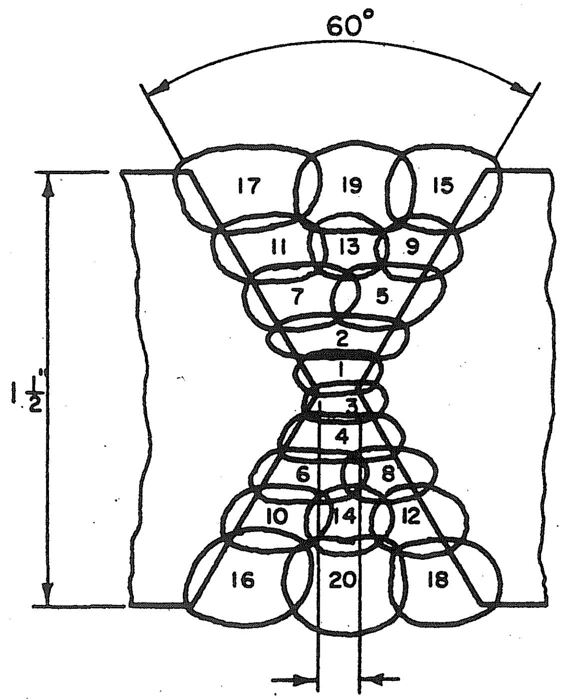
Arrows indicate direction of welding.

Surface of plate adjacent to weld cleaned by grinding before welding.

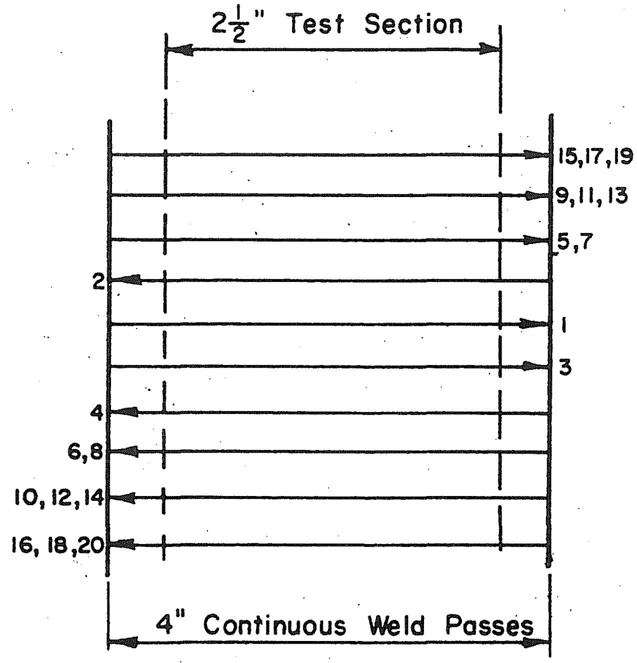
Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1, 2	$\frac{5}{32}$	140	3.5
3 – 18	$\frac{3}{16}$	230	6.0

Voltage: 21 Volts
Polarity: D.C. Reversed
Preheat: 150° F
Electrode: MIL 11018
Interpass Temperature: 300° F (Maximum)
Heat Input: 50,000 Joules /in. (Maximum)
All welding in flat position.
Underside of pass 1 back-gouged with air arc before pass 2.

FIG. D-1 WELDING PROCEDURE P80-11018-B
(Transverse Butt Welds)



Root opening 1/8 in.



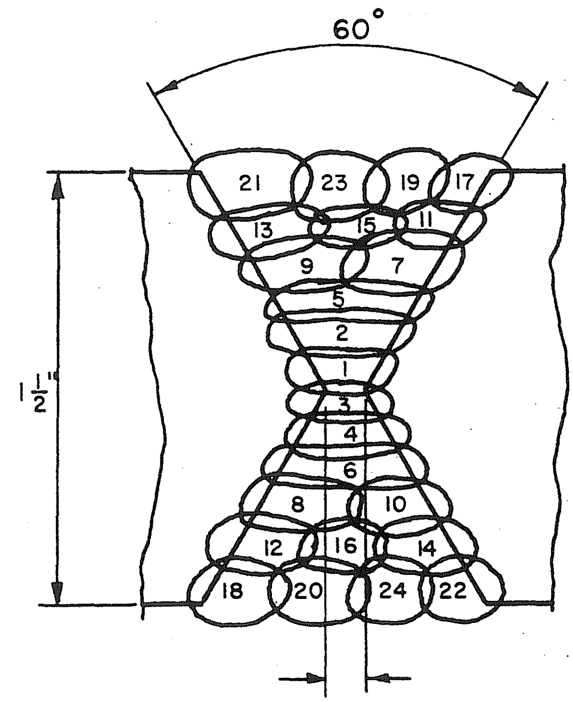
Arrows indicate direction of welding.

Surface of plate adjacent to weld cleaned by grinding before welding.

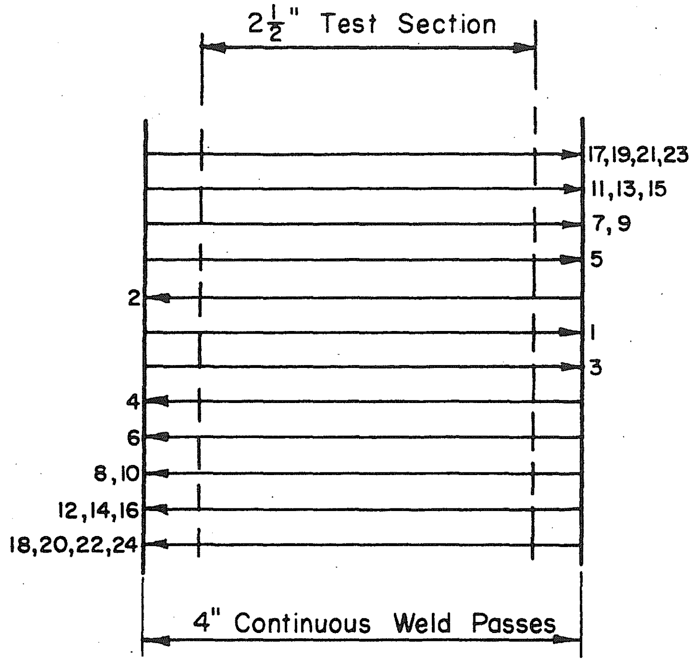
Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1	5/32	140	3.5
2	3/16	230	6.0
3	5/32	160	4.0
4–20	3/16	230	6.0

Voltage: 21 Volts
Polarity: D.C. Reversed
Preheat: 150° F
Electrode: MIL 11018
Interpass Temperature: 300° F (Maximum)
Heat Input: 50,000 Joules / in. (Maximum)
All welding in flat position.
Underside of pass 1 back-gouged with air arc before pass 3.

FIG. D-2 WELDING PROCEDURE P80-11018-C
(Transverse Butt Welds)



Root opening $\frac{1}{8}$ in.



Arrows indicate direction of welding.

Surface of plate adjacent to weld cleaned by grinding before welding.

Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1	$\frac{5}{32}$	140	3.5
2	$\frac{3}{16}$	230	6.0
3	$\frac{5}{32}$	160	4.0
4 — 16	$\frac{3}{16}$	230	6.0
17–24	$\frac{3}{16}$	200	5.0

Voltage: 21 Volts

Polarity: D.C. Reversed

Preheat: None

Electrode: MIL 11018

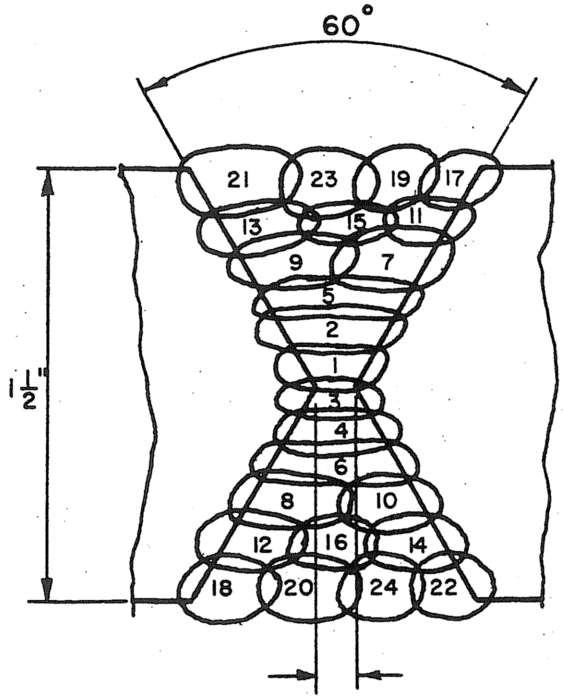
Interpass Temperature: Room

Heat Input: 50,000 Joules/in. (Maximum)

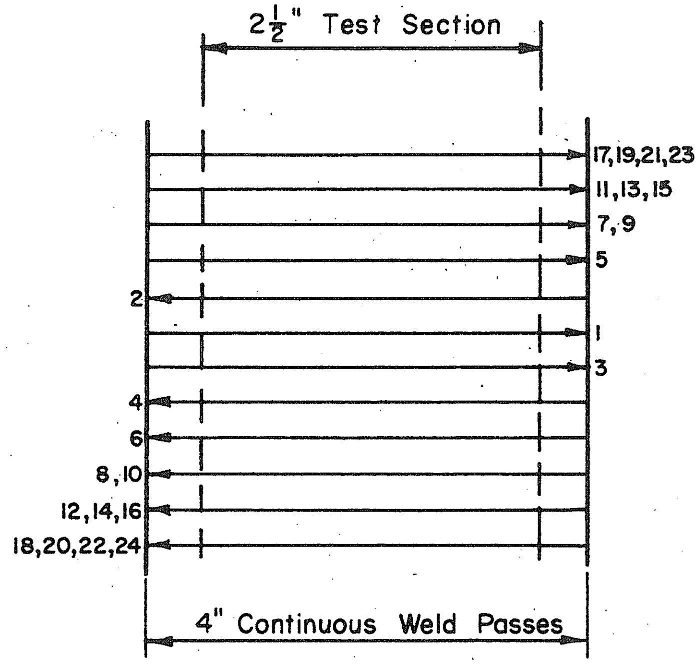
All welding in flat position.

Underside of pass 1 back-gouged with air arc before pass 3.

FIG. D-3 WELDING PROCEDURE P80-11018-S
(Transverse Butt Welds)



Root opening $\frac{1}{8}$ in.



Arrows indicate direction of welding.

Surface of plate adjacent to weld cleaned by grinding before welding.

Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1	$\frac{5}{32}$	140	3.5
2	$\frac{3}{16}$	230	6.0
3	$\frac{5}{32}$	160	4.0
4–16	$\frac{3}{16}$	230	6.0
17–24	$\frac{3}{16}$	200	5.0

Voltage: 21 Volts Electrode: MIL 11018

Polarity: D.C. Reversed Heat input: 50,000 Joules/in Maximum

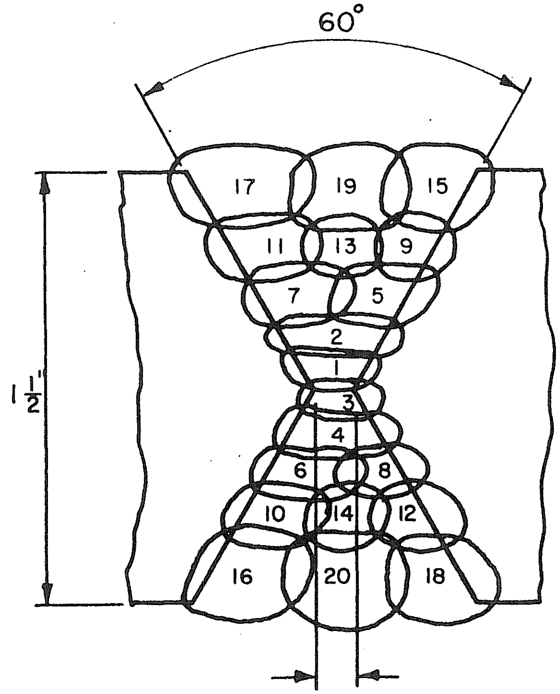
Preheat: 200° F

Interpass Temperature		Procedure
200°F	Max.	P80- 11018-D
300°F	Max.	P80- 11018-E
400°F	Max.	P80- 11018-T

All welding in flat position.

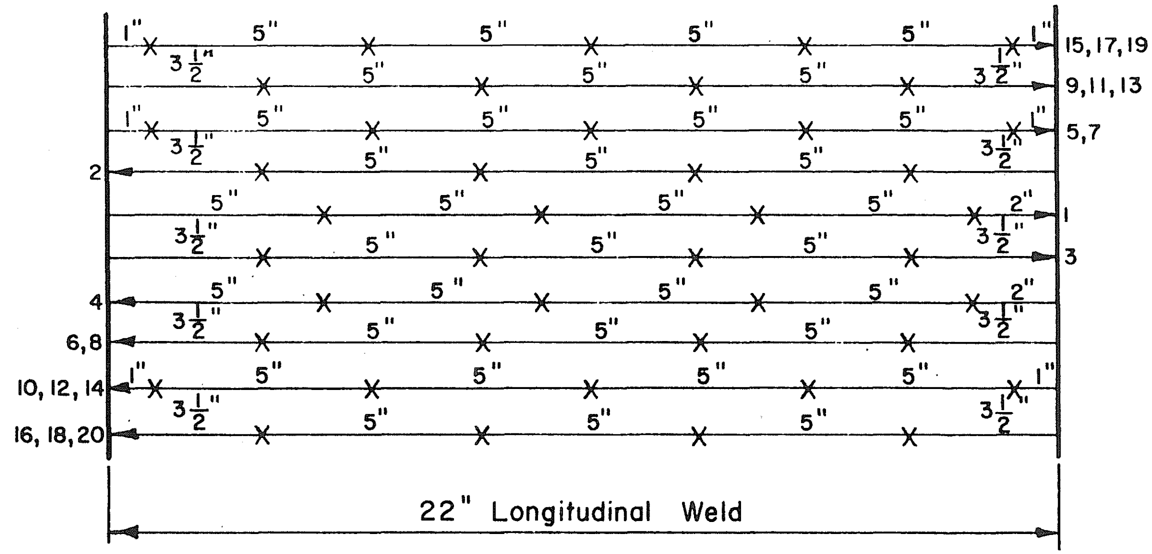
Underside of pass 1 back-gouged with air arc before pass 3.

FIG. D-4 WELDING PROCEDURE
(Transverse Butt Welds)



Root opening $\frac{1}{8}$ in.

Surface of plate adjacent to weld cleaned by grinding before welding.

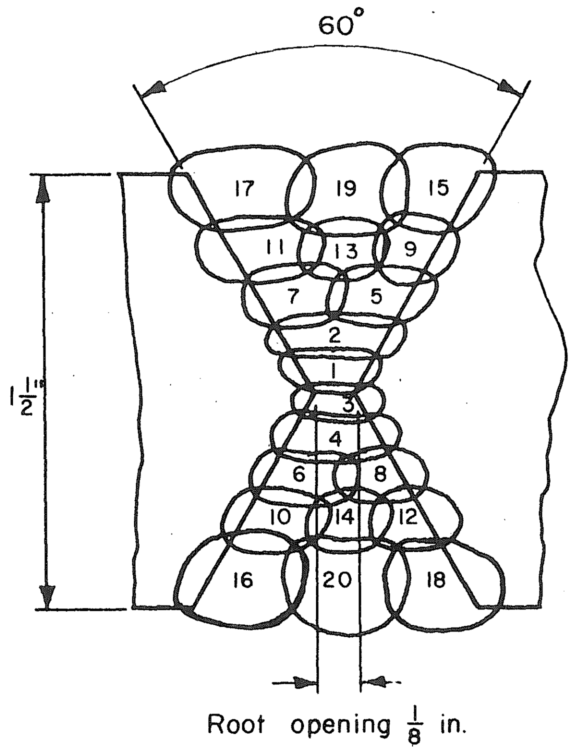


Arrows indicate direction of welding. X indicates change of electrode.

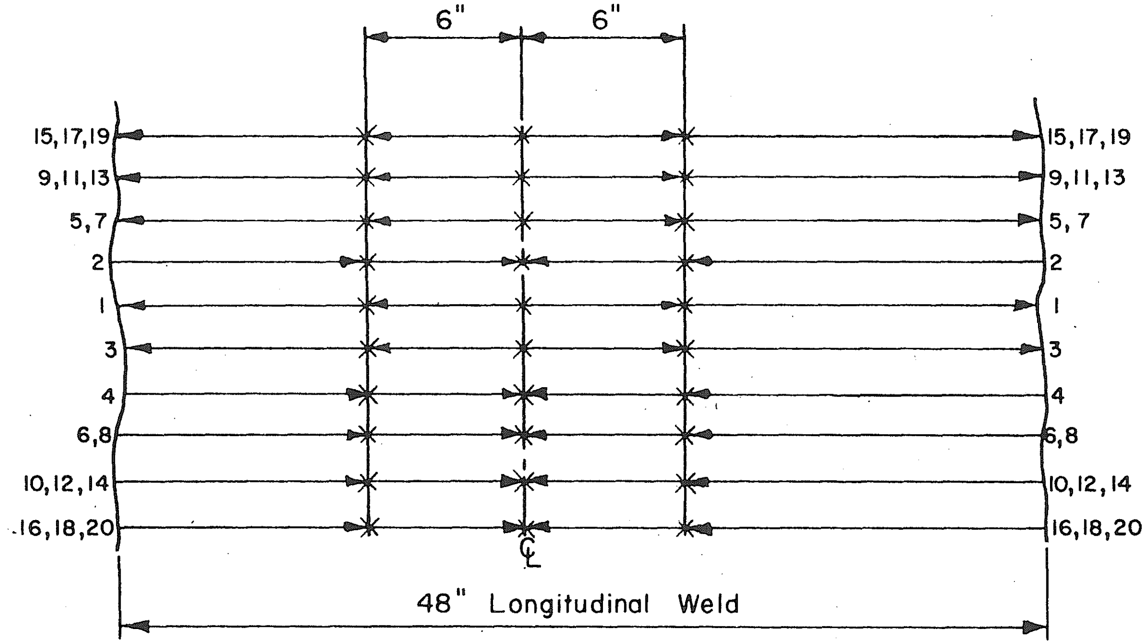
Voltage: 21 Volts
Polarity: D.C. Reversed
Preheat: 150° F
Electrode: MIL 11018
Interpass Temperature: 300° F (Max.)
Heat Input: 50,000 Joules/in. (Max.)
All welding in flat position.
Underside of pass 1 back-gouged with air arc before pass 3.

Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1	$\frac{5}{32}$	140	3.5
2	$\frac{3}{16}$	230	6.0
3	$\frac{5}{32}$	160	4.0
4 – 20	$\frac{3}{16}$	230	6.0

FIG. D-5 WELDING PROCEDURE P80-11018-F (Longitudinal Butt Welds)



Surface of plate adjacent to weld cleaned by grinding before welding.

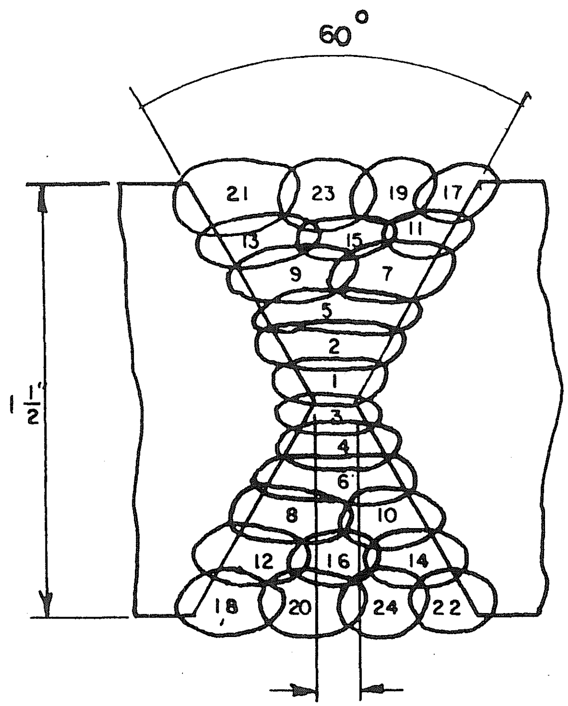


Arrows indicate direction of welding. X indicates change of electrode.

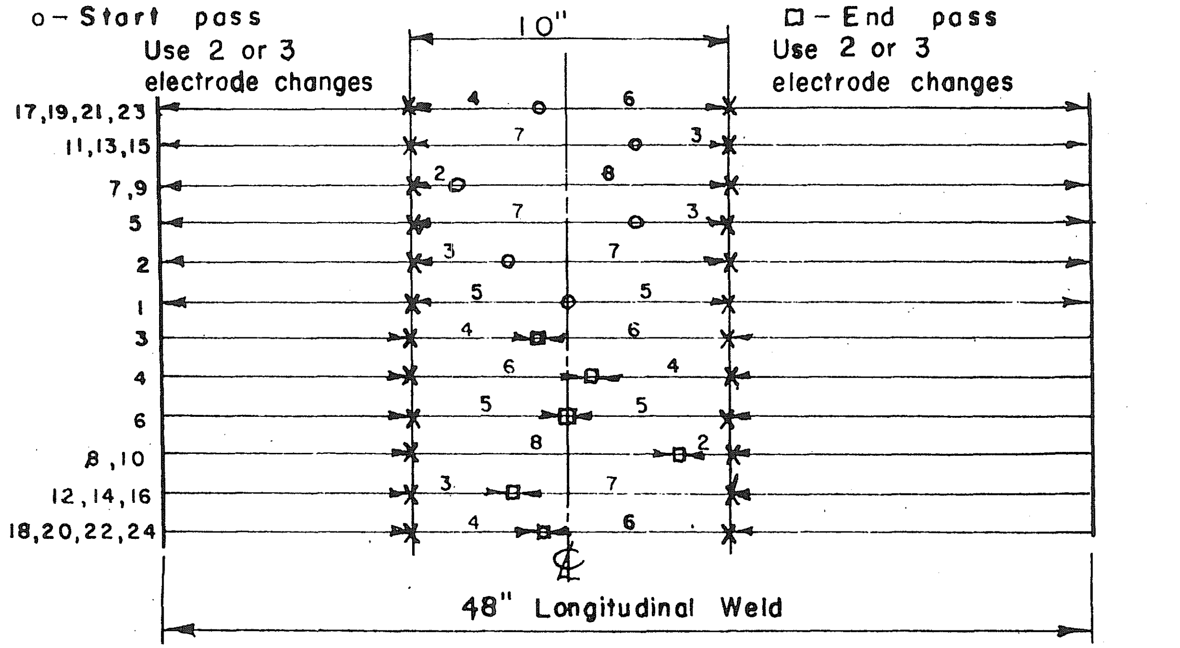
Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1	$\frac{5}{32}$	140	3.5
2	$\frac{3}{16}$	230	6.0
3	$\frac{5}{32}$	160	4.0
4–20	$\frac{3}{16}$	230	6.0

Voltage: 21 Volts
Polarity: D.C. Reversed
Preheat: 150° F
Electrode: MIL 11018
Interpass Temperature: 300° F (Max.)
Heat Input: 50,000 Joules / in. (Max.)
All welding in flat position.
Underside of pass 1 back-gouged with air arc before pass 3.

FIG. D-6 WELDING PROCEDURE P80-11018-G (Longitudinal Butt Welds)



Surface of plate adjacent to weld cleaned by grinding before welding.



Arrows indicate direction of welding. X indicates change of electrode.

Voltage: 21 Volts

Polarity: D.C. Reversed

Preheat: 200° F

Electrode: MIL 11018

Interpass Temperature: 300° F (Max)

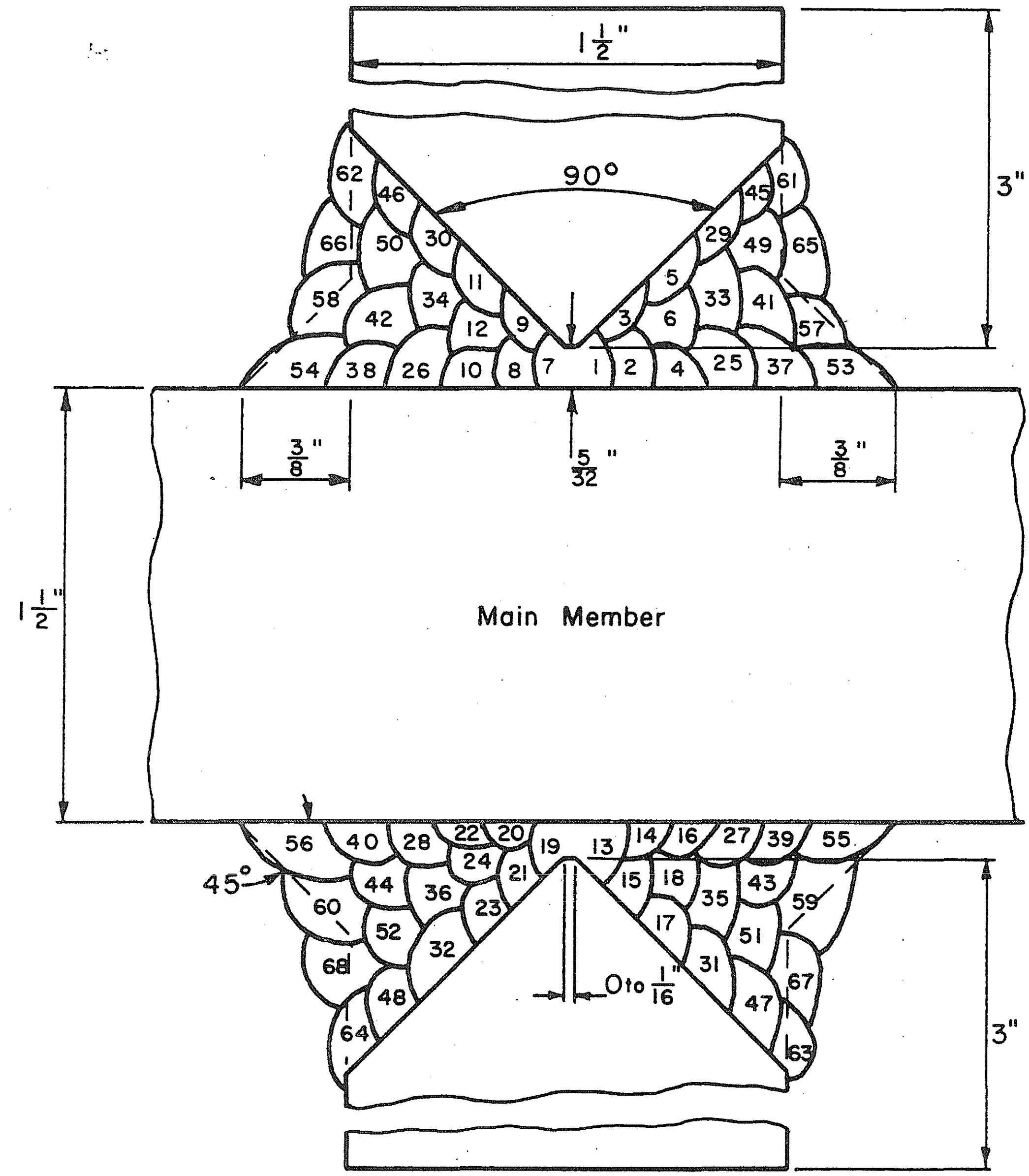
Heat Input: 50,000 Joules/in (Max.)

All welding in flat position.

Underside of pass 1 back-gouged with air arc before pass 3.

Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1	$\frac{5}{32}$	140	3.5
2	$\frac{3}{16}$	230	6.0
3	$\frac{5}{32}$	160	4.0
4 – 16	$\frac{3}{16}$	230	6.0
17 – 24	$\frac{3}{16}$	200	5.0

FIG. D-7 WELDING PROCEDURE P80-11018-0 (Longitudinal Butt Welds)



Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1–24	$\frac{5}{32}$	170	5.5
25–68	$\frac{3}{16}$	190	6.0

Voltage: 21 Volts
Polarity: D.C. Reversed
Interpass Temp.: 200°F (Max.)

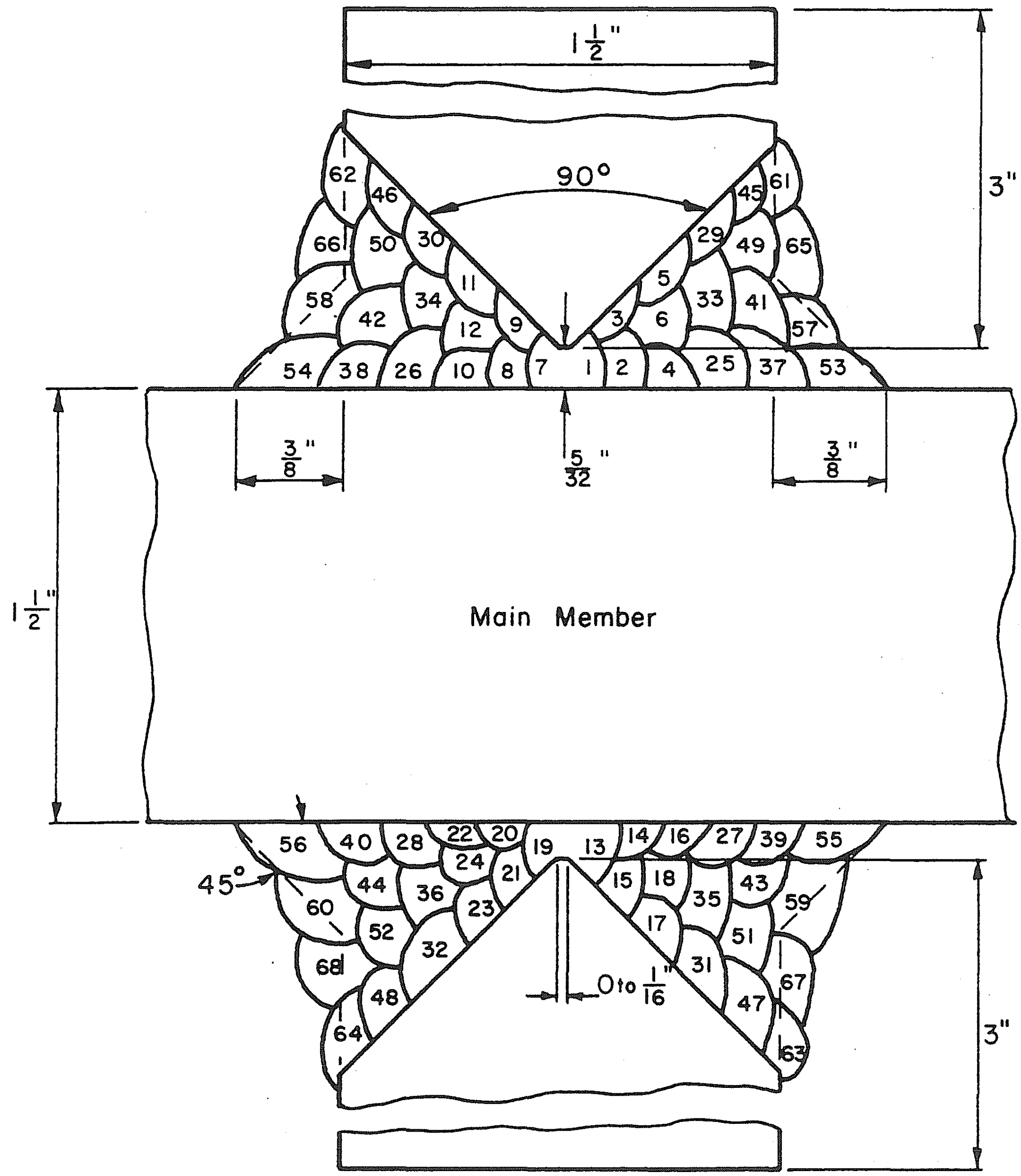
Preheat: 200° F
Electrode: MIL 11018
Heat Input: 40,000 Joules/in. (Max.)

Surfaces cleaned by grinding before welding.

After depositing passes 1-6, root chip. Then deposit passes 7-12. Repeat for other side.

All welding in flat position.

FIG. D-8 WELDING PROCEDURE P80-11018-J
(Full Penetration Transverse Attachments)



Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1–24	5/32	170	5.5
25–68	3/16	190	6.0

Voltage : 21 Volts

Polarity : D.C. Reversed

Interpass Temp.: 200° F (Max.)

Preheat : 200° F

Electrode : MIL 11018

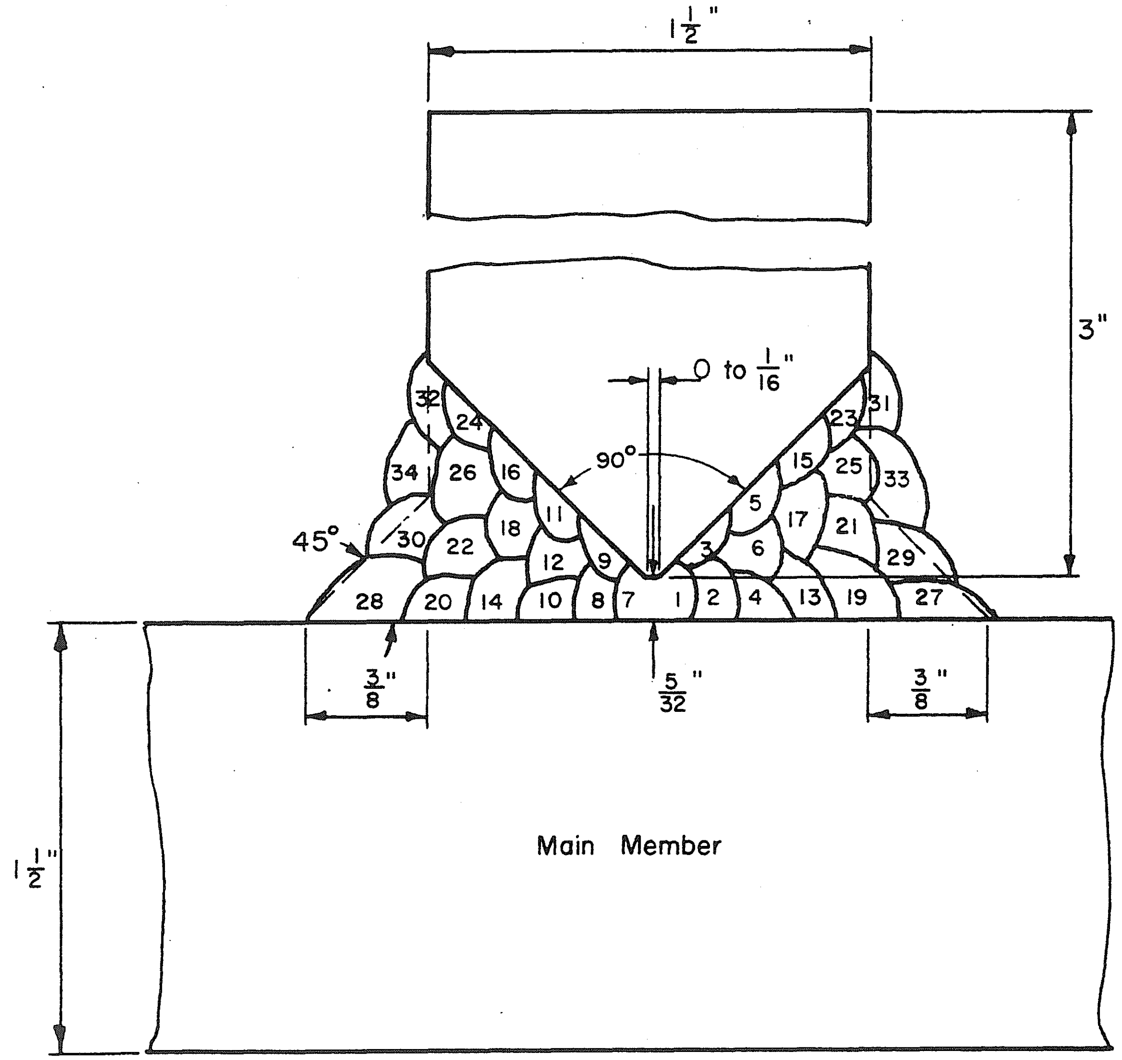
Heat Input : 40,000 Joules/in. (Max.)

Surfaces cleaned by grinding before welding.

After depositing passes 1-6, root chip. Then deposit passes 7–12. Repeat for other side.

All welding in horizontal position.

FIG. D-9 WELDING PROCEDURE P80-11018-P (Full Penetration Transverse Attachments)



Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1 – 12	$\frac{5}{32}$	170	5.5
13 – 34	$\frac{3}{16}$	190	6.0

Voltage: 21 Volts

Polarity: D.C. Reversed

Preheat: 200° F

Electrode: MIL 11018

Interpass Temperature: 200°F (Maximum)

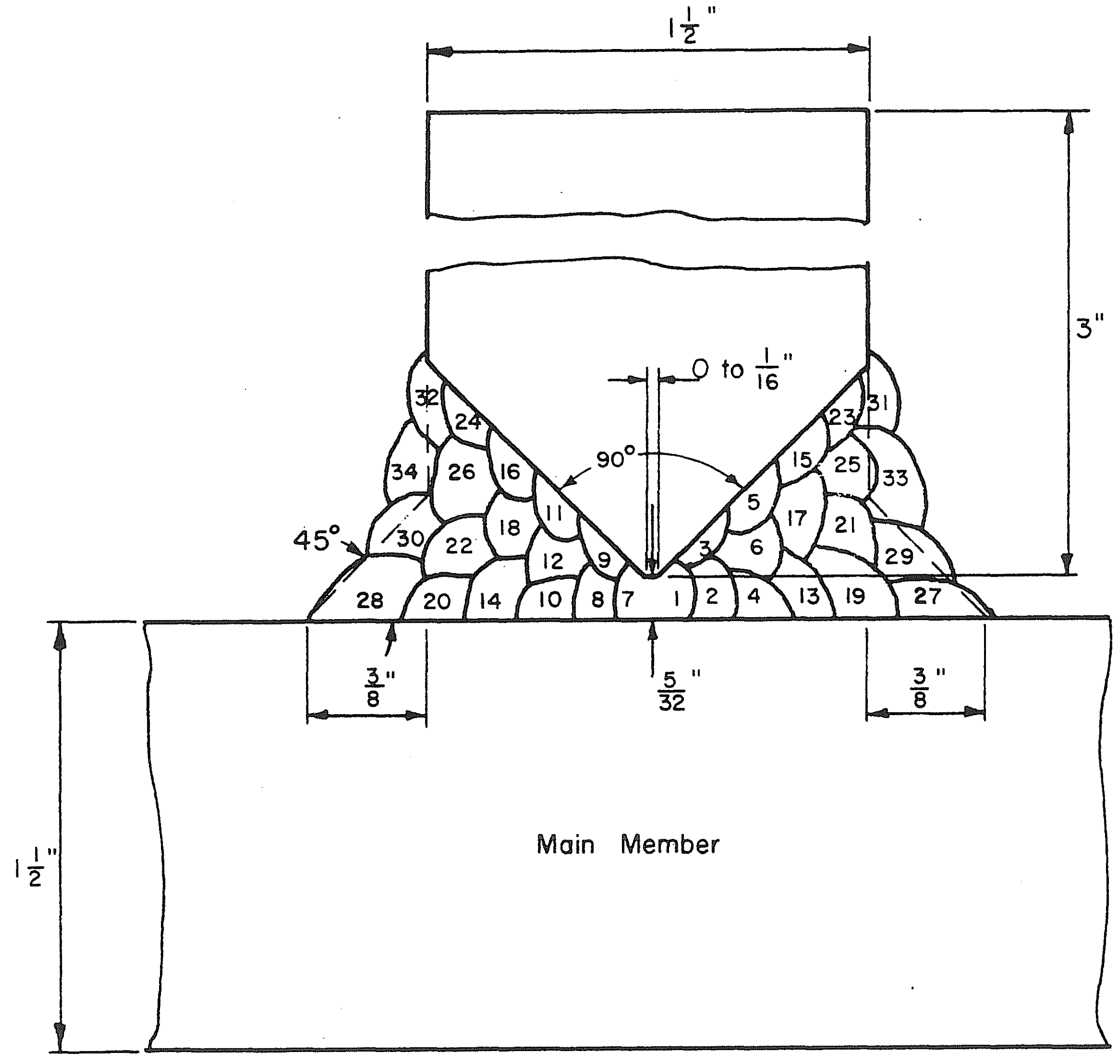
Heat Input: 40,000 Joules/in. (Maximum)

Surfaces cleaned by grinding before welding.

After depositing passes 1 – 6, root chip. Then deposit passes 7 – 34.

All welding in flat position.

FIG. D-10 WELDING PROCEDURE P80-11018-K
(Full Penetration Transverse Attachments)



Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1 – 12	5/32	170	5.5
13 – 34	3/16	190	6.0

Voltage: 21 Volts

Polarity: D.C. Reversed

Preheat: 200° F

Electrode: MIL 11018

Interpass Temperature: 200°F (Maximum)

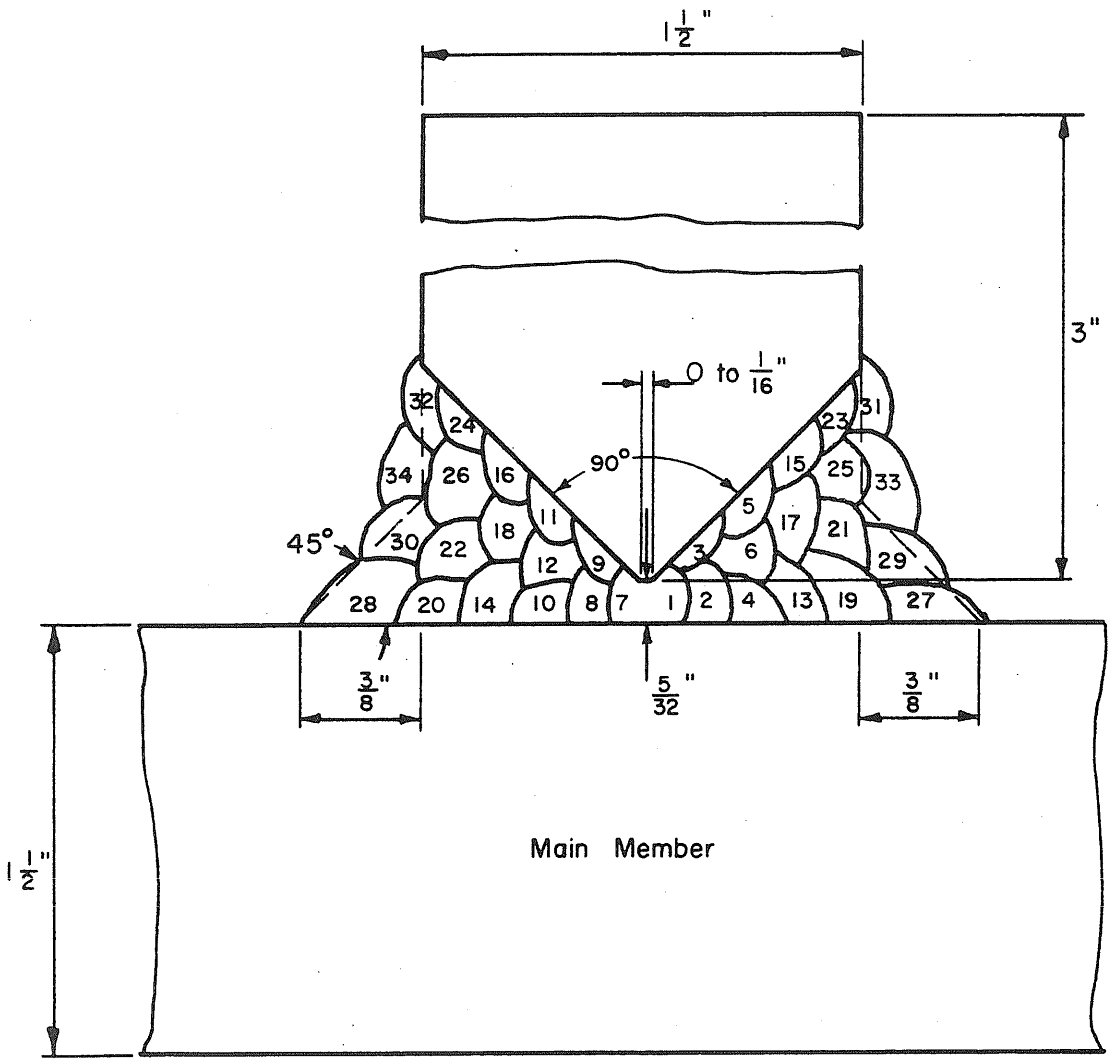
Heat Input: 40,000 Joules / in. (Maximum)

Surfaces cleaned by grinding before welding.

After depositing passes 1 – 6, root chip. Then deposit passes 7 – 34.

All welding in horizontal position.

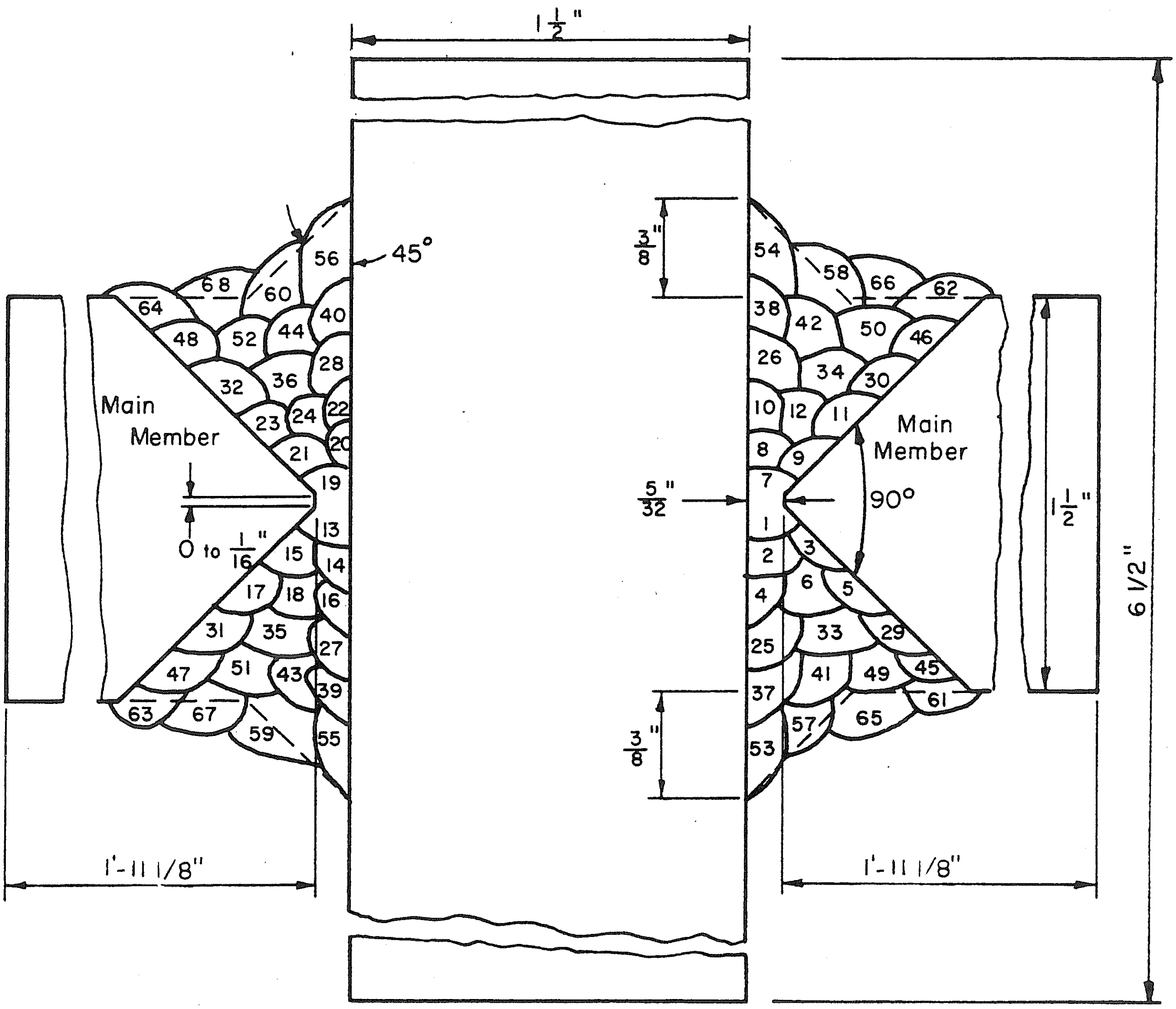
FIG. D-11 WELDING PROCEDURE P80-11018-Q
(Full Penetration Transverse Attachments)



Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1 – 12	$\frac{5}{32}$	170	5.5
13 – 34	$\frac{3}{16}$	190	6.0

Voltage: 21 Volts
Polarity: D.C. Reversed
Preheat: 200° F
Electrode: MIL 9018
Interpass Temperature: 200°F (Maximum)
Heat Input: 40,000 Joules/in. (Maximum)
Surfaces cleaned by grinding before welding.
After depositing passes 1 – 6, root chip. Then deposit passes 7 – 34.
All welding in horizontal position.

FIG. D-12 WELDING PROCEDURE P80-9018-A
(Full Penetration Transverse Attachments)



Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1–24	5/32	170	5.5
25–68	3/16	190	6.0

Voltage: 21 Volts
Polarity: D.C. Reversed
Interpass Temp.: 200° F (Max.)

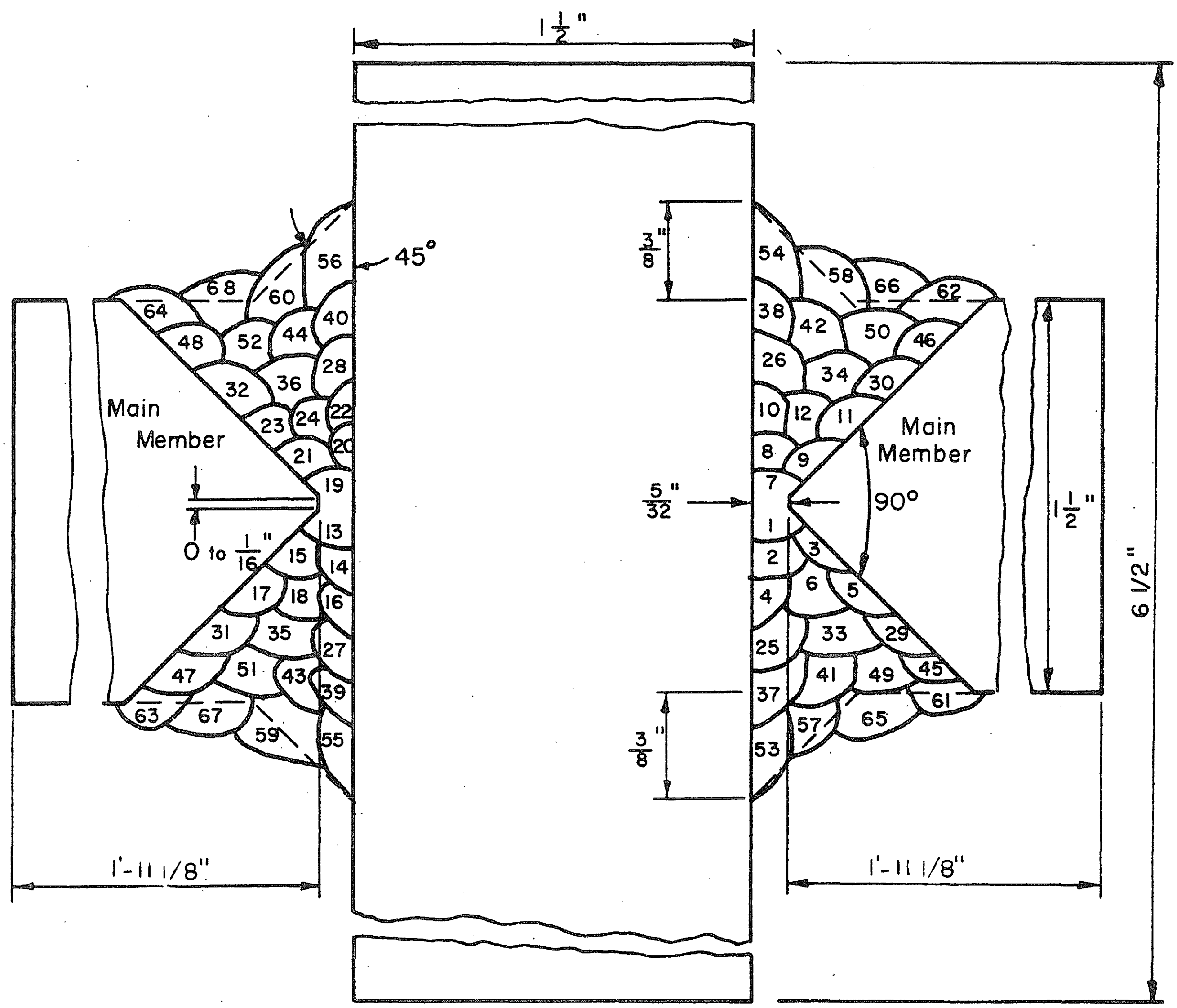
Preheat: 200° F
Electrode: MIL 11018
Heat Input: 40,000 Joules/in. (Max.)

Surfaces cleaned by grinding before welding.

After depositing passes 1-6, root chip. Then deposit passes 7-12. Repeat for other side.

All welding in flat position.

FIG. D-13 WELDING PROCEDURE P80-11018-L
(Tee Joint)



Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1–24	5/32	170	5.5
25–68	3/16	190	6.0

Voltage : 21 Volts

Polarity : D.C. Reversed

Interpass Temp.: 200° F (Max.)

Preheat : 200° F

Electrode : MIL 11018

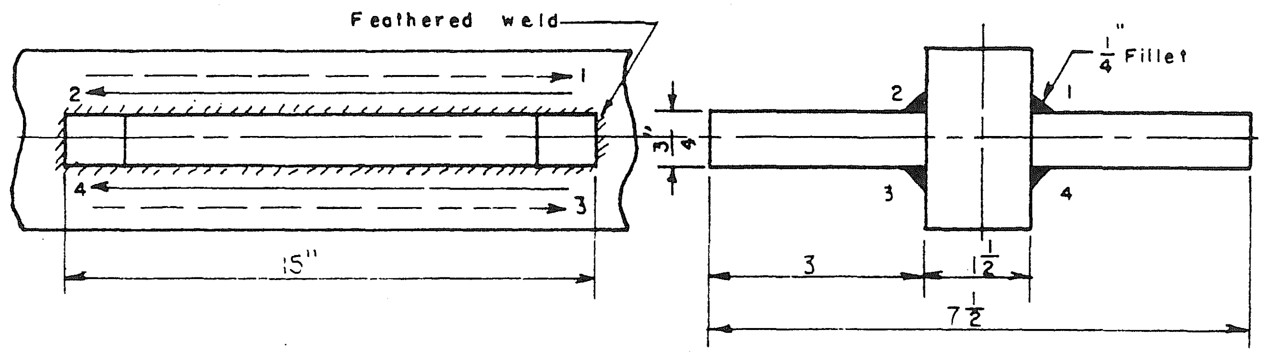
Heat Input: 40,000 Joules/in. (Max.)

Surfaces cleaned by grinding before welding.

After depositing passes 1-6, root chip. Then deposit passes 7–12. Repeat for other side.

All welding in horizontal position.

FIG. D-14 WELDING PROCEDURE P80-11018-R
(Tee Joint)



Solid arrows show direction of welding on front face
Dotted arrows show direction of welding on back face
Change electrodes at five inch intervals.

Pass	Electrode size, in.	Current, amps.	Rate of travel, in./min.
1 - 4	$\frac{3}{16}$	190	60

Voltage : 21 Volts
Polarity : D.C. Reversed
Preheat : 200°F
Electrode : MIL 11018
Interpass Temperature 200°F (Maximum)
Heat Input : 40,000 Joules/in. (Maximum)
Surfaces cleaned by grinding before welding.

FIG. D-15 WELDING PROCEDURE P80-11018-N
(Longitudinal Attachments)