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FATIGUE BEHAVIOR OF MECHANICALLY PEENED HY-80 WELDMENTS SUBJECTED TO AXIAL LOADING

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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-92240
Project Serial No. SR-007-01-01, Task 853

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Final Report

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ABSTRACT

An evaluation of the axial fatigue behavior of mechanically peened transverse tee-weldments and transverse butt-welded joints in HY-80 steel is presented. The data show that mechanical peening along the toe of the weld results in an improvement in the fatigue resistance of both types of weldment relative to the behavior of similar joints tested in the as-welded condition.

The process of fatigue crack initiation and propagation was examined for several of the mechanically peened weldments. In the majority of members cracks nucleated at the toe of the weld in the trough formed by the peening operation. Nucleation normally occurred within the first 20 percent of the cyclic lifetime of a specimen, and was followed by a long period of slow, erratic crack propagation, eventually culminating in a short final stage of rapid extension to failure.

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I. INTRODUCTION

1.1 Object of Study

Fatigue failures in butt-welded joints of HY-80 steel are generally found to initiate at the toe of the weld. This critical location for crack nucleation results primarily from the inherent stress raiser associated with the geometry of the weldment, and to some extent from the high tensile residual stresses localized in the weld surface region. Studies recently conducted at the U.S. Naval Applied Science Laboratory, Brooklyn, New York, have established that mechanical peening along the edge of the weld reinforcement can be used to improve the geometry and to induce high compressive residual stresses at the toe of such welds.[(1)*] In addition, it has been found that the flexural fatigue behavior of the welded HY-80 specimens, after being subjected to the peening treatment, is significantly improved in comparison to similar weldments tested in the as-welded condition without peening.[(2, 3)]

The purpose of the present investigation has been to evaluate the effect of mechanical peening on the fatigue resistance of butt-welded and tee-welded specimens of HY-80 steel subjected to direct uniaxial loading conditions. The data obtained from these tests have been used to establish S-N curves in the life range from 10^4 to 10^6 cycles to failure, and to construct Modified Goodman Diagrams suitable for application to design requirements. Further, the current axial fatigue data have been compared with similar axial test results of HY-80 weldments (as-welded) tested previously at the University of Illinois[(4, 5)] and with the flexural fatigue data obtained at the Naval Applied Science Laboratory.[(2,3)]

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* Numbers in parentheses refer to corresponding entries in the List of References.

The second phase of the investigation has been concerned with determining the modes of failure involved in the fatigue sequence, including the number of applied cycles required to initiate a fatigue crack, the point of origin of the crack, and the subsequent rate of propagation. The results of the initiation and propagation studies for both the transverse butt-welds and the tee-weldments have been compared for each of the stress cycles examined.

1.2 Scope of Investigation

A series of 24 transverse tee-weldments and 25 transverse butt-welded specimens, all mechanically peened along the toes of the weld, were fabricated at the Naval Applied Science Laboratory and submitted to the University of Illinois for axial fatigue testing. Details of the equipment and techniques used in the mechanical peening operation are presented in References 2 and 3.

The fatigue specimens were tested at stress cycles of zero-to-tension, half tension-to-tension, and complete-reversal; an approximately equal number of tests were conducted at each of the three stress cycles. To examine the course of fatigue crack initiation and propagation, a select number of specimens were examined periodically during fatigue cycling; the positions of the observed cracks on the specimen surfaces and the depths of the cracks into the 1-1/2 in. thickness of the weldments were recorded.

This report covers tests conducted during the period of February 1965 to June 1966. Much of the data analyzed herein has been reported previously in periodic status reports prepared during the course of the investigation.(6-12)

1.3 Acknowledgments

The information presented in this report represents the results of an investigation conducted in the Civil Engineering Department of the University of Illinois. The program was carried out with funds provided by the Bureau of Ships, U.S. Navy, under Contract NObs-92240, Project Serial No. SR-007-01-01, Task 853.

The investigation constitutes a part of the structural research program of the Department of Civil Engineering, of which Dr. N. M. Newmark is the Head. The program was conducted under the general direction of W. H. Munse, Professor of Civil Engineering. The testing program and data analyses were conducted by R. A. Ridha, H. A. Osman, and D. F. Meinheit, Research Assistants in Civil Engineering, under the direct supervision of J. B. Radziminski, Assistant Professor.

The authors wish to express their appreciation to those persons on the staff of the University who so ably assisted in the investigation.

II. DESCRIPTION OF TEST PROGRAM

2.1 Material

A total of 49 welded specimens using HY-80 grade steel were received from the Naval Applied Science Laboratory. The specimens were fabricated from three 1-1/2 in. thick plates of the base material; summaries of the chemical analyses, mechanical properties, and Charpy V-notch data are given in Tables 2.1, 2.2, and 2.3, respectively. Of the 49 specimens, 24 were transverse tee-weldments and 25 were transverse butt-welded joints. All of the specimens were welded using MIL-11018 grade electrodes. The material at the edge of the weld reinforcement was mechanically peened along each weld toe.

2.2 Preparation of Fatigue Test Specimens

The weldments were shipped to the University of Illinois in the form of 9 in. by 48 in. plates; the welds were positioned transverse to the long axis of the plate and were located at the plate mid-length.

Holes required for bolting the specimens into the fatigue testing machine were first drilled in the ends of the plates. The material adjacent to the test section was then saw cut and later milled down to the desired specimen configuration, Figs. 2.1 and 2.2. No material in the region of the test section was removed by flame-cutting. The net width at the test section was governed by the test load range and the capacity of the fatigue machine. This dimension was made as large as possible within the machine capacity. The width of the test section for each of the stress cycles examined is given in Table 2.4 for both the butt-welded joints and the tee-weldments.

To complete the specimen preparation, the milled edges of the test section were ground smooth. The grinder was manipulated so that any remaining surface scratches were oriented parallel to the longitudinal axis of the specimen. The mill scale surfaces and weld reinforcement on the faces of the test specimen were not altered in any manner.

2.3 Description of Test Equipment

All fatigue tests were conducted using the University of Illinois' 250,000 lb. lever type fatigue machines, which operate at speeds of 100 and 160 cpm. A photograph of the testing machines is shown in Fig. 2.3.

The essential features of the fatigue machines are shown schematically in Fig. 2.4. A 15 to 1 force multiplication is provided between the dynamometer and the test specimen by the lever system. The throw of the eccentric determines the load range, i.e., the algebraic difference between the maximum and minimum test loads. Once the load range has been set, the maximum load is adjusted by means of the turnbuckle mounted just below the dynamometer.

2.4 Testing Procedure

The test specimens were first bolted in place in the pullheads of the fatigue machine and the appropriate load range set. A micro-switch was then adjusted so that the machine would automatically shut off when a crack had propagated through approximately three-fourths of the specimen cross-section. The number of applied cycles at that time was considered the test life of the specimen.

To conclude each test, the fatigue machine was then restarted and run until complete specimen failure occurred so that the fracture surfaces could be examined and photographed. (In the tests reported herein, there was less than 0.5% additional cycling from the time of micro-switch shut-off to complete specimen fracture.)

For those specimens selected to study fatigue crack initiation and propagation, the specimen test section surfaces in the vicinity of the weldment were examined at periodic intervals during the lifetime of the member. The extent of the fatigue cracks on all faces of the specimen were measured and recorded; the techniques used to determine the crack lengths are detailed in Section 4.1. This procedure was repeated until a crack was of sufficient size to trip the pull-head micro-switch, thus determining the member test life. Cycling was then continued as above until the specimen was completely fractured.

III. FATIGUE TEST RESULTS

3.1 Method of Data Analysis

In order to obtain comparative estimates of the fatigue strengths of the two specimen types at various cyclic lifetimes, the technique described in the following paragraphs was used to evaluate the individual test results.

Investigations have shown that, for a wide range of fatigue lives, a linear log-log relationship exists between applied cyclic stress and the corresponding number of cycles to failure. Such a relationship may be expressed in the following manner:

$$S \cdot N^k = C \tag{3.1}$$

where S represents the applied maximum cyclic stress, N is the number of cycles to failure, and C and k are constants, the latter being the negative of the slope of the linear log S-log N curve. To evaluate the contribution of a particular test result in determining the complete S-N curve for a given set of test conditions, Eq. (3.1) may be expressed in the form:

$$F_n = S_N \left(\frac{N}{n}\right)^k \tag{3.2}$$

where S_N is the test stress level resulting in specimen failure at N cycles, and F_n is the calculated fatigue strength at n cycles.

The slope k has been found to vary considerably depending upon such parameters as type of stress cycle, material properties, conditions of specimen geometry, test temperature, etc. For a particular set of test conditions, then, k may best be determined empirically by appropriate fitting of the accumulated test data.

Since the S-N curves presented in the current study have been obtained from a rather limited amount of data, it must be recognized that the reported values for k are, at best, only approximate. Nevertheless, the error associated with a computed value of fatigue strength resulting from an error in k is generally relatively small. As a means of controlling the error due to extrapolation of test data, the permissible range of test specimen lives used to compute a particular fatigue strength were subjected to the following limitations:

Fatigue Strength	Range of N
$F_{10,000}$	$2,000 \leq N \leq 60,000$
$F_{20,000}$	$4,000 \leq N \leq 100,000$
$F_{50,000}$	$10,000 \leq N \leq 300,000$
$F_{100,000}$	$20,000 \leq N \leq 600,000$
$F_{200,000}$	$40,000 \leq N \leq 1,000,000$
$F_{500,000}$	$100,000 \leq N \leq 3,000,000$
$F_{2,000,000}$	$300,000 \leq N$

To construct an S-N curve, a trial and error procedure using Eq. (3.2) and the above tabulation was employed. An initial value of k was chosen which offered a good visual approximation to the slope of a curve through the plotted test data. Using this approximate k value the fatigue strengths at lives corresponding to those listed in the above table were determined from Eq. (3.2) and the individual test data. The individually computed strengths were then averaged and, by back substitution into Eq. (3.2), used in turn to calculate a new trial value of k. This slope served as the basis for a second cycle of calculations from which an improved value of k was obtained. The process was repeated until the assumed and computed k values converged; this is the number that appears as the slope of the S-N curves shown in the figures of the report.

3.2 Test Results for Tee-Weldments

3.2.1 Introductory Remarks

Examination of the tee-weldment specimens revealed that they had become distorted during the welding process which resulted in a pronounced curvature, concave on the surface to which the attachment had been welded. On the average, a 1/4 in. bow existed in the 4 ft. length of the test specimens.

Bolting of a specimen into the fatigue machine pull-heads partially reduced the initial specimen curvature, but at the same time introduced tensile stresses on the side containing the attachment. To obtain an indication of the magnitude of the induced stresses, 1/4 in. AD-7 strain gages were mounted on the face and ground edges of specimen M77AP7 near the attachment. When bolted in the fatigue machine a surface tensile stress of 1.4 ksi was produced on the face containing the welded attachment. The specimen was then subjected to fatigue cycling at a nominal stress range (measured by the testing machine dynamometer) of 0 to +58.8 ksi. The output of each strain gage was read periodically during the cycling process to determine the difference between the maximum nominal stresses and the stresses recorded by the gages on the specimen surface in the vicinity of the attachment.* The difference was found to be less than 3 ksi; it was concluded, therefore, that the nominal values measured by the dynamometer were sufficiently representative of the test stress conditions and that the slight actual increase in stress introduced in the bolting process would not significantly alter the resultant fatigue lives.

The fatigue test results for the 24 transverse tee-weldment specimens are given in Tables 3.1, 3.2, and 3.3, for tests conducted at stress cycles of complete-reversal, zero-to-tension, and half tension-to-tension, respectively. The computed fatigue strengths and S-N curve slopes (k) were obtained using the technique described in Section 3.1. The fatigue cracks in all but one of the specimens initiated along the toe of the weld in the trough created by the mechanical peening; details of the crack initiation and subsequent rate of propagation for a number of the specimens are presented in Section IV.

3.2.2 Complete-Reversal Tests

The fatigue results for the tee-weldment specimens tested at a complete-reversal stress cycle are recorded and evaluated in Table 3.1. Of the eight specimens tested, seven exhibited fatigue crack initiation in the mechanically peened region of the weld reinforcement. The critical fatigue crack for specimen M77AP23, on the other hand, initiated at the mill scale surface on the face opposite that to which the attachment was welded. This was the only tee-weldment to fail in this manner; details of the nucleation and propagation for specimen M77AP23 are discussed in Section 4.2.

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* Information concerning the particulars of this test are presented in Reference 6.

The fatigue data for the complete-reversal tests are plotted in Fig. 3.1, together with the results of similar axial fatigue tests of as-welded tee-weldment specimens (using the MIL-11018 electrode) which were tested previously at the University of Illinois[(4)]. The curves show that the advantage of peening in improving fatigue behavior is most pronounced at the longer test lives associated with the lower nominal stress levels. This advantage is less in evidence at the higher stress levels examined, however, with lives for the as-welded and mechanically peened specimens approaching covergence at nominal cyclic stresses about 20 ksi below the yield strength of the parent material (Fig. 3.1). The higher stresses in the low-life tests were apparently sufficient to relieve, during the initial stages of cycling, the high compressive residual stresses in the peened region, with the result that these specimens performed similar to the as-welded joints under continued cycling.

3.2.3 <u>Zero-to-Tension Tests</u>

The fatigue data for eight specimens tested at a stress cycle of zero-to-tension are given in Table 3.2 together with the corresponding fatigue strengths (k = 0.198) computed for various cyclic lives. All of the specimens initiated fatigue cracks in the peened region along the toe of the weld. (Specimen M77AP4 exhibited a crack at one corner from the very onset of fatigue cycling; this may account in part for the unexpectedly low life of that member at the 0 to +40.6 ksi stress level.)

The zero-to-tension test data, compared in Fig. 3.2a to similar axial test results for as-welded tee-weldment specimens tested at the University of Illinois,[(5)] indicate an increasing improvement in fatigue behavior resulting from peening as the nominal stresses are decreased.

The present axial fatigue results for the peened specimens are further compared, in Fig. 3.2b, to flexural fatigue data for both as-welded and mechanically peened tee-weldments tested at the Naval Applied Science Laboratory(2). The flexural tests were conducted on plates 1-1/2 in. thick x 29-5/8 in. x 32 in., to which attachments were welded along the entire plate width. These plates were then subjected to cyclic flexural loadings producing zero-to-tension stress cycles at the attachments, with maximum nominal stresses ranging from approximately 60 ksi to 120 ksi. The test lives presented in Fig. 3.2b for the flexural test specimens represent the number of cycles at which the deflection under maximum load had increased 10 percent beyond the maximum load deflection at the start of the test.

Examination of the data presented in Fig. 3.2b indicates a large difference in the fatigue lives obtained for the mechanically peened specimens tested in axial fatigue and those tested in flexure. The longer lives reported for the flexural fatigue specimens are likely a consequence of significant differences in the testing and stressing conditions, such as the larger size of the flexural plates, the biaxiality of stresses resulting from plate action, and the high stress gradient through the specimen cross-section (compared to the full nominal stresses acting over the entire cross-section in the axial test specimens).

3.2.4 Half Tension-To-Tension Tests

Eight tee-weldment specimens were tested at half tension-to-tension; the test results and computed fatigue strengths are given in Table 3.3. As with the other tests of this series, the fatigue cracks initiated in the peened region of the weld reinforcement in each of the eight specimens.

The test data are plotted in Fig. 3.3 and are compared with axial fatigue results for similar as-welded HY-80 joints tested previously[5]. The limited data again appear to indicate that mechanical peening is a beneficial factor in improving fatigue resistance, primarily at the lower stress levels.

3.2.5 General

For the tee-weldment specimens, the average values of the computed fatigue strengths, at 10,000, 50,000, 100,000 and 500,000 cycles, are compiled in the Modified Goodman Diagram of Fig. 3.4. The points plotted for stress cycles of complete-reversal, zero-to-tension, and half tension-to-tension were obtained from the calculated average values in Tables 3.1, 3.2, and 3.3. The curves through these data are extrapolated to the static tensile ultimate strength of the HY-80 base metal (plate 77), given in Table 2.2. Because of the limited number tests used in determining the fatigue strengths at certain of the stress cycles, it was not possible to present meaningful scatter bands about the average curves shown in Fig. 3.4. Some indication of the possible magnitude of this scatter may be obtained, however, by comparison of the maximum and minimum values of fatigue strength computed at 10,000 and 100,000 cycles for the specimens reported in Tables 3.1, 3.2, and 3.3; these values are accumulated in Table 3.7 for each of the stress cycles examined. It is important, then, to consider both the average curves and the extreme values in using the information from a Modified Goodman Diagram as a basis for determining allowable design criteria.

3.3 Test Results for Butt-Welded Joints

3.3.1 Introductory Remarks

A total of 25 mechanically peened transverse butt-welded specimens were tested using stress cycles of complete-reversal, zero-to-tension, and half tension-to-tension. The test results are presented and the fatigue strengths computed in Tables 3.4, 3.5, and 3.6; the procedure outlined in Section 3.1 was used to determine the slope (k) of the S-N curve for each of the three stress cycles. All of the butt-welded specimens tested at zero-to-tension and half tension-to-tension initiated fatigue cracks along the mechanically peened region at the edge of the weld reinforcement. Several specimens subjected to a complete-reversal stress cycle, on the other hand, exhibited failures initiating at small isolated internal defects in the weld. A discussion of these modes of crack initiation and subsequent propagation is presented in Section IV.

3.3.2 Complete-Reversal Tests

The data for nine transverse butt-welded members tested at a stress cycle of complete-reversal are given in Table 3.4 and plotted in Fig. 3.5. These data and the corresponding S-N curve (k = 0.227) are compared in Fig. 3.5 to the results of axial fatigue tests of similar HY-80 butt-welded specimens tested in the as-welded condition[(4)]. The as-welded joints, tested previously at the University of Illinois, were also prepared from 1-1/2 in. thick HY-80 steel plates using the MIL-11018 welding electrode. (It should be noted that the S-N curve for the as-welded specimen test results was computed excluding the data for those members which had failures in the weld, whereas all specimens were included in the analysis of the mechanically peened members.) The mechanically peened specimens provide a considerable improvement in fatigue behavior relative to the as-welded joints, with the most significant advantages of peening being manifested at the lower stress levels examined. In direct similarity to the tee-weldment specimens discussed in Section 3.2, however, the data for both the mechanically peened and the as-welded butt-welded joints appear to converge at stresses nearing the base metal yield strength.

The data given in Table 3.4 show that four of the nine specimens tested in complete-reversal initiated fatigue cracks at small internal weld flaws. The resultant fatigue lives for these specimens are generally within the same range as the lives for corresponding specimens initiating failure at the toe of the weld, indicating that the combination of residual stress and the geometrical conditions necessary for crack nucleation were about equally as critical internally as at the specimen surface. This observation should not be taken as conclusive, however, since the data from the as-welded specimens, Fig. 3.5, show that internal flaws can be of sufficient severity as to result in very low fatigue lives relative to specimens failing at the surface (cf., lives of as-welded members tested at stress levels of ±30.0 ksi and ±40.0 ksi).

3.3.3 Zero-To-Tension Tests

Eight specimens were tested at a stress cycle of zero-to-tension; the data and computed fatigue strengths ($k = 0.148$) are presented in Table 3.5. All of the specimens initiated fatigue cracks in the mechanically peened region of the weld reinforcement. The test results and S-N curve are plotted in Fig. 3.6a together with data from axial tests of as-welded HY-80 butt-welded joints which were tested previously[4]. These data again demonstrate the advantages of peening as reflected in fatigue lives considerably greater that the lives of corresponding as-welded specimens, notably at the lower stress levels. As with the tests reported earlier, however, the fatigue lives for both the mechanically peened and as-welded members are approximately the same at nominal maximum stresses approaching 80 ksi.

The current axial fatigue test data for peened butt welds are compared also, in Fig. 3.6b, to flexural fatigue results of both mechanically peened and as-welded members tested at the Naval Applied Science Laboratory[3]. The NASL data represent tests conducted on plates 1-1/2 in. x 28 in. x 32 in., in which the butt weld extended across the entire width of the plate. The lives plotted for the two as-welded plates are the number of cycles required to increase the maximum plate deflection 10 percent beyond the full load deflection at the beginning of the test. Flexural fatigue testing of the two mechanically peened weldments was discontinued at the lives indicated with no major cracks evident. The significant difference in fatigue lives between the peened specimens tested in flexure and those tested in axial fatigue may be explained by the same factors of specimen size and stress state considered earlier for the tee-weldments (Section 3.2.3).

3.3.4 Half Tension-To-Tension Tests

The test results for the transverse butt-welded members tested at a stress cycle of half tension-to-tension are listed and evaluated in Table 3.6. The data, with the exception of the points for two specimens as explained below, are plotted in Fig. 3.7. Because of the range of fatigue lives obtained for the specimens, it was not possible to compute fatigue strengths at 10,000 cycles using the extrapolation limits set in Section 3.1; Table 3.6, therefore, lists the fatigue strengths at 20,000 50,000, 100,000 and 500,000 cycles.

During the fatigue cycling of specimen M53MP4, considerable eccentricity of the external load occurred as a result of an accidental misalignment of the testing machine. This eccentricity produced bending on the specimen cross-section so that one surface sustained notably larger tensile stresses than indicated by the nominal stress level. Although the test is reported in Table 3.6, the result was not used to calculate the fatigue strengths nor is the specimen included in the plot of the fatigue data in Fig. 3.7.

Specimen M11MP18 was found to have a marked initial curvature which introduced a significant tensile stress on one specimen face when the member was bolted into the testing machine. The severity of this induced stress became obvious during the course of fatigue cycling, when cracks initiated and propagated from only one face of the member. As with specimen M53MP4, the fatigue life of member M11MP18 was not included in the fatigue strength computations, nor was it plotted in Fig. 3.7.

3.3.5 General

The Modified Goodman Diagram of Fig. 3.8 represents the average values of the computed fatigue strengths of the transverse butt-welded specimens at 10,000, 50,000, 100,000, and 500,000 cycles. The points plotted for each of the stress cycles examined were determined from the computed average values given in Tables 3.4, 3.5, and 3.6. One exception is the point representing $F_{10,000}$ for the half tension-to-tension stress cycle, which was obtained from an extrapolation of the S-N curve constructed in Fig. 3.7.

The curves through the points plotted in Fig. 3.8 were extended to the static tensile ultimate strength of the HY-80 base metal. This static strength, 106 ksi, was taken as the average of the values obtained for plates 11, 53, and 77, Table 2.2. Since the strength of the MIL-11018 welding electrode is higher than that of the HY-80 base material, it would be expected that a full penetration butt-welded joint of the type tested would fail in the base metal in a static tension test. Extrapolation of the fatigue data to the base metal strength is, therefore, reasonable.

As with the tee-weldment results, the limited number of data for butt-welded specimens available to compute the fatigue strengths precluded the possibility of presenting representative scatter bands about the average curves shown in the Modified Goodman Diagram of Fig. 3.8. Table 3.7 does offer some indication of the scatter of results obtained in calculating the fatigue strengths at 10,000 and 100,000 cycles for each of the stress cycles examined. There is, of course, a definite likelihood of incurring considerably larger deviations about the average fatigue strengths than those shown in Table 3.7 if additional test data were available. It would be desirable to consider the limits of this scatter if the curves in Fig. 3.8 were to be used to determine fatigue design relationships.

Examination of Table 3.7 shows that the fatigue strengths of the transverse butt-welded specimens are considerably higher that the corresponding values for the tee-weldment specimens for each of the three stress cycles. For purposes of comparison the computed axial fatigue strengths, at 100,000 cycles, for plain plates of the HY-80 base material in the as-received condition, are also given in Table 3.7. The values were obtained from data for fatigue tests conducted previously at the University of Illinois[5]. Since the lives studied for the plain plates were greater than for the current welded specimens, no fatigue strengths were computed for 10,000 cycles to failure. The approximate average values reported in Table 3.7 at that life were obtained by extrapolation of S-N curves constructed through the data using the appropriate slopes. In general, the data indicate that the percent reduction in fatigue strength, resulting from the inclusion of either a transverse butt weld or tee-weldment in an HY-80 plate, becomes greater with increasing fatigue lives (the tee-weldment, as noted above, producing a greater change than the butt-welded joint). This is true for both the complete-reversal and zero-to-tension stress cycles.

IV. STUDY OF FATIGUE CRACK INITIATION AND PROPAGATION

4.1 Measurement Procedure

A number of both the tee-weldment and butt-welded specimens were selected to study the location and number of cycles to the appearance of the first visable fatigue cracks, and to observe the subsequent rate of crack propagation. Representative specimens were chosen from those tested at each of the three stress cycles examined: complete-reversal, zero-to-tension, and half tension-to-tension. The specimens were then subjected to periodic examination during the course of fatigue cycling; the readings were spaced so that a sufficient number of observations could be made to completely trace the crack propagation histories. The procedures used in the measurement of the fatigue cracks are described below.

Each specimen used in the crack nucleation and propagation study was first positioned in the fatigue testing machine and the load range set, as described in Section 2.4. The member was then cycled to approximately one percent of its total expected fatigue life, the total life having been estimated by averaging the lives of other specimens tested at the same stress level. At this point, a thin film of light machine oil was spread over the specimen faces in the vicinity of the weldment, including the mechanically peened region of the weld reinforcement. With the fatigue machine continuing in operation, each of the specimen faces was examined with the aid of a magnifiying lens. Using the lens, the position and length of each visible crack measured to a precision of ±0.01 in., was then recorded. It should be noted that, during the early stages of cycling, a fatigue crack was often distinguishable only by small bubbles in the oil film caused by the repeated opening and closing of the crack under cycling of the load. As the crack progressed in length and depth, however, it was eventually detected without the aid of the oil film, even when the testing machine was set at the zero load level.

The above process was repeated at intervals regulated to obtain between 10 and 20 crack length readings during the life of a specimen. The readings were taken at progressively shorter cyclic intervals toward the latter stages of propagation, corresponding to approximately uniform incremental increases in the length of the more rapidly progressing crack. The final reading was made at the time that the testing machine was stopped by the tripped microswitch, marking the reported cyclic specimen life time. As noted earlier, less than 0.5% additional cycling was required from this point to complete fracture of the member.

4.2 Behavior of Tee-Weldments

4.2.1 Fatigue Crack Initiation

All but one of the 24 tee-weldment specimens initiated fatigue cracks along the trough formed at the toe of the weld by the mechanical peening process. The first visible cracks (observed under a film of oil as described above) were usually found well within the first 20 percent of the total specimen fatigue life, and in some instances after just a few hundred load repetitions. In general, these early cracks were observed along both weld toes and extended in a random pattern over sizeable portions of the entire length of weld. An example of a typical fatigue crack which had initiated in the mechanically peened region of the weld reinforcement is shown in the photographs of specimen M77AP18 (BN-22), Fig. 4.1.

Specimen M77AP23 (BN-11), tested at a stress level of ±40.0 ksi, also exhibited a number of hairline cracks in the peened region, which appeared in the early stages of cycling. However, after about 38,000 load cycles, another crack initiated in the mill scale surface of the main plate on the face opposite the one containing the welded attachment. This crack then propagated rapidly through the main member, the center of the weld, and into the attachment, resulting in failure at 43,300 cycles, the lowest life of those tee-weldment specimens tested at ±40.0 ksi. Photographs of the fracture surface and the crack path are shown in Fig. 4.2. Of all the specimens tested in this study, both tee-weldments and butt-welded joints, specimen M77AP23 was the only one which exhibited failure in the plain plate material well removed from the location of a weld. This may have been the result of a geometrical notch located on the plain plate surface; however, damage to this surface during the latter stages of cycling in complete-reversal precluded the possibility of examining the region of nucleation after completion of the test.

4.2.2 Fatigue Crack Propagation

The crack propagation histories for five of the 24 tee-weldment specimens were obtained during the course of the study. All five of the specimens initiated early fatigue cracks in the mechanically peened region of the weld reinforcement. The subsequent rate of propagation was determined by measuring the observed crack lengths on each face of the member at various intervals during the fatigue test, as outlined in Section 4.1. For each of the five specimens, the position and length of the fatigue cracks observed at a select number of the readings were sketched to scale and reproduced in References 6 through 9. In general, these plots show the cracks to extend over large segments of the peened region of each weld toe early in a specimen life, and, thereafter, to propagate through the thickness of the member perpendicular to the direction of external axial load. Fig. 4.3 contains a series of sketches of the position of the fatigue cracks for one of the fatigue cracks for one of the tee-weldments studied, M77AP14. The shaded portions of the sketches represent the weld surfaces, including the peened areas. The fatigue cracks are indicated by wavy lines plotted to scale as they were observed on the specimen surfaces at the time of the various readings. The location of the critical fatigue crack, i.e., that one which eventually propagated to complete fracture, is noted by the arrows in Fig. 4.3.

Since the fatigue cracks usually were observed over the length of each weld toe at a small fraction of the total specimen lifetime, the only significant representation of the rate of crack growth into the plate was the measured depths of the cracks as seen on the polished specimen edges (see Figs. 4.1b and 4.2b). Measurement of these cracks showed the depth of crack to increase very slowly and erratically (periods of growth followed by periods of stagnation) for a large part of the total fatigue life of the member. Eventually, however, one of the cracks would predominate and extend at a continually increasing rate to the point of complete failure. This crack was not always the first to be observed nor was it necessarily the largest crack existing in the early stages of cycling.

The extent of the predominant or "critical" fatigue crack (measured on the specimen edges) at each of the readings taken for four of the five specimens examined is normalized and plotted in Fig. 4.4. The data show the long period of slow propagation, occupying from 60 to 80 percent of the total specimen fatigue life, followed by a short span in which the critical crack depth increased from about 20 percent of the full member thickness to failure. During the initial stage of slow, erratic crack growth, the load measured at the testing machine dynamometer remained essentially constant, indicating that a reasonably constant state of stress existed at the extending tip of the very shallow fatigue crack. As the crack region widened, however, the peak tensile load began to gradually drop with continued cycling (beginning at about 80 percent of the specimen fatigue life). Counter-balancing the drop in load was the fact that the remaining net cross-sectional area was becoming substantially reduced. Additionally, since the critical crack was extending from only one face of the member, the remaining net area became eccentrically loaded, resulting in a superposition of stresses due to the combined axial and flexural loads. The net result of these external factors was that the maximum stresses were continually increasing at the crack tip (beyond 80 percent of the member life) leading to an attendant acceleration in the rate of crack propagation. Toward the end of the test, the final few load repetitions were marked by a tearing or shear-type failure which concluded in complete specimen fracture.

One observation of particular note may be drawn from the data presented in Fig. 4.4. Under conditions of approximately constant range of external cyclic load, 80 percent or more of the total lifetime of a member may be occupied in the initiation of a fatigue crack, and the propagation of this crack through a small percentage of the member thickness.

Cognizance of this behavior is important in setting the inspection intervals in service structures, for a fatigue crack extending through only half the thickness of a component may well indicate that the range of useful service of that component has been practically exhausted.

The crack propagation history of a fifth tee-weldment specimen, M77AP9 (Table 3.1), was also obtained, but is not recorded in Fig. 4.4. As with the other members, specimen M77AP9 exhibited surface cracks which had slowly extended, for the major part of the specimen life, through only a fraction of the thickness of the plate. Unexpectedly, a new crack appeared on the surface in the peened region of the weld (just above an existent crack) and propagated within 1500 cycles to complete failure at a total of 11,400 cycles. This mode of failure is somewhat similar to that of specimen M77AP23, discussed earlier, which failed from a crack initiating at the mill scale surface of the plain plate late in the cyclic lifetime of the specimen. Another similarity is that both of the specimens had the lowest lives of those tested at their particular stress levels. Thus, it must be recognized that although Fig. 4.4 is representative of most of the tee-weldment failures, it is not necessarily a conservative representation of other crack propagation sequences possible at the stress levels examined, as evidenced by the two tests just cited.

4.3 Behavior of Butt-Welded Joints

4.3.1 Fatigue Crack Initiation

Of the 25 transverse butt-welded specimens examined, 21 failed in fatigue as a result of cracks which had initiated in the mechanically peened region of the weld reinforcement. The majority of these surface-initiated cracks were observed within the first 20 percent of the specimens' fatigue lives, similar to the behavior of the tee-weldment members. Although the cracks were found to initiate along large segments of the length of each of the four weld toes, usually only one or two of these cracks subsequently propagated to any sizable depth into the thickness of the member. The fracture surface and crack path in a typical butt-welded specimen, M53MP9 (BT-5), which initiated failure in the trough at the toe of the weld, is pictured in Fig. 4.5.

Four of the butt-welded members, Table 3.4, initiated critical fatigue cracks of small singular internal weld flaws. These isolated defects (< 0.05 in. dia) were probably not of sufficient size to be detected by the usual radiographic examination so that each of the four members would be classified as a sound weldment. The fracture surface of one of these specimens, M53MP5 (BT-9), showing the region of fatigue crack nucleation at the flaw location, is presented in Fig. 4.6a.

It is interesting to note that of all the axially loaded butt-welded fatigue specimens reported, both in the as-welded condition and with the weld toe mechanically peened, only those tested at a complete-reversal stress cycle exhibited occasional failures initiating at an internal flaw, Figs. 3.5, 3.6, and 3.7. Since similar flaws undoubtedly existed in those specimens tested at the other stress levels as well, it appears that the cyclic stress state of complete-reversal offers the most critical superposition of applied stress range with the initial residual stress pattern to create the condition necessary for internal crack initiation. It must be emphasized, however, that if flaws of greater size or severity were to be introduced in similar weldments, other stress cycles could also produce internal weld failures. (The results of comprehensive studies of the effects of various weld defects on the axial fatigue behavior of HY-80 welded joints are reported in References 13, 14, and 15).

4.3.2 <u>Fatigue Crack Propagation</u>

Crack propagation studies were performed for six of the transverse butt-welded specimens examined in this investigation. Five of these specimens initiated fatigue cracks in the mechanically peened region along the toe of the weld early in the lifetime of the member. The procedures used to measure the crack lengths observed on each of the specimen surfaces are described in Section 4.1. Sketches of the position and lengths of the fatigue cracks observed at the time of several of the readings during the propagation study for each of the six specimens are presented in References 10, 11, and 12. These sketches show the early appearance of the fatigue cracks along the toes of the welds (except for specimen M77MP22, which initiated a crack at an internal flaw) followed by the progression of these cracks through the member thickness approximately perpendicular to the direction of external loading. Typical illustrations of the appearance of the fatigue cracks on the surfaces of one of the members examined M77MP23, are shown in the sequential sketches of Fig. 4.7. The arrow indicates the location of the critical fatigue crack for that particular specimen. Note, also, the presence of cracks extending into the member from the other weld toes as well.

As with the tee-weldment specimens, the surface-initiated fatigue cracks in the butt-welded members extended over major portions of the length of one or more of the weld toes from early in the cyclic lifetime of the members. Thus, only those crack depth measurements obtained from the polished specimen edges could be used to indicate the rate of fatigue crack propagation. These measurements showed the cracks to increase in depth in a slow, erratic manner for the major part of a specimen lifetime. Toward the latter stages of cycling, one of the cracks would usually extend more rapidly than the others, resulting in failure shortly thereafter. Examination of the specimen fracture surfaces revealed these final cycles to be identified by a coarse contoured surface easily distinguished from the flat, fine-grained appearance of the region of initial fatigue crack extension.

For the five specimens studied which exhibited surface-initiated failures, the fatigue crack propagation rate of the critical crack (that crack which led to ultimate specimen failure) is plotted in a normalized manner in Fig. 4.8. The data for each specimen show the aforementioned initial period of slow, erratic propagation, followed by a short period (approximately the last 20 percent of fatigue life) of very rapid propagation in which the critical crack grew from a depth covering some 20 percent of the specimen thickness to the point of failure. During this latter stage of rapid fatigue crack extension in the butt-welded joints, the comments mentioned in Section 4.2.2 concerning the state of increasing stress at the crack tip in the tee-weldments are equally applicable. That is, the eccentricity of load resulting from a large crack extending inward from one specimen face and the decreasing net area combine to continually increase the plastic deformations at the crack front, thereby further accelerating the rate of propagation.

The normalized rates of fatigue crack propagation of the butt-welded members and the tee-weldments, Fig. 4.4 and 4.8, are quite similar for those specimens initiating cracks in the peened region of the weld reinforcement. In fact, the same scatter band could be used to encompass the data for all of the specimens examined. No analytical relationship is presented to represent an average curve through these data because of the limited number of tests conducted, the uncertainty of the stress state at the crack tip during the final stage of cycling, and the possible unconservatism of such a relationship if applied to specimens initiating failures at locations other than at the toe of a weld.

The pattern of crack initiation and propagation of a sixth butt-welded member, M77MP22, was studied, but is not presented in Fig. 4.8. This specimen, tested at ±40.0 ksi, initiated fatigue failure at a small internal weld defect, as did three other specimens tested in complete-reversal, Table 3.4. Two observations (in addition to examination of the fracture surface after complete failure) may be noted to distinguish this type of internal failure from fatigue initiating with surface cracks. First, after propagating to the specimen surface from its point of internal nucleation, the path of the fatigue crack was seen to pass diagonally through the weld reinforcement at a pronounced angle to the direction of external loading, Fig. 4.6b. It then followed the trough at the toe of the weld created by the peening, with complete fracture occurring soon thereafter. This is in contrast to the propagation of cracks initiated on the surface of a specimen, where such cracks normally followed a straight path along the toe of the weld reinforcement and extended into the plate normal to the direction of loading. Also, the internally initiated crack did not intersect the member surface until approximately half the total specimen lifetime, compared to the considerably earlier visible evidence of cracking in specimens where failure initiated at the

the surface. This indicates that the crack extending from the internal flaw may have been propagating for a relatively long period before being detected on the surface. Such a crack would be quite critical in service, offering no visual warning of failure until well into the latter stages of propagation. This points to the necessity in service structures of providing careful periodic inspection of weldments, by appropriate non-destructive testing techniques, to insure the early detection of internally nucleated fatigue cracks.

V. SUMMARY AND CONCLUSIONS

5.1 Summary

The purpose of the investigation was to evaluate the effect of mechanical peening on the fatigue resistance of welded HY-80 members under conditions of axial loading, and to compare the results with available information on similar members tested in flexure. Two specimen types were examined, transverse tee-weldments and transverse butt-welded joints. The only special preparation of these members consisted of mechanically peening the region along the toe of each weld, thereby improving the geometry and introducing compressive residual stresses in that region.

A total of 24 tee-weldments and 25 butt-welded members were tested in axial fatigue at stress cycles of complete-reversal, zero-to-tension, and half tension-to-tension. The test data were used to construct S-N curves for each of the stress cycles examined, and combined on Modified Goodman Diagrams to compare the computed fatigue strengths at 10,000, 50,000, 100,000, and 500,000 cycles. The current data were also compared to the fatigue lives obtained for similar HY-80 members in the as-welded condition (not subjected to peening and tested under identical axial fatigue conditions), and to plate specimens, both as-welded and mechanically peened, which were tested in flexural fatigue. Several tee-weldment and transverse butt-welded specimens were examined periodically during the course of fatigue cycling to determine the location and number of cycles required to initiate surface cracks, and to obtain a measure of the subsequent rate of fatigue crack propagation. To obtain the crack propagation histories, representative specimens were selected from those tested at each of the three stress cycles studied. The general pattern of behavior of those specimens initiating surface fatigue cracks were then compared to the members which incurred failure from internally nucleated cracks.

5.2 Conclusions

It must be recognized that the evaluations and conclusions offered herein are based in most instances on minimal test data, and must be viewed accordingly. There are, however, several basic observations which are considered significant; these are briefly discussed in the following paragraphs.

5.2.1 Fatigue Behavior of Mechanically Peened Weldments

Axial fatigue tests 1-1/2 in. thick plates of HY-80 steel containing either transverse tee-weldments or transverse butt welds have indicated that:

1. Mechanical peening of the region along the toe of the weld results in an improvement in the axial fatigue resistance of both types of welded connection relative to the behavior of similar weldments not subjected to the mechanical peening process. For each of the three stress cycles studied, the improvement in fatigue resistance increased as the maximum cyclic stress decreased, with fatigue lives for the peened specimens ranging from approximately three to ten times the lives of corresponding as-welded members at a cyclic nominal stress level of half the yield strength of the base metal. The beneficial effect of peening is less pronounced at higher stress levels, however, as the fatigue lives for both the as-welded and the mechanically peened weldments are about the same at nominal stresses approaching the material yield strength.

2. The fatigue lives of the mechanically peened weldments tested in axial fatigue were lower than the lives of corresponding flexural fatigue specimens tested at the same nominal stress levels. This may be attributed in part to the differences between the two types of fatigue test, including specimen size, state of stress, and stress gradient through the specimen cross-section.

3. For each of the stress cycles examined, complete-reversal, zero-to-tension, and half tension-to-tension, the fatigue strengths of the butt-welded specimens were higher than the corresponding strengths of the tee-weldments over the range of cyclic lifetimes obtained in this study. The geometry of the joint in the tee-weldment specimens, which results in an eccentricity of the load acting on the member cross-section, develops a more critical condition for fatigue crack initiation and propagation than exists in the simple butt-welded joint. This relative behavior has been found to be the case for axial fatigue members both in the as-welded condition and with the weld toe mechanically peened.

The fatigue strengths of the tee-weldments and the butt-welded members (both mechanically peened) were lower than the axial fatigue strengths of the HY-80 base material at comparable stress cycles. Such reductions should be taken into consideration when designing the components of welded service structures subjected to similar cyclic variations in stress.

5.2.2 Crack Initiation and Propagation

Examination of the fatigue crack initiation and propagation histories of several of the mechanically peened HY-80 transverse tee-weldments and butt-welded members has revealed that:

1. Surface fatigue cracks in both types of member were found to initiate in the trough of the weld reinforcement which was produced by the mechanical peening process. The first surface cracks were visible early in the cyclic lifetime of a test specimen, usually well within the first 20 percent of the total life. The majority of both the tee-weldments and the butt welds exhibited this mode of fatigue crack initiation.

Four of the transverse butt-welded members, tested at a stress cycle of complete-reversal, initiated critical fatigue cracks at small internal weld defects. Since these internally nucleated cracks were not detected until they had propagated to a free surface, no direct measurement of the number of cycles to the time of initiation was possible. The total fatigue lives of these specimens were generally within the same range as those tested at the same stresses and which initiated surface failures. This suggests that the internal fatigue cracks also originated relatively early in the specimen lifetime.

2. The surface-initiated fatigue cracks in the tee-weldments and butt-welded joints generally propagated slowly and erratically (intermittent periods of crack growth followed by periods of stagnation) through the thickness of a test member from the time of initiation until approximately 70-80 percent of the total specimen fatigue life had been exhausted. At some time during this period of slow growth, a crack progressing from one of the peened surfaces would predominate and thereafter propagate rapidly to complete failure (encompassing the last 20 percent of the specimen life). This latter stage of propagation was marked by a continual increase in the axial stresses at the crack tip concurrent with the decreasing net area of the specimen; this in turn further accelerated the growth rate and led to a ductile shear-type failure in the final few cycles.

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TABLE 2.1

CHEMICAL ANALYSES OF BASE PLATES

(Data Supplied by U.S. Naval Applied Science Laboratory)

Chemical Content (percent)	Plate Number 11	Plate Number 53	Plate Number 77	Specification MIL-S-16216G
C	0.17	0.16	0.15	0/0.18
Mn	0.28	0.33	0.32	0.10/0.40
P	0.010	0.010	0.014	0/0.025
S	0.019	0.008	0.010	0/0.025
Si	0.24	0.27	0.28	0.15/0.35
Ni	2.94	2.68	2.90	2.00/3.25
Cr	1.47	1.71	1.77	1.00/1.80
Mo	0.43	0.48	0.36	0.20/0.60
Ti	--	0.007	< 0.002	0/0.020
Cu	--	0.05	0.03	0/0.25
V	--	--	< 0.003	0/0.030

TABLE 2.2

MECHANICAL PROPERTIES OF BASE PLATES
(Data Supplied by U.S. Naval Applied Science Laboratory)

Properties	Plate Number 11 L*	11 T*	53 L	53 T	77 L	77 T	Specification MIL-S-16216G L	MIL-S-16216G T
Yield Strength** (ksi)	83	87	78	79	87	88	80/95	
Ultimate Strength (ksi)	105	103	105	106	108	107	To be recorded for information	
Elong. in 2 inches (percent)	29	26	29	26	26	23	20	
Reduction in Area (percent)	75	69	75	65	74	63	55	50

* L represents samples whose length is parallel to the direction of rolling

T represents samples whose length is perpendicular to the direction of rolling

** 0.2 percent offset

TABLE 2.3

CHARPY V-NOTCH VALUES FOR BASE PLATES*

(Data Supplied by U.S. Naval Applied Science Laboratory)

Test Temperature (degrees F)	Plate Number						Specification MIL-S-16216G	
	11		53		77			
	L**	T**	L	T	L	T	L	T
+80	123	84	147	77	135	76	--	--
-60	--	--	136	72	124	69	--	--
-120	109	66	105	54	110	51	50	--
-180	--	--	70	31	50	26	--	--
-240	--	--	--	--	23	19	--	--

* Charpy V-Notch Values in foot-pounds

** L represents samples whose length is parallel to the direction of rolling

T represents samples whose length is perpendicular to the direction of rolling

TABLE 2.4

FATIGUE SPECIMEN NET TEST SECTION WIDTHS

Plate Thickness (inches)	Net Test Section Width (inches) (see Figs 2.1, 2.2)	Fatigue Test Stress Cycle (ksi)
1-1/2	1-3/4	+40.0 to +80.0
		±55.0
1-1/2	2	+35.0 to +70.0
		+30.0 to +60.0
		0 to +80 0
1-1/2	2-1/2	0 to +60.0
		0 to +50.0
		0 to +40.0
		±40.0
		±30.0
		±20.0

TABLE 3.1

RESULTS OF FATIGUE TESTS OF HY-80 PLATES
WITH TRANSVERSE TEE-ATTACHMENT

(Complete-Reversal)

Specimen Number	Special Treatment	Stress Cycle (ksi)	Life (cycles)	Location of Fracture**	Computed Fatigue Strength, ksi*			
					$F_{10,000}$	$F_{50,000}$	$F_{100,000}$	$F_{500,000}$
M77AP11	Mech. Peened	±55.0	19,800	a	65.0	43.8	37.0	-
M77AP17	Mech. Peened	±55.0	15,000	a	60.7	41.0	-	-
M77AP9	Mech. Peened	±55.0	11,400	a	56.8	38.3	-	-
M77AP2	Mech. Peened	±40.0	84,800	a	-	45.9	38.4	-
M77AP10	Mech. Peened	±40.0	83,700	a	-	45.4	38.2	
M77AP23	Mech. Peened	±40.0	43,300	b	57.2	38.7	32.6	-
M77AP3***	Mech. Peened	±40.0	< 147,000	a	-	-	-	-
M77AP21	Mech. Peened	±20.0	1,027,300	a	-	-	-	23.8
				Average	59.9	42.2	36.6	23.8

* k = 0.245

** a: initiation in mechanically peened region of weld reinforcement
b: initiation at mill scale surface of plain plate opposite attachment

*** micro-switch did not shut off fatigue machine; data not used to compute fatigue strengths

TABLE 3.2

RESULTS OF FATIGUE TESTS OF HY-80 PLATES
WITH TRANSVERSE TEE-ATTACHMENT

(Zero-To-Tension)

Specimen Number	Special Treatment	Stress Cycle (ksi)	Life (cycles)	Location of Fracture**	Computed Fatigue Strength, ksi*			
					$F_{10,000}$	$F_{50,000}$	$F_{100,000}$	$F_{500,000}$
M77AP6	Mech. Peened	0 to +80.0	10,800	a	81.2	58.9	-	-
M77AP5	Mech. Peened	0 to +80.0	9,800	a	80.0	57.9	-	-
M77AP7	Mech. Peened	0 to +58.8	63,900	a	-	63.0	54.8	-
M77AP8	Mech. Peened	0 to +60.0	48,100	a	81.9	59.6	51.8	-
M77AP1	Mech. Peened	0 to +60.0	38,500	a	78.4	56.9	49.6	-
M77AP12	Mech. Peened	0 to +40.0	339,400	a	-	-	51.0	37.0
M77AP24	Mech. Peened	0 to +40.0	312,500	a	-	-	50.2	36.4
M77AP4	Mech. Peened	0 to +40.6	81,900	a	-	44.2	38.4	-
				Average	80.4	56.8	49.3	36.7

* k = 0.198

** a: initiation in mechanically peened region of weld reinforcement

TABLE 3.3

RESULTS OF FATIGUE TESTS OF HY-80 PLATES
WITH TRANSVERSE TEE-ATTACHMENT

(Half Tension-To-Tension)

Specimen Number	Special Treatment	Stress Cycle (ksi)	Life (cycles)	Location of Fracture**	Computed Fatigue Strength, ksi*			
					$F_{10,000}$	$F_{50,000}$	$F_{100,000}$	$F_{500,000}$
M77AP15	Mech. Peened	+40.0 to +80.0	54,600	a	104.2	81.1	72.8	-
M77AP18	Mech. Peened	+40.0 to +80.0	48,700	a	102.2	79.7	71.6	-
M77AP14	Mech. Peened	+35.0 to +70.0	176,300	a	-	85.1	76.4	59.6
M77AP20	Mech. Peened	+35.0 to +70.0	91,200	a	-	76.7	68.9	-
M77AP16	Mech. Peened	+35.0 to +70.0	70,300	a	-	73.8	66.3	-
M77AP22	Mech. Peened	+35.0 to +70.0	64,900	a	-	72.9	65.5	-
M77AP19	Mech. Peened	+30.0 to +60.0	405,700	a	-	-	74.6	58.1
M77AP13	Mech. Peened	+30.0 to +60.0	342,400	a	-	-	72.6	56.6
				Average	103.2	78.2	71.1	58.1

* k = 0.155

** a: initiation in mechanically peened region of weld reinforcement

TABLE 3.4

RESULTS OF FATIGUE TESTS OF HY-80 PLATES
WITH TRANSVERSE BUTT WELD

(Complete-Reversal)

Specimen Number	Special Treatment	Stress Cycle (ksi)	Life (cycles)	Location of Fracture**	Computed Fatigue Strength, ksi*			
					$F_{10,000}$	$F_{50,000}$	$F_{100,000}$	$F_{500,000}$
M77MP21	Mech. Peened	±55.0	45,100	a	77.8	53.7	45.8	-
M11MP10	Mech. Peened	±55.0	33,400	a	72.6	50.1	42.8	-
M77MP24	Mech. Peened	±55.0	24,100	a	67.3	46.5	39.6	-
M77MP22	Mech. Peened	±40.0	270,800	d	-	59.0	50.2	34.8
M53MP9	Mech. Peened	±40.0	190,000	a	-	54.4	46.8	32.0
M53MP5	Mech. Peened	±40.0	136,700	d	-	50.4	43.0	29.7
M77MP15	Mech. Peened	±30.0	568,000	d	-	-	44.7	30.9
M53MP12	Mech. Peened	±30.0	407,600	d	-	-	41.5	28.6
M77MP25	Mech. Peened	±30.0	182,800	a	-	40.4	34.4	23.8
				Average	72.6	50.6	43.2	30.0

* k = 0.227

** a: initiation in mechanically peened region of weld reinforcement
d: initiation at an internal weld flaw

TABLE 3.5

RESULTS OF FATIGUE TESTS OF HY-80 PLATES
WITH TRANSVERSE BUTT WELD

(Zero-To-Tension)

Specimen Number	Special Treatment	Stress Cycle (ksi)	Life (cycles	Location of Fracture**	Computed Fatigue Strength, ksi*			
					$F_{10,000}$	$F_{50,000}$	$F_{100,000}$	$F_{500,000}$
M11MP17	Mech. Peened	0 to +80.0	22,800	a	90.4	71.2	64.2	-
M11MP20	Mech. Peened	0 to +80.0	19,100	a	88.6	69.4	-	-
M53MP3	Mech. Peened	0 to +60.0	100,700	a	-	66.5	60.1	47.3
M53MP6	Mech. Peened	0 to +60.0	97,000	a	-	66.2	59.7	-
M53MP2	Mech. Peened	0 to +60.0	79,600	a	-	64.3	58.0	-
M53MP1	Mech. Peened	0 to +50.0	643,900	a	-	-	-	51.9
M53MP8	Mech. Peened	0 to +50.0	408,100	a	-	-	61.6	48.5
M11MP11	Mech. Peened	0 to +50.0	365,100	a	-	-	60.6	47.7
				Average	89.5	67.5	60.7	48.9

* k = 0.148

** a: initiation in mechanically peened region of weld reinforcment

TABLE 3.6

RESULTS OF FATIGUE TESTS OF HY-80 PLATES
WITH TRANSVERSE BUTT WELD

(Half Tension-To-Tension)

Specimen Number	Special Treatment	Stress Cycle (ksi)	Life (cycles)	Location of Fracture**	Computed Fatigue Strength, ksi*			
					$F_{20,000}$	$F_{50,000}$	$F_{100,000}$	$F_{500,000}$
M11MP19	Mech. Peened	+40.0 to +80.0	104,900	a	98.6	87.8	80.5	65.7
M77MP14	Mech. Peened	+40.0 to +80.0	101,900	a	98.2	87.5	80.2	65.4
M77MP13	Mech. Peened	+40.0 to +80.0	72,700	a	94.1	83.9	76.8	--
M53MP7	Mech. Peened	+35.0 to +70.0	336,300	a	--	--	81.6	66.6
M77MP23	Mech. Peened	+35.0 to +70.0	282,100	a	--	87.1	81.2	65.1
M53MP4+	Mech. Peened	+35.0 to +70.0	133,600	a	--	--	--	--
M11MP18++	Mech. Peened	+30.0 to +60.0	262,100	a	--	--	--	--
M11MP16	Mech. Peened	+26.8 to +53.6	584,100	a	--	--	66.4	54.3
				Average	97.0	86.6	77.8	63.4

* k = 0.126

** a: initiation in mechanically peened region of weld reinforcement

+ test void as a result of testing machine misalignment; data not used to compute fatigue strengths

++ specimen severly bent initially, causing large variation in stress over cross-section; data not used to compute fatigue strengths

TABLE 3.7

COMPARISON OF FATIGUE STRENGTHS OF HY-80
TEE-WELDMENT AND BUTT-WELDED SPECIMENS

Specimen Type	Special Treatment	Stress Cycle	S-N Curve Slope (k)	Fatigue Strength, ksi $F_{10,000}$ Avg.	$F_{10,000}$ Max.	$F_{10,000}$ Min.	$F_{100,000}$ Avg.	$F_{100,000}$ Max.	$F_{100,000}$ Min.
Tee-Weldment	Mech. Peened	Complete-Reversal	0.245	59.9	65.0	57.2	36.6	38.4	32.6
		Zero-to-Tension	0.198	80.4	81.9	78.4	49.3	54.8	38.4
		Half Tension-to-Tension	0.155	103.2	104.2	102.2	71.1	76.4	65.5
Butt Weld	Mech. Peened	Complete-Reversal	0.227	72.6	77.8	67.3	43.2	50.2	34.4
		Zero-to-Tension	0.148	89.5	90.4	88.6	60.7	64.2	58.0
		Half Tension-to-Tension	0.126	104*	-	-	77.8	81.6	66.4
Plain Plate**	As-Received	Complete-Reversal	0.174	75*	-	-	50.0	51.5	47.2
		Zero-to-Tension	0.149	96*	-	-	67.9	72.7	62.4

* average values obtained by straight-line extrapolation of S-N curves to a fatigue life of 10,000 cycles

** data from Ref. 5

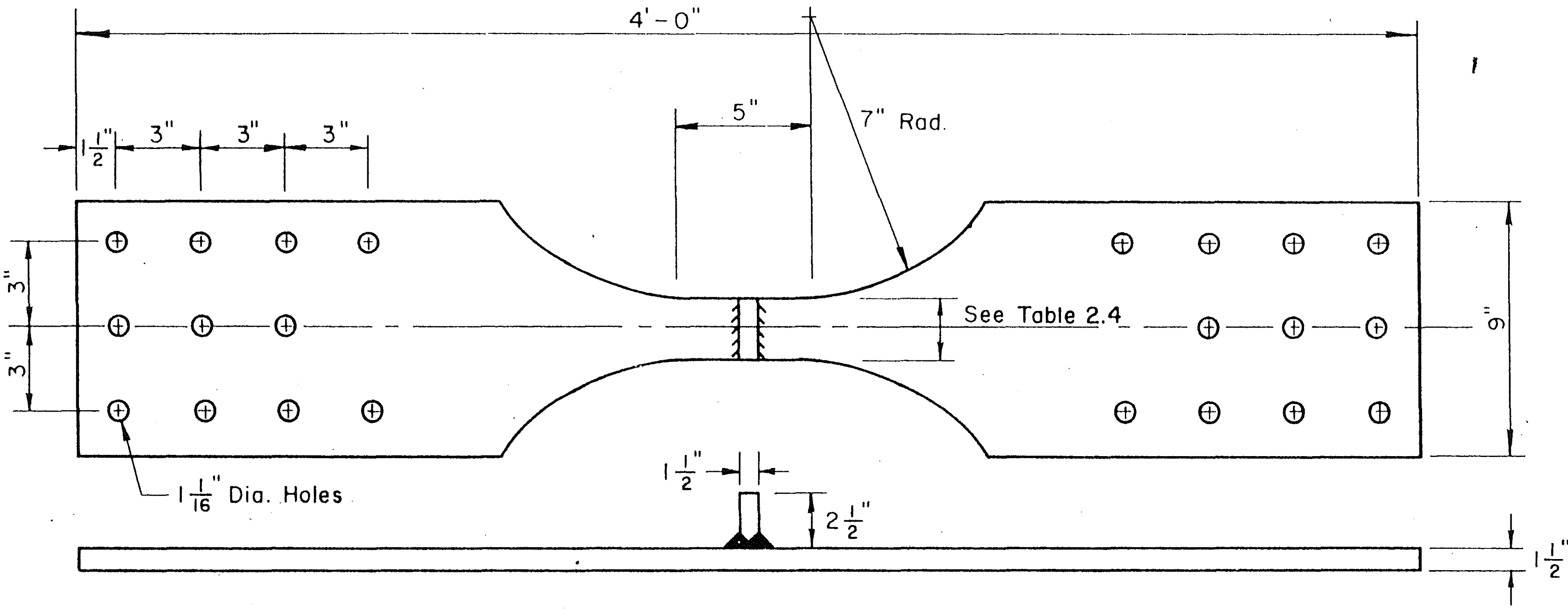


FIG. 2.1 DETAILS OF FATIGUE TEST SPECIMEN
WITH TRANSVERSE TEE-ATTACHMENT

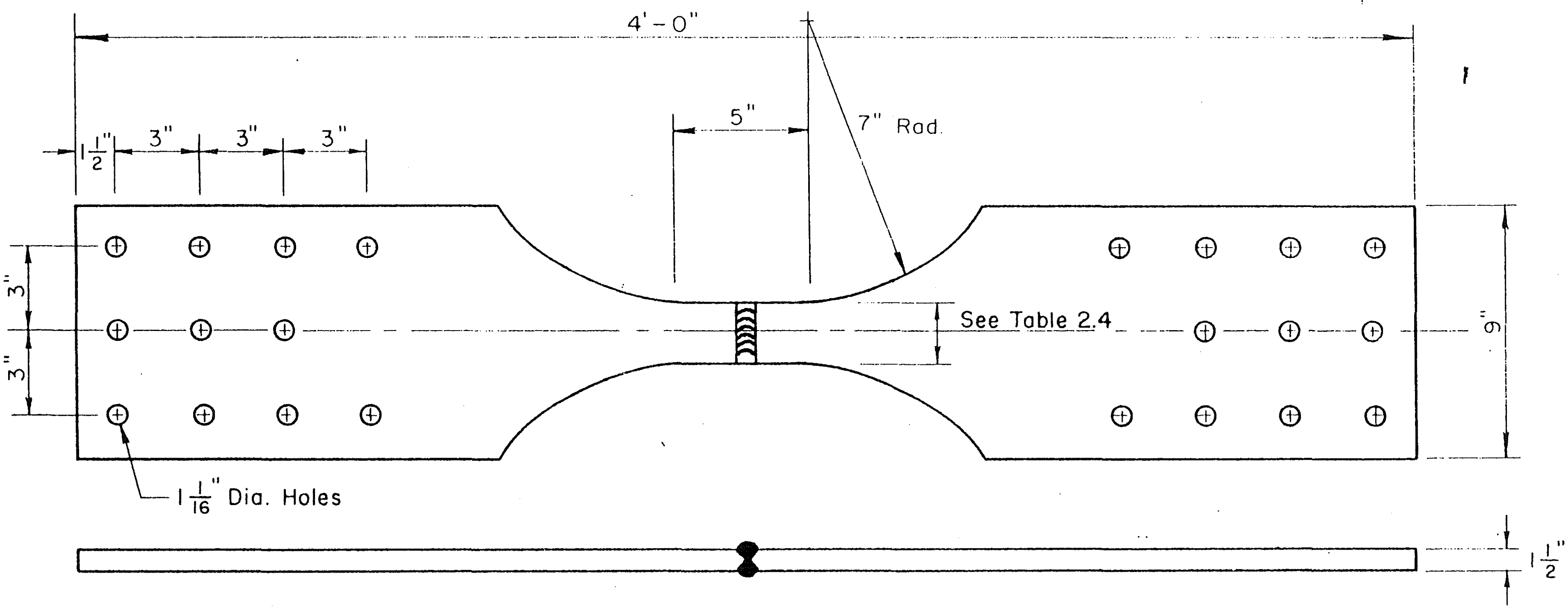


FIG. 2.2 DETAILS OF FATIGUE TEST SPECIMEN
WITH TRANSVERSE BUTT WELD

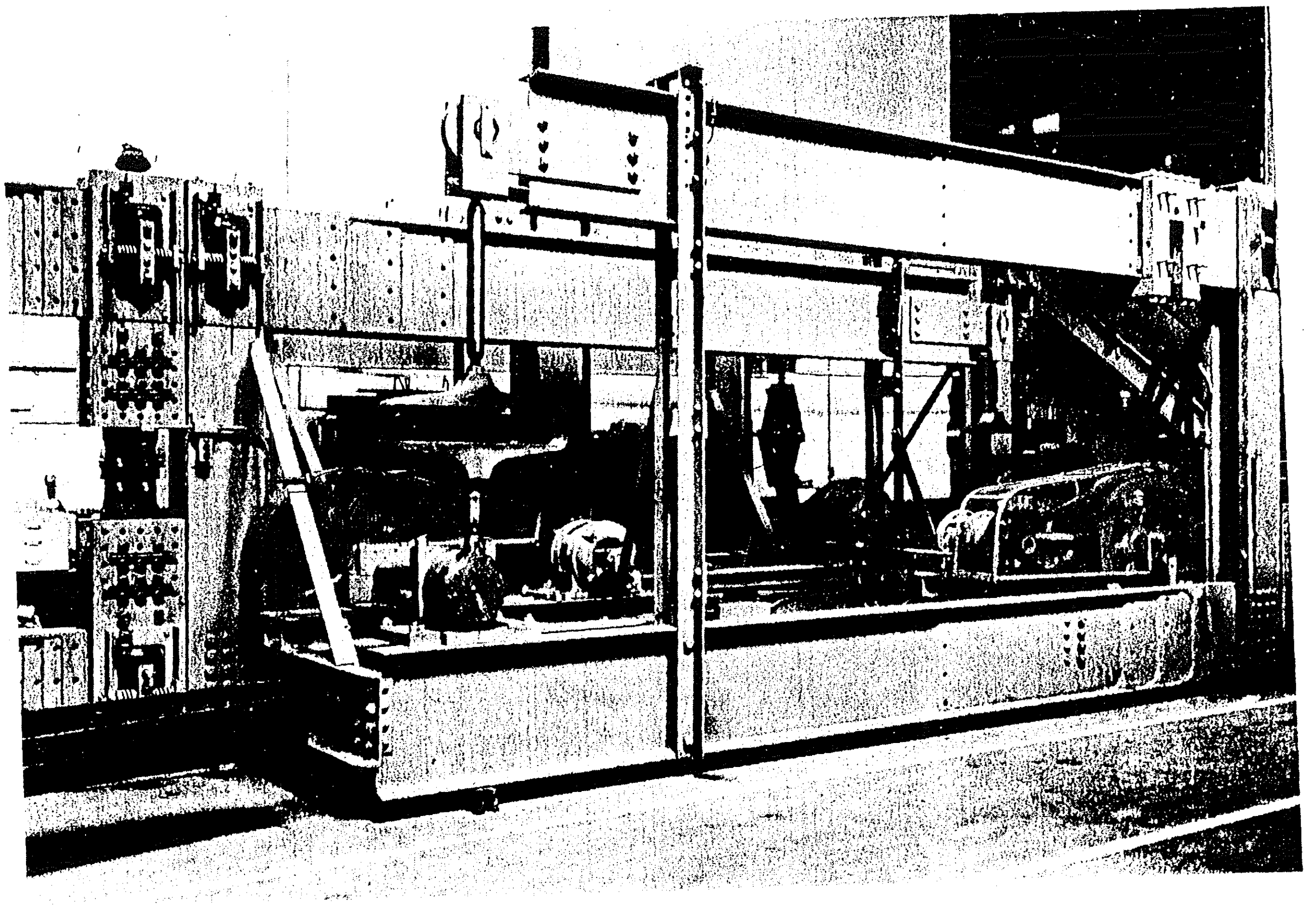


FIG. 2.3 PHOTOGRAPH OF ILLINOIS' FATIGUE TESTING MACHINES

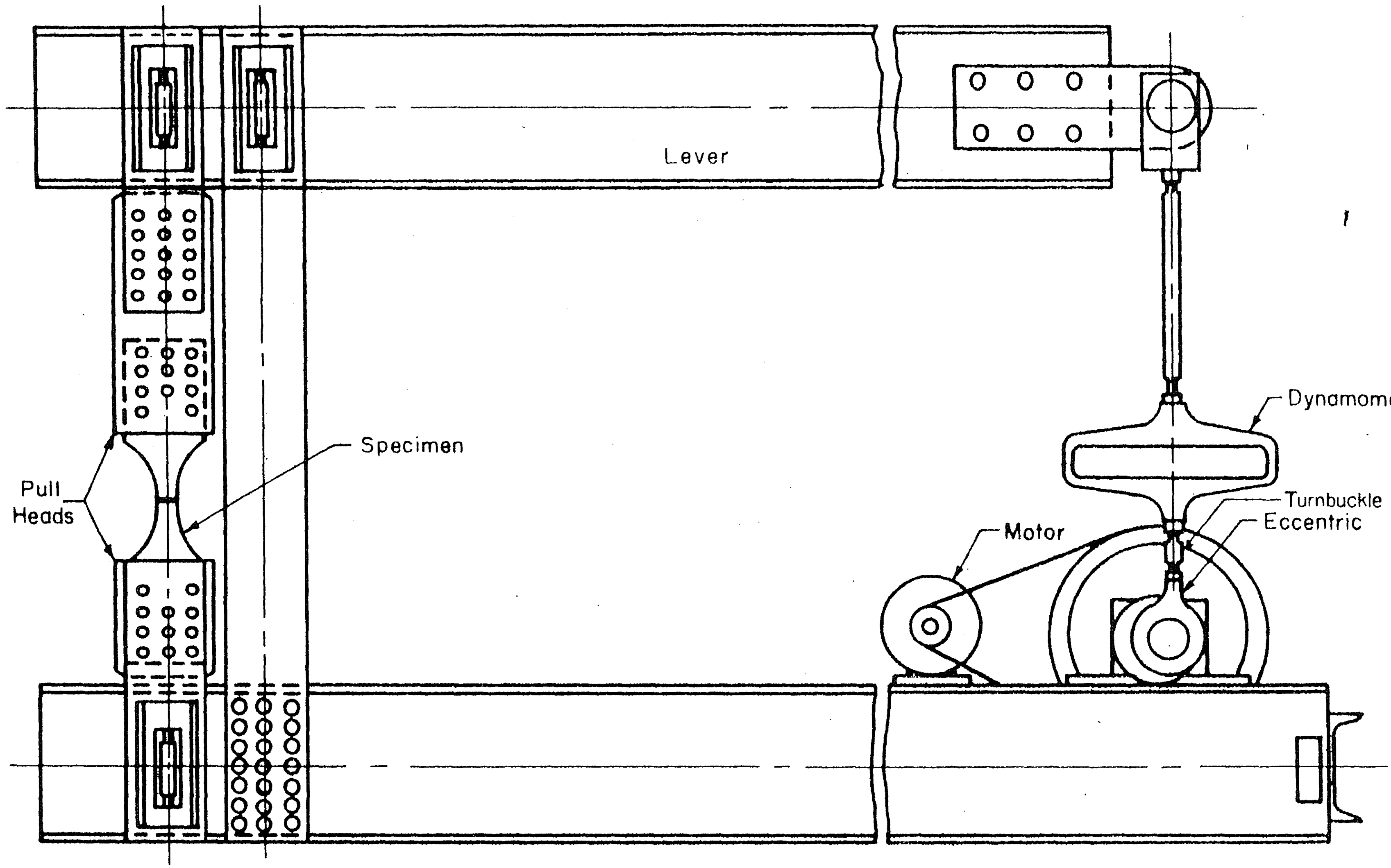


FIG. 2.4 ILLINOIS' FATIGUE TESTING MACHINE AS USED FOR AXIAL LOADING OF WELDED JOINTS

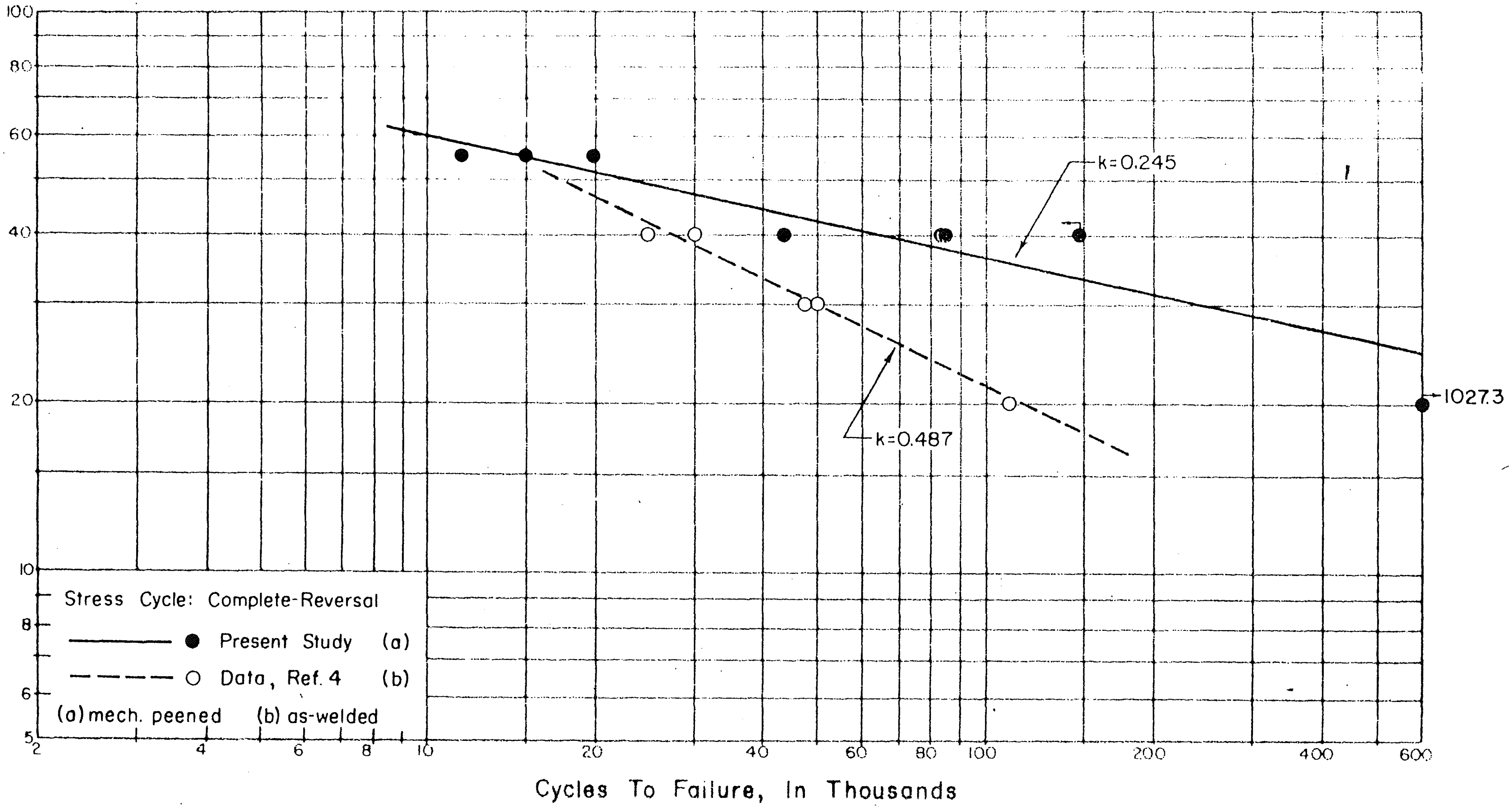


FIG. 3.1 RESULTS OF FATIGUE TESTS OF HY-80 PLATES WITH TRANSVERSE TEE-ATTACHMENT (COMPLETE-REVERSAL)

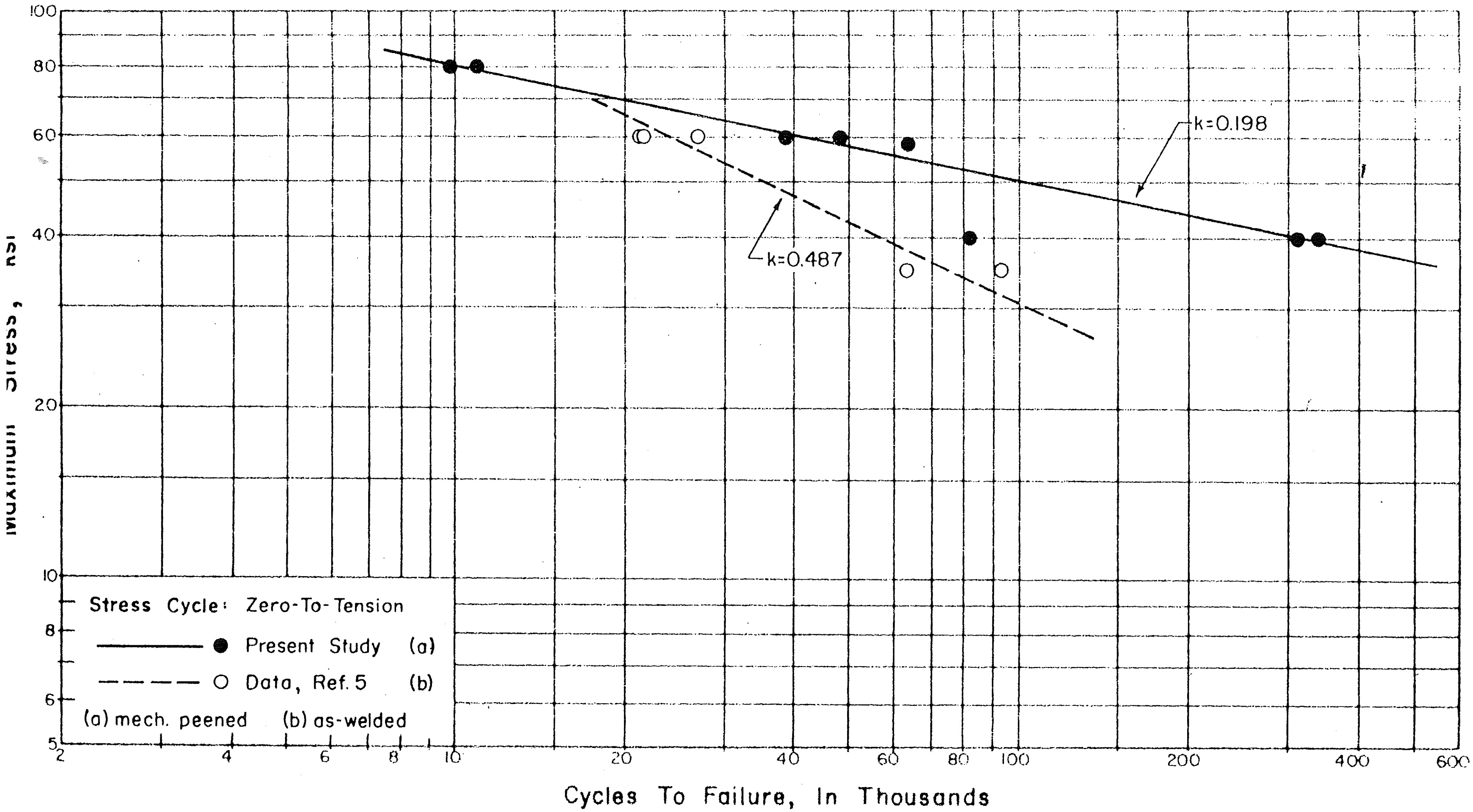


FIG. **3.2a** RESULTS OF FATIGUE TESTS OF HY-80 PLATES WITH TRANSVERSE TEE-ATTACHMENT (ZERO-TO-TENSION)

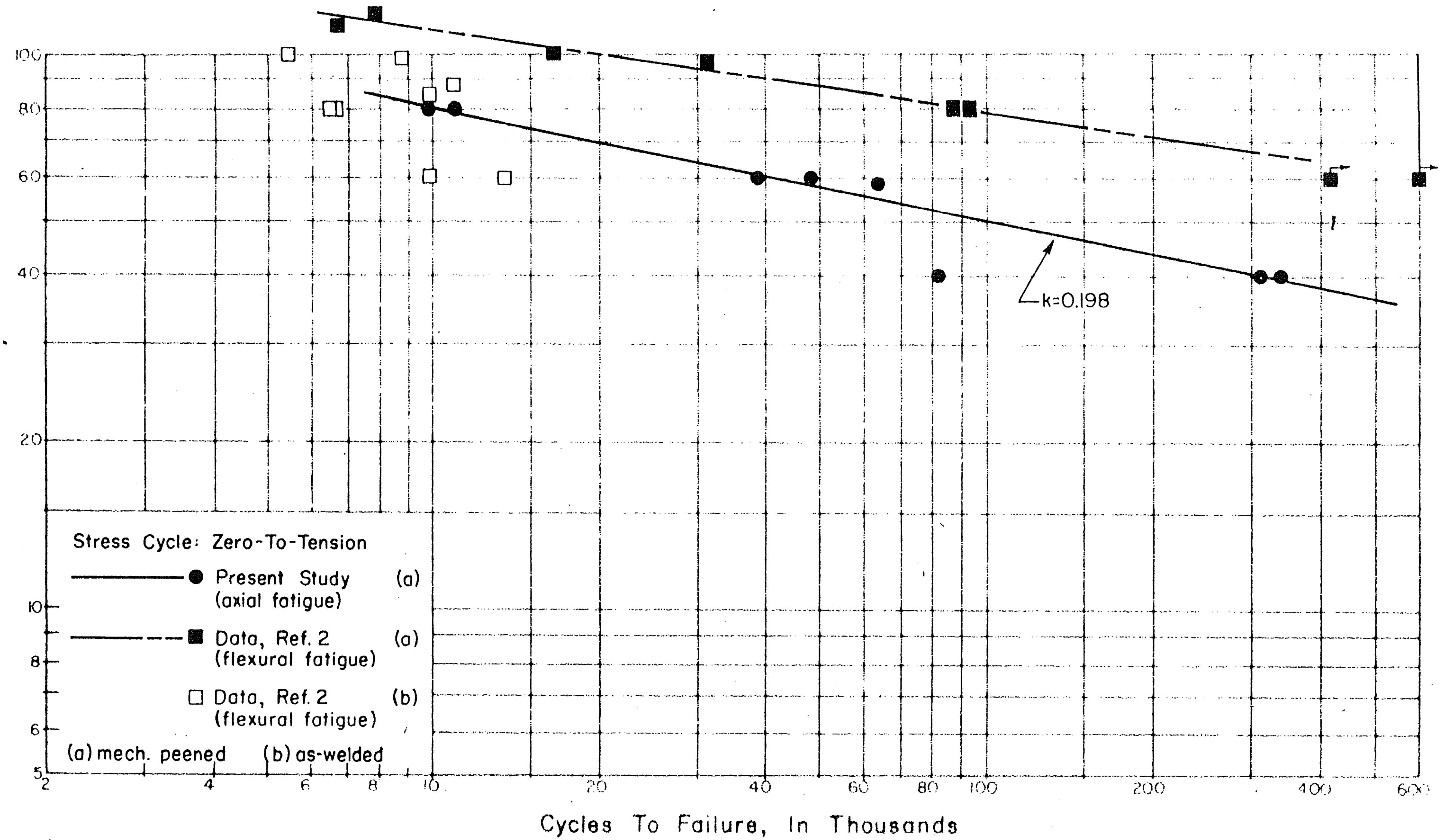


FIG. **3.2 b** RESULTS OF FATIGUE TESTS OF HY-80 PLATES WITH TRANSVERSE TEE-**ATTACHMENT** (ZERO-TO-TENSION)

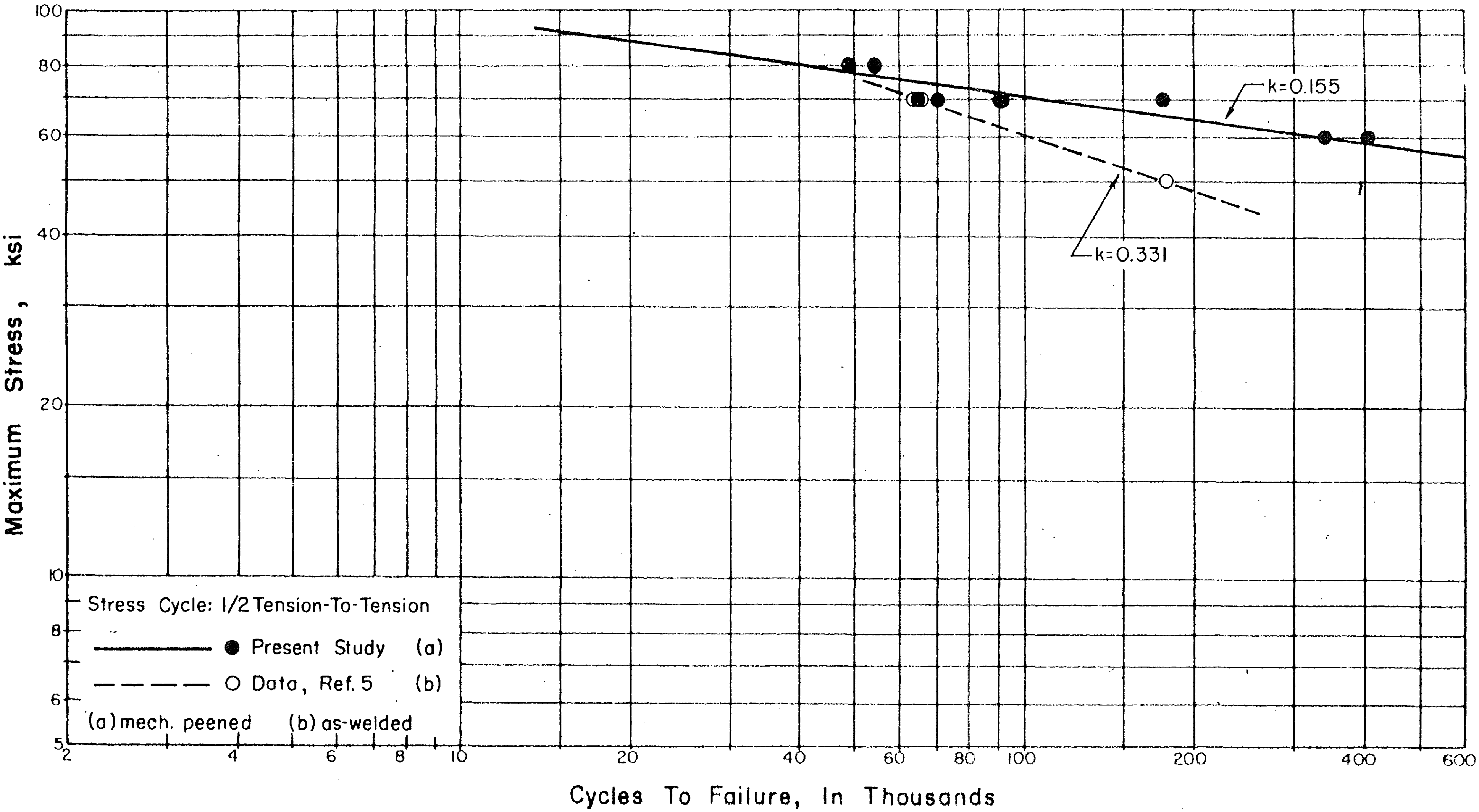


FIG. 3.3 RESULTS OF FATIGUE TESTS OF HY-80 PLATES WITH TRANSVERSE TEE-ATTACHMENT (HALF TENSION-TO-TENSION)

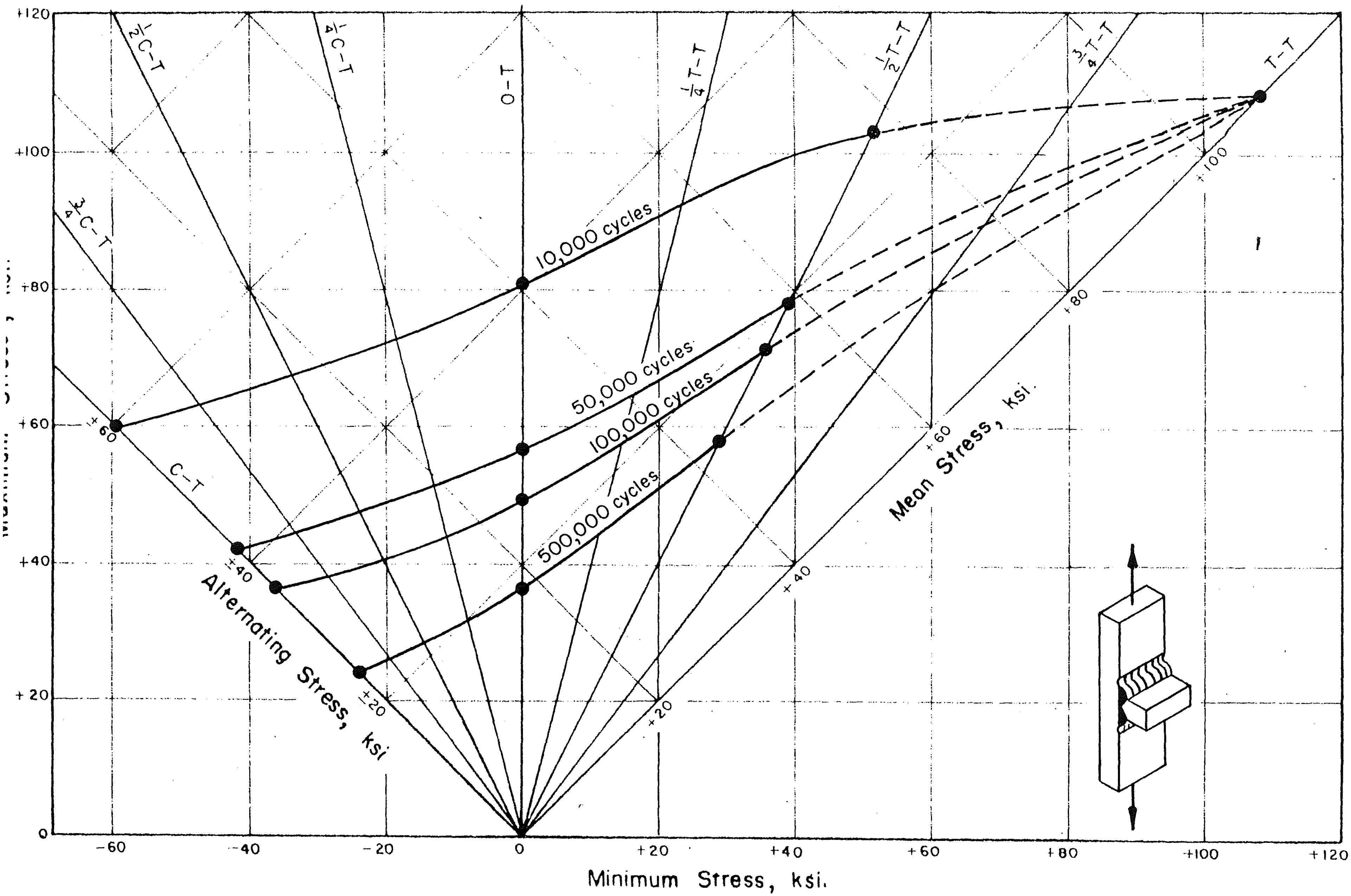


FIG. 3.4 MODIFIED GOODMAN DIAGRAM FOR HY-80 PLATES WITH TRANSVERSE TEE-ATTACHMENT (MECHANICALLY PEENED)

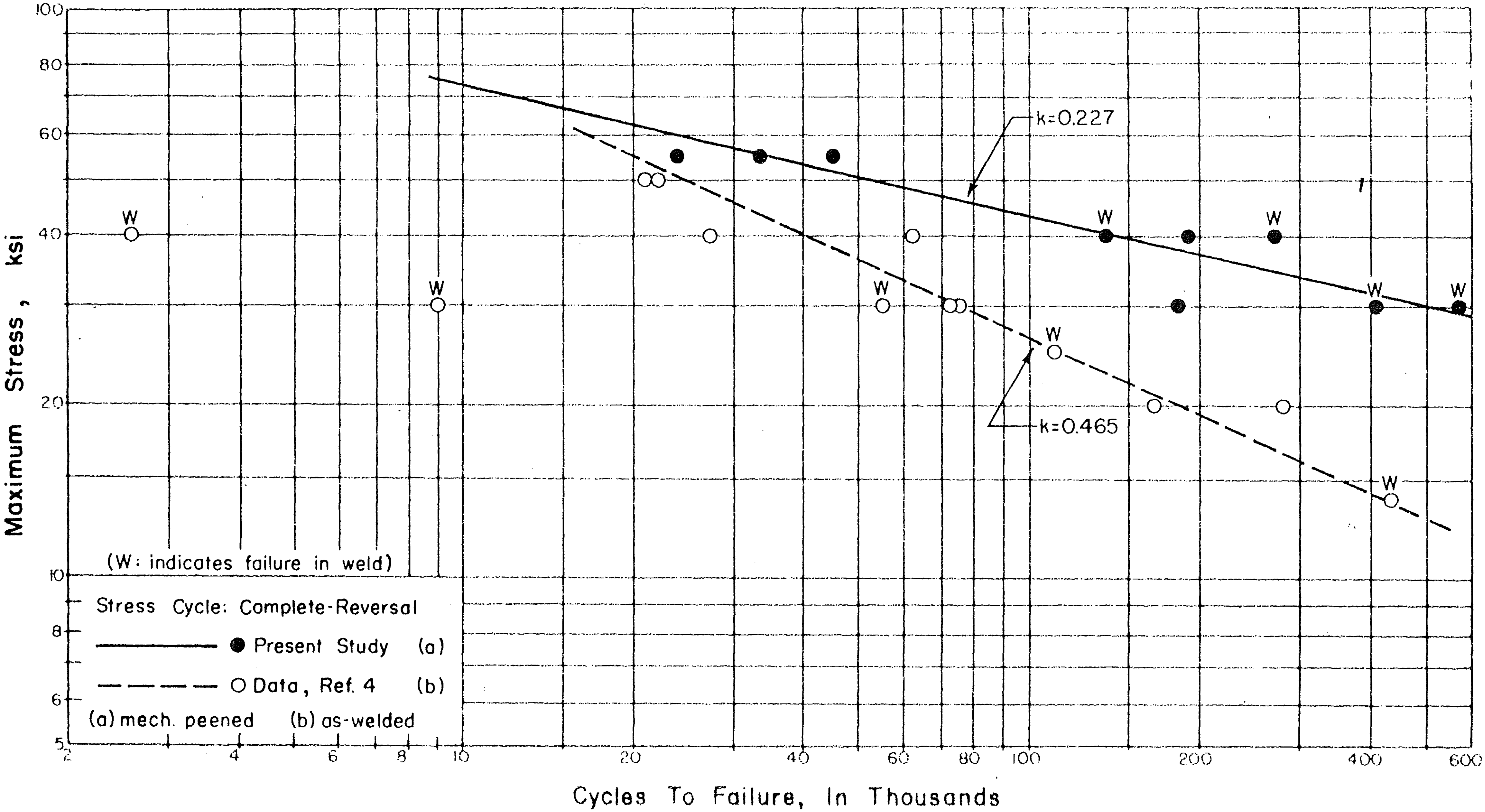


FIG. **3.5** RESULTS OF FATIGUE TESTS OF HY-80 PLATES WITH TRANSVERSE BUTT WELD (COMPLETE-REVERSAL)

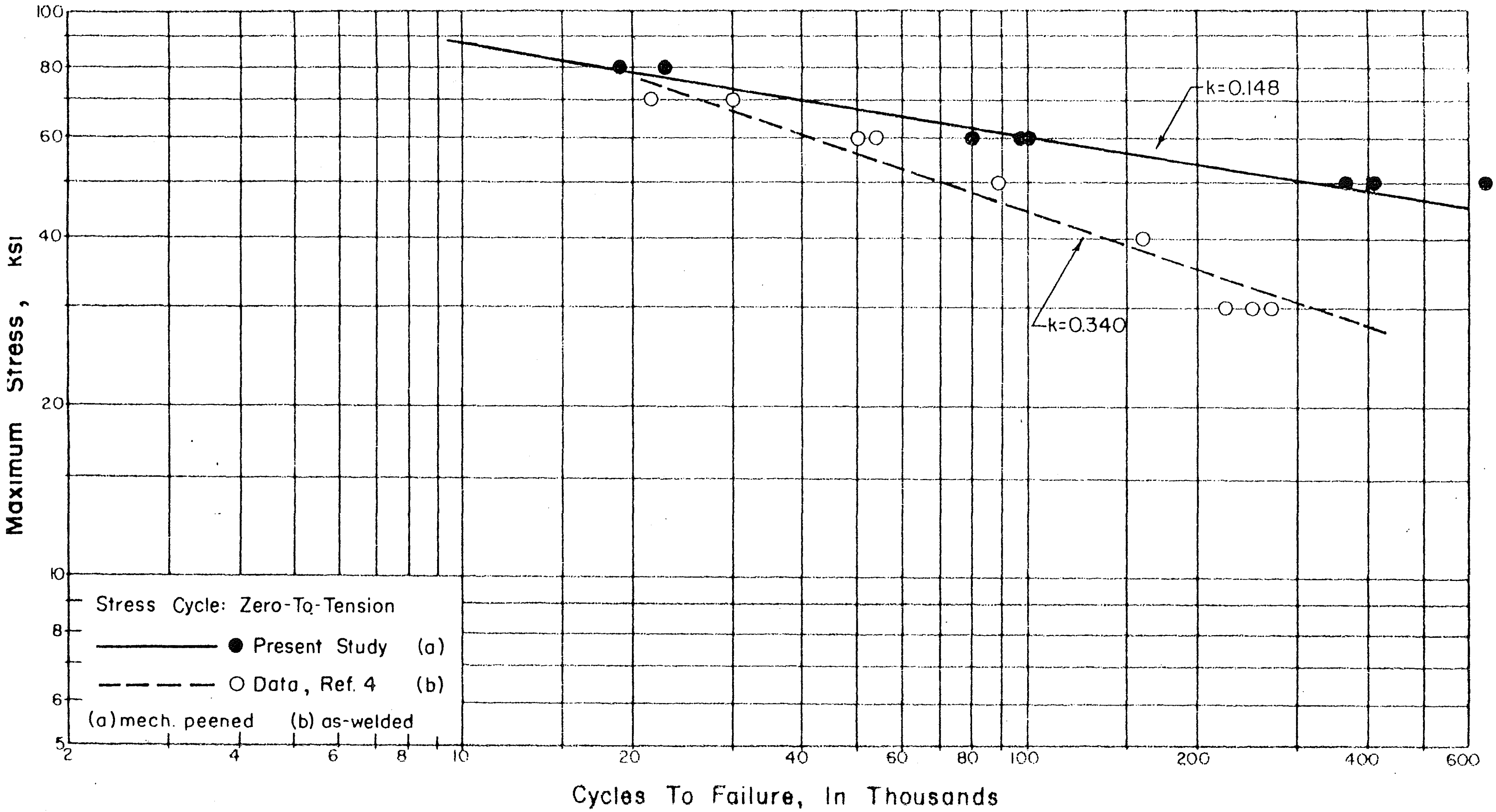


FIG. **3.6a** RESULTS OF FATIGUE TESTS OF HY-80 PLATES WITH TRANSVERSE BUTT WELD (ZERO-TO-TENSION)

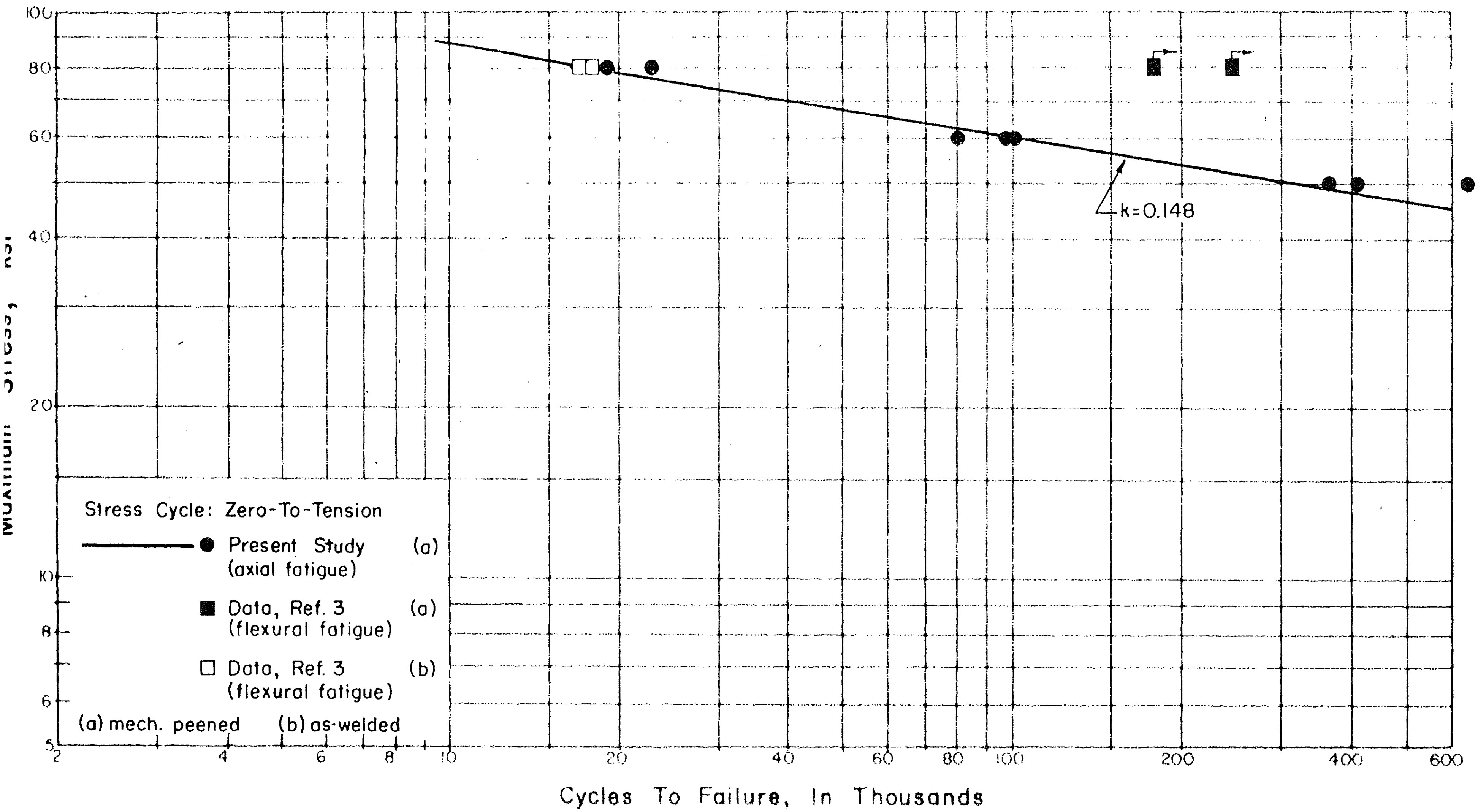


FIG. **3.6b** RESULTS OF FATIGUE TESTS OF HY-80 PLATES WITH TRANSVERSE BUTT WELD (ZERO-TO-TENSION)

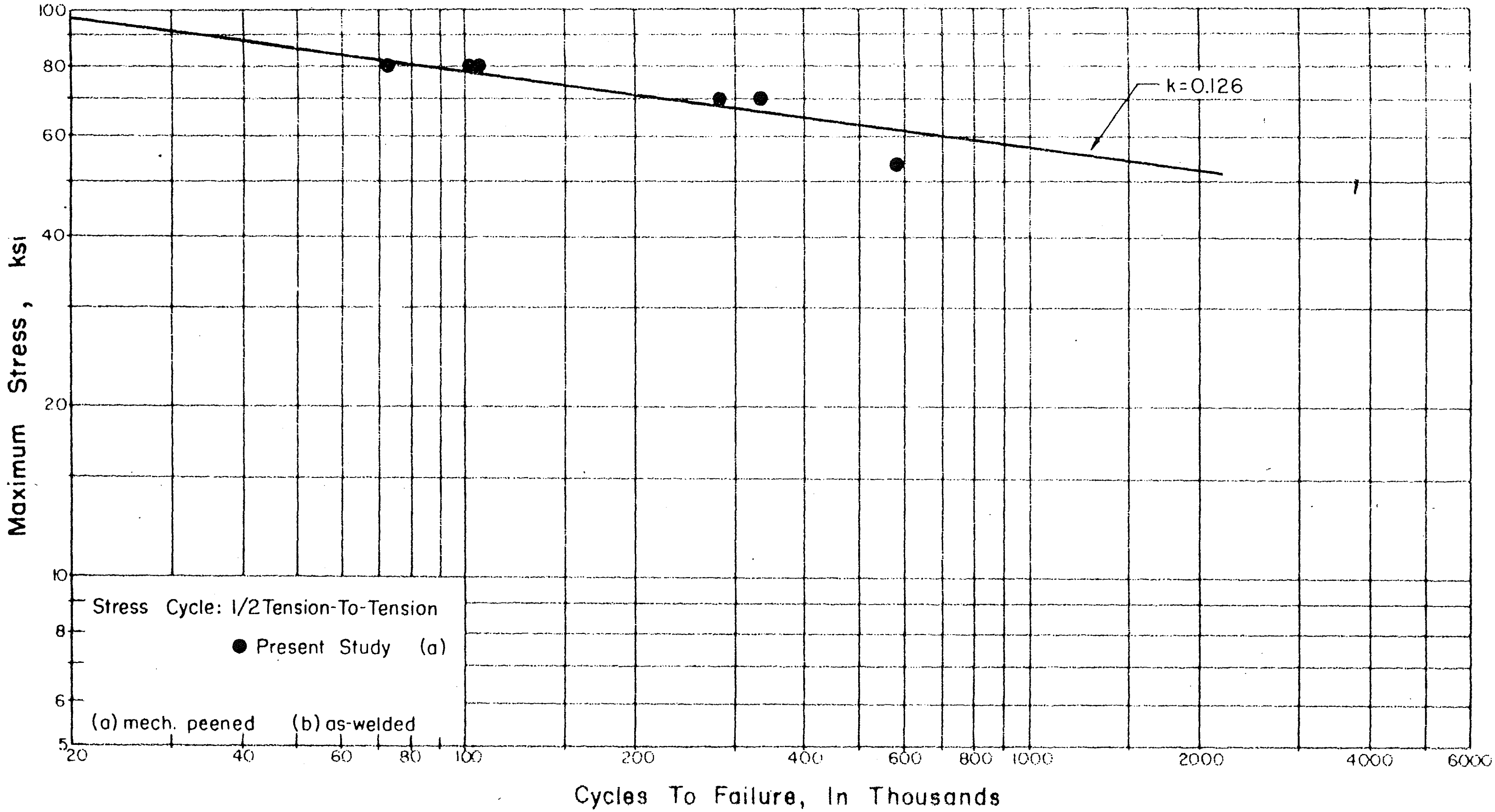


FIG. 3.7 RESULTS OF FATIGUE TESTS OF HY-80 PLATES WITH TRANSVERSE BUTT WELD (HALF TENSION-TO-TENSION)

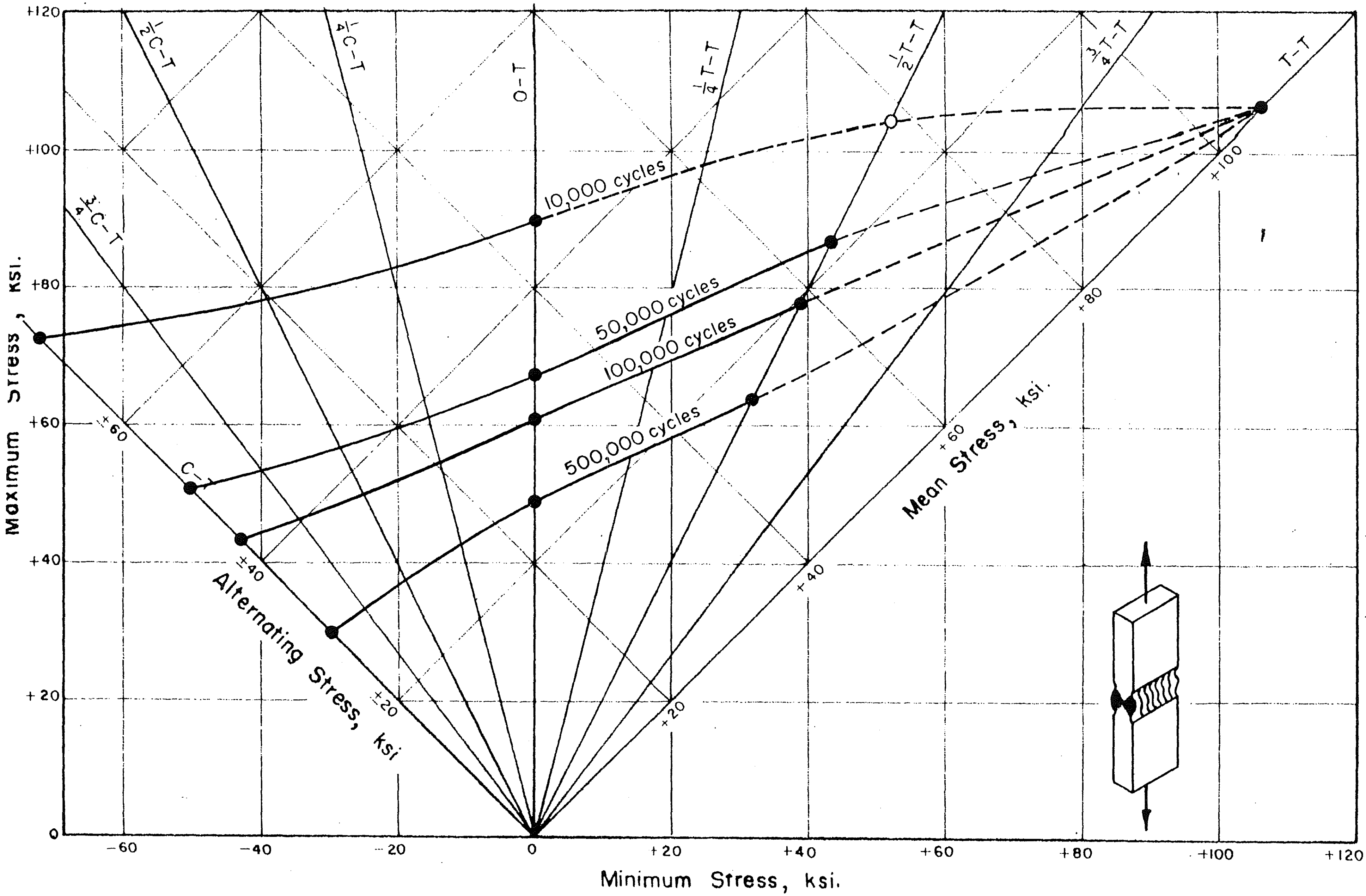
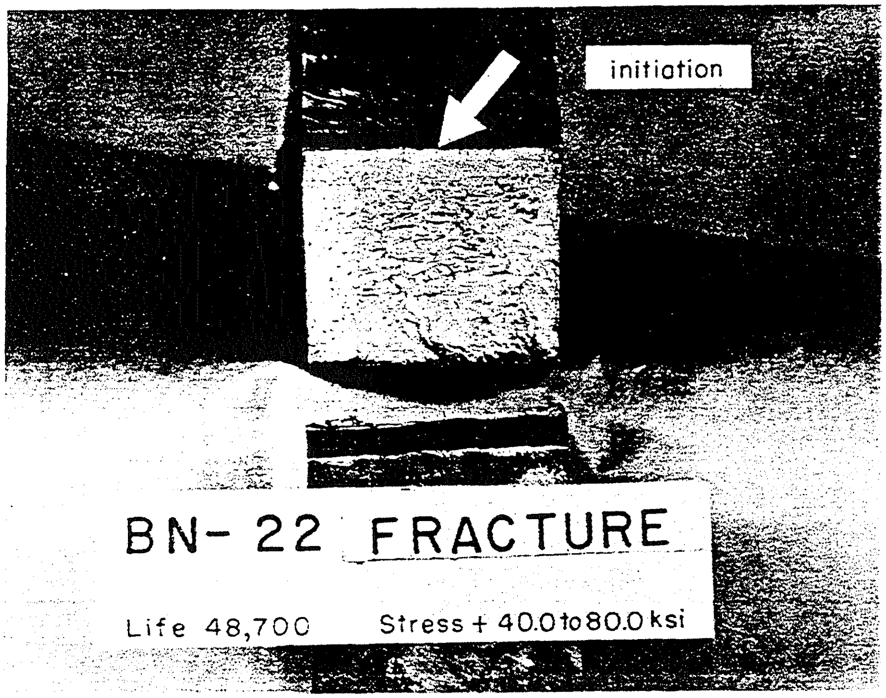
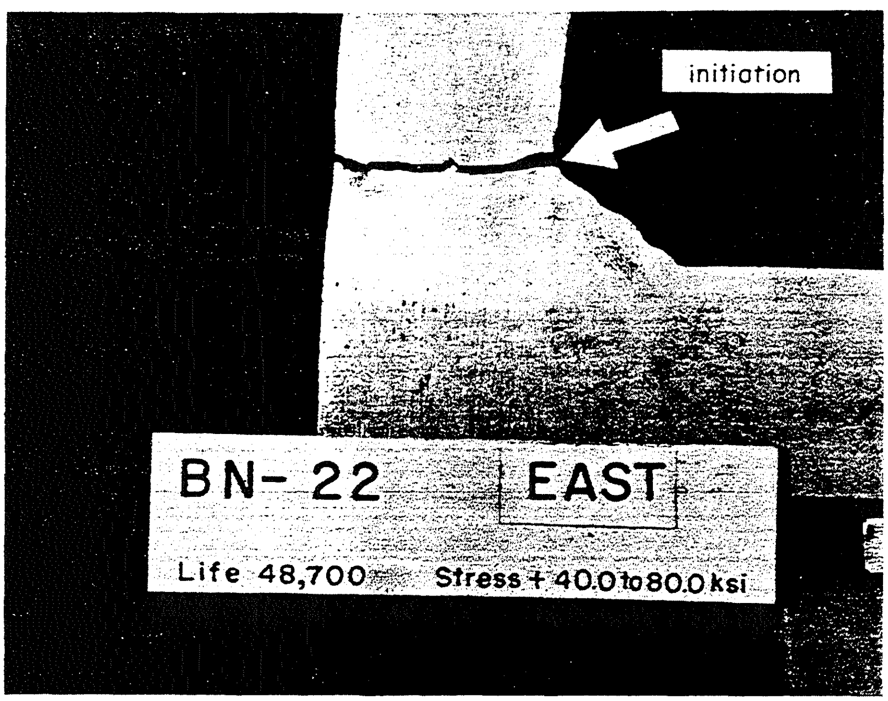


FIG.3.8 MODIFIED GOODMAN DIAGRAM FOR HY-80 PLATES WITH TRANSVERSE BUTT WELD (MECHANICALLY PEENED)

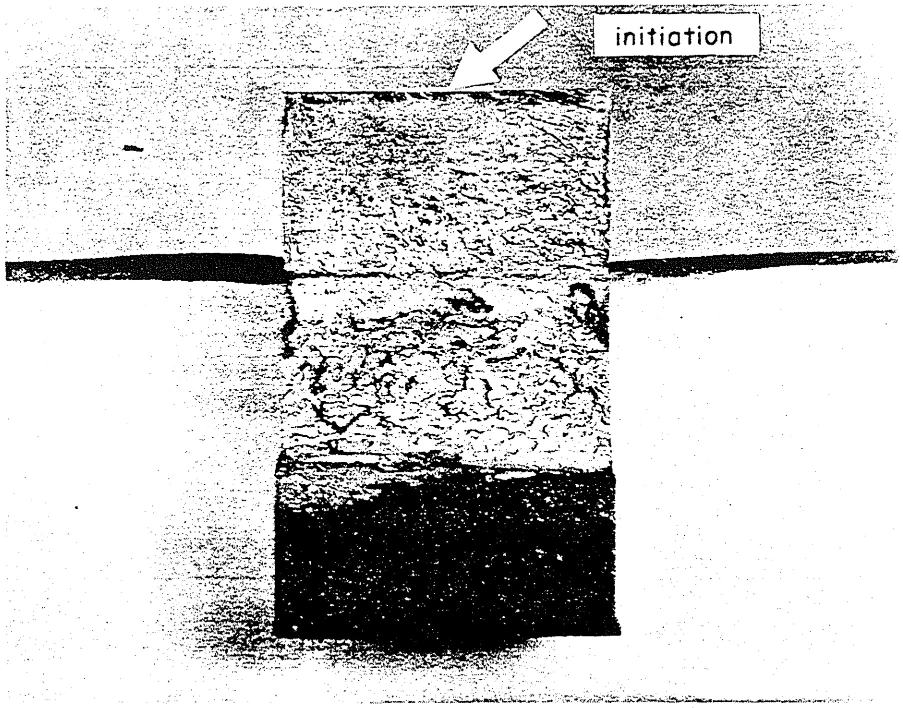


(a) Fracture Surface

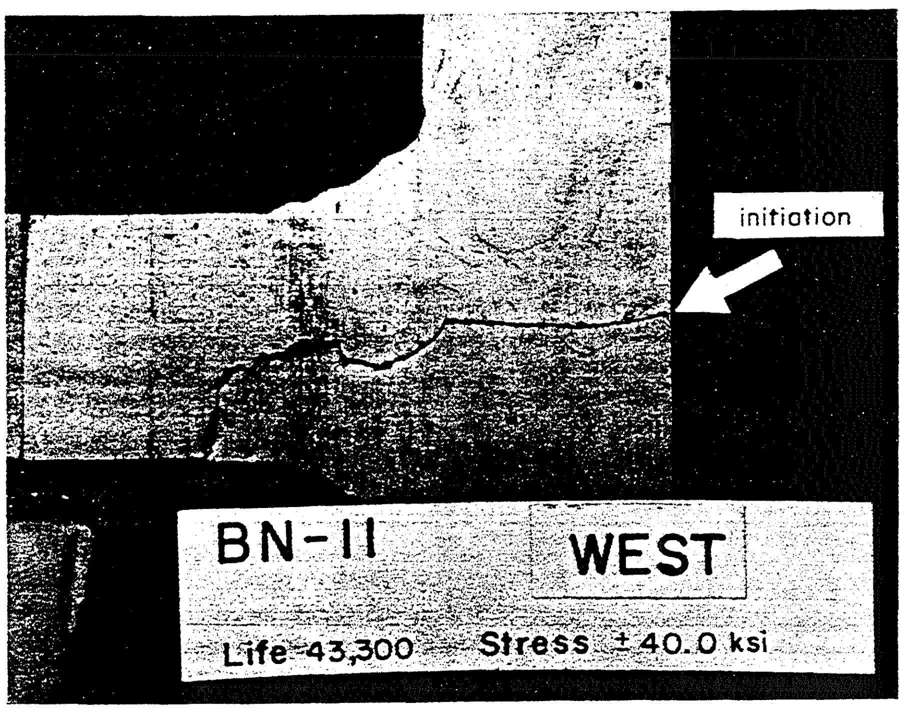


(b) East Edge

FIG. 4.1 TYPICAL FATIGUE FRACTURE APPEARANCE OF HY-80 PLATE WITH TRANSVERSE TEE-ATTACHMENT



(a) Fracture Surface



(b) West Edge

FIG. 4.2 FATIGUE FRACTURE OF SPECIMEN M77AP23 (BN-11)

SPECIMEN NO. **M77AP14** STRESS CYCLE **+35.0 to +70.0 ksi** LIFE **176,300**

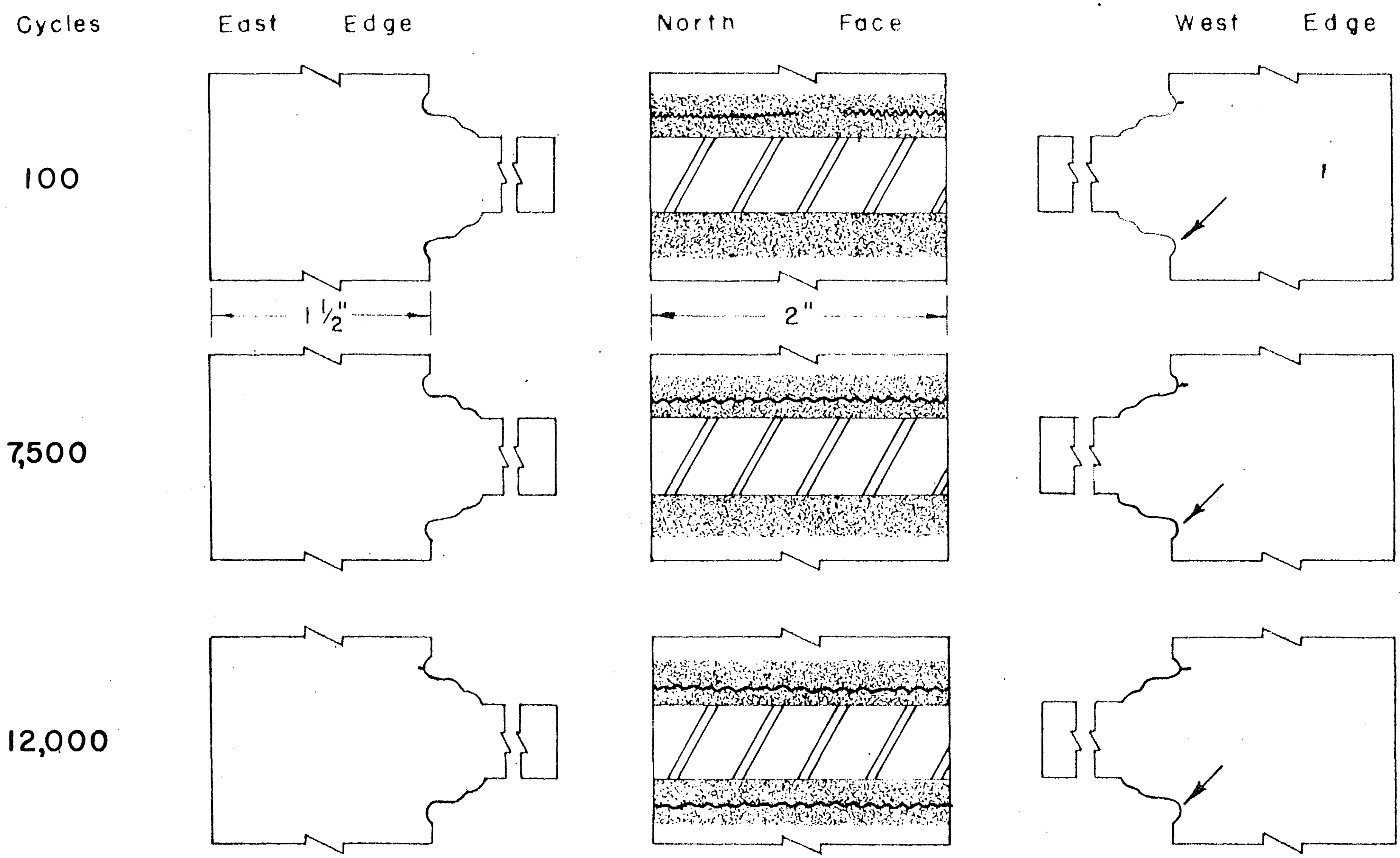


FIGURE 4.3a LOCATION AND PROGRESSION OF FATIGUE CRACKS IN HY-80 PLATE WITH TRANSVERSE TEE-ATTACHMENT

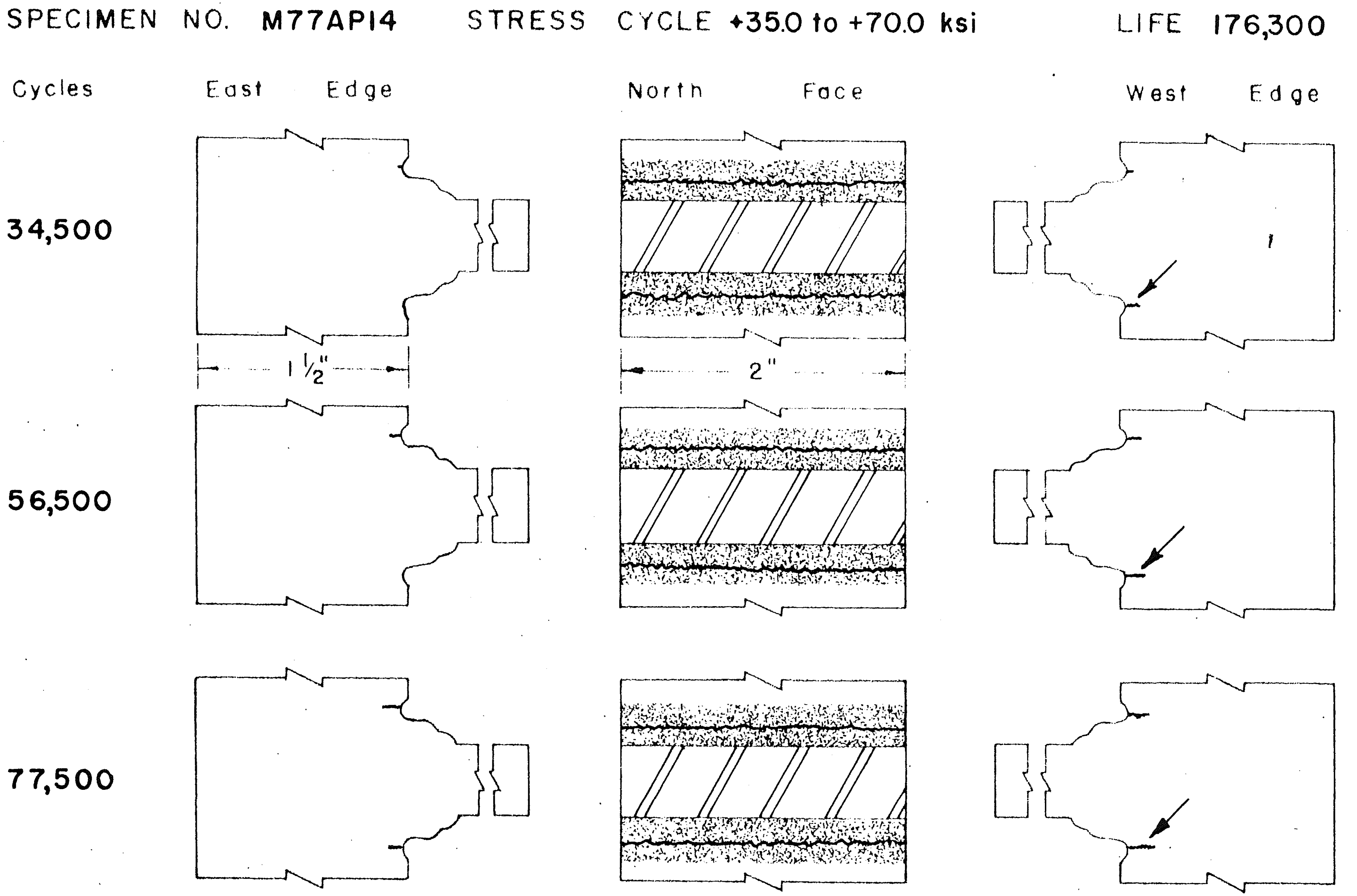


FIGURE 4.3b LOCATION AND PROGRESSION OF FATIGUE CRACKS IN HY-80 PLATE WITH TRANSVERSE TEE-ATTACHMENT

SPECIMEN NO. **M77AP14** STRESS CYCLE **+35.0 to +70.0 ksi** LIFE **176,300**

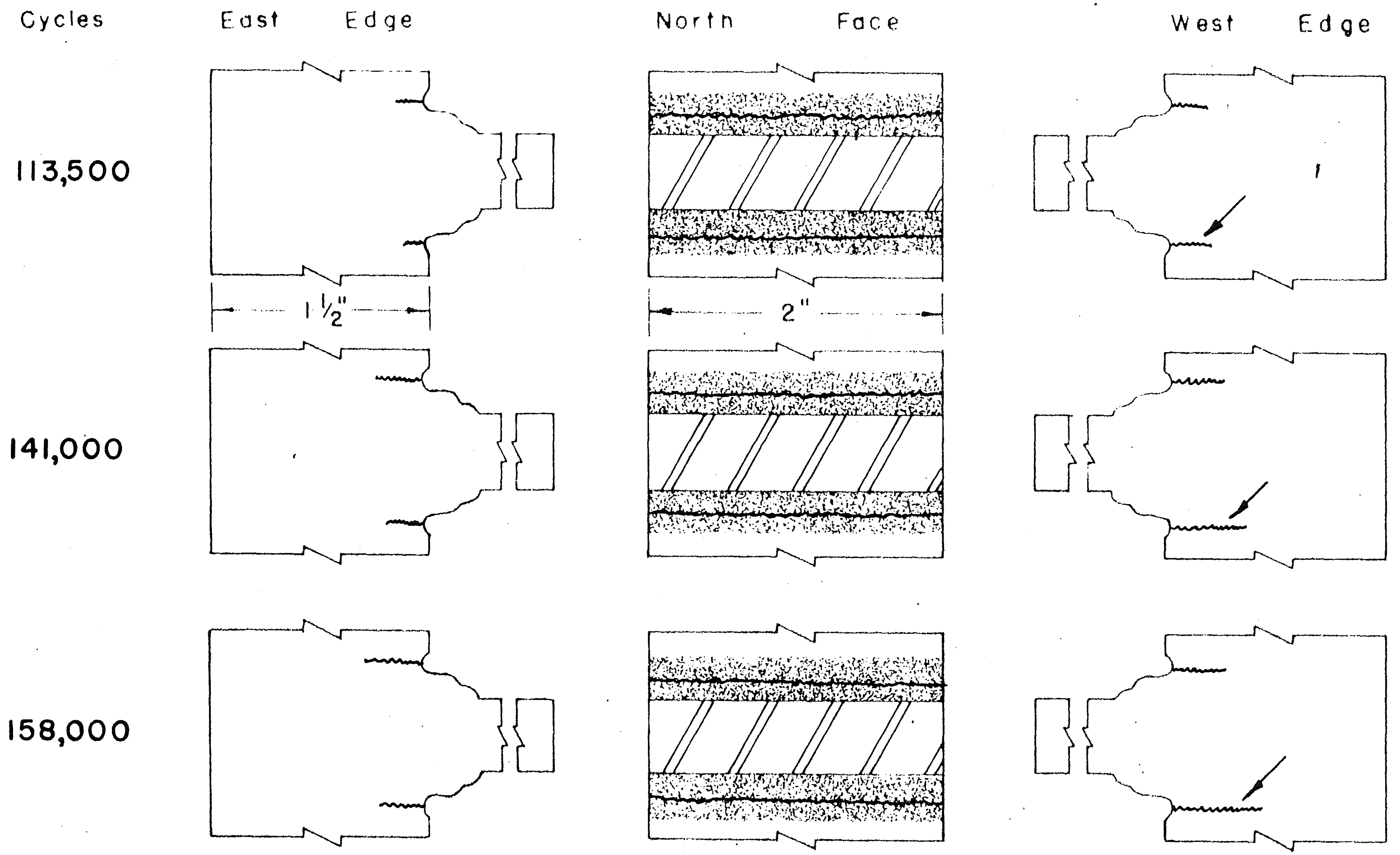


FIGURE 4.3 c LOCATION AND PROGRESSION OF FATIGUE CRACKS IN HY-80 PLATE WITH TRANSVERSE TEE-ATTACHMENT

SPECIMEN NO. M77AP 14 STRESS CYCLE +35.0 to +70.0 ksi LIFE 176,300

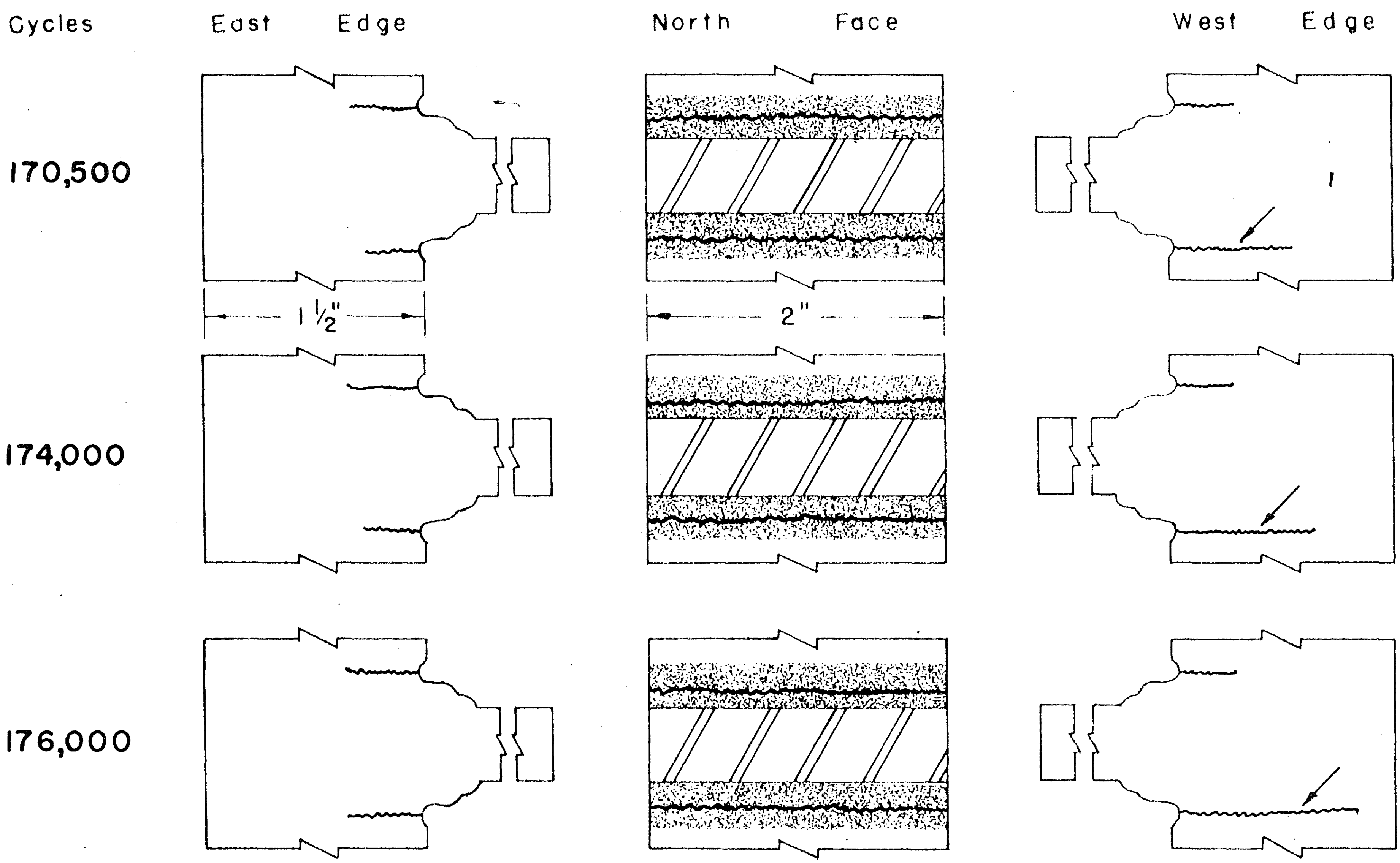


FIGURE 4.3d LOCATION AND PROGRESSION OF FATIGUE CRACKS IN HY-80 PLATE WITH TRANSVERSE TEE-ATTACHMENT

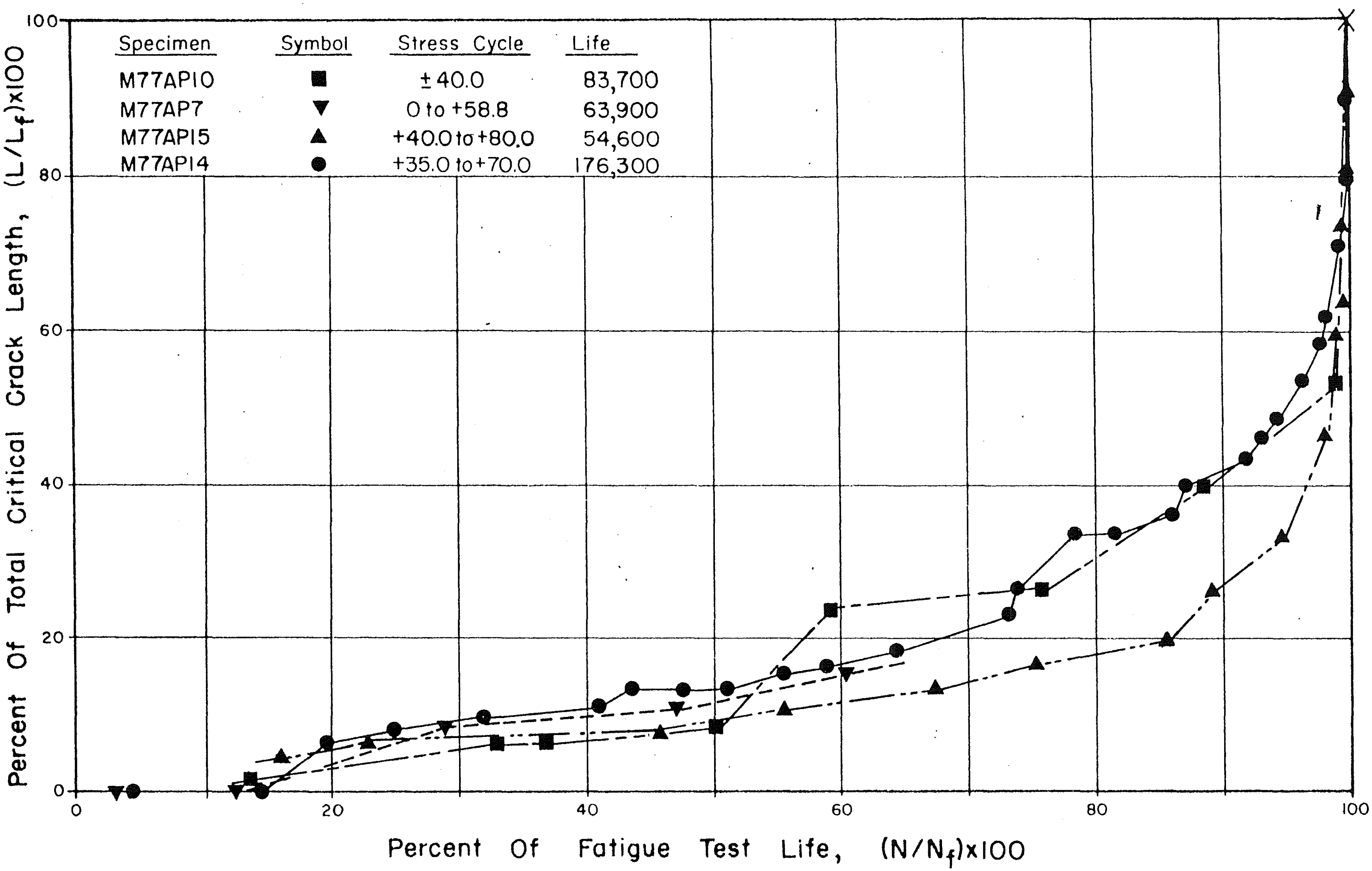
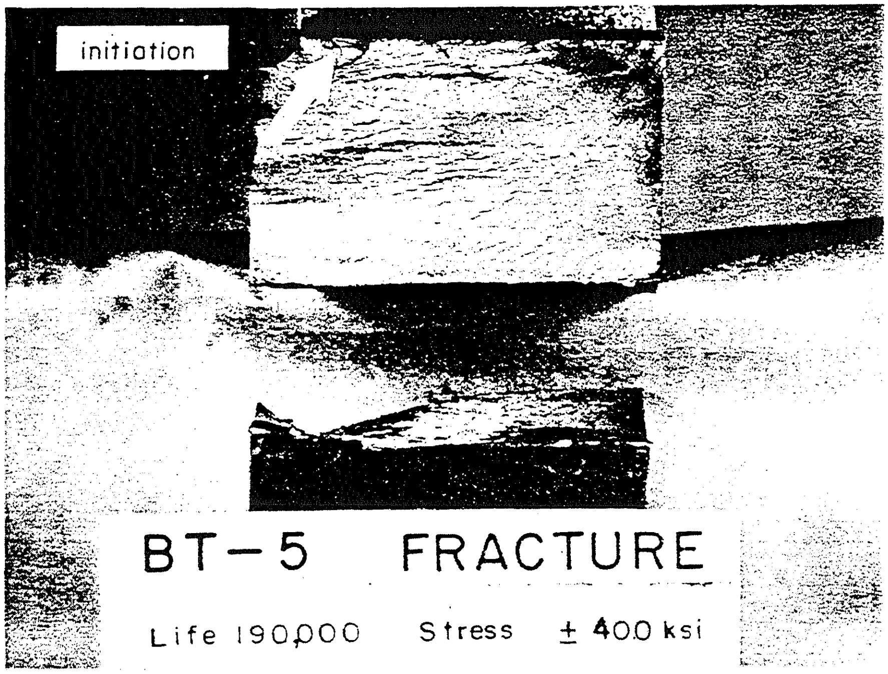
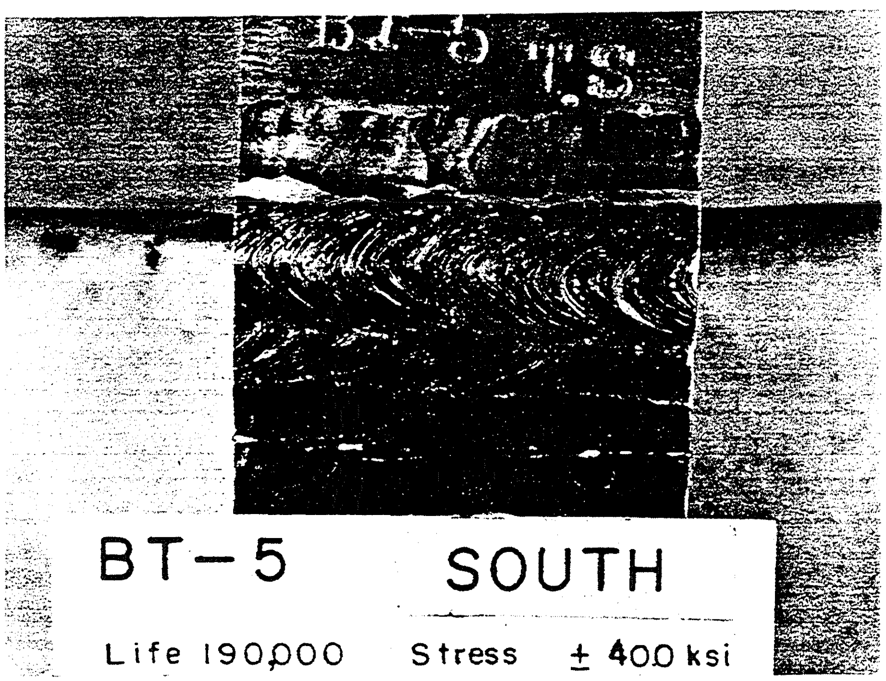


FIG. 4.4 PROPAGATION OF CRITICAL FATIGUE CRACK IN HY-80 PLATES WITH TRANSVERSE TEE-ATTACHMENT (MECHANICALLY PEENED)

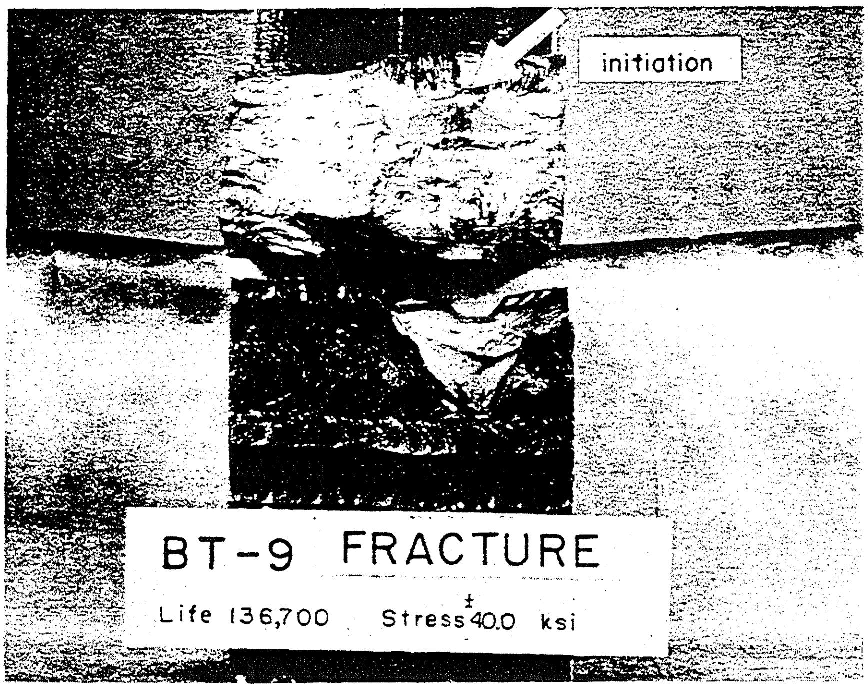


(a) Fracture Surface

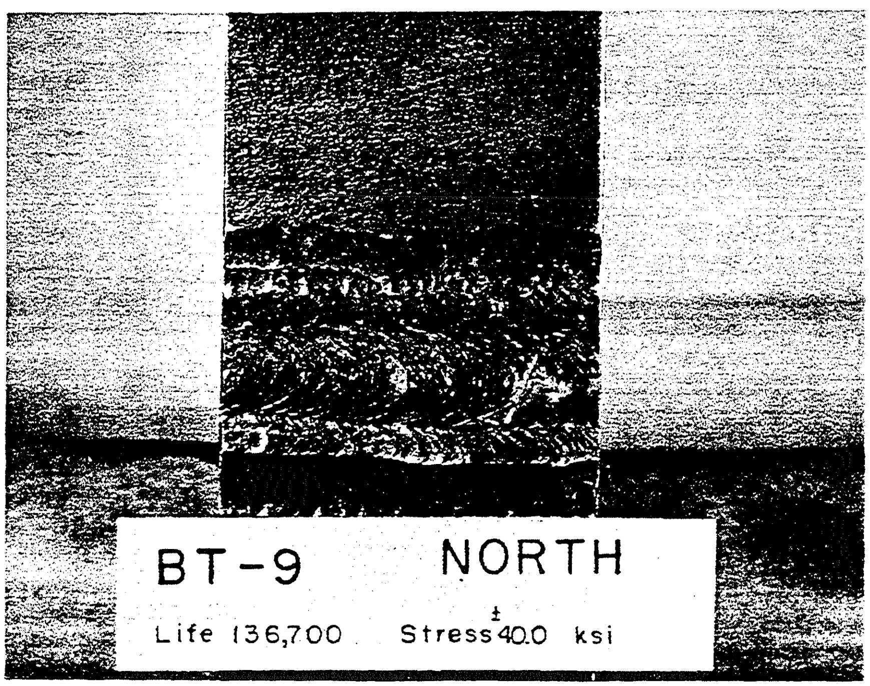


(b) South Face

FIG. 4.5 TYPICAL FATIGUE FRACTURE APPEARANCE OF HY-80 PLATE WITH TRANSVERSE BUTT WELD



(a) Fracture Surface



(b) North Face

FIG. 4.6 FATIGUE FRACTURE INITIATING AT INTERNAL FLAW IN HY-80 PLATE WITH TRANSVERSE BUTT WELD

SPECIMEN NO. M77MP23 STRESS CYCLE +35.0 to +70.0 ksi LIFE 282,100

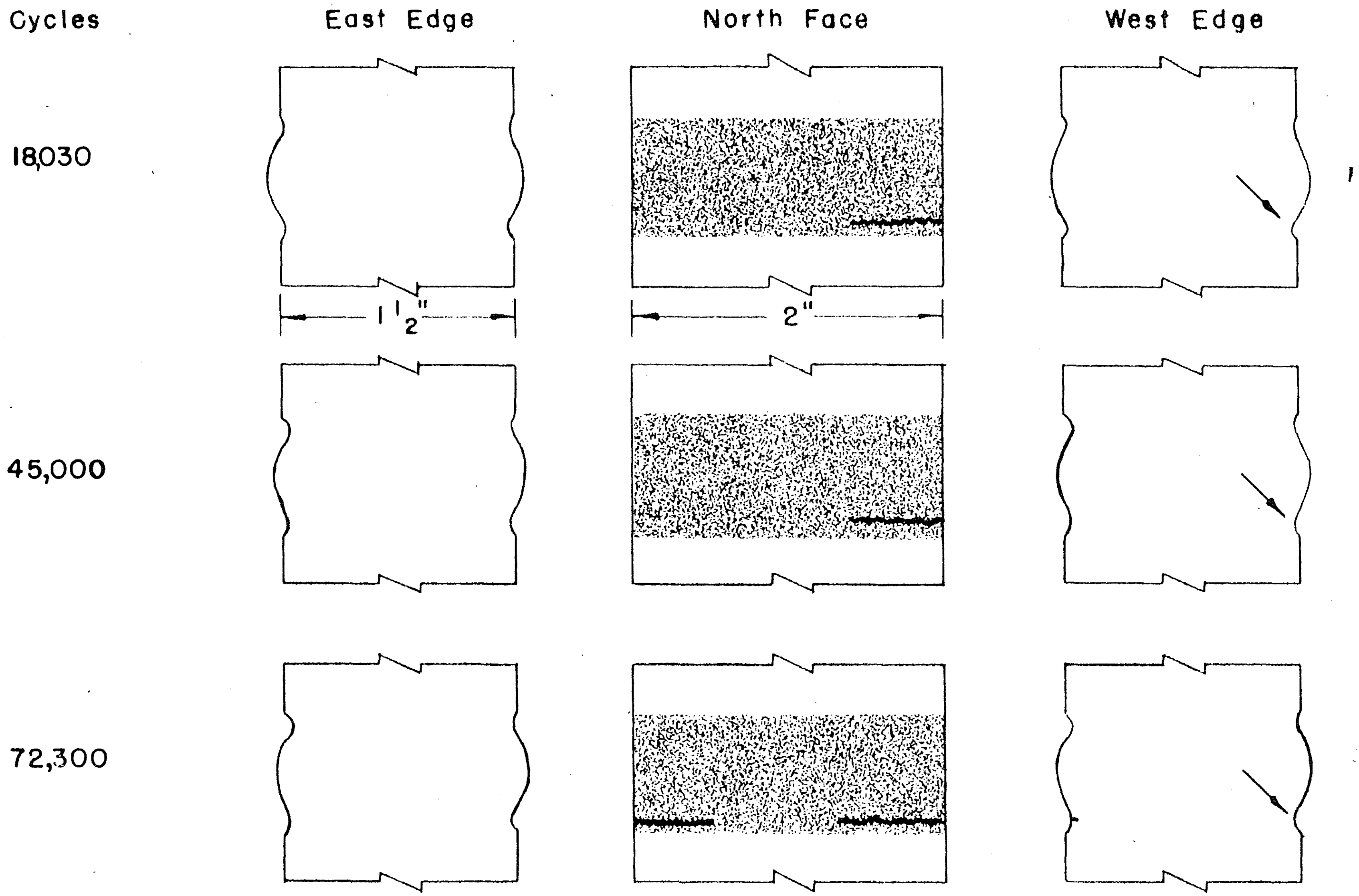


FIGURE 4.7a LOCATION AND PROGRESSION OF FATIGUE CRACKS IN HY-80 PLATE WITH TRANSVERSE BUTT WELD

SPECIMEN NO. M77MP23 STRESS CYCLE +35.0 to +70.0 ksi LIFE 282,100

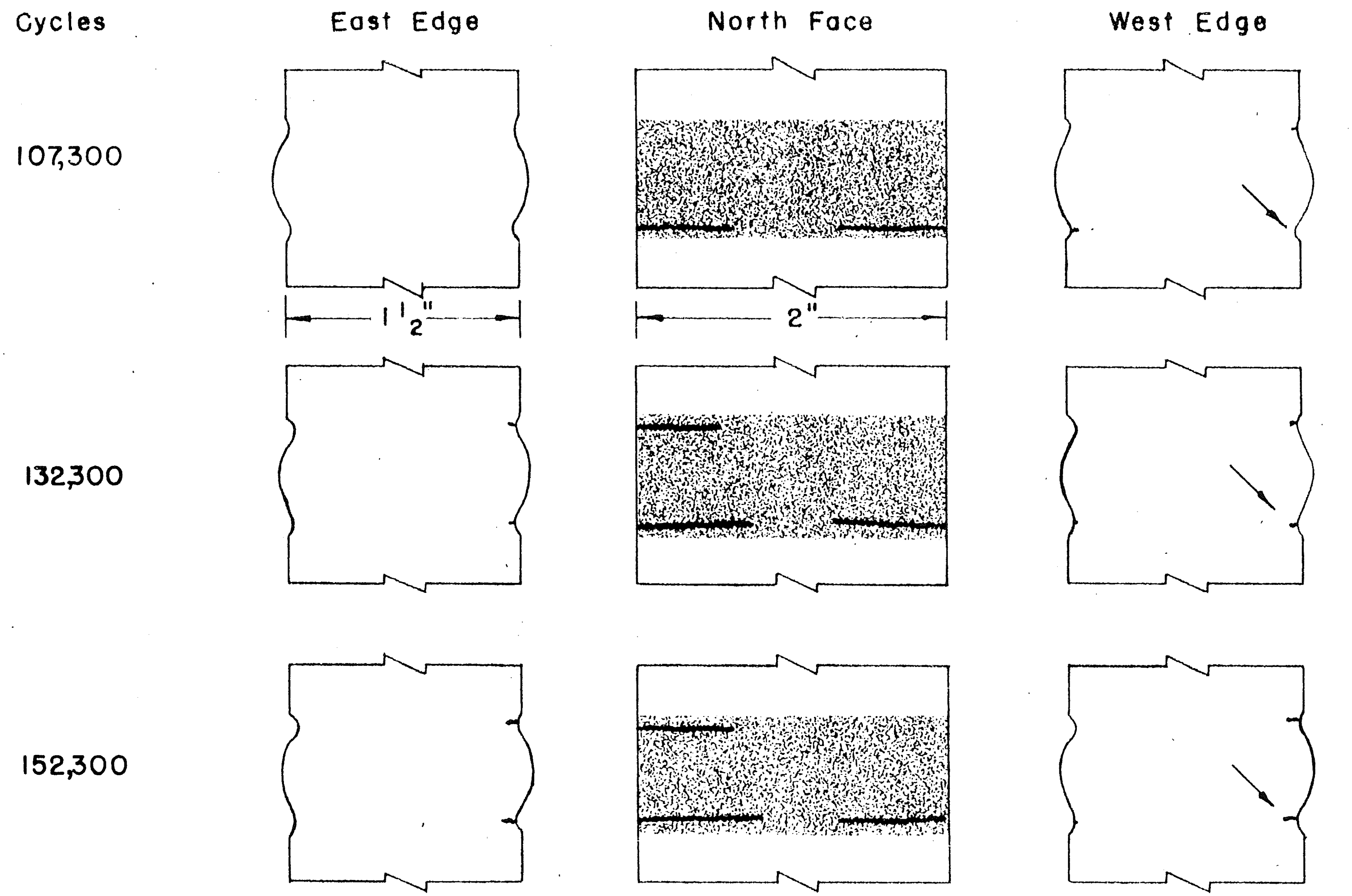


FIGURE 4.7b LOCATION AND PROGRESSION OF FATIGUE CRACKS IN HY-80 PLATE WITH TRANSVERSE BUTT WELD

SPECIMEN NO. M77MP23 STRESS CYCLE +35.0 to +70.0 ksi LIFE 282,100

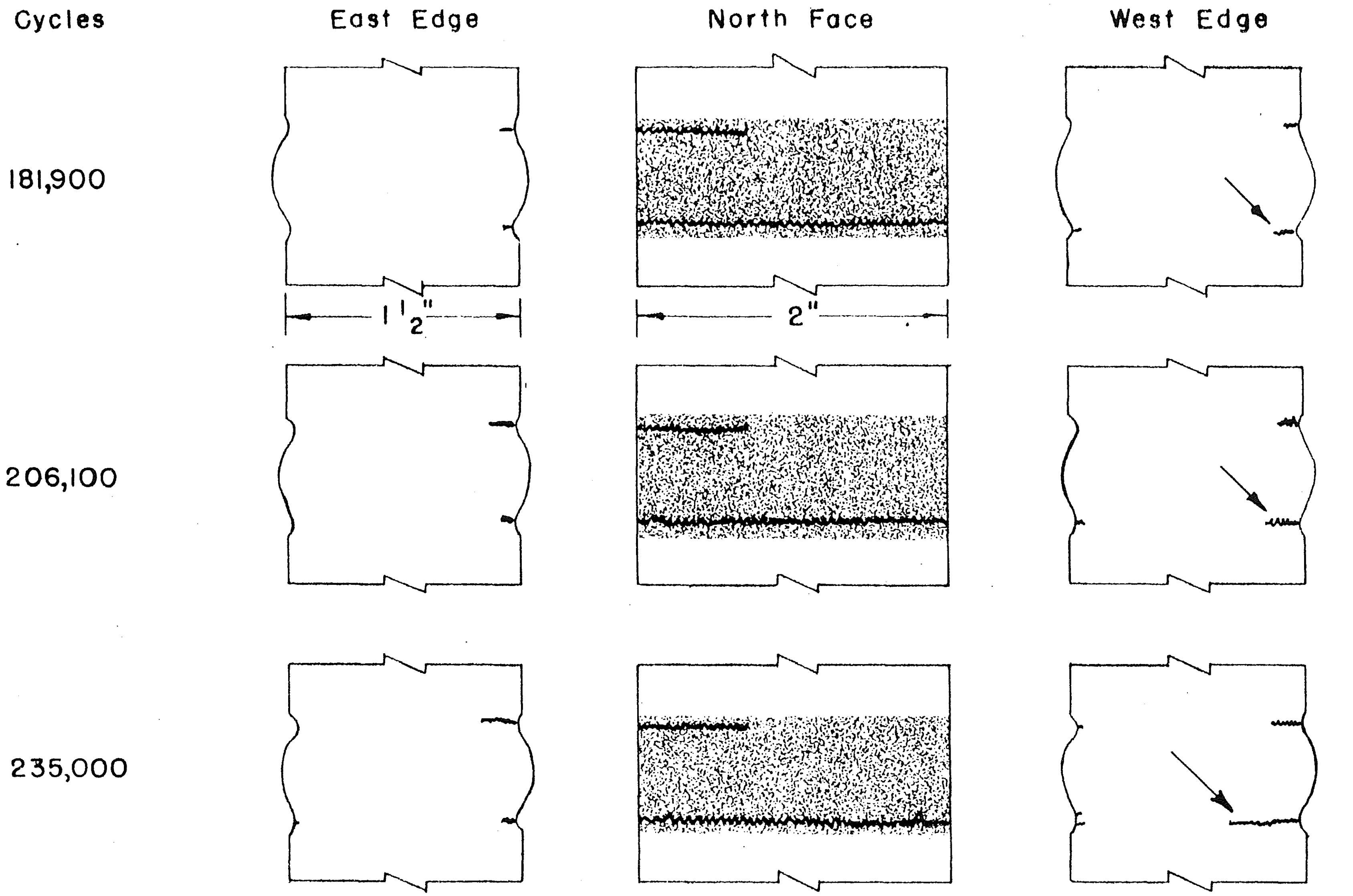


FIGURE 4.7c LOCATION AND PROGRESSION OF FATIGUE CRACKS IN HY-80 PLATE WITH TRANSVERSE BUTT WELD

SPECIMEN NO. M77MP23 STRESS CYCLE +35.0 to +70.0 ksi LIFE 282,100

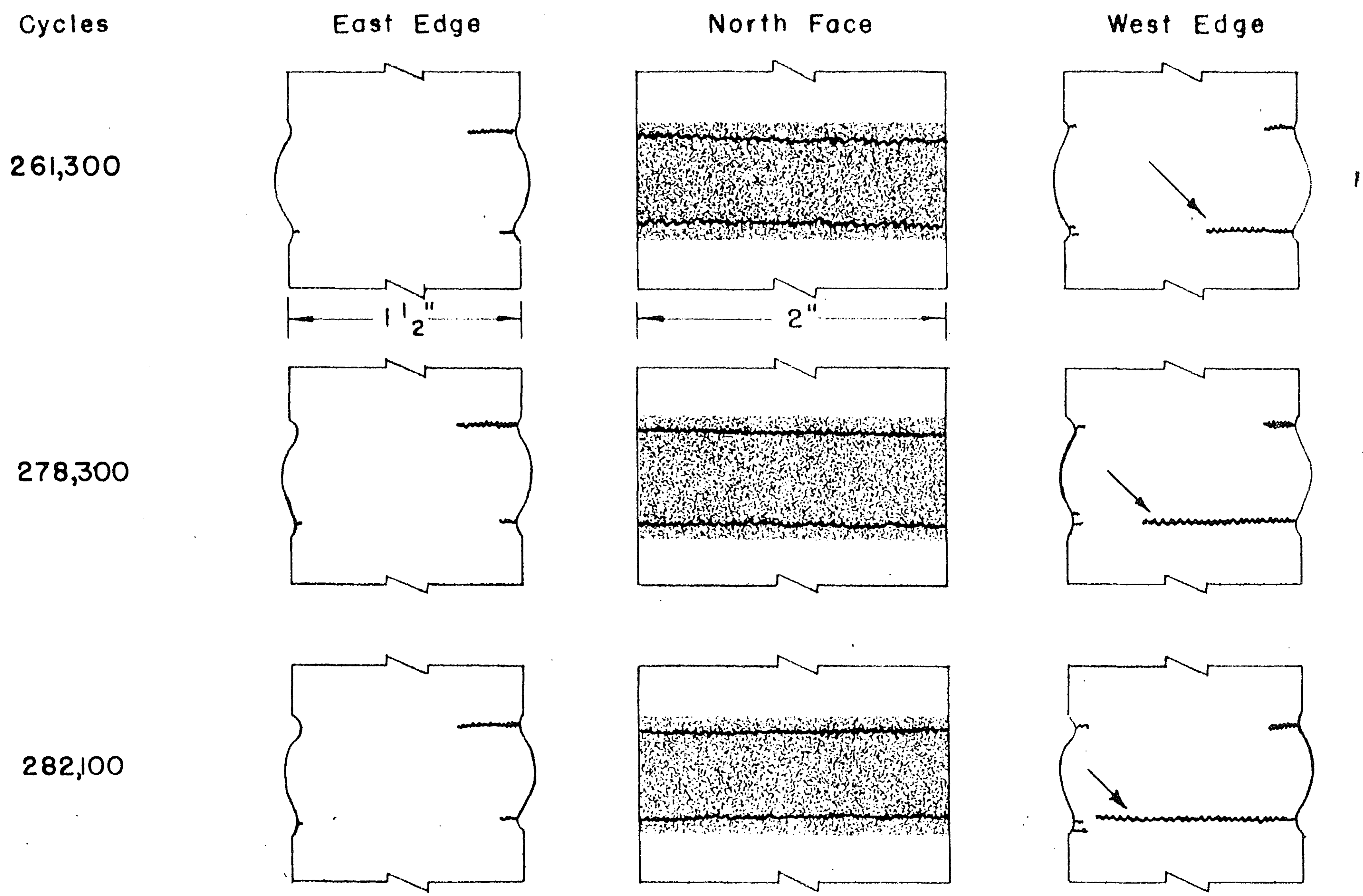


FIGURE 4.7d LOCATION AND PROGRESSION OF FATIGUE CRACKS IN HY-80 PLATE WITH TRANSVERSE BUTT WELD

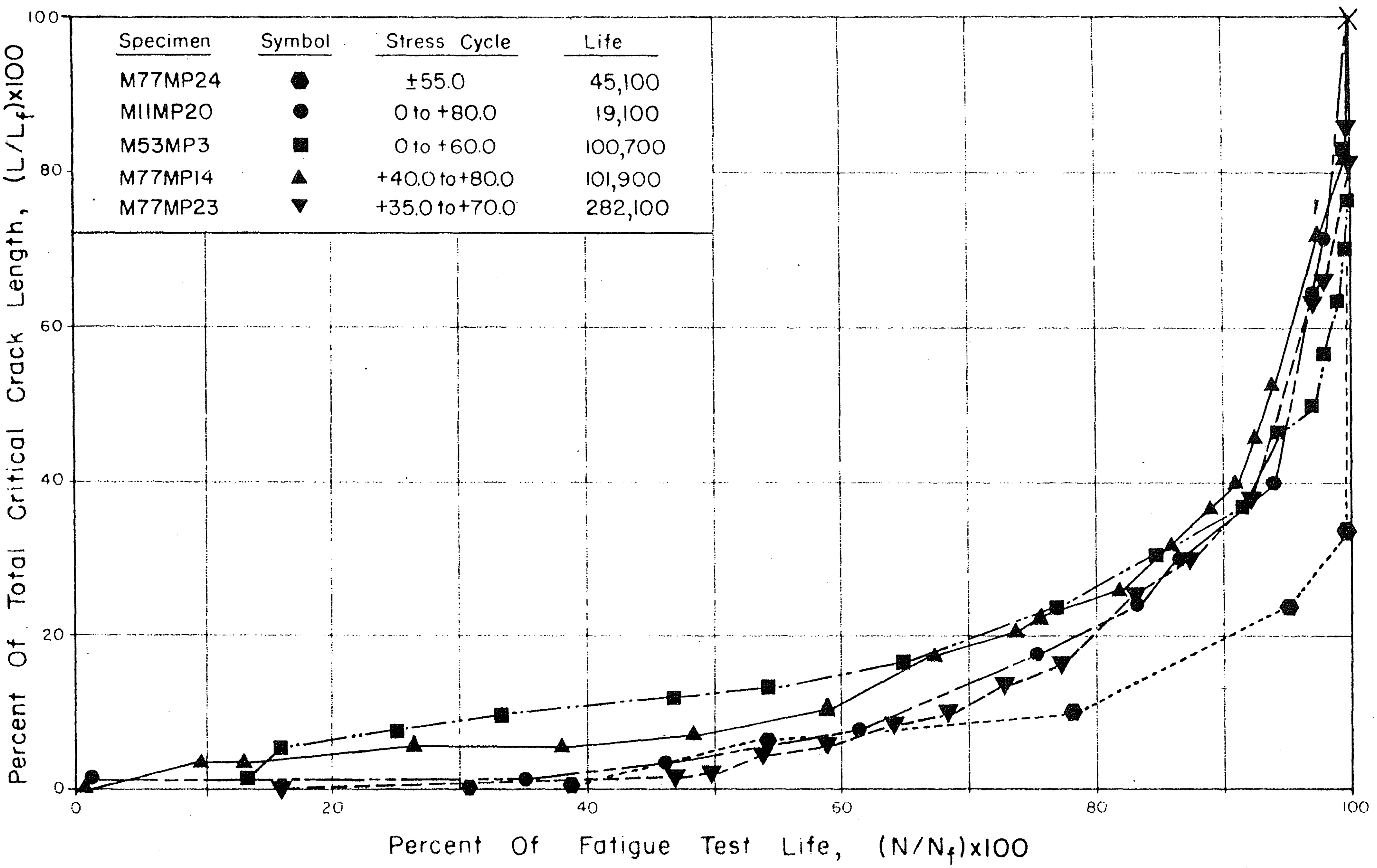


FIG. **4.8** PROPAGATION OF CRITICAL FATIGUE CRACK IN HY-80 PLATES WITH TRANSVERSE BUTT WELD (MECHANICALLY PEENED)

ILLINOIS UNIVERSITY, URBANA. DEPARTMENT OF CIVIL ENGINEERING.

FATIGUE BEHAVIOR OF MECHANICALLY PEENED HY-80 WELDMENTS SUBJECTED TO AXIAL LOADING, By J. B. Radziminski, R. A. Ridha, H. A. Osman, D. F. Meinheit, and W.H. Munse

Aug. 1966, 48p.
Structural Research Series No. 312
Contract NObs 92240, Project Serial No. SR-007-01-01, Task 853

AN EVALUATION OF THE AXIAL FATIGUE BEHAVIOR OF MECHANICALLY PEENED TRANSVERSE TEE-WELDMENTS AND TRANSVERSE BUTT-WELDED JOINTS IN HY-80 STEEL IS PRESENTED. THE DATA SHOW THAT MECHANICAL PEENING ALONG THE TOE OF THE WELD RESULTS IN AN IMPROVEMENT IN THE FATIGUE RESISTANCE OF BOTH TYPES OF WELDMENT RELATIVE TO THE BEHAVIOR OF SIMILAR JOINTS TESTED IN THE AS-WELDED CONDITION.

THE PROCESS OF FATIGUE CRACK INITIATION AND PROPAGATION WAS EXAMINED FOR SEVERAL OF THE MECHANICALLY PEENED WELDMENTS. IN THE MAJORITY OF MEMBERS CRACKS NUCLEATED AT THE TOE OF THE WELD IN THE TROUGH FORMED BY THE PEENING OPERATION. NUCLEATION NORMALLY OCCURRED WITHIN THE FIRST 20 PERCENT OF THE CYCLIC LIFETIME OF A SPECIMEN, AND WAS FOLLOWED BY A LONG PERIOD OF SLOW, ERRATIC CRACK PROPAGATION, EVENTUALLY CULMINATING IN A SHORT FINAL STAGE OF RAPID EXTENSION TO FAILURE.

KEYWORDS:
Axial Fatigue Testing, HY-80 Steel, Weldments, Mechanical Peening, Crack Propagation

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KEYWORDS:
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KEYWORDS:
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