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THE FATIGUE PROPERTIES OF LOW ALLOY AND CARBON STRUCTURAL STEELS

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and the
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I. INTRODUCTION

A. General Background

During the past few years a number of investigations have been conducted to determine whether the use of alloy steels is beneficial in connections subjected to fatigue loading. In no case has a report been made of a steel, when tested under actual conditions, exhibiting a fatigue resistance proportional to its high static resistance.

A summary of fatigue tests previously completed at the University of Illinois on full-sized riveted and welded connections is included in Table 1. All test data is for a zero to tension stress cycle. An examination of the results (9)* showed that riveted joints made of carbon, silicon, and nickel steels had little or no difference in fatigue resistance even though their respective yield points were 34,000 psi, 47,000 psi, and 57,000 psi and their respective ultimate strengths 64,000 psi, 80,000 psi, and 99,000 psi. Similarly, in fatigue tests of welded joints in A-7 (1) and A-242 (6,7) steels, using several different electrodes, a maximum increase of approximately 10 per cent in the fatigue strength of the alloy steels was reported. The yield point of the A-242 steels, however, was 80 per cent higher than that of the A-7 steel.

In another series of tests (10) the fatigue strengths of transverse butt-welded joints in carbon and silicon steels were compared. Again, the difference in fatigue resistance was slight although both yield point and ultimate strength were more than 60 per cent higher for the silicon steel.

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* Numbers in parentheses refer to items in the bibliography.

On the basis of test results now available it appears that for structures subjected to fatigue type loadings the use of high strength steels may have little or no advantage over the use of ordinary low carbon A-7 steels. Present specifications for bridges constructed of alloy steel will not permit the designer to take advantage of the additional static strength of the material if the members, during the life of the bridge, must withstand a large number of stress cycles, either reversed stresses or pulsating stresses in which the minimum stresses are low. For such conditions the design stresses are the same as those provided for A-7 steel.

A considerable number of high strength structural steels have been developed over the past decade. To evaluate their resistance to fatigue through tests of full-scale members and connections would be extremely costly and time consuming. It would prove highly advantageous, therefore, to develop a method of coupon testing by which an indication of the actual fatigue resistance of a structural connection could be obtained.

B. Object and Scope

The object of the investigation discussed in this report was to determine a method of evaluating the relative fatigue resistance of high strength, low alloy steels in large scale structural connections. In such applications the fatigue strengths are considerably lower than those obtained from small, carefully-machined specimens tested in the laboratory. These reductions are attributable to stress concentrations arising from fabrication processes, unavoidable changes in section, and surface conditions of the material supplied. However, the extent to which stress raisers lower the fatigue strength is dependent upon the notch sensitivity of the steels in fatigue. The objective was approached, therefore, by developing a small-scale notched specimen which yielded fatigue strengths comparable to those of full-sized transverse butt-welded joints.

ASTM A-7 steel was used in fatigue tests to establish a suitable notched specimen. Steel from the same heat had been previously employed in fatigue tests of full-scale welded connections, and the results of these tests served as a basis for isolating a desirable notch configuration.

After testing 86 notched A-7 steel specimens, two notch configurations were selected; both of these yielded fatigue strengths at all stress levels comparable to those of the transverse butt-welded joints. An endurance limit at 2×10^6 cycles of approximately 24,000 psi and a fatigue strength of 37,000 psi at 100,000 cycles were obtained for the notched specimens.

Since the basic objective was to determine a method of evaluating the relative fatigue resistance of high strength steels in structural applications, the scope of the investigation was expanded to include specimen tests, using both of the notch configurations, in three other steels having known fatigue resistance under service conditions. The steels used for this phase of the testing program were ASTM A-242, ASTM A-373, and T-1. By comparing the fatigue strengths of the notched specimens in a given steel with the fatigue strengths of the full-scale joints, it was possible to judge how well the objective had been achieved.

A final test series on HY 80 steel was completed for the purpose of determining the fatigue behavior of notched specimens in a high strength steel whose physical properties were not derived from heat treatment. Unfortunately, no full-scale members, fabricated from this steel, have been tested; hence a comparison could not be made of the fatigue strengths with those obtained from the notched specimens.

C. Acknowledgments

The work described in this report was carried out in the Engineering Experiment Station of the University of Illinois under the joint sponsorship of the Engineering Foundation, the Chicago Bridge and Iron Company, the American Iron and Steel Institute, and the Welding Research Council. The Fatigue Committee of the Welding Research Council acted in an advisory capacity.

The investigation constitutes a part of the structural research program of the Civil Engineering Department under the general direction of N. M. Newmark, Head of the Department and Professor of Civil Engineering, and under the general supervision of W. H. Munse, Professor of Civil Engineering.

The authors wish to express their appreciation to E. E. Kirby, laboratory machinist, for the excellent job of specimen preparation.

II. ANALYTICAL STUDY OF EXISTING FATIGUE DATA

Before any phase of the experimental work could be initiated, it was necessary to compile a summary of the fatigue results obtained from tests conducted at the University of Illinois on plain plates and welded joints. Included were tests of members made from structural grade carbon, silicon, and low alloy steels.

To facilitate a comparison of the results, use was made of the parameter, K_f, termed the fatigue-strength reduction factor where

$$K_f = \frac{\text{Fatigue strength of plain plate specimen at N cycles}}{\text{Fatigue strength of structural connection at N cycles}}$$

When the results of the various tests were compared using this factor, two fairly distinct ranges in values appeared. For either transverse or longitudinal butt-welded joints, K_f values ranged from 1.07 to 1.60. (See Table 1.) This was the maximum range even though values were computed on the basis of fatigue strengths at 100,000 cycles and 2×10^6 cycles for joints of low alloy or carbon steels in the as-welded condition or with the reinforcement removed. If only transverse butt joints in the as-welded condition are considered, the range of K_f is 1.20 to 1.51 with an average value of 1.38.

Similarly, the data on the tee-fillet welded joints gave a range for K_f from 1.85 to 3.60 with an average of 2.60. Here, however, considerably more scatter was evident, and the variation in K_f at 100,000 cycles and at 2×10^6 cycles was more pronounced.

It is interesting to note that the test results obtained by Wilson and Thomas (9) for double-lap riveted joints in carbon, silicon, and nickel steels gave K_f values between 1.13 and 1.48 with an average of 1.34. This average value is approximately the same as the average value of K_f determined for the transverse butt-welded joints.

Previous studies related to the evaluation of the fatigue strength reduction factor have indicated a dependence upon the number of cycles for which the fatigue lives were computed. That is, for a certain type of member the K_f value computed at a fatigue strength of 100,000 cycles will differ from the K_f value computed at a fatigue strength of 2×10^6 cycles. In this study, as shown in Table 1, no consistent variation is evident for butt-welded joints; however, for tee-fillet welded joints there is a tendency for K_f to be larger when computed at 2×10^6 cycles.

On the basis of the foregoing study a program of fatigue tests involving small, notched, tensile specimens was planned. Work was carried out on the assumption that a single notch configuration would give a fatigue life in the small-scale specimens approximately equal to that obtained for the full-sized butt-welded members at comparable stress levels.

III. SPECIMEN PREPARATION AND TEST PROCEDURE

A. Description of Material

Five structural grade steels were used in the test program. Their chemical analyses and physical properties are presented in Tables 2 and 3 respectively.

As previously explained, fatigue tests of ASTM A-7 steel were conducted to determine a notch configuration meeting the basic objective of the project. Specimens were cut from a 3/4 in. plate which came from the same heat as that steel used by Harris and Nordmark (1) in their fatigue tests of welded connections. The steel meets the ASTM A-7 specification for chemical composition but not the tensile strength requirement.

In evaluating the notch configuration, four different steels were used: ASTM A-242; ASTM A-373; T-1; and HY 80. The low alloy A-242 sample was taken from the same 3/4 in. plate used by Nordmark, Shoukry and Stallmeyer (7). (This steel, designated "T" in the previous reference, is marketed under the trade name "USS-Triten".) Coupon tests on this plate indicated full compliance with chemical composition and physical property requirements except for yield point which was low. Mill tests, however, showed an acceptable strength.

Specimens of structural steel for welding, ASTM A-373, were made from 1 in. thick plate. All chemical composition and physical property requirements were satisfied in coupon tests.

The third steel used is a high strength structural type marketed under the trade name "T-1"; at present it has no ASTM designation. Again, specimens were cut from a 3/4 in. thick plate. Table 3 includes average results of coupon tests made on specimens of T-1 steel which were furnace-heated to 1650 deg. F. and then allowed to air cool. A more detailed discussion of the properties of T-1 and of the changes resulting from heating is given in a later section.

The final material tested is a Navy steel designated HY 80. The average physical properties of coupons taken from the 3/4 in. thick plate can be found in Table 3. A chemical analysis of this steel was not available.

B. Test Specimens

In order to meet the objective of the program, with regard to ease of preparation and consistent reproduction, a small axial fatigue specimen was adopted. This choice permitted the best use of existing laboratory equipment and best justified a comparison of fatigue strengths with those obtained from direct tension tests of full-scale members. In selecting the type of specimen, consideration was given to such desirable features as economical machining of a large number of identical specimens and good control during the subsequent notching operation.

One basic specimen was chosen, but after preliminary tests of both notched and unnotched specimens it was found necessary to increase the diameter of the minimum section. With the small cross-sectional area in the original specimen, the tolerances on load setting were such that sufficiently accurate stresses could not be determined. This was particularly true of tests conducted in the Wilson fatigue machine.

The two specimen configurations shown in Fig. 1 have basically the same geometric shape, an over-all length of 4 in., a 3/4 in. nominal diameter, and a straight test section at mid-length of 1/4 in. For the reason discussed in the preceding paragraph, the diameter of the test section was increased from 3/8 in. to 1/2 in. The radius of the transition curve was maintained at 2-1/8 in.

C. Design of Notch Configurations

The major problem to be resolved was the selection of a suitable notch configuration which would yield the desired fatigue strengths in the small tensile specimens. The average value of the fatigue strength reduction factor for transverse butt-welded joints was determined by analyzing test results. (See Chapter II.) With this information only, however, it was not possible to proceed directly to the design of a notch.

For a given notch configuration in which no sharp discontinuities occur, the theoretical stress concentration factor, K_t, may be determined by an elastic analysis. However, the relationship between K_f and K_t is not constant, being influenced by such variables as the loading condition, type and severity of notch.

One of the simplest and most widely used relationships is:

$$q = \frac{K_f - 1}{K_t - 1} \qquad \text{or} \qquad K_t = \frac{K_f - 1}{q} + 1$$

where q is the notch sensitivity index. The value of q in this expression may range from zero, indicating no reduction in fatigue strength, to 1.0, designating full reduction. The latter value is determined by means of a maximum stress theory of failure.

A survey of fatigue literature gave a considerable range for q values; therefore, limited use was made of the above relationship in the search for a suitable notch configuration. By selective testing, using notches for which the theoretical stress concentration factors were known, it was soon possible, however, to isolate a configuration yielding the approximate desired fatigue strengths.

No attempt will be made to develop the theory of notch stresses. Rather, it should be sufficient to state that the theoretical stress concentration factor for a particular notch is dependent upon the minimum radius at the root of the notch, the flank angle, and the depth of the notch compared to the diameter of the specimen. In this investigation the calculations of theoretical stress concentration factors were based on the work of Heinz Neuber (3). The nomograph which is contained in his classical work was of particular benefit.

Figure 2 shows all the notch configurations, their computed theoretical stress concentration factors, and the designation assigned to each to permit rapid identification of the various test series. No K_t value is given for notch "Y" because of the sharp discontinuities at its root. For notch "X" at K_t value was computed on the assumption that a smooth radius existed at the root. This assumption was not without justification since localized yielding during the first few load cycles would tend to erase any sharp change in section.

D. Specimen Preparation

All specimens were cut from plate material having a 3/4 in. thickness except those of A-373 steel which were taken from a plate having a 1 in. thickness. The first operation in preparing the specimens was to flame-cut a strip of steel from the parent plate. This section was marked and sawed into 4-1/8 in. wide strips measured in the direction of rolling. These strips were then subdivided to give 3/4 in. square blanks. In laying out the plate for cutting, care was taken to avoid using material in the test section which was closer than 1-1/2 in. from a sheared edge or 2 in. from a flame-cut edge. The location of each specimen in the parent plate was recorded but is not reported here because changes in the physical properties would be insignificant due to the small area of steel required for each series of specimens.

After sawing, the blanks were placed in a lathe and their ends turned parallel. Centering, rough turning, finish turning, and threading followed in sequence.

The final operation, contouring of the specimens, was carried out i a lathe equipped with a template which controlled movement of the carriage. A heavy spring tension applied against the template assured uniformity of all specimens. Cutting oil flowed continuously over the specimens during all machining operations, and heating effects were therefore minimized, if not completely eliminated.

Those specimens to be notched required no additional surface treatment. Polishing of the unnotched specimens was imperative, however, in order to remove machining defects and so improve the consistency of fatigue results.

The polishing procedure selected was similar to that used by Merritt, Mosborg and Munse (2). The specimen was left between the centers of the lathe, and the tool holder was replaced by a support capable of holding a Black and Decker Holdgun having an operating speed of 3,700 rpm. An abrasive cloth holder was clamped in the chuck and a small section of abrasive cloth attached through the center of the holder in such a manner as to protrude equally from either side.

Throughout the polishing operation the lathe was operated at approximately 160 rpm, while the axis of the holdgun was set at right angles to the axis of the specimen. Surface striations introduced during polishing were essentially longitudinal and in the direction of applied stress. Since contact between the specimen and the abrasive cloth was very light, little heat was developed.

Polishing was completed in four stages. Three grades of aluminum oxide cloth, Numbers 80, 120, and 320, were used successively. A final polish with Crocus Cloth followed.

A variety of notch configurations were used in the test program. Tools ground to the proper dimensions were employed to cut the notches to the required depth. Care was taken to avoid excessive tool wear. Tool feed rates were kept low, and a constant flow of cutting oil was played on the contact surfaces at all times.

A number of the notching tools were ground to the desired shape in the laboratory. These proved satisfactory, and only a limited amount of wear occurred. However, in view of the fact that, ultimately, a large number of specimens made from a variety of steels were to be identically notched, a carbide tool commercially available was also used. This type proved very satisfactory, particularly since duplicate tools could be obtained.

E. Testing Equipment

Two fatigue machines were used in carrying out the testing program. Four series of tests were run in a 50,000 lb. W. M. Wilson lever type fatigue machine which operates at 300 rpm. Nine series or approximately 150 specimens were tested in a 10,000 lb. capacity Sonntag Universal fatigue testing machine, model SF-10-U, which operates at 1,800 rpm.

1. Wilson Fatigue Machine

Essentially, this machine consists of a variable throw eccentric which transmits force through a dynamometer (for determining the load on the specimen) to a lever which in turn transmits the force to the upper pull head at a multiplication ratio of approximately 10 to 1. A schematic diagram is shown in Fig. 3a. The range of stress to be applied to the specimen is adjusted by means of the eccentric. An adjustable turnbuckle, mounted between the eccentric and the dynamometer, is used to set the maximum load.

Since uniform stress over the cross-section was desired, loading heads, adapted to the use of hand-lapped spherical seats were employed. This arrangement is shown in Fig. 3b. The spherical surfaces were well lubricated to prevent corrosion and to permit easy movement of the parts during seating. As an added means of reducing the eccentricity of loading, adjustable guide links were attached to the upper pull head. These links controlled the direction of movement of the pull head and were adjusted to attain as nearly as possible concentric loading of the specimen.

A measure of the eccentricity of loading was obtained through the use of a 3/8 in. diameter specimen upon which 3 A-18 strain gages had been mounted at 120 deg. intervals around the perimeter. This specimen was clamped in the pull heads and a static load applied. From the individual strain readings of the three gages it was possible to calculate the eccentricity of loading. Following a trial and error adjustment of the guide links, eccentricities of less than 0.005 in. were measured, even when relatively small static loads were applied. Generally, the amount of eccentricity decreased as the applied load increased.

As previously mentioned, a dynamometer was used to measure the applied loads. To facilitate calibration of the dynamometer, A-7 strain gages were mounted on a 3/4 in. diameter weigh bar and the stress-strain relationship determined in a 120,000 lb. Baldwin hydraulic testing machine. This specimen was then secured in the pull heads of the fatigue machine and the load-strain relationship determined for the dynamometer. Strains in the dynamometer were measured with electric strain gages wired into a four arm bridge. The calibration constant for this machine was 29.9 lbs. per micro-inch. It should be mentioned that this calibration procedure eliminates any error in the determination of load on a specimen which could result from frictional forces in the lever system.

2. Sonntag Fatigue Machine

The Sonntag fatigue machine is a constant load type in which the alternating load is obtained from the vertical component of centrifugal force produced by an adjustable eccentric weight revolving at a constant speed of 1,800 rpm. The rotating mass is driven by a synchronous speed, two-horsepower motor. The drive assembly is equipped with a friction clutch which allows the main motor to reach synchronous speed almost instantaneously. The eccentric weight lags by a time interval of from eight to twelve seconds thus preventing an overload of the specimen.

The eccentric weight may be adjusted to give any desired vertical component of force between zero and 5,000 lbs. Thus, the maximum range of load which may be developed is 10,000 lbs. The horizontal component of the centrifugal force is absorbed by four flexplates attached to the oscillator of the machine.

The foregoing discussion explains the manner in which the alternating load on the specimen may be varied to give the desired stress range. A second loading mechanism to apply a static or preload is necessary in order to vary the maximum stress. The loading system used involves four calibrated springs which extend between a moveable preloading platform and the base of the oscillator. An electric motor coupled to a slow speed vertical gearbox drives two chain-coupled screws, one on either side of the oscillator, which, in turn, raise or lower the platform and thereby apply load to the specimen. These screws were specially designed to prevent backlash in the threads and thus enable preload adjustment during the progress of a test.

The preload is measured by determining the change in mean length of the preload springs. For this purpose, an automatic load maintainer is employed. It consists essentially of an inductance bridge in which the balance of one arm is controlled by an adjustable iron core moving in an activated coil of the electronic circuit. The core is rigidly attached to the vibrating assembly, and the coil is held to the preload platform by an adjustable screw mechanism. A Weston Sensitrol is used to indicate the balance position of the coil and core. The position of the coil can be adjusted manually by means of a crank attached to the screw mechanism. A counter records the number of revolutions through which the crank is turned. Each revolution of the crank changes the relative position of the coil and core by 0.001 in. Any relative displacement of the coil and core from the balanced position will be indicated on the Sensitrol. The preload may be controlled manually or automatically, but, in either case, when an unbalance exists in the inductance bridge the Sensitrol closes a relay which excites the preload motor. In turn, the latter raises or lowers the platform as desired until the balance position of the coil and core is once again reached. When a test is in progress and the specimen creeps or yields under the load, the result is a relative displacement of the coil and core. Should a sufficiently great unbalance occur, the Sensitrol will close the relay, repeating the process explained previously.

It should be obvious that since each revolution shown on the preload counter corresponds to a relative displacement of 0.001 in. between coil and core, an equal change in length of the springs must have occurred when balance is restored. The calibration constant for the 4 springs acting simultaneously is 21.8 lbs. per 0.001 in. of deflection.

The Sonntag is so designed that the maximum preload which may be applied to a specimen is 5,000 lbs., either tension or compression. By setting the proper preload, the maximum load on the specimen may be varied from 10,000 lbs. tension to 10,000 lbs. compression.

A sectional view of the tension-compression loading apparatus is shown in Fig. 4. Its main component is a loading frame to which is attached the upper specimen holder and seating block. The lower seating block is fastened to the oscillating assembly. Hand-lapped spherical specimen holders are used to clamp the specimens in the machine and to assist in obtaining concentric loading.

The procedure adopted for placing a specimen in the machine completely eliminated all clamping stresses and, in addition, reduced the eccentricity of loading as much as possible. The seating block for each spherical specimen holder is held in place by 6 bolts. These bolts are tightened down to securely clamp the specimen holder in position. When the Sonntag machine was first placed in operation, the initial specimen was screwed into position and the spherical specimen holders so adjusted that clamping of the seating blocks did not place any stress on the specimen. That is, after clamping, the specimen could still be screwed up or down in the holders. Assuming the spherical surfaces to be true, this condition could only exist when the top and bottom specimen holders were properly aligned. In all subsequent tests only the top specimen holder was unclamped and the entire top seating block raised by means of its threaded support when removing a specimen or when placing a new specimen in the machine. In this way, any eccentricity of loading which did occur was kept constant throughout all of the tests.

During a previous investigation (2) considerable time was spent calibrating the Sonntag machine and determining the degree of backlash. In view of the results, calibration of the dynamic load was unnecessary. A check of the preload calibration was made using a 3/8 in. diameter weighbar for which the stress-strain relationship was known. Within the limit of experimental error, the preload constant so determined agreed with that given by the manufacturer.

F. Testing Procedure

All tests were conducted at room temperature. The stress cycle for every fatigue test reported herein varied from a minimum tension of approximately 1,000 psi, to ensure clamping of the specimen, to a maximum tension. A sufficient number of identical specimens in each series were tested at various stress levels to adequately determine the S-N curve.

A depth gage equipped with a mechanical dial was employed to measure the diameter of the specimens to the nearest 0.001 in. In one test series a very narrow notch was cut; for these specimens measurements were made with an optical comparator. During the testing of polished specimens, and in one series of notched specimens, yielding reduced the diameter of the net section. Where this occurred, measurements were taken after yielding had ceased, and stresses were computed using the reduced cross-sectional area. In all other test series, the restraint provided by the shoulders of the notch was adequate to prevent a reduction in area, even at stresses considerably above the yield point.

Following failure, which was assumed to have occurred with the development of a fatigue crack, specimens were removed from the machine and broken statically in a hydraulic testing machine. This permitted observation of the fracture surfaces.

1. Wilson Fatigue Machine

To obtain fatigue failures it was necessary to apply loads which caused at least a limited amount of yielding. Therefore, when setting the eccentric of the Wilson machine to obtain the desired load range, the calibrated weigh bar was substituted for the actual test specimen. This procedure permitted a finer setting than would have been otherwise possible.

Following adjustment of the eccentric, the machine was cranked manually to the bottom of the throw. The specimen was then placed in the pull heads and the spherical seats tightened down until the desired minimum load was obtained. This method was used in preference to adjusting the turnbuckle between the dynamometer and the eccentric because only a very small load was to be applied. Next, the machine was turned on and the pull heads gently tapped with a mallet to assure proper seating of the lubricated spherical surfaces.

At the beginning of each test, the load was checked and adjusted approximately every ten minutes until no drop in load occurred. Periodic load checks were then made until the specimen failed. Once a fatigue crack developed, the increase in movement of the pull heads tripped a micro-switch which automatically stopped the machine.

2. Sonntag Fatigue Machine

The alternating force in the Sonntag is obtained from a rotating eccentric weight. To loosen the grease in the bearings, the main motor of the machine was run for at least 1/2 hour prior to starting a test. If, however, a specimen was placed in the machine immediately following the failure of a previous specimen, no warm-up period was necessary.

After clamping the specimen in the holders, the desired mean load was set on the preload counter and the selected alternating load set by adjusting the eccentric weight. To apply the preload, the control system was operated manually. Finally, the main motor was turned on and the preload control switched to "automatic".

In all tests at least a limited amount of yielding occurred during the first few load cycles. The behavior of the machine was observed until stability was reached, and additional observations were made periodically until failure. A limit switch stopped the machine once a fatigue crack had developed.

G. Specimen Designation

Since 13 series of fatigue tests were conducted in connection with the project, a designation system which permitted rapid identification of the various series was adopted. From the designation for any given series it is possible to establish such essential features as material, type of notch, number of the particular specimen, and the fatigue machine in which the tests were run.

Table 3 and Fig. 2, respectively, show the letters used to define the various steels and notches. In addition, it was imperative that any notation system indicate in which machine the tests were run as two basically different fatigue machines were employed. Thus, tests carried out in the Sonntag fatigue machine were designated "S" and tests run in the Wilson fatigue machine, "W".

It should be observed that the notation "S" applies to both A-7 steel and the Sonntag fatigue machine. No confusion should result, however, for the machine designation always precedes the steel designation.

In every case, the letter "A" is placed at the beginning of the designation to signify the project as a whole. In one series of tests the specimens were heat-treated following notching; the letter "H" at the end of a designation denotes this treatment.

Three examples of series notations follow. If the reader carefully notes the order of designation, there should be no difficulty in understanding the subsequent discussion of test results.

AWS-21

Test Specimen Number 21
A-7 Steel
Wilson Fatigue Machine
Alloy Steel Project

ASS-24-V

Notch "V"
Test Specimen Number 24
A-7 Steel
Sonntag Fatigue Machine
Alloy Steel Project

ASD-14-Y

Notch "Y"
Test Specimen Number 14
A-373 Steel
Sonntag Fatigue Machine
Alloy Steel Project

IV. TEST RESULTS

A total of 204 specimens, comprising 13 different series, were tested. Table 4 has been drawn up to give, in so far as possible, the particular features of each series. Results obtained for the various test series are presented in separate semi-log plots. The values are also given in Tables 5 to 17, but in the following discussion reference generally will be made only to the graphical presentation.

A. Fatigue Properties of A-7 Steel Specimens

1. Fatigue Properties of Unnotched Specimens

In both the Wilson and Sonntag fatigue machines polished 3/8 in. diameter specimens were used to establish basic S-N curves. The results of these preliminary tests are shown in Figs. 5 and 6. Scatter in the results is surprisingly limited except for two tests in series ASS. It may be observed in Table 6 that the reduction in area for these two specimens was above average.

Although almost identical in shape, the plots for tests in the Wilson and Sonntag machines show rather poor correlation in fatigue strengths. This peculiarity may result from the basic differences in the two machines. The Sonntag machine is a constant load type and continues to apply the same load even though yielding occurs in the specimen. The Wilson machine, on the other hand, operates with a constant throw, and unless manual adjustment is made the load drops off when yielding takes place. Although frequent load adjustment was made it was practically impossible to maintain a constant value at all times. A second, but perhaps less tangible factor to which the discrepancy could be partially attributed is the higher rate of yielding which occurred in the Sonntag machine. It is felt that the differential rate of testing between the two machines was not sufficient to cause a change in fatigue strength.

2. Fatigue Properties of Notched Specimens

a. Wilson Fatigue Machine

Originally, seventy 3/8 in. diameter specimens were turned out for the Wilson fatigue testing machine. Fourteen of these were tested in the unnotched condition, while 11 were retained for calibration purposes. The remaining 45 specimens were tested in three series, using three different notches.*

Series AWS-U was run as a control. The semi-circular notch of 0.044 in. radius gave a theoretical stress concentration factor of 1.92. The results of this series are shown in Fig. 7. It was not anticipated that the fatigue strengths obtained from these tests would correspond to those for full-sized, butt-welded members. Nevertheless, the approximately equal slopes of the S-N curves should be observed.

The notch for series AWS-X was designed with a smooth radius at the root. With the available laboratory equipment, however, it proved impossible to grind a tool to this specification. The root of the notch therefore consisted of a series of flats. The designed notch, with a depth of 0.032 in. and a width of 0.013 in., had a theoretical stress concentration factor of 4.00. Fig. 8 indicates reasonable agreement of fatigue strengths between the results of this series and of those tests on transverse butt-welded joints. While this

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* The fatigue strengths of all the following series of tests of A-7 notched specimens are compared to the average results of the full-sized transverse butt-welded joints reported in Structural Research Series Number 81. For the two series of tests involving A-242 steel a comparison is made with the results of full-sized transverse butt-welded joints reported in Structural Research Series Number 90 and Number 114. Both comparisons were facilitated by drawing the best fit line for the butt-welded joint tests on each of the semi-log plots.

notch yielded the desired fatigue strengths, its configuration was such as to render reproduction of identical specimens difficult, if not impossible.

The final series of notched 3/8 in. diameter specimens tested has the designation AWS-v. The notch, cut with a commercial carbide tool, had an approximate K_t value of 2.8. An exact value is difficult to determine because of the complicating effect of the flank angle. A study of Fig. 9 reveals that this notch was not severe enough to give fatigue strengths meeting the objective of the program.

b. Sonntag Fatigue Machine

All of the notched specimens tested in the Sonntag fatigue machine had a 1/2 in. diameter test section. (See Fig. 1b.)

The results of series ASS-Y are shown in Fig. 10. The notch configuration was, in effect, a truncated "V". Because of the resulting sharp discontinuities at the root, no attempt was made to determine the theoretical stress concentration factor. The fatigue strengths obtained for the ASS-Y notched specimens approximated the values obtained for transverse butt-welded joints. Considerable scatter in the results is evident, particularly at stresses approaching the endurance limit. While part of this diffusion may be attributed to the type of notch configuration, all tests run in the Sonntag machine tended, in general, to give a relatively wider scatter band than those run in the Wilson machine.

The notch used in the final test series of A-7 steel was the same as that used for series AWS-v. In these tests the K_t value was increased to approximately 3.1 by changing the depth of the notch to diameter of specimen ratio. The designation for this series is ASS-V, and the results are presented in Fig. 11.

It was decided that in the ASS-V series the effect of polishing the notch should be investigated. To this end, 8 specimens were tested, all at the same stress level. Four of these specimens had the notch root polished in the direction of applied stress with an 0.01 in. diameter copper wire, while the other four were left in their original notched condition. Equal scatter occurred in the fatigue lives of all specimens. The remaining specimens, therefore, were tested as notched by the tool.

This series was similar to the previous one, ASS-Y, in that a "V" shaped notch was cut to the same depth. A comparison of fatigue strengths for these two series shows good correlation despite the fact that conditions at the notch roots differed greatly. The chief benefit of using a notch with a smooth root radius appears to be in the reduction of scatter at stresses near the endurance limit.

While the exact desired fatigue strengths were not obtained, additional testing on A-7 steel would be of little value considering the unavoidable scatter which occurs in all types of fatigue tests. However, either of the notches yielding the results shown in Figs. 10 and 11 could be accepted as satisfying the program's objective. The scope of the investigation was widened, therefore, to encompass tests, using both notches, on a number of different structural steels. For all but one of these steels, the fatigue results of full-scale transverse butt-welded members were available, thus making it possible to judge how well the basic aim had been achieved.

B. Fatigue Properties of Notched Steel Specimens Made from Various Structural Steels

1. Fatigue Properties of Notched ASTM A-242 Steel Specimens

The results of the two test series, ASB-V and ASB-Y, for which specimens were made of ASTM A-242 steel, are shown in Figs. 12 and 13, respectively. Although considerable overlap of the scatter bands occurred, the fatigue strengths obtained in both series are lower than the corresponding values for transverse butt-welded joints. Since only a limited number of full-scale A-242 steel members have been tested, and since the majority of these tests have been conducted at stresses considerably above the endurance limit, a comparison of fatigue strengths at lower stress levels was not possible. In both the ASB-V and ASB-Y series the endurance limit for the notched specimens was approximately 23,000 psi.

The slope of the best-fit line obtained for test series ASB-Y was identical to that plotted for the transverse butt-welded connections. As indicated above, the fatigue strengths at the same number of cycles were lower by approximately 3,000 psi. Conversely, the slopes for series ASB-V did not correspond although the fatigue strengths did appear to approach one another at higher stress levels.

2. Fatigue Properties of Notched ASTM A-373 Steel Specimens

Specimens of ASTM A-373 steel were tested in series ASD-Y. For these tests a fatigue strength at 100,000 cycles of 39,000 psi and an endurance limit at 2×10^6 cycles of 22,000 psi were obtained.

A-373 steel is presently being used for a flexural fatigue study (8) in progress at the University of Illinois Civil Engineering Department. In connection with this project, three full-sized transverse butt-welded joints were tested, all at the same stress level. The results are shown in Fig. 14, as are those obtained from tests of notched specimens. The extremely good correlation in fatigue strengths is not surprising since the chemical composition and physical properties of A-373 steel are similar to those of the A-7 steel used in selecting the notch configuration.

3. Fatigue Properties of Notched T-1 Steel Specimens

In evaluating the notch configuration, it was decided to investigate the fatigue properties of a high strength steel having a yield point and ultimate strength in excess of 100,000 psi. T-1 steel was selected because it not only met these requirements but was also readily available in the laboratory.

The results yielded by the notched T-1 steel specimens of series ASC-V are presented in Fig. 15. This figure further shows the curve of fatigue results of butt-welded specimens determined by the manufacturers as part of their testing program.

The notched specimens exhibited an abnormal amount of scatter, making it virtually impossible to draw a best-fit curve. There was no apparent reason for this extreme scatter. A record of the location of individual specimens in the parent plate and a review of the sequence of preparation did not indicate any correlation between these factors and the fatigue lives.

It should be noted that the endurance limit for the small, machined specimens is considerably higher than the endurance limit for the butt-welded joints. This difference appears to be in excess of 9,000 psi.

The physical properties of T-1 steel are obtained by a tempering and quenching process. During welding there is a significant change in the metallurgical structure of T-1 steel in the vicinity of the weld. It is felt that this change may affect the properties which accrued from the quenching and tempering. With this as a basis, a second series of notched specimens was tested.

The specimens in test series ASC-V-H were prepared in the same manner as those used for the previous series in T-1 steel. After notching, however, specimens were heat-treated. This treatment consisted of placing specimens in a furnace, preheated to 1,650 deg. F., for a period of ten minutes, following which they were removed and allowed to air cool in the atmosphere of the laboratory. The interval of ten minutes was selected since it allowed sufficient time for the specimen to acquire a uniform temperature. The oxide scale resulting from the heat treatment was easily removed from the surfaces of the specimens by a light brushing. No additional operations were performed prior to testing.

The effect of heat treatment was evidenced in the lowering of fatigue strengths at all ranges of stress. The endurance limit was reduced by an amount in excess of 10,000 psi. A comparison of results shows, in fact, that heat treatment so reduced the fatigue strengths of the notched specimens that they fell below the corresponding values obtained for butt-welded joint tests at all stress levels.

Results of the ASC-V-H tests are given in Fig. 16, while a further discussion of the effects of heat treatment on T-1 steels is included in Chapter V.

4. Fatigue Properties of Notched HY 80 Steel Specimens

The HY 80 Navy steel used in the final series of tests possesses a high strength, 93,600 psi ultimate, and yet retains considerable ductility. As seen in Table 3, the reduction in area, as determined from coupons, was 74.0 per cent for this steel compared to 62.0 per cent for A-7 structural steel.

The results of this test series, designated ASE-V, are shown in Fig. 17. An endurance limit of 28,000 psi and a fatigue strength at 100,000 cycles of 47,000 psi were obtained. No full-scale joint tests have been conducted on this steel; hence a comparison of fatigue strengths cannot be made.

V. DISCUSSION

Before beginning a discussion of test results in general, it would be well, perhaps, to review in more detail the behavior of notched T-1 steel specimens. As shown in Fig. 15, the endurance limit obtained from tests on notched specimens of this steel (in the as-received condition) was considerably higher than the endurance limits obtained through similar tests for all other steels considered. One possible exception is HY 80 steel. Heat treating, as mentioned on page 27, lowered the endurance limit of T-1 steel to a minimum of 3,000 psi below that of any other steel tested. In contrast, the results of static tests on heat-treated coupons showed a slight increase in ultimate strength.

In an attempt to determine the cause of this reduction of fatigue strengths, a brief metallurgical study was initiated. Fatigue specimens of T-1 in both as-received and heat-treated conditions were sectioned and photomicrographs made. By heating T-1 steel to 1,650 deg. F. the A_3 temperature was exceeded and a fine grained martensitic microstructure produced. The resulting metallurgical change causes a reduction in ductility and an increase in hardness. Other physical properties are not greatly affected.

The aim of heat treatment was to obtain the same microstructure in the specimens which occurs in the heat-affected zone of a weld.

The composite Figs. 18 and 19 were devised to facilitate a comparison of fatigue strengths obtained from the various series of notched specimen tests. Perhaps one of the most notable features evident in these figures is the difference in endurance limits of the steels. Those possessing the respective ultimate strengths of 134,000 psi, 73,600 psi, and 67,000 psi yielded endurance limits in the notched specimen tests below the corresponding value for specimens of A-7 steel having an ultimate strength of only 56,900 psi. It should be pointed out that of the former three steels two gave fatigue strengths higher than that for A-7 steel at 100,000 cycles.

When compared to A-7 steel, none of the low alloy, high strength structural steels indicated an increase in fatigue resistance proportional to its higher ultimate strength. However, HY 80 and T-1 steel, in the as-received condition, did show a significant improvement in fatigue resistance. Further, on the basis of notched specimen tests on heat-treated T-1, and from the results of butt-welded joint tests, it would seem that for high strength, heat-treated steels the detrimental effect of welding, and the subsequent metallurgical change, renders this type of steel unsuitable for members in which fatigue loadings are critical. Conversely, since the fatigue resistance of notched T-1 steel specimens tested in the as-received condition was relatively high, it may be assumed that a considerable increase in fatigue strength over that of butt-welded joints could be obtained in connections fastened with either rivets or bolts.

The fatigue results of series ASE-V appear to indicate that the HY 80 steel possesses good fatigue resistance even in the presence of a high stress raiser. A similar resistance to fatigue should be obtained in either riveted or bolted connections. Before predicting the fatigue resistance of a welded joint, however, a study of the weldability of HY 80 would be necessary.

An interesting feature, shown in Figs. 18 and 19 concerns the point at which the S-N curve becomes horizontal. The number of stress cycles required to reach this point seems dependent upon the ductility of the steel, and, in particular, upon the per cent reduction of area as determined in coupon tests. For HY 80 steel, having a reduction in area of 74.0 per cent, the knee of the curve occurs at 600,000 cycles, whereas the curve for A-373 steel, having a reduction in area equal to only 48.6 per cent, breaks at slightly more than 1,500,000 cycles. Although mainly of academic interest, the relationship between location of the knee and ductility could be of benefit in interpreting fatigue test data. Much more research, of course, would be necessary before any definite conclusions could be drawn.

The results of the investigation indicate that the objective of the project has considerable merit. In most cases, the fatigue strengths of the notched specimens agreed reasonably well with the results obtained from full-sized joint tests. It is clear, however, that conclusions drawn from notched specimen tests will be completely erroneous for steels in which the metallurgical changes resulting from heat of welding are of more significance in governing the fatigue resistance than is the stress concentration due to the presence of the weld.

Much valuable information regarding the fatigue properties of a material is obtainable from tests of small notched specimens. It has been shown that for a number of different steels the results of such tests, when properly analyzed, may be of benefit in predicting the fatigue behavior of full-scale structural connections. While there is no doubt that certain steels may prove to be exceptions, the method of testing small-scale notched specimens does permit, to at least a degree, rapid and economical evaluation of the fatigue resistance of low alloy and carbon structural steels.

VI. CONCLUSIONS

Following are the major conclusions drawn from this investigation of the fatigue properties of carbon and low alloy structural steels.

1. For fatigue type loadings it is possible to determine a notch configuration which, in a small tensile specimen, will act as a stress raiser in the same manner as a weld in a structural connection.

2. A notched steel specimen yielding fatigue strengths comparable to those of A-7 butt-welded joints may be used to predict the fatigue resistance of a high strength, low alloy steel butt-welded joint. The predicted value, however, would only be approximate. Before the specific fatigue resistance of a member could be determined, tests on full-scale joints would be necessary.

3. The welding of T-1 steel, and possibly of other heat-treated steels, produces detrimental metallurgical changes. These changes, when synthetically produced, lower the fatigue strengths of the small, notched specimens considerably below those which would be obtained from tests on the original material.

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TABLE 1

AVERAGE RESULTS FROM PAST FATIGUE TESTS OF WELDED JOINTS ON A ZERO TO TENSION STRESS CYCLE

Reference	Material	Average Yield Point psi	Average Ultimate Strength psi	Type of Joint	Electrode	Average Fatigue Strength $f_{100,000}$ psi	K_f	f_{2x10^6} psi	K_f
University of Illinois Structural Research Series No. 81	A-7	33,300	57,400	Plain Plate					
				(a) mill scale on		53,500*		34,600	
				(b) mill scale removed				35,300	
				Longitudinal Butt Weld	E6010				
				(a) as-welded		37,400	1.42	24,500	1.41
				(b) reinforcement removed		39,800	1.34	29,600	1.17
				Longitudinal Butt Weld	E7016				
				(a) as-welded		41,700	1.28	26,300	1.32
				(b) reinforcement removed		48,300	1.10	30,200	1.15
				Transverse Butt Weld	E6010				
				(a) as-welded		34,900	1.52	24,000	1.44
				(b) reinforcement removed		33,300	1.60	21,800	1.59
				Transverse Butt Weld	E7016				
				(a) as-welded		37,900	1.40	23,800	1.45
				(b) reinforcement removed		35,400	1.50	29,100	1.19
S.R.S. 82	A-7 (same steel as above)	33,300	57,400	Tee Fillet-Welded Joints	E6010	22,600	2.34	11,300	3.06
					E7016	25,700	2.06	12,200	2.86
					MIL 180	28,700	1.85	15,800	2.19
				Longitudinal Fillet-Welded Joints	E6010	22,700	2.34		
					E7016	21,500	2.46		

*Estimated value

TABLE 1 (Continued)

Reference	Material	Average Yield Point psi	Average Ultimate Strength psi	Type of Joint	Electrode	Average Fatigue Strength $f_{100,000}$ psi	K_f	f_{2x10^6} psi	K_f
S.R.S. 90	A-242(P)	56,300	76,700	Plain Plate					
				(a) mill scale on		53,500		34,500	
				(b) mill scale removed		58,700		47,600	
				Transverse Butt Weld	E7016				
				(a) as-welded		38,600	1.39	26,300	1.46
				(b) reinforcement removed		34,000	1.57	27,600	1.39
				Longitudinal Butt Weld	E7016				
				(a) as-welded		44,700	1.20	30,300	1.27
				(b) reinforcement removed		50,100	1.07	34,800	1.11
				Tee Fillet-Welded	E7016	23,000	2.32	12,300	3.13
S.R.S. 114	A-242(T)	47,800	73,600	Plain Plate		57,800		42,500	
				Transverse Butt Weld	MIL 180	39,400	1.47	26,700	1.59
				Longitudinal Butt Weld	MIL 180	45,100	1.28		
	A-242(Q)	53,100	77,600	Plain Plate		55,300		40,000	
				Transverse Butt Weld	MIL 180	39,400	1.40		
				Longitudinal Butt Weld	MIL 180	42,200	1.31		
	A-242(P)*	56,800	76,700	Longitudinal Fillet Weld	MIL 180	22,400	2.39	12,200	3.16

* Same steel as used for tests in S.R.S. 90

TABLE 1 (Continued)

Reference	Material	Average Yield Point psi	Average Ultimate Strength psi	Type of Joint	Electrode	Average Fatigue Strength			
						$f_{100,000}$ psi	K_f	f_{2x10^6} psi	K_f
University of Illinois Bulletin No. 302	Carbon	31,800	63,600	Plain Plate				30,300	
	Nickel	60,000	99,200	Plain Plate				39,500	
	Silicon	47,300	80,200	Plain Plate				35,800	
	Carbon			Double Lap Riveted				25,900	1.13
	Nickel			Double Lap Riveted				26,700	1.48
	Silicon			Double Lap Riveted				25,600	1.40
Bulletin 310	Carbon*	30,960	54,500	Plain Plate				30,300	
	Silicon*	49,800	80,700	Plain Plate				35,800	
	Carbon			Transverse Butt Weld					
				(a) as-welded				21,800	1.39
				(b) reinforcement removed				27,900	1.08
	Silicon			(a) as-welded				24,000	1.49
				(b) reinforcement removed				23,700	1.51
Bulletin 327	Carbon	34,800	61,300	Plain Plate		49,800		31,600	
				Transverse Butt Weld					
				(a) as-welded		33,100	1.51	22,500	1.41
				(b) reinforcement removed		44,500	1.12	26,300	1.20

* Same steels used for tests in Bulletin 302

TABLE 1 (Continued)

Reference	Material	Average Yield Point psi	Average Ultimate Strength psi	Type of Joint	Electrode	Average Fatigue Strength $f_{100,000}$ psi	K_f	f_{2x10^6} psi	K_f
Bulletin 344	A-7			Transverse Butt Weld					
		30,700	58,960	as-welded	E6012	34,700	1.28	21,200	1.39
		39,500	62,300	as-welded	E6030	31,600	1.41	21,500	1.37
		31,000	60,230	as-welded	E6010	30,800	1.45	21,200	1.39
				as-welded*		34,000	1.31	22,300	1.32
Bulletin 380	A-7	38,820	63,730	Fillet Welds Connecting Plates		21,640	2.27	9,640	3.60
				Transverse Tee Fillet		19,100	2.57	9,630	3.60
				Longitudinal Fillet Weld		27,200	1.80	19,700	1.76
				Transverse Fillet Weld		30,300	1.62	18,500	1.87
				Longitudinal and Transverse Fillet Welds		28,300	1.73	20,500	1.69
Bulletin 384	A-7	35,800	60,800	Plain Plate					
				(a) half in.		49,000		34,700	
				(b) seven-eighth in.		44,500		29,500	
				Transverse Butt Weld	E6010	35,600	1.38	28,900	1.20
					E6012	38,100	1.29	26,500	1.31

* Joints commercially manufactured

TABLE 2

CHEMICAL COMPOSITION OF STEEL PLATES

Steel	Designation	C	Mn	P	S	Si	Cu	Cr	Ni	Al
		Chemical Content in Per Cent*								
A-7	S	0.17	0.68	0.016	0.039	0.03	----	----	----	----
A-242	B	0.20	1.08	0.010	0.025	0.10	0.38	----	0.60	----
A-373	D	0.21	0.60	0.030	0.030	0.053	0.20	----	----	----
T-1	C	0.15	0.83	0.013	0.015	0.28	0.19	0.54	0.93	0.031
HY 80	E	Not available								

*Check analysis

TABLE 3

PHYSICAL PROPERTIES OF STEEL PLATES

Steel	Designation	Yield Point psi	Maximum Strength psi	Per Cent Elongation	Per Cent Reduction of Area
A-7	S	34,500	56,900	33.0	62.0
A-242	B	47,800	73,600	27.0	58.0
A-373	D	34,600	67,000	28.0	48.6
T-1	C	111,900*	126,600	22.0**	69.1
T-1 (Heat-treated)		97,000*	134,100	15.7**	55.4
HY 80	E	82,700	93,600	23.5**	74.0

* Based on 0.2 per cent offset

** Based on 2 in. gage length

TABLE 4

OUTLINE OF TESTING PROGRAM

Series Designation	Fatigue Machine	Steel	Number of Specimens Tested	Nominal Diameter of Specimen	Notched Diameter	Theoretical Stress Concentration Factor
AWS	Wilson	A-7	14	0.375		
ASS	Sonntag	A-7	16	0.375		
AWS-U	Wilson	A-7	21	0.375	0.287	1.92
AWS-X	Wilson	A-7	10	0.375	0.311	4.00
AWS-v	Wilson	A-7	13	0.375	0.295	2.80
ASS-Y	Sonntag	A-7	19	0.500	0.400	
ASS-V	Sonntag	A-7	23	0.500	0.400	3.10
ASB-V	Sonntag	A-242	21	0.500	0.400	3.10
ASB-Y	Sonntag	A-242	10	0.500	0.400	
ASD-Y	Sonntag	A-373	14	0.500	0.400	
ASC-V	Sonntag	T-1	15	0.500	0.400	3.10
ASC-V-H	Sonntag	T-1*	15	0.500	0.400	3.10
ASE-V	Sonntag	HY 80	13	0.500	0.400	3.10

* Heat-treated

TABLE 5

FATIGUE RESULTS OF UNNOTCHED THREE-EIGHTH INCH DIAMETER SPECIMENS

SERIES AWS

Specimen	True Stress Range Minimum psi	True Stress Range Maximum psi	Percent Change in Area	Cycles to Failure in Thousands	Remarks
AWS-4	2,900	56,800	5.7	684.6	
AWS-6	1,700	40,000	---	2,090.3+	No failure
AWS-7	1,700	55,600	3.3	1,234.3	
AWS-9	2,700	54,200	5.2	2,686.9	
AWS-10	1,800	57,000	5.4	552.1	
AWS-11	1,800	58,000	6.4	690.3	
AWS-12	2,700	56,000	8.5	975.3	
AWS-13	2,100	54,500	5.7	890.3	
AWS-14	1,000	53,500	5.4	1,175.5	
AWS-15	1,700	68,700	16.8	143.8	
AWS-16	1,200	64,000	10.5	299.6	
AWS-17	1,300	62,700	10.4	349.9	
AWS-18	1,200	57,000	7.2	581.9	
AWS-19	1,400	53,000	3.2	2,009.5	

TABLE 6

FATIGUE RESULTS OF UNNOTCHED THREE-EIGHTH INCH DIAMETER SPECIMENS

SERIES ASS

Specimen	True Stress Range Minimum psi	True Stress Range Maximum psi	Percent Change in Area	Cycles to Failure in Thousands	Remarks
ASS-3	3,900	60,000	12.6	380.0	
ASS-4	1,100	56,500	11.4	400.0	
ASS-5	1,100	47,500	5.4	3,524.0+	No failure
ASS-6	1,100	51,800	7.4	929.0	
ASS-7	1,300	62,500	21.6	564.0	
ASS-8	1,200	58,600	19.8	795.0	
ASS-10	1,200	61,700	17.4	277.0	
ASS-11	1,200	58,400	13.5	390.0	
ASS-12	1,000	48,800	4.8	864.0	
ASS-13	1,100	55,000	12.0	632.0	
ASS-14	1,100	48,600	5.8	1,836.0+	Specimen failed in the threads
ASS-15	1,100	48,600	5.2	1,577.0	
ASS-16	1,100	50,400	6.9	910.0	
ASS-17	1,000	48,330	4.8	2,124.0	
ASS-18	1,100	49,000	5.4	1,126.0	
ASS-19	1,000	48,800	3.7	3,173.0	

TABLE 7

FATIGUE RESULTS OF NOTCHED THREE-EIGHTH

INCH DIAMETER SPECIMENS

SERIES AWS-U

Specimen	True Stress Range Minimum psi	True Stress Range Maximum psi	Cycles to Failure in Thousands	Remarks
AWS-20-U	1,500	44,500	960.0	Micro-switch failed to trip
AWS-21-U	1,400	43,000	649.4	
AWS-22-U	1,400	43,000	566.9	
AWS-23-U	1,400	48,500	116.3	
AWS-24-U	1,400	48,000	132.0	
AWS-25-U	1,400	47,600	136.0	
AWS-26-U	1,400	43,800	330.5	
AWS-27-U	1,400	43,700	361.5	
AWS-28-U	1,000	43,700	344.5	
AWS-29-U	1,400	44,800	237.0	
AWS-30-U	1,400	44,000	388.5	Micro-switch failed to trip
AWS-31-U	1,400	45,900	211.7	
AWS-32-U	1,400	46,400	145.1	
AWS-33-U	1,900	43,200	387.6	
AWS-35-U	2,400	44,800	207.7	
AWS-36-U	1,000	41,100	926.6	
AWS-37-U	1,400	41,700	415.8	
AWS-39-U	1,400	41,100	615.1	
AWS-40-U	1,400	38,600	985.0	
AWS-41-U	3,400	37,000	2,386.0	
AWS-43-U	2,000	37,000	1,068.4	Micro-switch failed to trip

TABLE 8

FATIGUE RESULTS OF NOTCHED THREE-EIGHTH

INCH DIAMETER SPECIMENS

SERIES AWS-X

Specimen	True Stress Range		Cycles to Failure in Thousands	Remarks
	Minimum psi	Maximum psi		
AWS-44-X	1,600	37,800	118.8	
AWS-45-X	1,600	38,700	97.6	
AWS-46-X	1,200	34,800	154.7	
AWS-47-X	1,600	31,000	391.0	
AWS-48-X	1,600	29,700	338.2	
AWS-49-X	1,600	22,200	2,608.5+	No failure
AWS-50-X	1,600	26,500	2,359.6	
AWS-51-X	1,600	26,000	1,091.1	
AWS-52-X	1,200	26,500	1,286.9	
AWS-53-X	1,200	27,700	646.8	

TABLE 9

FATIGUE RESULTS OF NOTCHED THREE-EIGHTH

INCH DIAMETER SPECIMENS

SERIES AWS-v

Specimen	True Stress Range Minimum psi	True Stress Range Maximum psi	Cycles to Failure in Thousands	Remarks
AWS-54-v	1,700	28,870	2,119.2	
AWS-55-v	1,300	29,300	1,396.2	
AWS-56-v	1,700	33,690	398.3	
AWS-57-v	1,700	33,700	365.2	
AWS-58-v	1,700	35,000	367.8	
AWS-59-v	1,700	40,700	120.4	
AWS-60-v	1,300	39,000	152.9	
AWS-61-v	1,300	29,500	1,255.4	
AWS-62-v	1,300	30,850	634.5	
AWS-63-v	2,200	31,100	1,028.5	
AWS-64-v	1,700	30,410	839.7	
AWS-65-v	1,300	38,100	160.1	
AWS-66-v	1,300	38,300	173.7	

TABLE 10

FATIGUE RESULTS OF NOTCHED ONE-HALF

INCH DIAMETER SPECIMENS

SERIES ASS-Y

Specimen	True Stress Range Minimum psi	True Stress Range Maximum psi	Cycles to Failure in Thousands	Remarks
ASS-22-Y	1,000	25,300	4,223.0	
ASS-23-Y	1,000	27,000	1,953.0	
ASS-24-Y	1,000	30,000	283.0	
ASS-25-Y	1,000	27,000	401.0	
ASS-26-Y	1,000	27,000	1,215.0	
ASS-27-Y	1,000	27,000	5,597.0+	No failure
ASS-28-Y	1,000	30,000	586.0	
ASS-29-Y	1,000	35,000	153.0	
ASS-30-Y	1,000	35,000	121.0	
ASS-31-Y	1,000	35,000	141.0	
ASS-32-Y	1,000	30,000	331.0	
ASS-33-Y	1,000	30,000	217.0	
ASS-34-Y	1,000	30,000	566.0	
ASS-35-Y	1,000	35,000	111.0	
ASS-36-Y	1,000	30,000	342.0	
ASS-37-Y	1,000	26,000	1,014.0	
ASS-38-Y	1,000	26,000	675.0	
ASS-39-Y	1,000	26,000	454.0	
ASS-40-Y	1,000	25,000	2,373.0	

TABLE 11

FATIGUE RESULTS OF NOTCHED ONE-HALF

INCH DIAMETER SPECIMENS

SERIES ASS-V

Specimen	True Stress Range Minimum psi	True Stress Range Maximum psi	Cycles to Failure in Thousands	Remarks
ASS-42-V	1,000	29,800	517.0	
ASS-43-V	1,000	30,000	469.0	
ASS-44-V	1,000	30,000	308.0	
ASS-46-V	1,000	30,000	238.0	
ASS-47-V	1,000	30,000	272.0	
ASS-48-V	1,000	30,000	216.0	
ASS-49-V	1,000	30,000	573.0	
ASS-50-V	1,000	25,000	1,210.0	
ASS-51-V	1,000	25,000	1,740.0	
ASS-52-V	1,000	24,000	1,036.0	
ASS-53-V	1,000	24,000	565.0	
ASS-54-V	1,000	24,000	4,262.0+	No failure
ASS-55-V	1,000	35,000	136.0	
ASS-56-V	1,000	35,000	132.0	
ASS-57-V	1,000	35,000	236.0	
ASS-58-V	1,000	35,000	173.0	
ASS-59-V	1,000	23,000	5,069.0+	No failure
ASS-60-V	1,000	24,000	8,249.0+	No failure
ASS-61-V	1,000	30,000	295.0	
ASS-62-V	1,000	24,000	2,607.0	
ASS-63-V	1,000	25,000	600.0	
ASS-64-V	1,000	35,000	147.0	
ASS-65-V	1,000	35,000	140.0	

TABLE 12

FATIGUE RESULTS OF NOTCHED ONE-HALF

INCH DIAMETER SPECIMENS

SERIES ASB-V

Specimen	True Stress Range Minimum psi	True Stress Range Maximum psi	Cycles to Failure in Thousands	Remarks
ASB-1-V	1,000	30,000	597.0	
ASB-2-V	1,000	35,000	337.0	
ASB-3-V	1,000	35,000	229.0	
ASB-4-V	1,000	30,000	622.0	
ASB-5-V	1,000	30,000	238.0	
ASB-6-V	1,000	26,000	437.0	
ASB-6'-V	1,000	26,000	630.0	
ASB-7-V	1,000	24,000	1,726.0	
ASB-8-V	1,000	23,000	6,015.0+	No failure
ASB-9-V	1,000	35,000	272.0	
ASB-10-V	1,000	35,000	154.0	
ASB-11-V	1,000	35,000	144.0	
ASB-12-V	1,000	24,000	1,294.0	
ASB-13-V	1,000	25,000	1,062.0	
ASB-14-V	1,000	30,000	388.0	
ASB-15-V	1,000	25,000	336.0	
ASB-16-V	1,000	25,000	857.0	
ASB-17-V	1,000	23,000	2,117.0	
ASB-18-V	1,000	23,000	1,019.0	
ASB-19-V	1,000	22,000	1,708.0	
ASB-20-V	1,000	22,000	8,074.0	

TABLE 13

FATIGUE RESULTS OF NOTCHED ONE-HALF

INCH DIAMETER SPECIMENS

SERIES ASB-Y

Specimen	True Stress Range Minimum psi	True Stress Range Maximum psi	Cycles to Failure in Thousands	Remarks
ASB-21-Y	1,000	25,000	774.0	
ASB-22-Y	1,000	25,000	613.0	
ASB-23-Y	1,000	35,000	297.0	
ASB-24-Y	1,500	24,000	3,955.0+	No failure
ASB-25-Y	1,000	35,000	123.0	
ASB-26-Y	1,000	35,000	171.0	
ASB-27-Y	1,000	24,000	2,206.0	
ASB-28-Y	1,000	24,000	1,697.0	
ASB-29-Y	1,000	35,000	165.0	
ASB-30-Y	1,000	30,000	493.0	

TABLE 14

FATIGUE RESULTS OF NOTCHED ONE-HALF

INCH DIAMETER SPECIMENS

SERIES ASD-Y

Specimen	True Stress Range Minimum psi	True Stress Range Maximum psi	Cycles to Failure in Thousands	Remarks
ASD-1-Y	1,000	30,000	417.0	
ASD-2-Y	1,000	25,000	1,296.0	
ASD-3-Y	1,000	35,000	200.0	
ASD-4-Y	1,000	25,000	601.0	
ASD-5-Y	1,000	30,000	485.0	
ASD-6-Y	1,000	35,000	86.0	
ASD-7-Y	1,000	35,000	219.0	
ASD-8-Y	1,000	24,000	1,472.0	
ASD-9-Y	1,000	23,000	1,710.0	
ASD-10-Y	1,000	23,000	1,166.0	
ASD-11-Y	1,000	22,000	2,897.0	
ASD-12-Y	1,000	22,000	3,733.0	
ASD-13-Y	1,000	35,000	197.0	
ASD-14-Y	1,000	30,000	321.0	

TABLE 15

FATIGUE RESULTS OF NOTCHED ONE-HALF

INCH DIAMETER SPECIMENS

SERIES ASC-V

Specimen	True Stress Range Minimum psi	True Stress Range Maximum psi	Cycles to Failure in Thousands	Remarks
ASC-1-V	1,000	34,100	1,368.0	
ASC-2-V	1,000	39,000	207.0	
ASC-3-V	1,000	39,000	170.0	
ASC-4-V	1,000	33,000	592.0	
ASC-5-V	1,000	33,000	212.0	
ASC-6-V	1,000	30,000	3,518.0	
ASC-7-V	1,000	31,000	6,590.0+	No failure
ASC-8-V	1,000	35,000	2,823.0	
ASC-9-V	1,000	35,000	329.0	
ASC-10-V	1,000	35,000	202.0	
ASC-11-V	1,000	32,000	579.0	
ASC-12-V	1,000	35,000	519.0	
ASC-13-V	1,000	35,000	4,972.0+	No failure
ASC-14-V	1,000	39,000	330.0	
ASC-15-V	1,000	33,000	1,167.0	

TABLE 16

FATIGUE RESULTS OF NOTCHED ONE-HALF

INCH DIAMETER SPECIMENS

SERIES ASC-V-H

Specimen	True Stress Range Minimum psi	True Stress Range Maximum psi	Cycles to Failure in Thousands	Remarks
ASC-24-V-H	1,500	30,000	235.0	
ASC-25-V-H	1,500	24,000	573.0	
ASC-26-V-H	1,500	30,000	256.0	
ASC-27-V-H	1,500	30,000	221.0	
ASC-28-V-H	1,500	22,000	1,067.0	
ASC-29-V-H	1,500	35,000	119.0	
ASC-30-V-H	1,500	35,000	121.0	
ASC-31-V-H	1,500	21,000	845.0	
ASC-32-V-H	1,500	24,000	415.0	
ASC-33-V-H	1,500	24,000	408.0	
ASC-34-V-H	1,500	21,000	472.0	
ASC-35-V-H	1,500	20,000	610.0	
ASC-36-V-H	1,500	19,000	3,777.0+	No failure
ASC-37-V-H	1,500	20,000	949.0	
ASC-38-V-H	1,500	20,000	3,117.0+	No failure

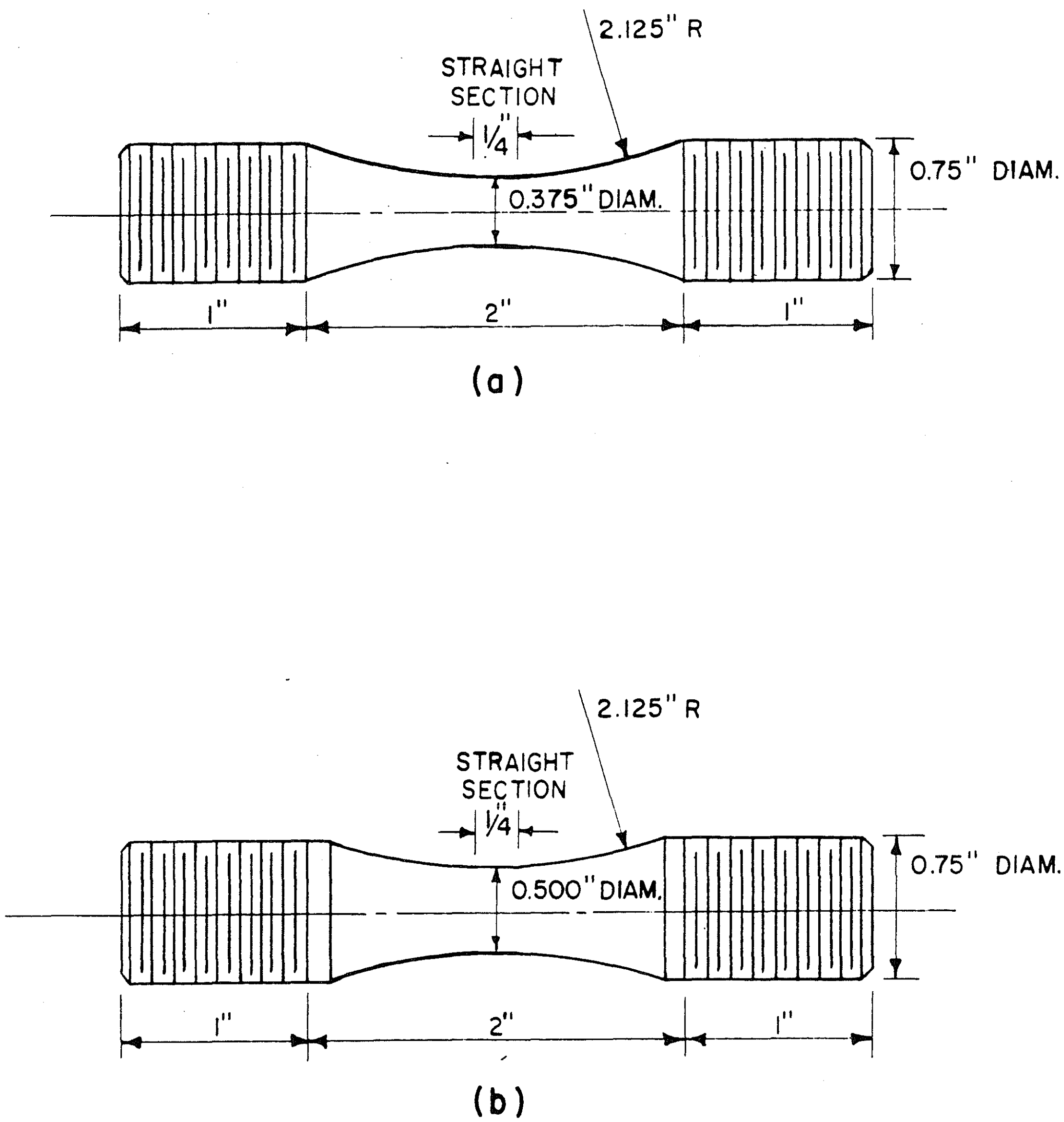
TABLE 17

FATIGUE RESULTS OF NOTCHED ONE-HALF

INCH DIAMETER SPECIMENS

SERIES ASE-V

Specimen	True Stress Range Minimum psi	True Stress Range Maximum psi	Cycles to Failure in Thousands	Remarks
ASE-1	1,500	30,000	476.0	
ASE-2	1,500	26,000	2,865.0+	No failure
ASE-3	1,500	30,000	510.0	
ASE-4	1,500	27,000	2,985.0+	No failure
ASE-5	1,500	28,000	2,213.0+	No failure
ASE-6	1,500	35,000	511.0	
ASE-8	1,500	39,000	202.0	
ASE-9	1,500	35,000	377.0	
ASE-11	1,500	45,000	128.0	
ASE-12	1,500	45,000	139.0	
ASE-13	1,500	39,000	305.0	
ASE-14	1,500	29,000	2,569.0	
ASE-15	1,500	35,000	1,839.0	



NOTE: Thread - 3/4-16NF-2 for SONNTAG SPECIMENS
Thread - 3/4-10NC-2 for WILSON SPECIMENS

FIG. 1 DETAILS OF AXIAL FATIGUE SPECIMENS

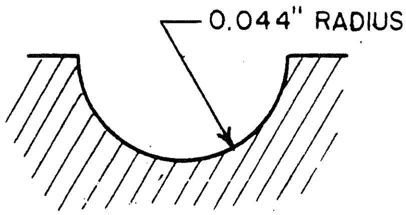
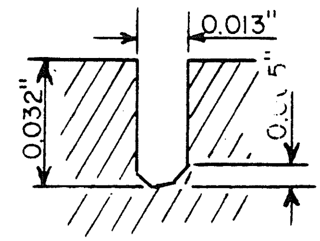
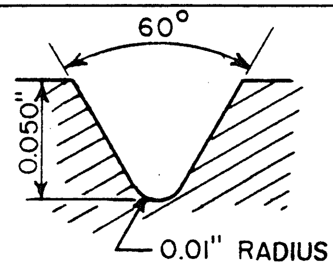
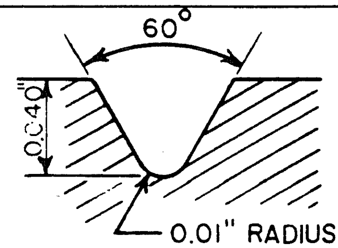
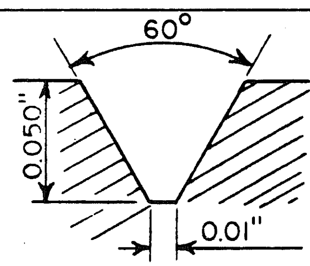
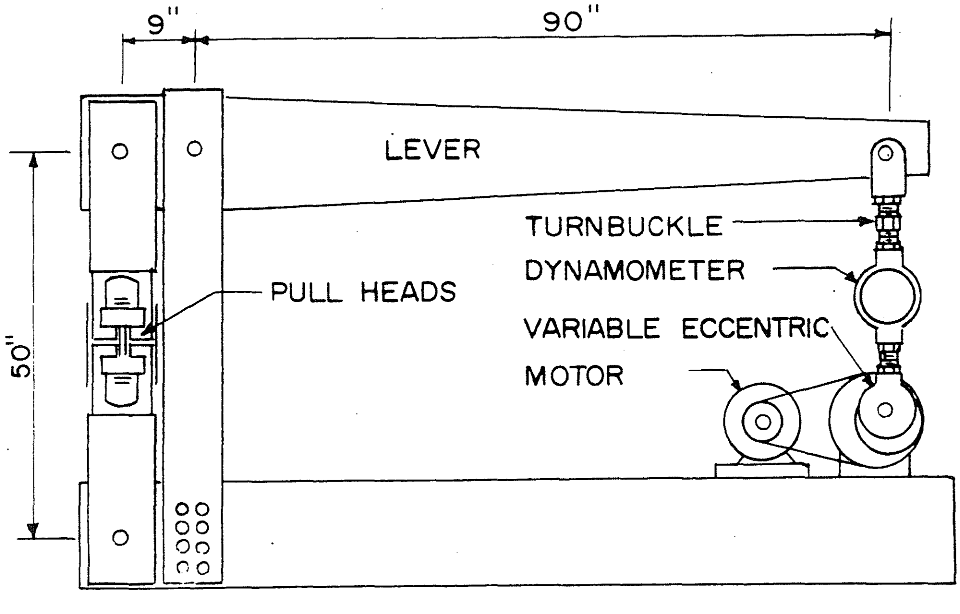
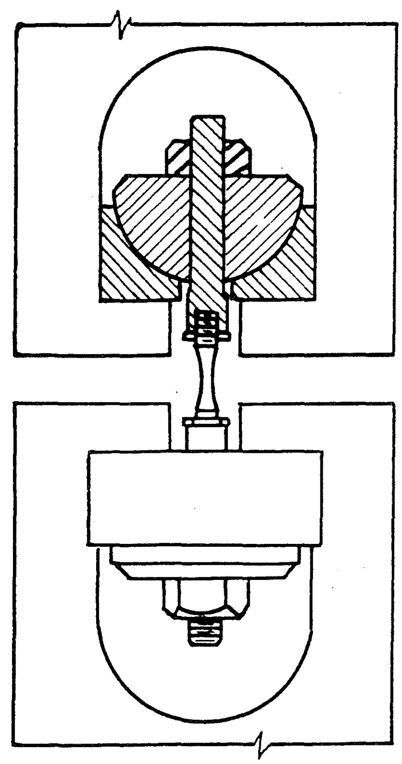
DETAIL OF NOTCH	THEORETICAL STRESS CONCENTRATION FACTOR	NOTCH DESIGNATION
	$K_t = 1.92$	U
	$K_t = 4.00$ Assumed root radius = 0.0065"	X
	$K_t = 3.10$	V
	$K_t = 2.80$	⌐v⌐
	—	Y

FIG. 2 NOTCH DETAILS AND DESIGNATIONS



a. DIAGRAMATIC SKETCH OF WILSON FATIGUE TESTING MACHINE



b. DETAIL OF SPHERICAL SEATS

FIG. 3 WILSON FATIGUE MACHINE ADAPTED FOR SMALL AXIAL TESTS

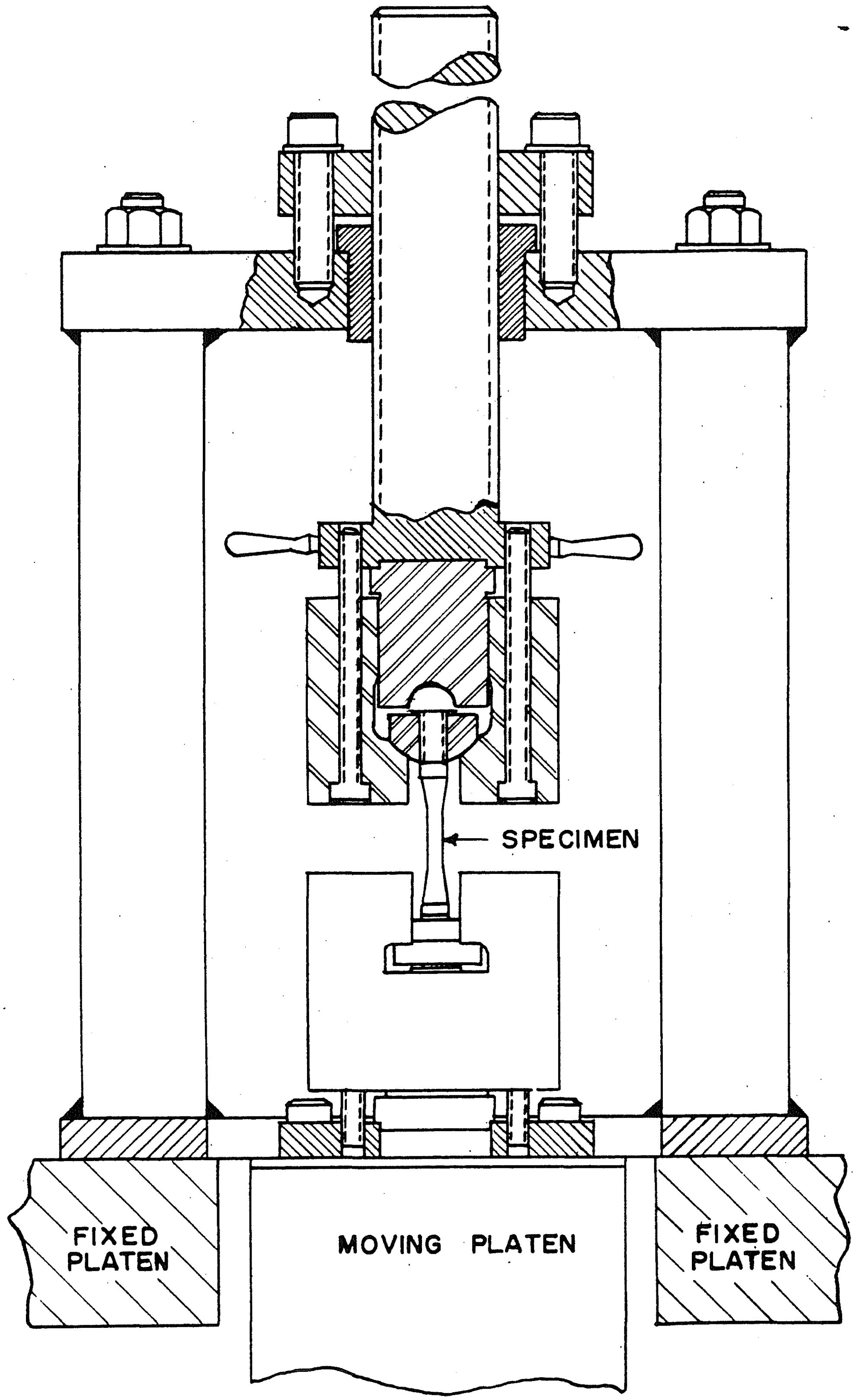


FIG. 4 SECTION DRAWING OF THE SONNTAG TENSION—COMPRESSION APPARATUS

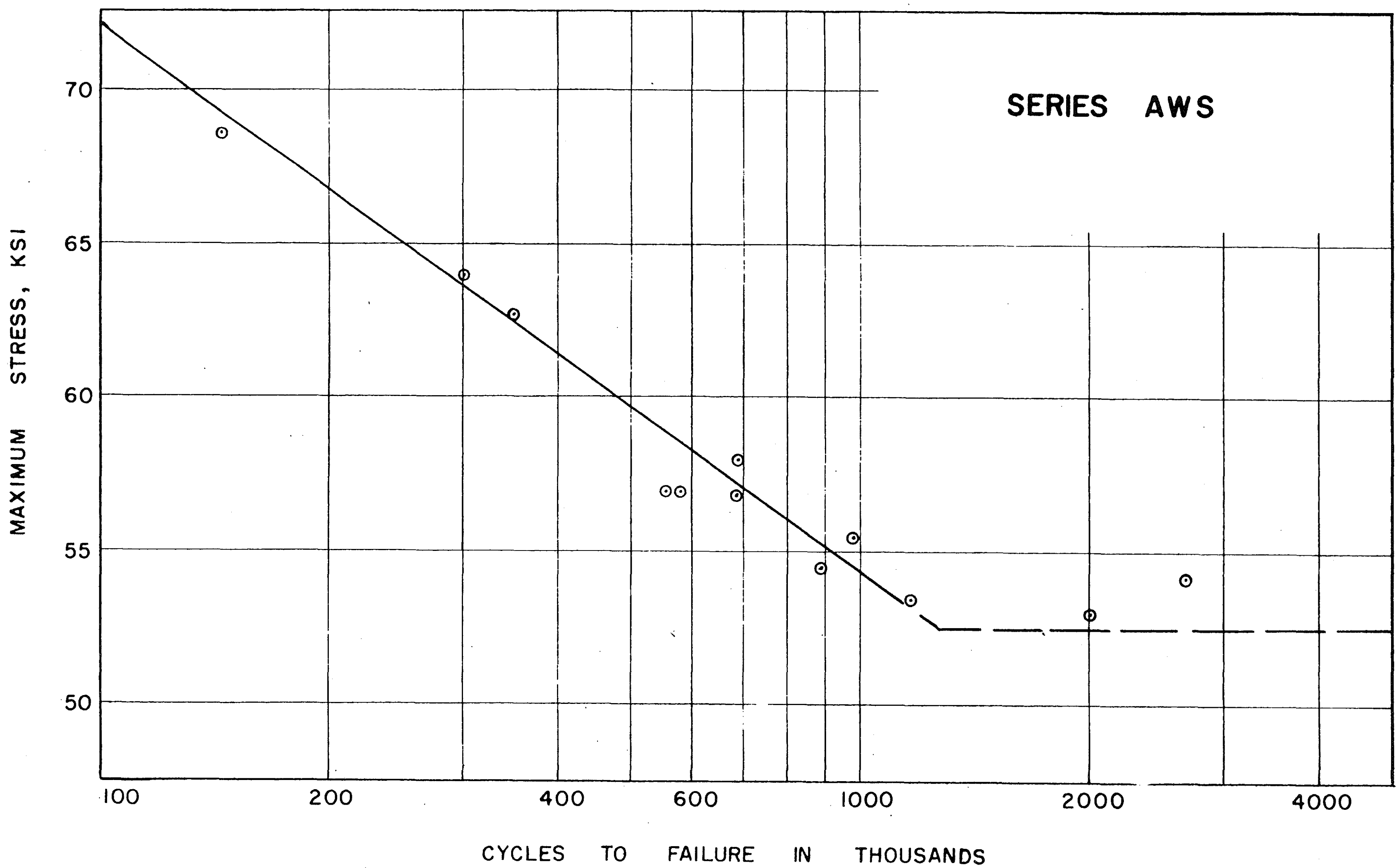


FIG. 5 FATIGUE RESULTS FOR THREE-EIGHTH INCH DIAMETER UNNOTCHED SPECIMENS IN A-7 STEEL

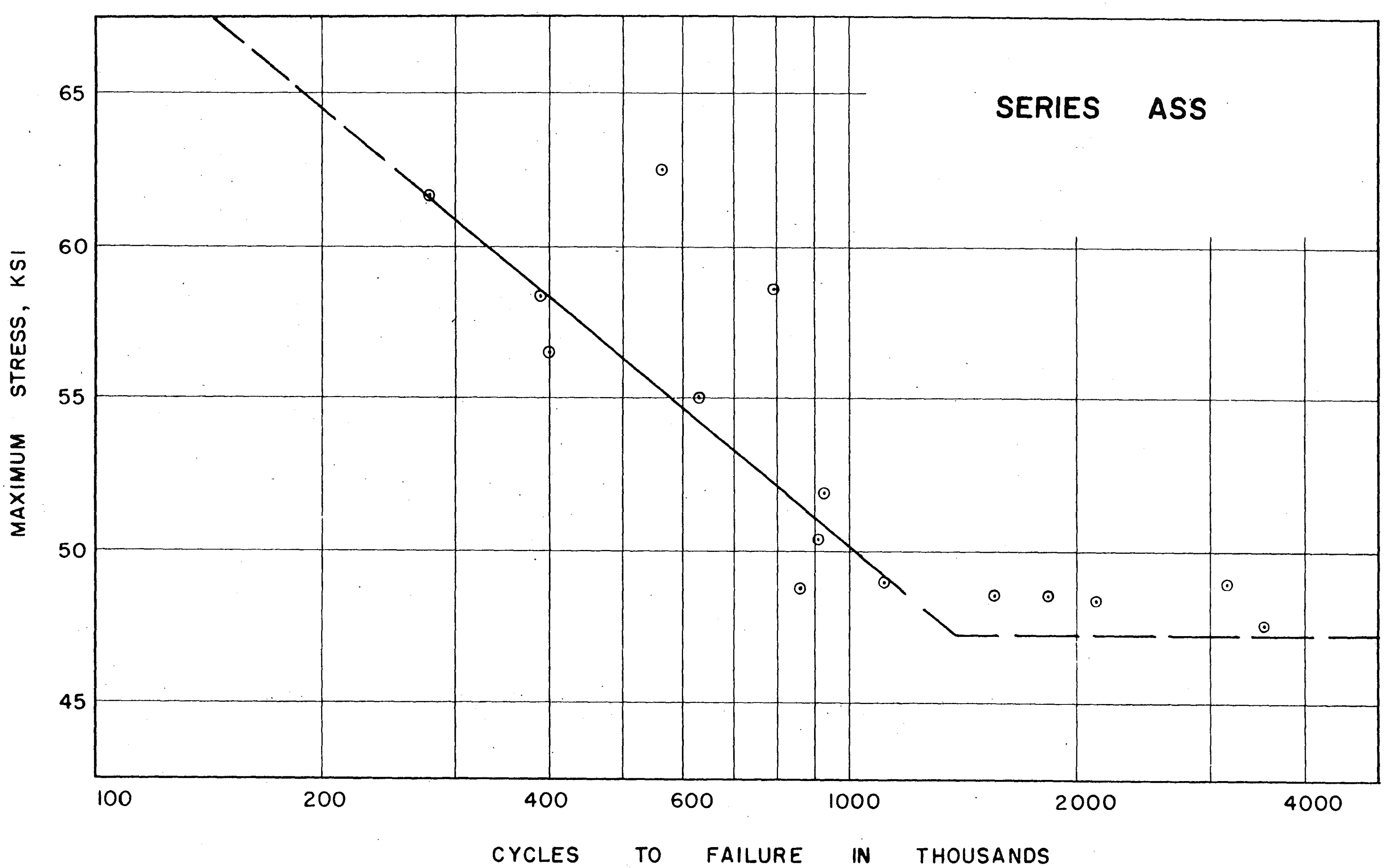


FIG. 6 FATIGUE RESULTS FOR THREE-EIGHTH INCH DIAMETER UNNOTCHED SPECIMENS IN A-7 STEEL

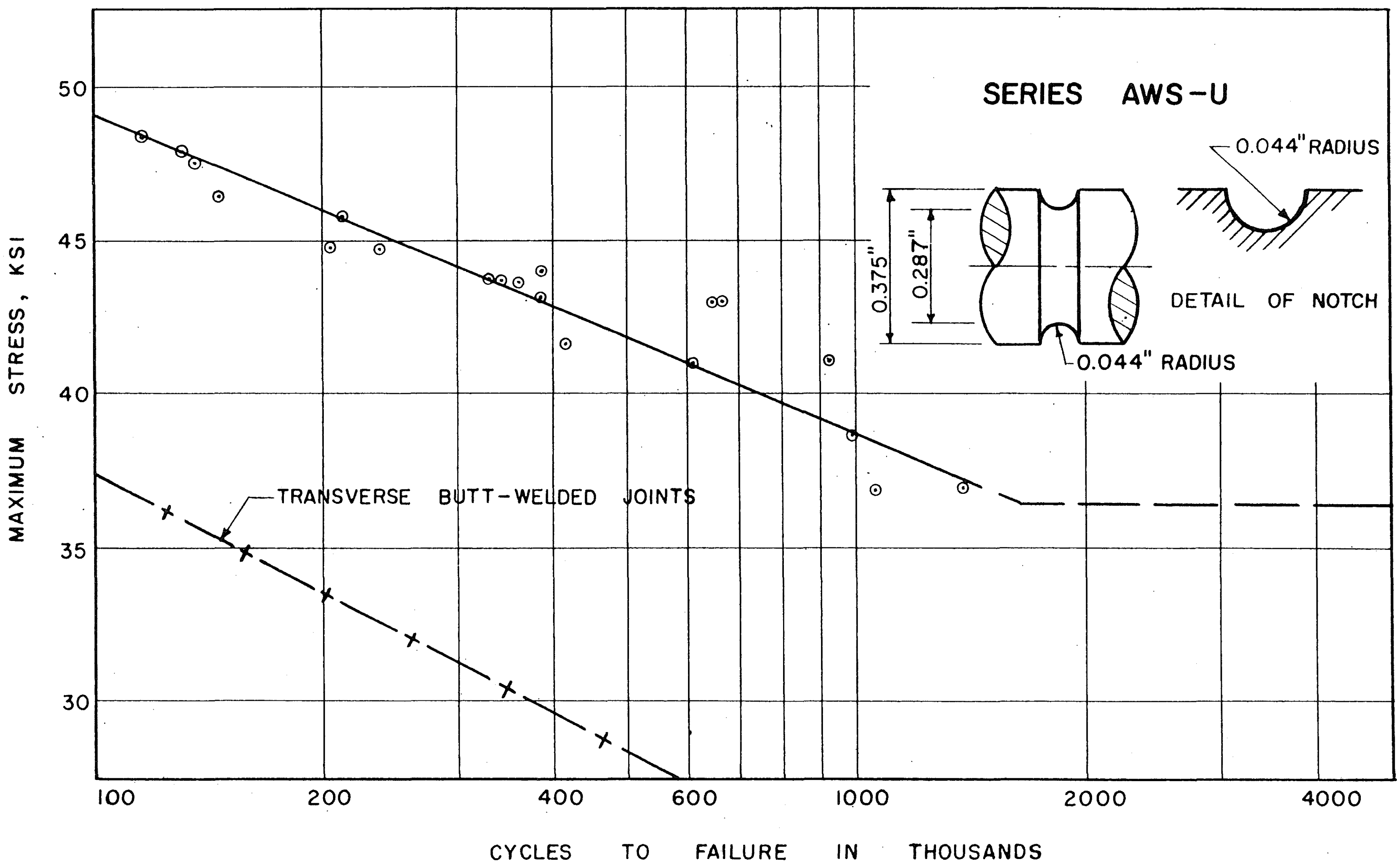


FIG. 7 FATIGUE RESULTS FOR THREE-EIGHTH INCH DIAMETER NOTCHED SPECIMENS IN A-7 STEEL

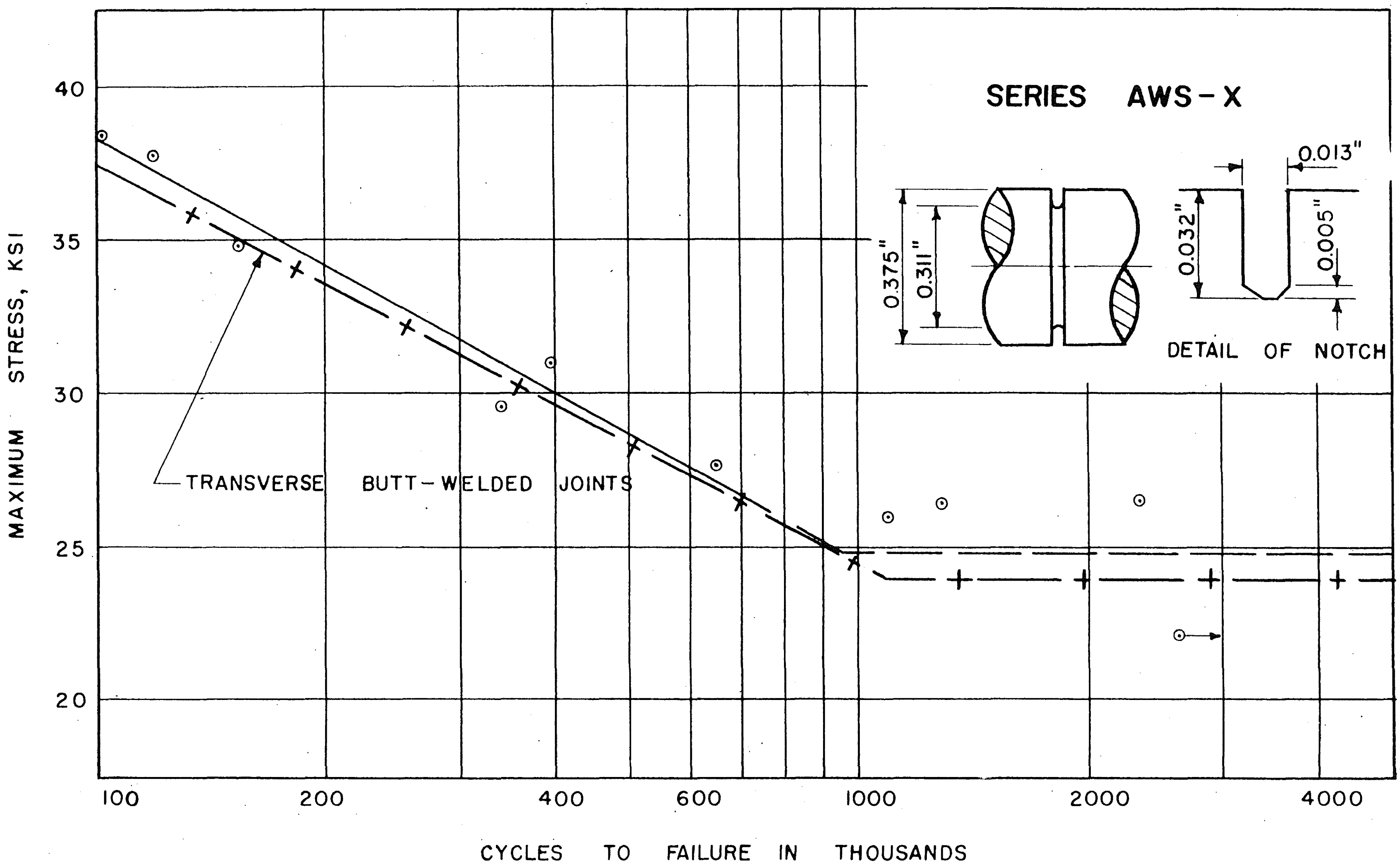


FIG. 8 FATIGUE RESULTS FOR THREE-EIGHTH INCH DIAMETER NOTCHED SPECIMENS IN A-7 STEEL

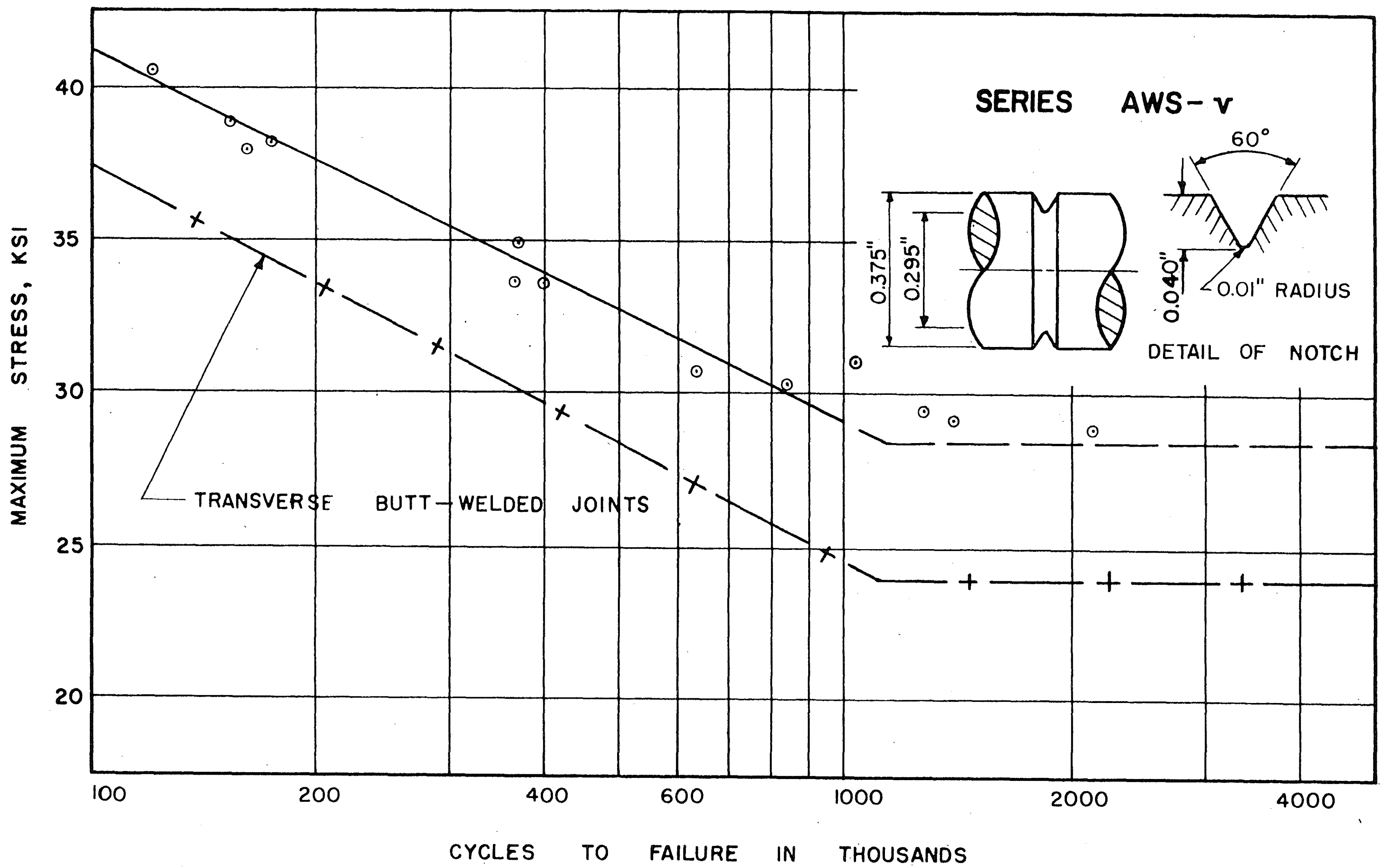


FIG. 9 FATIGUE RESULTS FOR THREE-EIGHTH INCH DIAMETER NOTCHED SPECIMENS IN A-7 STEEL

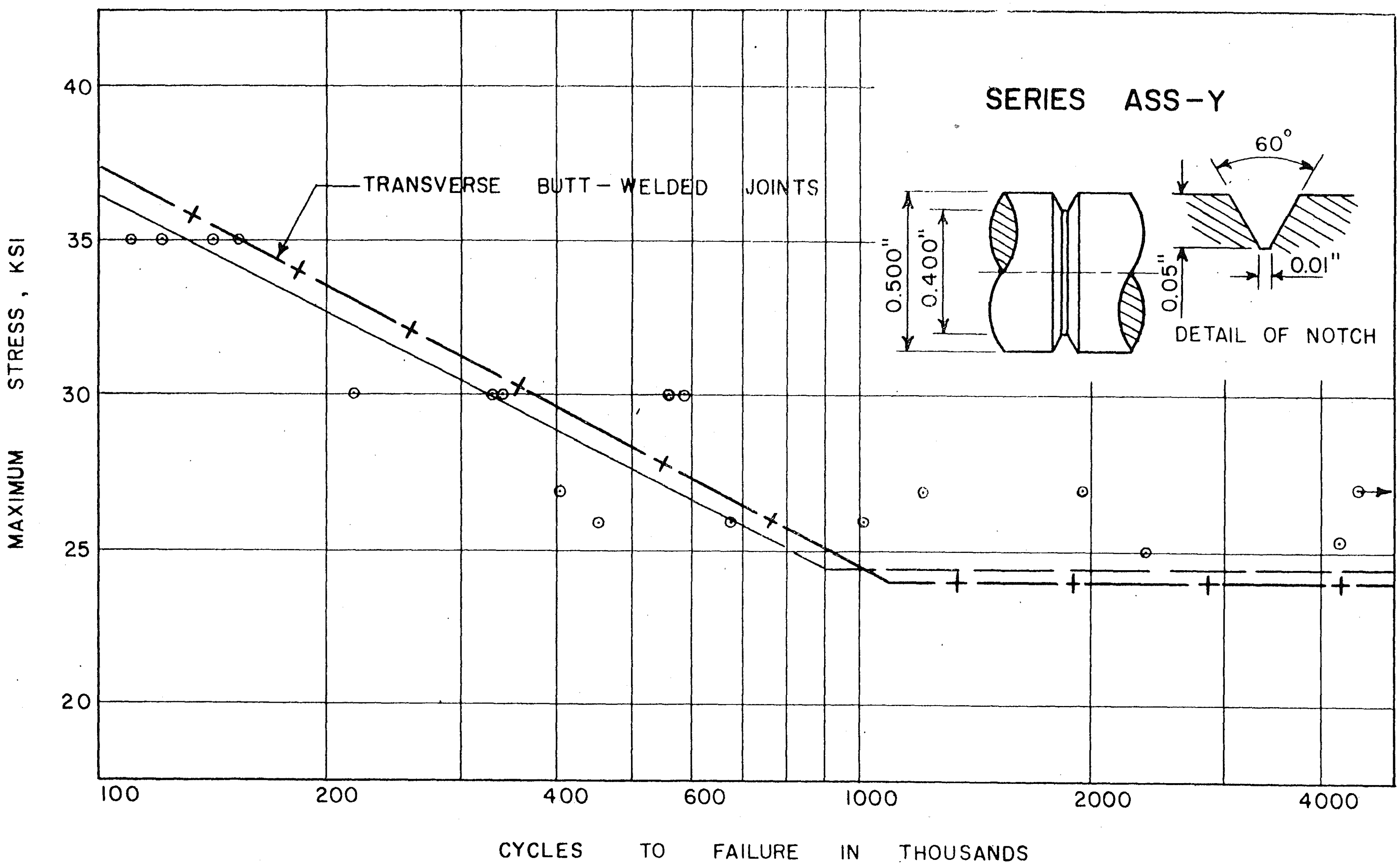


FIG. 10 FATIGUE RESULTS FOR ONE-HALF INCH DIAMETER NOTCHED SPECIMENS IN A-7 STEEL

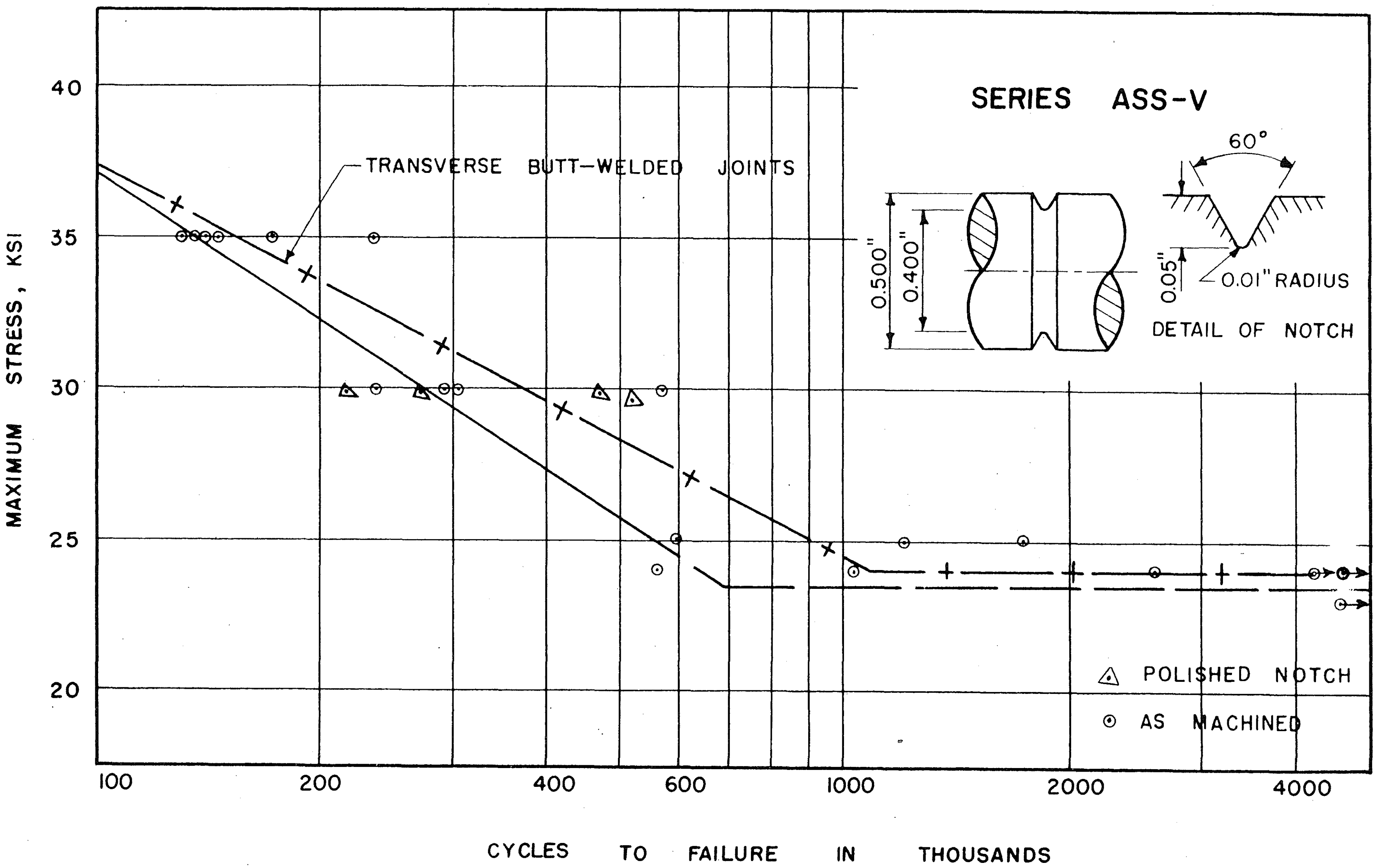


FIG. 11 FATIGUE RESULTS FOR ONE-HALF INCH DIAMETER NOTCHED SPECIMENS IN A-7 STEEL

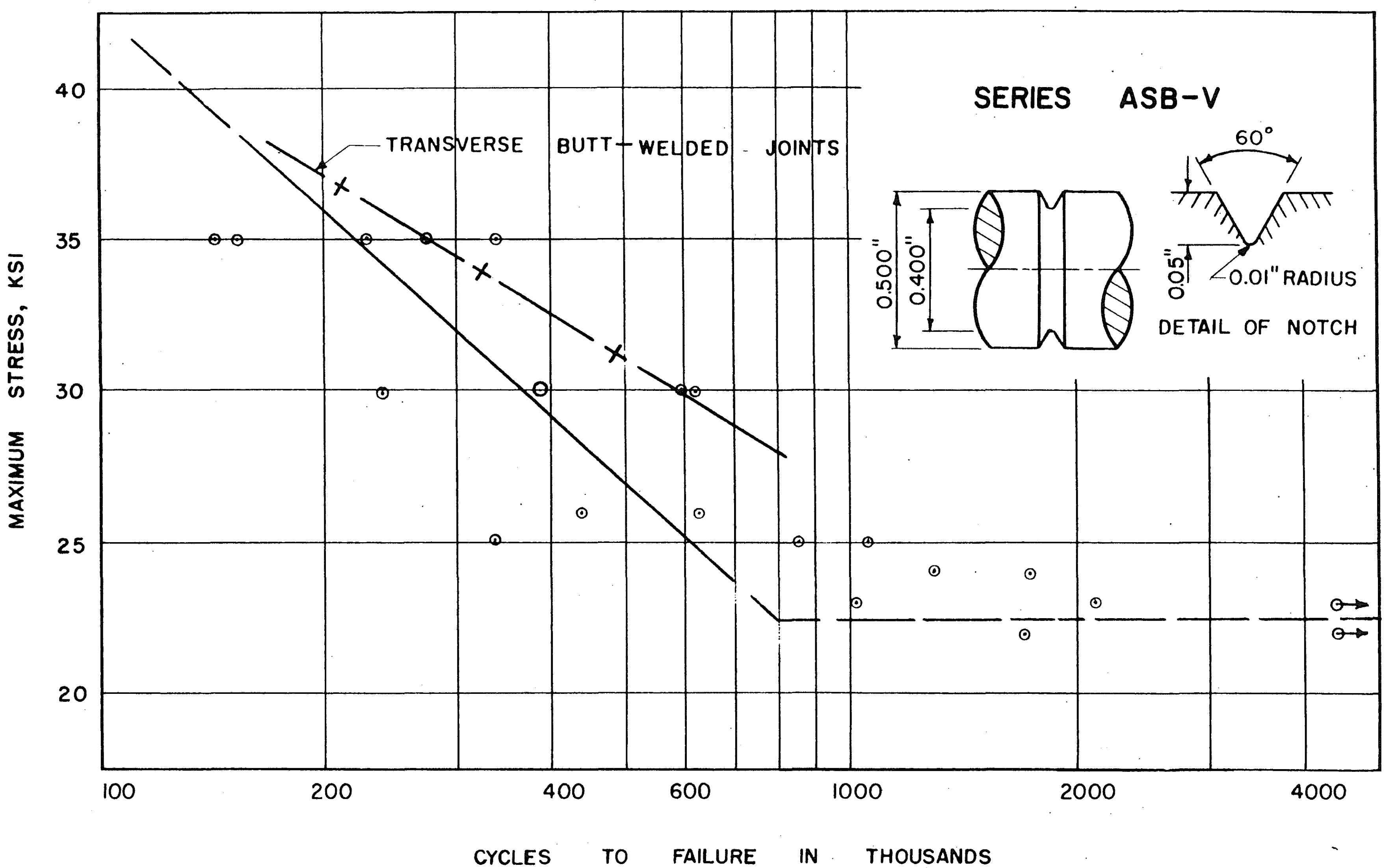


FIG. 12 FATIGUE RESULTS FOR ONE-HALF INCH DIAMETER NOTCHED SPECIMENS IN A-242 STEEL

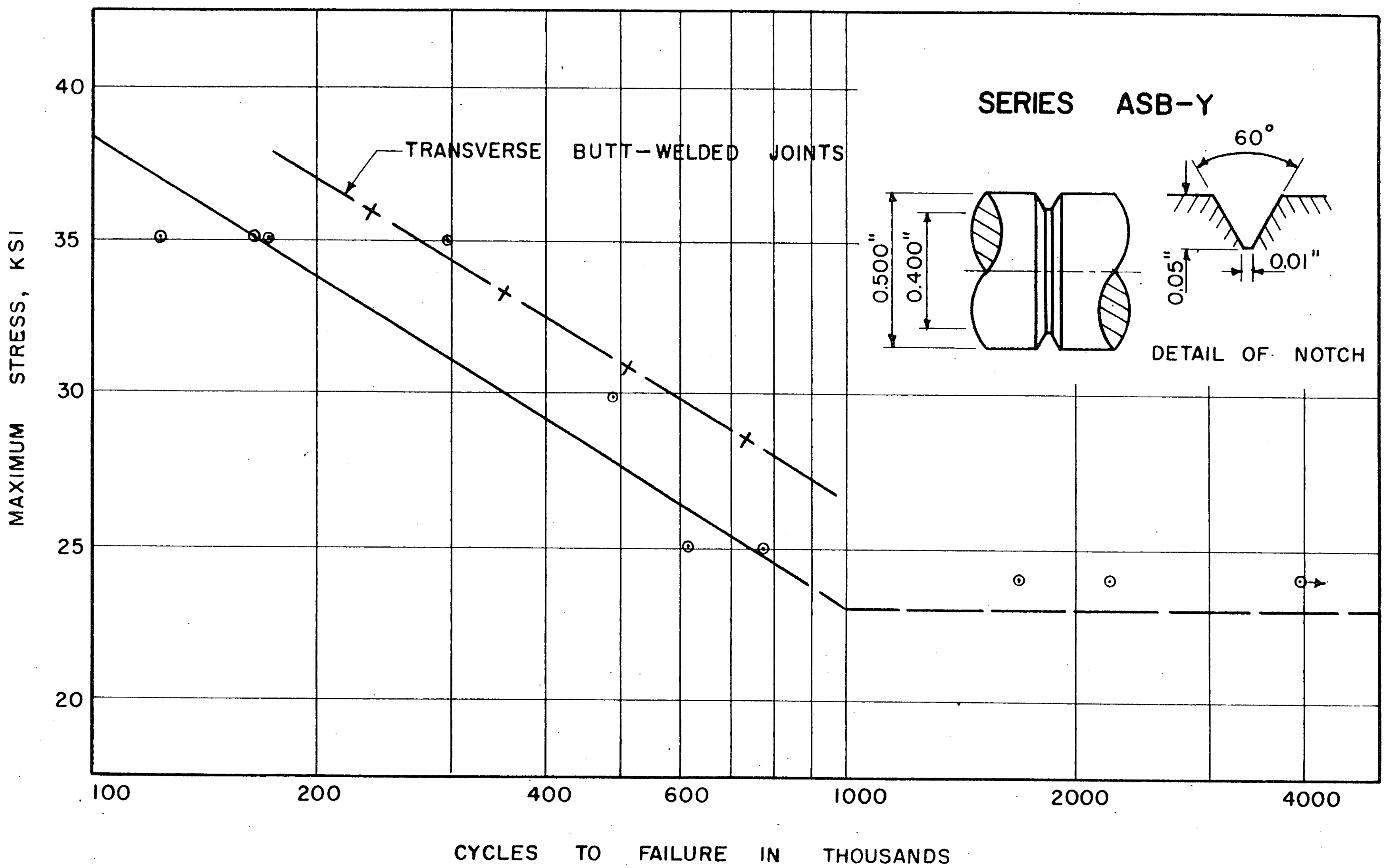


FIG. 13 FATIGUE RESULTS FOR ONE-HALF INCH DIAMETER NOTCHED SPECIMENS IN A-242 STEEL

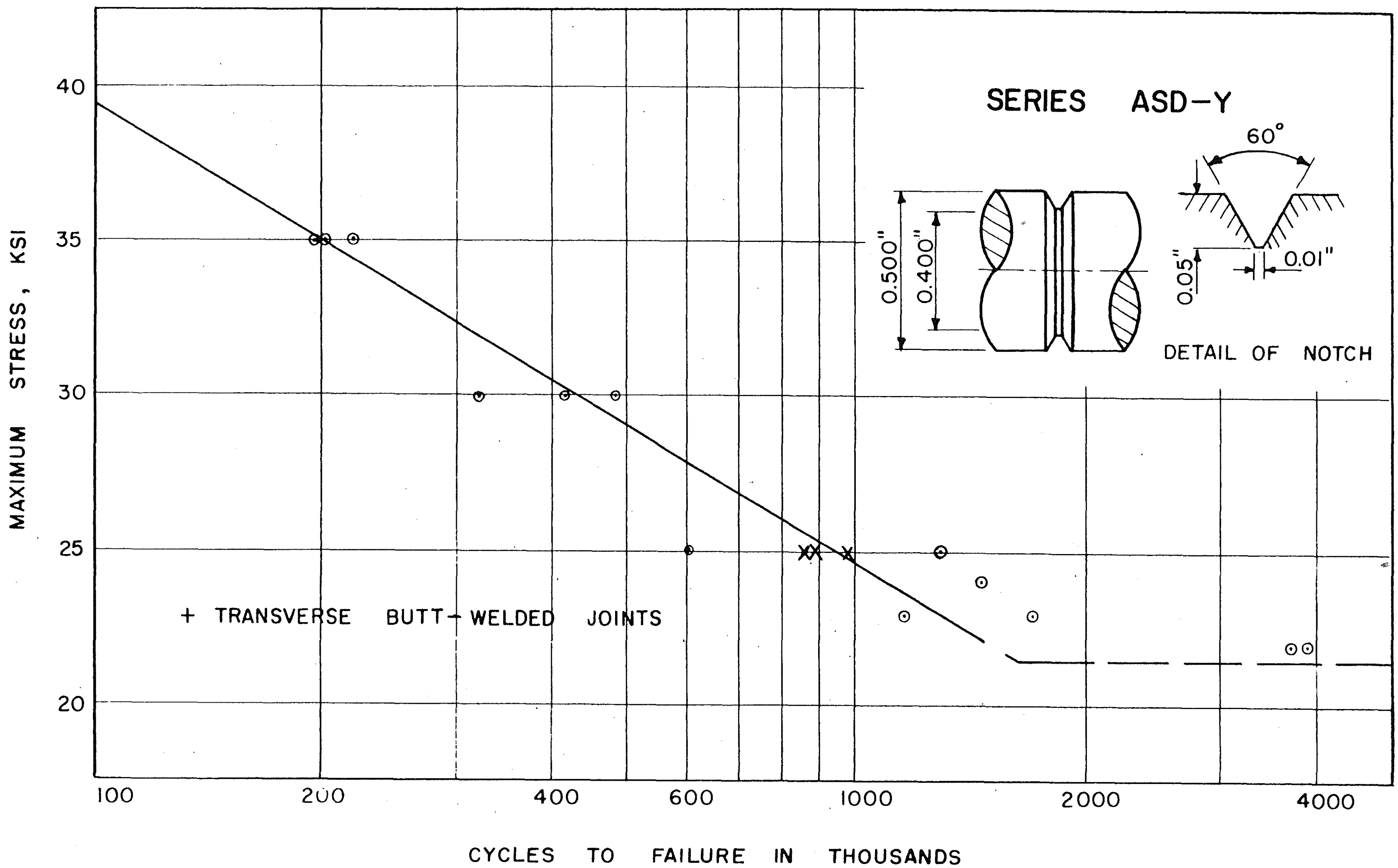


FIG. 14 FATIGUE RESULTS FOR ONE-HALF INCH DIAMETER NOTCHED SPECIMENS IN A-373 STEEL

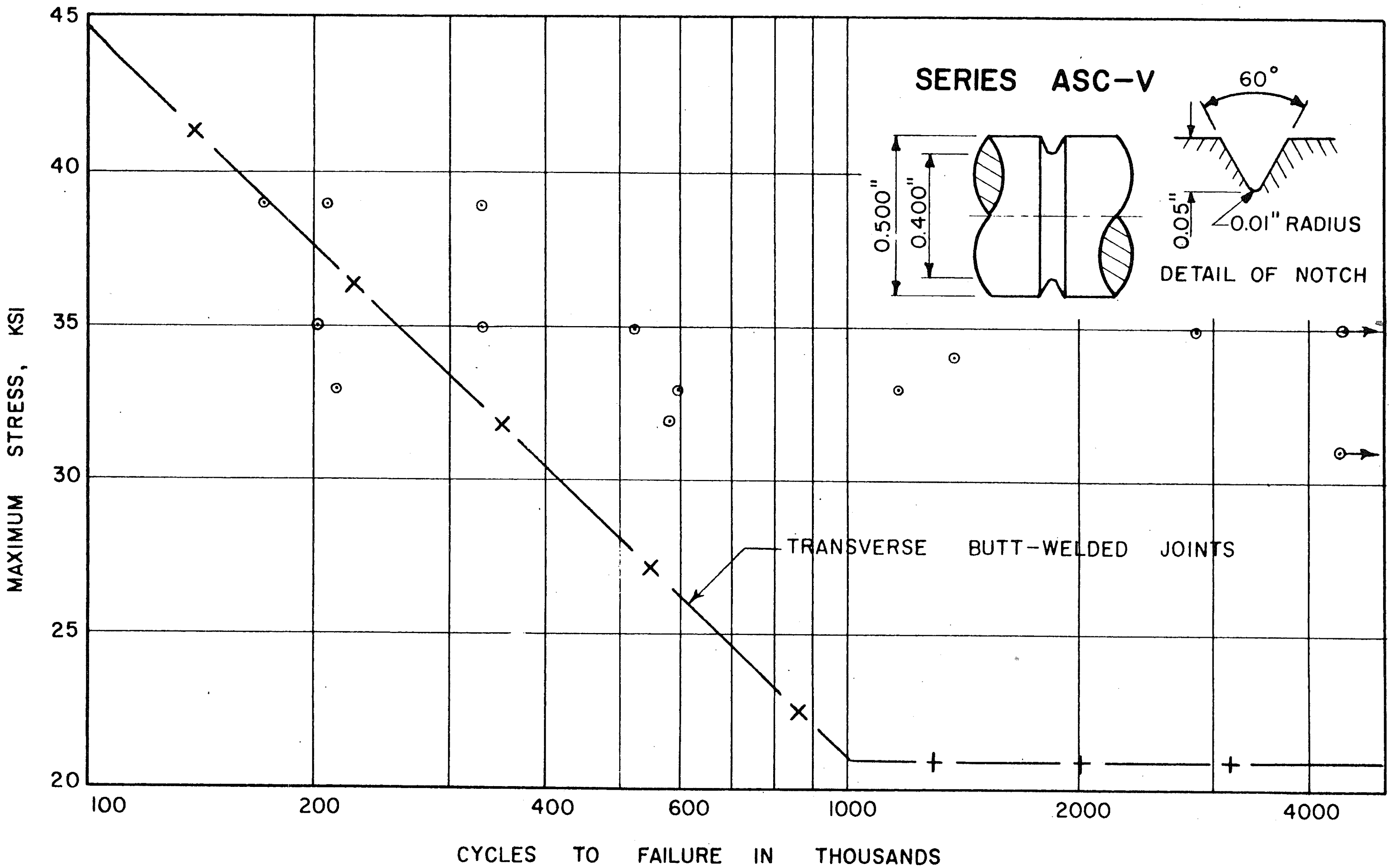


FIG. 15 FATIGUE RESULTS FOR ONE-HALF INCH DIAMETER NOTCHED SPECIMENS IN T-1 STEEL

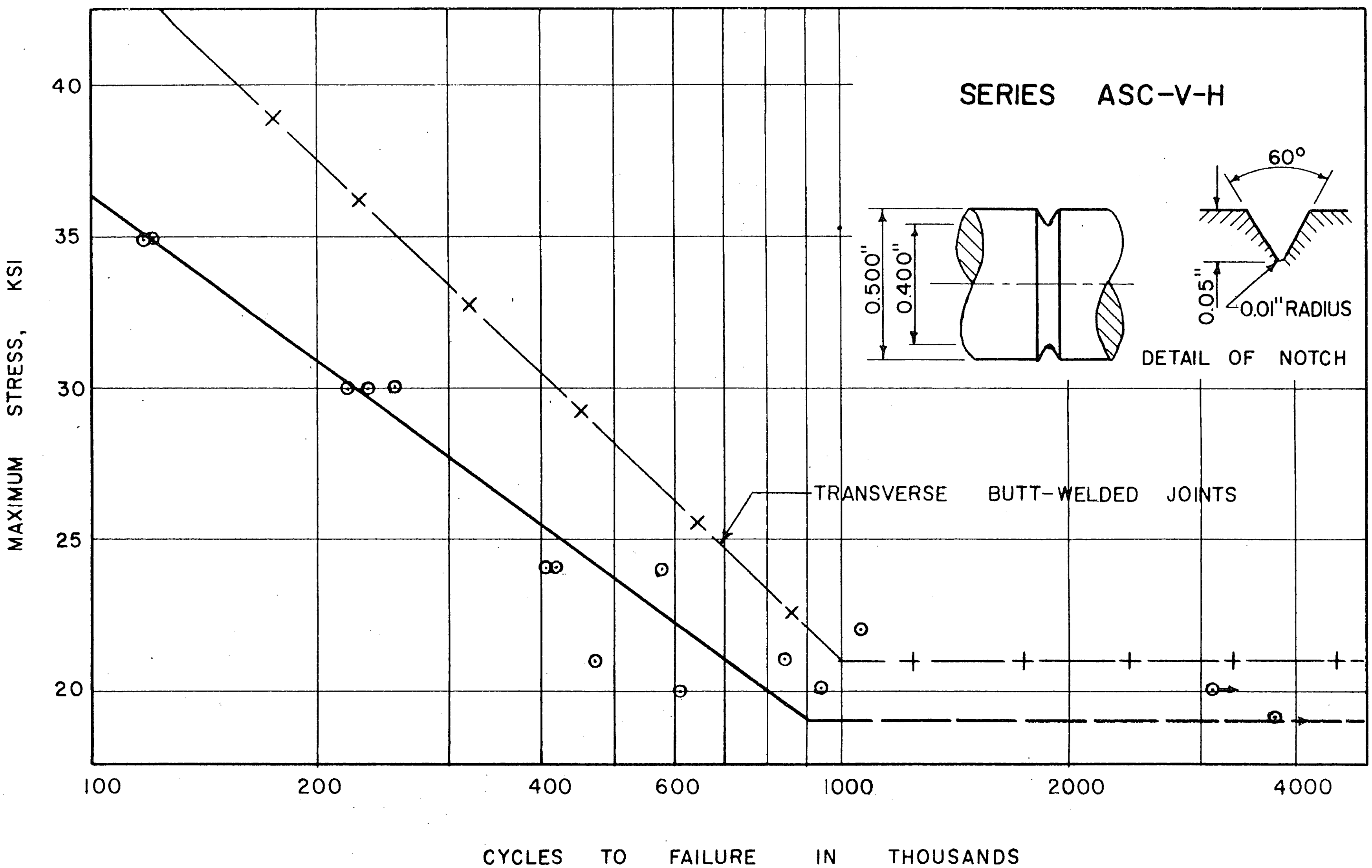


FIG. 16 FATIGUE RESULTS FOR ONE-HALF INCH DIAMETER NOTCHED SPECIMENS IN HEAT-TREATED T-1 STEEL

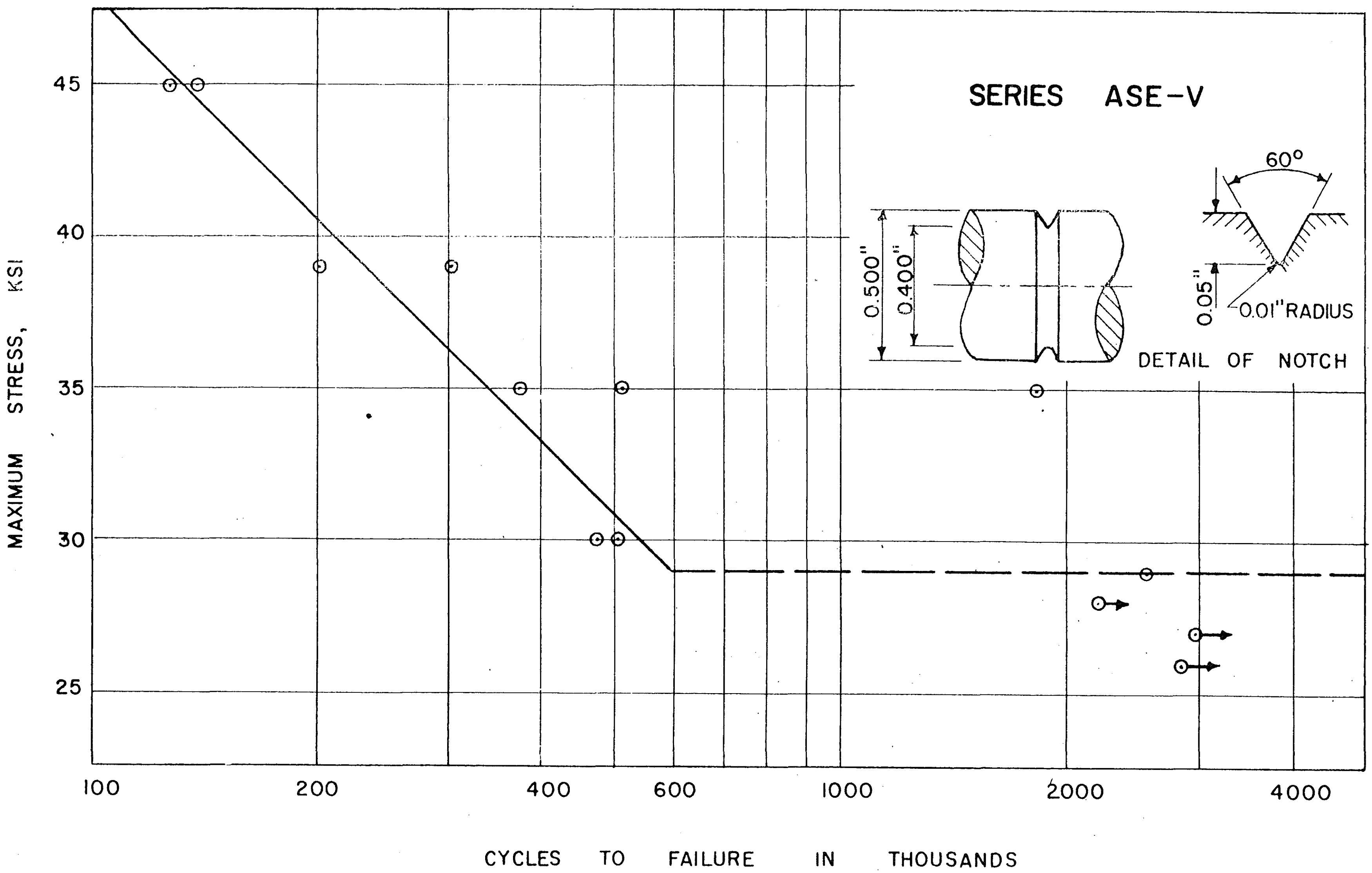


FIG. 17 FATIGUE RESULTS FOR ONE-HALF INCH DIAMETER NOTCHED SPECIMENS IN HY 80 STEEL

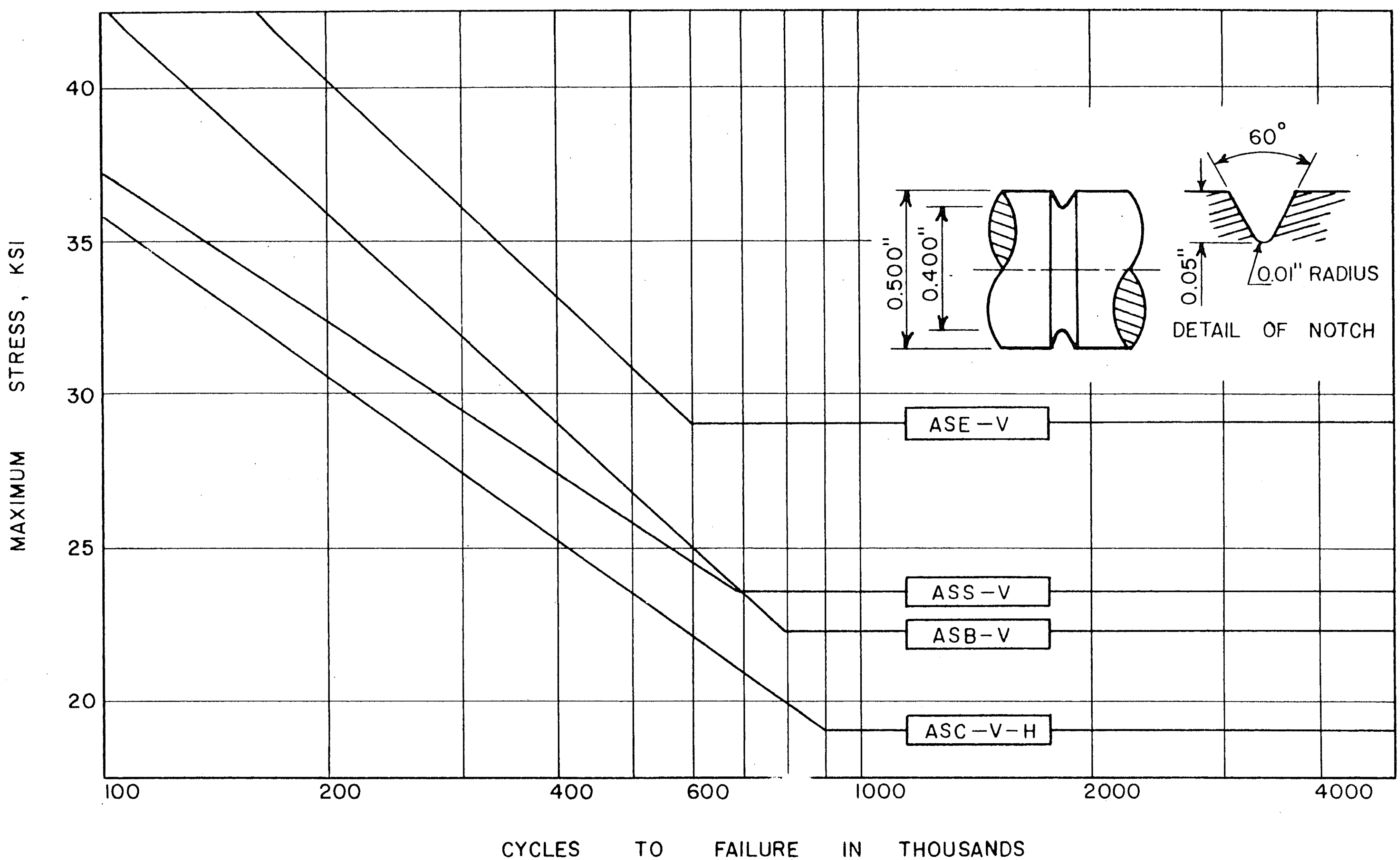


FIG. 18 COMPOSITE DIAGRAM OF FATIGUE RESULTS FOR ONE-HALF INCH DIAMETER NOTCHED SPECIMENS

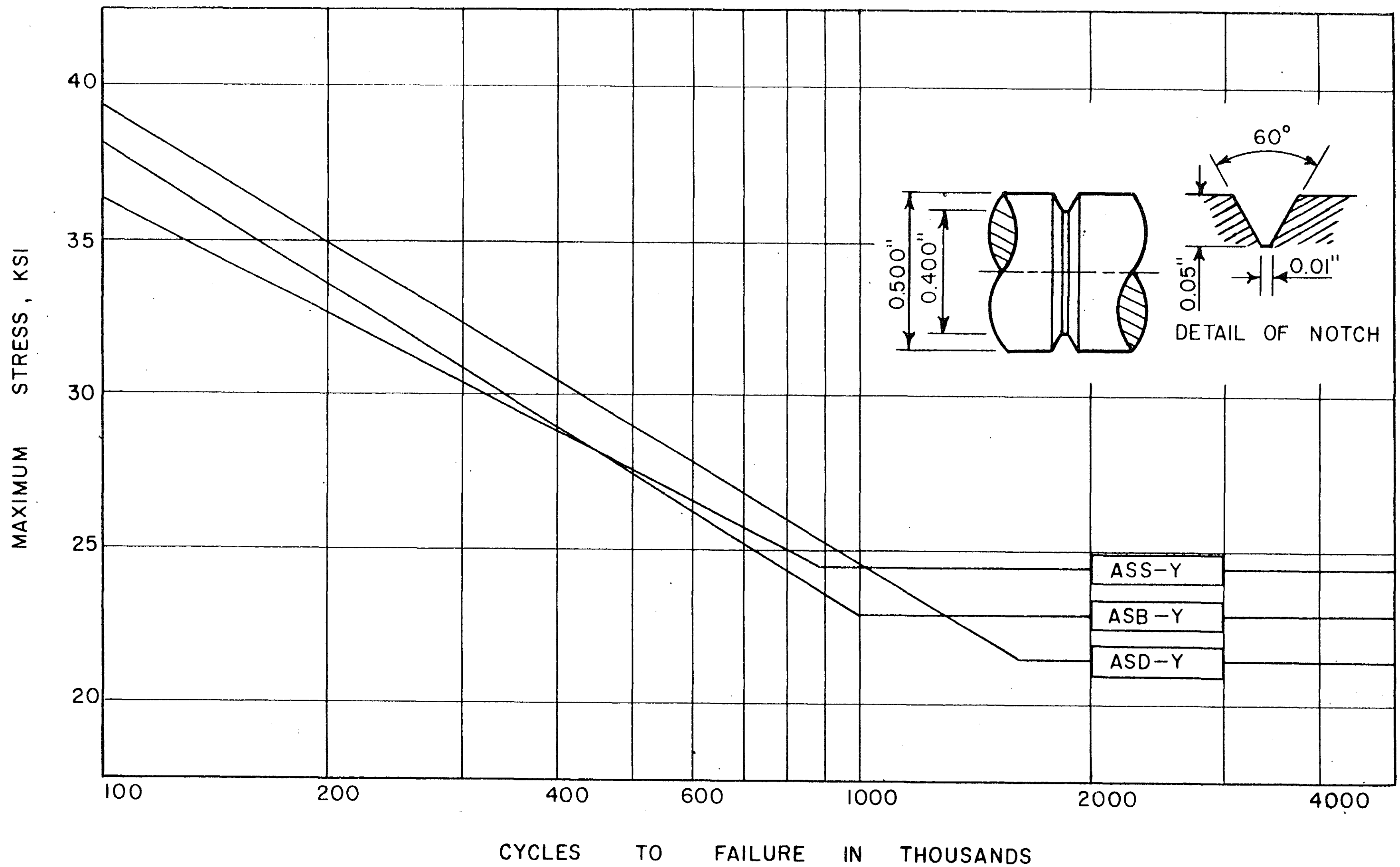


FIG. 19 COMPOSITE DIAGRAM OF FATIGUE RESULTS FOR ONE-HALF INCH DIAMETER NOTCHED SPECIMENS