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THE BEHAVIOR OF STIFFENED BEAMS UNDER REPEATED LOADS

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for the
Bureau of Public Roads, Department of Commerce
Welding Research Council Fatigue Committee

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I. INTRODUCTION

A. General Summary

Pursuant to recent advances in the welding industry, the use of built-up all-welded flexural members has become commonplace in American industry. Structures which are subjected to comparatively few cycles of loading have benefitted through this economical method of fabrication for a considerable number of years. World War II introduced mass production welding and since the end of the war, considerable study has been given to its further development.

During this same era, engineers also began to realize that the fatigue problem could be coped with in design. Investigators pointed out that abrupt changes in geometry in members under direct tensile stress caused a stress raiser which was quite detrimental to the fatigue life of the member. Furthermore, it was believed that welding seems to enhance the fatigue failure.

The problem was not of particular concern to the building industry because of the small number of repetitions of stress, but highway and railway engineers were reluctant to adopt welding for structures subjected to repeated loading. It was evident that additional study was necessary.

The Bureau of Public Roads (Department of Commerce) and the Association of American Railroads who were very interested in the problem responded by sponsoring a research project at the University of Illinois to study flexural fatigue behavior in all-welded built-up girders. The stiffener phase as described in this report is part of this project.

The project was strictly an experimental program and is believed to be the most comprehensive investigation of the effect of flexural fatigue on stiffener specimens carried out to date.

Since it was impossible to test full scale specimens in the quantity necessary to obtain sufficient fatigue data in a reasonable amount of time and since testing machines for this purpose were of insufficient capacity without exorbitant modifications, full-size girders were out of the question. A representative girder was chosen for an 8-ft. 6-in. span length. The beam was simply supported and the common two-point loading system was used to allow a pure moment area and a varying moment-shear area (see Fig. 1). The girder consisted of a 3/16-in. by 10-in. web with 5-in. by 1-in. flanges for the basic section. This 12-in. specimen was standard except for three 16-in. specimens which were built from a 14-in. web. Steel fabricators were consulted to suggest the most common shop practice. Two welding sequences (A and B) were patterned after those used on full-sized girders. Distortion problems were more evident in sequence A than sequence B; however, careful control by the shop personnel held these distortions to a minimum. The girders were fabricated from A-373 steel to insure adequate weldability, and standard E7016 electrodes were used.

The 200,000-lb. Wilson fatigue testing machine was modified to test flexural specimens and this modification reduced the total load capacity to about 100,000 lb. The loading cycle approximated a zero to full tension cycle, however, a true zero was never achieved. A small load ranging between 844 lb. and 2530 lb. (363 - 1065 psi in the extreme fiber) was left on the beam to prevent "slapping" of the parts of the machinery at all times during the test. The testing machine and the modification was first used by W. M. Wilson for flexural tests at the University of Illinois on rolled sections. Stiffeners were used on only a limited number of specimens in that investigation but the results did indicate that the fatigue life was influenced by the method of fastening the stiffener to the rolled section (4)*.

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* Numbers in parentheses, unless otherwise indicated, refer to the Bibliography.

Lea and Whitman (5) reported on flexural fatigue tests carried out in England, however, the stiffeners used in that program were under the concentrated load points and were welded to the tension area of the beam only at the supports.

The investigation, discussed herein, does not attempt to establish a new design criteria. It does offer further evidence that the present specification is inadequate in certain respects. The present specification states that the ends of stiffeners may be welded to the compression flange at any point and to the tension flange only at points where the tensile stress does not exceed 75 per cent of the maximum allowable stress (1). No attempt is made in the specifications to ascertain the effects of shearing stresses in the member nor its effect on the value of the maximum tensile principal stress at the point of stress concentration.

The results of the present investigation show that the specimens failed at stiffeners which were located at points in which the flexural stress was not at a maximum, and that the effect of welding to the tension flange had less effect than that of welding to the tension area of the web where the contribution of shear created a relatively high principal tensile stress.

B. Object and Scope

During the course of this investigation 45 stiffener specimens were tested. The basic section was a 12-in. all-welded built-up girder with the exception of three 16-in. sections. The five different types of stiffeners tested, designated as Types A through E are shown in Fig. 8. Three other specimens were also investigated, two of which were designated as F-type stiffener specimens and the other as "CX"-type which is similar to stiffener Type C.

The various stiffener types were selected to study the effect of welding to the web at various distances from the tension flange, to consider the use of stiffeners on both sides of the web, and to determine the use of intermittent welding to the web.

Two different welding sequences were used for the attachment of stiffeners. In this way it was possible to study the distortion produced by the two different procedures and the effect of this distortion on the fatigue life. In addition, two different welders were used to prepare the specimens used in this program. The effect of characteristic differences in electrode manipulation can also be studied with the data presented herein.

The specimens were tested on essentially a zero to tension cycle. The basic nominal maximum stresses in the extreme fiber of the tension flange were 30, 24, and approximately 20 ksi. These stresses were chosen to obtain sufficient data to establish an approximate S-N diagram for each stiffener type. Since the parts of the basic section were flame-cut before welding, the web dimension did vary from + 1/8 in. to - 1/4 in. This difference affected the total depth of the beam and made it necessary to measure the cross section of each beam at the centerline and at points of failure. The actual stresses were computed from these measurements on the basis of the accepted theory, i.e., linear distribution of stress.

The results also offer information on the location of failure, not only its location with respect to the beam span, but also with respect to the stiffener itself. (Most of the failures initiated at points where stiffeners were fastened.) The propagation of the crack was also recorded and the angle between the horizontal and the direction of propagation was measured. An attempt was made to correlate this angle with the computed angle formed between the plane of maximum principal compressive stress and the horizontal.

S-N curves have been plotted on the basis of maximum flexural stress at the centerline for the various stiffener types. A combined S-N curve has also been plotted on the basis of maximum principal tensile stress at the failure section.

Also, the stress on three specimens was increased after a considerable number of cycles in an effort to determine what damage had been done to a beam which had undergone repeated loading yet had shown no outward signs of failure.

It must be pointed out that the stiffeners were placed for convenience purposes only and the location of stiffeners had no relation to conventional design procedures. In fact, for the 12-in. specimens, the ratio of the clear depth between flanges to the thickness of the web was well within most specifications requiring no stiffeners at all.

C. Acknowledgments

The test results described herein are a part of an investigation initiated from a cooperative agreement between the Engineering Experiment Station of the University of Illinois; the Department of Commerce, Bureau of Public Roads; and the Association of American Railroads. This investigation is a part of the Structural Research Program of the University under the general direction of N. M. Newmark, Head, Department of Civil Engineering, and W. H. Munse, Professor of Civil Engineering. The research reported in this paper was conducted by N. G. Kouba, Research Assistant in Civil Engineering under the immediate supervision of J. E. Stallmeyer, Associate Professor of Civil Engineering. The author wishes to make special acknowledgment to W. E. Fisher, Research Associate in Civil Engineering, who initiated the preliminary testing for the stiffener specimen series. The Fatigue Committee of the Welding Research Council is acting in an advisory capacity for the investigation.

The metallurgical studies were conducted by C. A. Robertson under the direction of W. H. Bruckner, Professor of Metallurgical Engineering. In addition, the author wishes to express his appreciation to the Civil Engineering Shop personnel for the care and attention they have given to the preparation of test specimens.

II. DESCRIPTION OF TEST SPECIMENS AND TEST PROCEDURE

A. Materials

All tests reported herein were carried out on specimens fabricated from ASTM A373-54T steel which was purchased for use on this research program. The chemical composition and physical properties of the materials are given in Tables 1 and 2. The chemical properties were determined from check analyses, and the physical properties were determined from standard flat specimens cut from the parent plates. The stiffeners were cut from ASTM A7-56T steel bars, 1/4 in. thick. The width of the stiffener was 2 1/4 in. for all specimen numbered below AA-48(O)B + SD and 2 in. for all those above.

Manual arc welding with E7016 electrodes was used exclusively on the specimens reported. All welds were made with reversed polarity in the flat position with 5/32-in. diameter electrodes for the assembly of the basic section and 1/8-in. diameter electrodes for the attachment of stiffeners. After the seal on the electrodes had been broken, the electrodes were stored in an oven to prevent absorption of moisture.

B. Fabrication of Test Specimens

The basic section of the stiffener specimens was fabricated in accordance with two different welding sequences designated A and B. Each welding sequence had its own arrangement for the placing of the stiffeners. In one case, specimen AA-37(O)B + SA, the basic section was fabricated using welding sequence B while the stiffeners were placed in accordance with the locations established for sequence A.

The basic section of all beams was uniform throughout the span length. Flange and web plates were cut from the mill plates with a dual-torch oxygen cutting machine to eliminate as much distortion as possible. Where plates were flame-cut next to a sheared edge, a strip adjacent to the sheared edge about 1 in. wide was discarded. Any plates which had severe notches or other defects due to cutting or handling of the material were not used. Plates with minor defects were accepted but the severity was lessened by grinding them to a smooth transition. All slag and burrs on all edges of the plates and the mill scale in the region of the weld were removed.

The plates were then placed in a tacking jig which was especially prepared for the project and could accomodate both 12-in. and 16-in. specimens. After the plates were aligned and securely clamped, the web-plate was tack-welded to the flange by full-size fillet welds spaced about 16 in. apart. The specimen was then removed from the tacking jig. The beam was then placed in a special welding stand which permitted the specimen to be rotated into the best position (downhand) for deposition of each phase of the welding sequence. The basic section was completed before any stiffeners were attached. When all the stiffeners had been welded to the basic beam, the specimen was removed from the welding stand and was ready for testing.

1. Welding Sequence A. Table 3 describes welding sequence A for the fabrication of the basic section. Three 6-in. passes were deposited in one step. The first step carried the fillet weld 3 in. past the centerline of the beam. All welding was carried out using a back step procedure. The welds remained symmetrically placed with respect to the vertical axis of the beam as shown in Fig. 2.

After the basic section was completed, the desired stiffener types were fastened to the beam as shown in the location drawing in Fig. 4. It was hoped that each specimen would supply data for two tests and therefore the following procedure was adopted. Two stiffener types were welded to each basic section. In the central portion of the beam the stiffeners of the type to be tested were welded, and stiffeners of another type were added at the ends of the specimen. This second group of stiffeners would be tested after the first group was completed, by sawing the beam at the centerline and butt welding the original ends together. Stiffener 10 would become the new centerline stiffener. Therefore, the stiffeners in Group I (Nos. 1 through 5) were replaced by the group II stiffeners (Nos. 6 through 10) in the same location of the test span.

This method proved inadequate. The fractures did not confine themselves to the location occupied by Group I. (Specimen AA-16(0)A + SE had its primary fracture located at Stiffener 6 and its secondary fracture at Stiffener 7, both of which were A-type stiffeners and not E-type for which the test had been planned. The results, however, were plotted for an E-type stiffener specimen.) The effect of the butt weld and a part of the span which was to undergo a second loading was also considered as a highly indeterminate factor, and as a result, the Group II series was never tested.

The welding procedure used for the attachment of stiffeners to the basic section is given in Table 5 and is shown in Fig. 5. The procedure was developed to minimize the heat input due to welding in any given area and to duplicate the use of multiple passes required to weld a full-size stiffener to a full-size girder. The welding procedure was divided into five phases, three on the web and one on each flange, and each phase was subdivided into a number of passes to be deposited at each stiffener. Within each phase the stiffeners were welded in numerical order, and the weld beads at each stiffener were deposited in alphabetical order. The "a" and "c" passes were on the inner side of the stiffeners (nearest the centerline of the span) and the "b" and "d" weld beads were on the side of the stiffeners nearest the end of the beam.

2. Welding Sequence B. After ten stiffener specimens, which were fabricated using welding sequence A, had been tested and it became apparent that because of the location of failure these specimens could not be rewelded and tested, certain modifications were required. Therefore, welding sequence B was adopted (see Table 4 and Fig. 3). This modification reduced the distortion considerably and thereby reduced the slight lateral displacement which was present when the specimen was being tested.

The initial stiffener locations were abandoned in favor of a new stiffener layout shown in Fig. 6. To make the most economical use of the material available for this program, stiffeners were located on one end of the basic beam and were offset from the centerline. In this manner a maximum overhand was provided on the end of the specimen without stiffeners. Fractures that developed within the specimen would initiate on the half of the specimen to which stiffeners had been welded. Therefore, the non-stiffener half of the specimen, when spliced with the non-stiffener half of another specimen, could be employed to test plain butt welded specimens for another phase of the investigation. Therefore, with the revised stiffener specimen, three specimens could be tested from the material required for two.

An investigation of the test results of the initial ten stiffener specimens also indicated that the use of multiple passes on the webs could be eliminated. No fractures initiated within a weld bead or at an internal crater. The fractures initiated at the lower end of the weld bead attaching the stiffener to the web. In one case the fracture initiated at the upper end of the lower intermittent weld of a Type C stiffener. The initial welding sequence for the attachment of stiffeners to the basic beams had one major disadvantage. This sequence "locked in" stresses on the lower portion of the stiffener. At the time welding sequence B was developed, a revised welding sequence for the attachment of stiffeners was also initiated. Stiffeners were attached to the web in two continuous passes, one on each side of the stiffener. The first bead was deposited from the lower end of the stiffener to its upper end, and the second bead was deposited in the reverse direction. The stiffeners were also welded to the flanges with one pass in the same general manner as they were attached to the web. The first stiffener was placed at the centerline of the test span and the other stiffeners were welded outward to the support (see Table 6 and Fig. 7). With this sequence the major "locked in" stresses occur at the top of the beam in the compression flange.

C. Stiffener Types and Their Designations

Five basic types of stiffeners were adopted for testing (see Fig. 8). Type A was considered because it allowed no welding to the tension flange and it can be compared to Type B which is the same stiffener welded to the tension flange. Type C considers the use of intermittent welding. Type D is similar to Type A except that stiffeners are placed on both sides of the web. Type E was adopted to determine what effect would be produced by holding the weld 2 in. from the tension flange. Forty-two specimens were run using these five basic stiffener types.

Three other special specimens were also tested and are reported herein. One "CX"-type stiffener was tested. This stiffener was the same as Type C except that it was welded to both flanges.

Another specimen used a Type F_1 stiffener as shown in Fig. 8. The objective here was to determine what effect welding to the tension area of the web had on the beam's fatigue life.

One Type F_2 stiffener specimen was also tested. This stiffener was similar to F_1 except that the stiffener was cut off square, 2 in. short of the tension flange. The stiffener was welded to the web continuously for its entire length of 8 in.

The stiffener designation herein used is in keeping with the one developed for the entire welded beam investigation (3). A typical designation, for example, is AA-14(O)A + SC. The first two letters AA indicate that the specimen was a plain beam, that is, no splices, cover plates, butt welds, cope holes, etc. The number 14 refers to the number of specimen being run. The (O) means that it is an original specimen and not a rerun. The next letter A refers to the welding sequence used and SC refers to the C-type stiffener which was attached to the basic section.

D. Test Procedure

The 200,000-lb. Wilson lever-type fatigue testing machine used in performing the tests reported herein is shown in Fig. 1.

The specimens were tested on a span of 8 ft. 6 in. Load was applied as two concentrated loads, one on each side of the centerline, 12 in. apart, as shown. All beams were tested in the as-welded condition. In all tests carried out on a nominal stress cycle of zero to maximum the actual stress varied from a minimum of 363 - 1065 psi to the maximum value. The minimum load was necessary to hold the specimen positioned and to maintain parts of the machine in place.

The maximum values were chosen to give a good picture of the S-N relationship in the overstress portion of the diagram. The total load applied was calculated on the basis of the nominal dimensions of the section.

After failure had occurred the actual dimensions of the section in the region of failure and at the centerline of the test span were measured and the final stress values were calculated. The variation of the actual value from the theoretical value exceeded 1000 psi in a few rare cases.

The load was derived from an adjustable throw cam that raised and lowered the outer end of the overhead I-beam, thereby subjecting the flanges of the specimen to cycles of flexural stress. The load was measured with the open-loop dynamometer. The machine was cranked by hand while the cam was being adjusted to give the desired load. From time to time the machine was stopped to check the load. The stresses were computed from the load indicated by the dynamometer using the flexural formula commonly used in design.

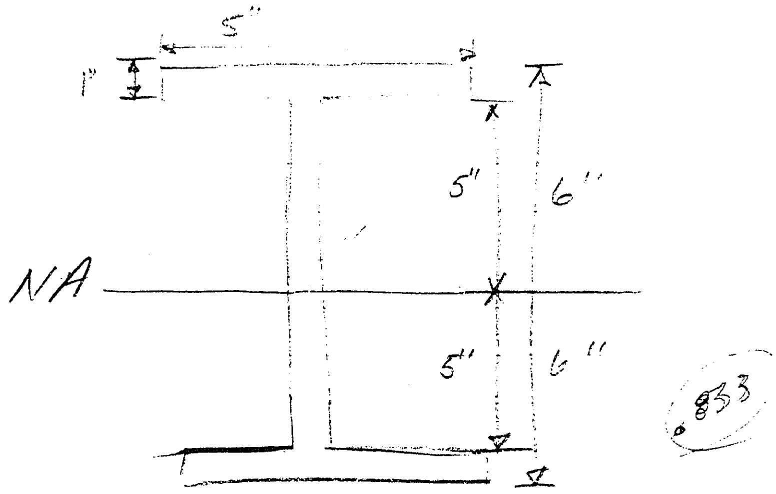
The load and supporting rollers rested in cylindrical grooves in the loading and supporting blocks. The grooves were somewhat larger in diameter than the rollers, to prevent the rollers from introducing a horizontal restraint. The compression flange had no lateral support except that afforded by the loading head of the testing machine. The machine operated at a speed of approximately 150 revolutions per minute.

A problem which remains to be solved is the exact determination of the number of cycles at failure. In the earlier tests a micro-switch placed under the bottom flange at the centerline would stop the machine when a certain vertical deflection was exceeded. The number of revolutions of the loading cycle at this point was taken as failure. The clearance between the micro-switch and the maximum deflected position at peak load was originally set at 0.05 in. In some cases the micro-switch cut off after a relatively small number of cycles.

On other occasions, the cut-off would occur after a greater number of cycles; however, no visible crack could be detected. In still other cases, a relatively large fatigue crack did appear and yet the deflection did not exceed that needed to engage the micro-switch.

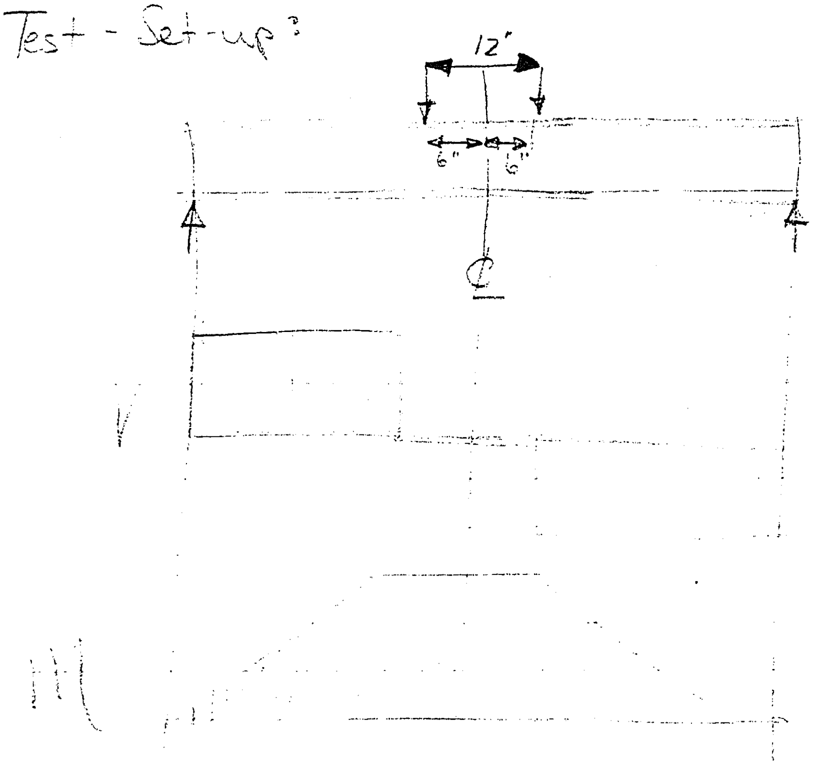
In view of the foregoing, an arbitrary procedure was used to define failure. As soon as a crack had reached approximately 2 in. in length, the beam was considered to have failed. This was normally accompanied by a noticeable drop in load. All specimens were run beyond this point to propagate the failure for photographic purposes.

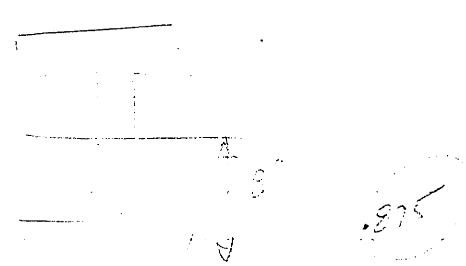
$$\sigma = \frac{Mc}{I_x}$$



$$I_x = \left[\frac{1^3 \times 5}{12} + (5.5)^2(5)\right]2 + \left(\frac{1}{12}\right)\left(\frac{5}{16}\right)(10^3) = 318.96\,in^4$$

Test - Set-up:





III. PRESENTATION OF TEST RESULTS

A. Discussion of Failures and Their Locations (See Table 7)

1. A-Type Stiffener Specimens. Three 16-in. Type A specimens were tested on a zero to 30 ksi nominal stress range. The specimens were numbered 27, 28, and 37*. Specimen 27 failed at the end of 293,900 cycles. The crack initiated at Stiffener 3, 12 in. west of the centerline. The sectional view of the failure after the test had been completed indicated that the crack had initiated at the bottom of the weld material which joined the stiffener to the web. The crack initiated on the side closest to the centerline of the beam. The crack propagated horizontally along the top of the fillet weld into panel 3-5 and also diagonally upward into the web in panel 1-3 at an angle of 60 deg. The specimen had noticeable distortion and wobbled considerably during the fatigue test and much doubt exists as to the reliability of the result.

Specimen 37* ran for 574,900 cycles and failed at Stiffener 4, 25 1/2 in. east of the centerline, in a manner very similar to Specimen 27 (see Fig. 16a). The crack initiated at the lower portion of the fillet weld closest to the centerline joining the stiffener and the web. It proceeded diagonally upward into panel 4-2 at an angle of 50 deg. and also horizontally along the top of the fillet weld in panel 4-6.

Specimen 28 developed failure cracks in three locations. Actually, this specimen was inadvertently modified by the welder and was not noticed until testing had been completed. The normal stiffener specimen was to be welded and stopped at a triangular 1/2-in. cope which was intended to clear the web-flange fillet weld. The welder on this specimen carried the stiffener weld

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* See page 9 for modification to the welding sequence for specimen 37.

beyond the end of the cope right into the web-flange fillet weld. A careful study of the cross-sectional view of the primary fracture indicated that fracture initiated at Stiffener 5 at the junction of the fillet weld on the centerline side of the stiffener and the web-flange fillet web on the tension side of the beam. The crack proceeded diagonally upward into panel 5-3 at an agle of 50 deg. The crack did not proceed horizontally, seemingly because of the fusion of the two welds at the junction. The specimen also had a secondary fracture at Stiffener 2.

This second carck proceeded upward into the web along the stiffener for a distance of 2 1/2 in. and then diagonally toward the centerline at an angle of 53 deg. About 1 in. from the initial portion of the crack, a supplementary crack occurred approximately parallel to the main stem. It should be noted that the portion of the crack that ran along the stiffener vertically did so in an erratic saw-tooth fashion. Failure 3 initiated at Stiffener 4. The crack progressed diagonally upward toward the centerline of the beam at an angle of 48 deg. Failure occurred at the end of 695,800 cycles.

Nine other A-type stiffener specimens were run at varying stress cycles on the standard 12-in. specimens. Four of these, numbered 10, 11, 12, and 18, were run at the zero to 30 ksi nominal stress range. As noted in Table 7, all of the fractures occurred at Stiffener Nos. 3 and 5. All of the fractures initiated at the point as previously described, i.e., at the bottom of the fillet weld connecting the stiffener with the web on the centerline side of the stiffener. The cracks proceeded upward diagonally into the web in the panel closest to the centerline. With the exception of Specimen 11, the cracks also propagated horizontally along the top of the web-flange fillet weld away from the centerline as in the 16-in. specimens. Specimen 11, however, deviated from this pattern. The crack traveled downward until it met the web-flange fillet weld and proceeded directly into the flange. A cross-sectional view of the fracture later revealed poor penetration of the web-flange fillet weld. It is interesting to note that the fatigue life of these four specimens averaged 629,800 cycles. For the three 16-in. specimens the fatigue life averaged 521,500 cycles but disregarding Specimen 27, for which lateral deflection during testing was believed to have affected the fatigue life, it is noted that the other two specimens averaged 635,300 cycles.

Also for comparison, control specimens which were run without stiffeners at the same nominal stress range for another phase of the investigation, showed an average fatigue life of approximately 1,100,000 cycles. Therefore, at this stress cycle the fatigue life, due to the effect of welding A-type stiffeners, was reduced about 43 per cent.

Three stiffener specimens, numbered 38, 39 and 40 were tested at a nominal stress range of zero to 24 ksi. All three of these specimens followed the same general pattern with respect to the initiation of failure. Specimen 38 ran for 1,182,700 cycles. At the end of this time, three fractures had developed. Figure 19a shows an intermediate view of the specimen from the back side. The primary fracture developed at the tension side of Stiffener 2 and proceeded diagonally upward into panel 2-1 at an angle of 55 deg. The secondary fracture initiated at Stiffener 3 and proceeded diagonally upward into panel 3-2 at an angle of 52 deg. The third fracture occurred in the compression side of the web on the top side of Stiffener 2. All three fractures initiated on the centerline side of the stiffener at the end of the weld metal joining the stiffener to the web. This specimen was the first to exhibit the fact that the same type of fracture could occur in the compression side of the web.

Specimen 39 ran for 1,349,500 cycles before it failed. The main fracture occurred at Stiffener 3 in the tension side of the web. Again, the crack initiated on the centerline side of the stiffener at the end of the fillet weld joining the web and the stiffener. The crack propagated diagonally upward at an angle of 48 deg. The second crack that developed was located at Stiffener 2. This crack initiated at the same relative location as the primary fracture and progressed diagonally upward at an angle of 57 deg. At the top of this stiffener a third fracture was noticed. The third fracture initiated at the end of the fillet weld which joins the stiffener to the web on the centerline side of the stiffener. The failure was similar to the other "compression" failure in Specimen 38 and the crack propagated horizontally downward at an angle of 52 deg.

The third specimen in this group, Specimen 40, had three failures in the tension area of the beam. At the end of 1,412,100 cycles, the beam had failed. The main fracture occurred at Stiffener 3, the secondary fracture at Stiffener 2, and the last fracture at Stiffener 4. The fractures proceeded diagonally upward at angles of 50 deg., 56 deg., and 47 deg., respectively. All three fractures initiated at points similar to those previously described.

Two other A-type stiffener specimens were tested at lower stress cycles. Specimen 53 was tested on a zero to 20 ksi nominal stress range. It ran for 2,733,100 cycles. Only one crack developed and it was located at Stiffener 2 (see Fig. 15a and 16b). Failure initiated at the end of the fillet weld joining the web and stiffener together on the centerline side of the stiffener. The crack proceeded horizontally upward at an angle of 55 deg.

The last A-type stiffener specimen tested was number 54. It ran at a nominal stress range of zero to 18.5 ksi for 4,955,500 cycles. At the end of this time, no crack or drop in load had been detected. Therefore, the nominal stress cycle was increased to zero to 24 ksi. At the end of an additional 142,900 cycles a crack developed at Stiffener 2 and also over the stiffener at the west support. The main fracture at Stiffener 2 occurred in the tension side of the beam similar to the other failures. It propagated diagonally upward at an angle of 56 deg. The secondary crack initiated at the lower end of the fillet weld joining the stiffener at the support to the web. This crack propagated in both directions almost horizontally for a total length of about 12 in.

2. B-Type Stiffener Specimens. Eight specimens with B-type stiffeners were tested. These specimens differed from the A-type only insofar as the stiffeners were also welded to the tension flange. Three of the specimens, numbered 29, 30, and 31, were tested on a zero to 30 ksi nominal stress range.

Specimen 29 failed at Stiffener 2 after it had run 627,800 cycles. Two different cracks seemed to develop almost simultaneously. One crack started at the lowest end of the fillet weld which joined Stiffener 2 to the web on the centerline side of the stiffener. The crack proceeded diagonally upward at an angle of 59 deg. into panel 2-1. This was exactly the same type of initiation as that which occurred with the A-type stiffener. Another crack initiated along the toe of the fillet weld which connected the stiffener to the flange on the centerline side of the stiffener. This crack propagated downward into the flange.

Specimen 30 ran for 446,700 cycles. This specimen failed at the toe of the fillet weld which connected the stiffener at the centerline to the tension flange on the east side. The crack also was noted to have extended straight upward about 1/2 in. into the web. A cross-sectional view of the failure section indicated that the majority of the crack initiated due to the welding of the stiffener to the flange although the vertical stem into the web was initiated by the end of the fillet weld which connects the web with the stiffener.

Specimen 31 failed in the same manner. The influence of the weld which connected the web and Stiffener 1 was somewhat greater as the vertical stem proceeded upward a greater distance (1 1/2 in.). The welding of the flange had a lesser effect than on Specimen 30. The specimen failed at 523,600 cycles.

The average fatigue life of these three specimens was 532,700 cycles. The fatigue life for Type B stiffener specimens is approximately 50 per cent of specimens without stiffeners at the zero to 30 ksi nominal stress range. Also, this indicates that the effect of welding to the tension flange decreases the fatigue life an additional 10 to 15 per cent compared to the case in which the stiffeners are not welded to the tension flange at the zero to 30 ksi nominal stress range. This statement needs clarification. The actual stresses for the B-type stiffeners when computed from the measured dimensions showed that they ran slightly greater than the A-type stiffener specimen (see Table 7). Therefore, this percentage should be reduced somewhat, possibly even to the point where the effect is negligible.

Three other B-type specimens were tested on a zero to 24 ksi nominal stress range. However, the actual stresses were all over 25 ksi. These specimens, 41, 42, and 43, showed surprising results.

Specimen 41 ran 1,110,300 cycles. The failure occurred at Stiffener 2. As before, the fracture initiated at two different locations. One part initiated at the lower end of the fillet weld which connects the stiffener to the web on the centerline side of the stiffener. The crack proceeded diagonally upward at an angle of 55 deg. Another phase of the failure initiated along the toe of the fillet weld which connected the stiffener to the tension flange. See Fig. 16c for a cross-sectional view of the failure.

Specimen 43 ran for 1,271,900 cycles and failed at Stiffener 3. The crack initiated at the lower end of the fillet weld which connected the stiffener to the web and propagated upward diagonally toward the centerline at an angle of 52 deg. No cracks had developed where the stiffeners were welded to the tension flange.

Specimen 42 ran 4,031,000 cycles (see Fig. 15b). The primary and secondary failures occurred in the compression area of the beam. Failure 1 was detected at the end of 2,362,400 cycles; however, no relatively large drop in load was noticed. This crack initiated at the end of the fillet weld which joins the web and the stiffener together, on the centerline side of Stiffener 2. The crack progressed downward diagonally at an angle of 51 deg. Crack Number 2 occurred at the end of 3,799,800 cycles. This crack initiated at the same general location, except at Stiffener 1, and propagated diagonally downward at an angle of 75 deg. Still, no relatively large drop in load occurred. Finally, crack Number 3 initiated and the beam failed. Crack Number 3 occurred in the tension side of the beam at Stiffener 3. It initiated at a crater in the fillet weld which joined the stiffener to the flange. As can be noted from the picture the crack progressed diagonally upward into panel 2-1 at an angle of 48 deg. and horizontally downward into panel 2-3 at an angle of 52 deg. The failure also propagated horizontally about halfway into the stiffener.

The last two B-type stiffener specimens tested were numbered 55 and 56. Specimen 55 was tested on a zero to 19 ksi nominal stress cycle and failed at the end of 4,114,900 cycles. Specimen 56 was tested on a zero to 20.5 ksi nominal stress range and ran for 5,078,100 cycles. Since no drop in load or any cracks were detected, the nominal stress range was increased to zero to 24 ksi. The specimen ran an additional 153,500 cycles before it failed. Both failures occurred in the tension flange. Failure in Specimen 55 occurred 5 1/2-in. east of the centerline and Specimen 56 failed 7 1/2-in. east of the centerline. Both cracks initiated at the edge of a crater which joined the web and the flange. Both failures progressed into the flange and vertically upward into the web (see Figs. 15c and 16d).

3. C-Type Stiffener Specimens. The Type C stiffener is connected to the beam by three intermittent fillet welds on the web and is not welded to the flanges. Eight C-type stiffener specimens were tested. The first three, 13, 14 and 15, were tested on a zero to 30 ksi nominal stress range. They failed at 911,300, 649,300 and 864,200 cycles, respectively.

The use of this type of specimen at this stress cycle seems to indicate that the fatigue life is reduced to about 80 per cent of that of the plain beam. The fatigue life of this stiffener is about 13 per cent better than Stiffener A and about 30 per cent better than Stiffener B at this zero to 30 ksi nominal stress cycle.

Specimen 13 failed at Stiffener 5 with a secondary fracture at Stiffener 4. A slight amount of spatter from the weld metal was deposited on the web near the bottom of the lower intermittent weld at Stiffener 5. The crack initiated at this point and proceeded diagonally upward into panel 5-3 at an angle of 47 deg. and also horizontally along the top of the fillet weld joining the web to the flange in panel 5-7. The secondary crack progressed similarly at Stiffener 4 except that the crack initiated at the bottom of the lower intermittent fillet weld.

Specimen 14 failed at Stiffener 3. The crack initiated at the top of the lower intermittent fillet weld and propagated diagonally upward into panel 3-1 and also downward into panel 3-5 at an angle of 51 deg.

Specimen 15 failed at Stiffener 5. The crack initiated at the bottom of the lower intermittent fillet weld and progressed upward into panel 5-3 and downward into panel 5-7 at an angle of 50 deg. The specimen was then run for an additional number of cycles to enlarge the crack for photographic purposes. At this time similar smaller cracks initiated at Stiffeners 2, 3 and 4.

Specimens 44, 45 and 46 were Type C stiffener specimens which were tested on a zero to 24 ksi nominal stress range. They failed at the end of

1,902,500, 1,752,700 and 1,048,700 cycles, respectively. All three failures occurred at Stiffener 4. The fractures on Specimens 44 and 46 were similar. The crack initiated at the lower end of the bottom intermittent fillet weld on the centerline side of the beam (see Figs. 17a, 18b and 18c). The cracks propagated diagonally upward into panel 4-3 and diagonally downward into panel 4-5 to the fillet weld joining the web and the flange. At this point the crack changed direction and continued horizontally away from the centerline along the top of this fillet weld. The diagonal angles were 46 deg. for Specimen 44 and 49 deg. for Specimen 46. In Specimen 45 the fracture initiated at the top of the lower intermittent fillet weld (see Fig. 15d). The crack progressed diagonally upward into panel 4-3 and diagonally downward into panel 4-5 at an angle of 46 deg. The fracture initiated at the top of the intermittend weld on the side of the stiffener nearest the centerline.

Two other specimens with Type C stiffeners were tested at a zero to 19 ksi nominal stress range. These specimens were numbered 57 and 58. Specimen 57 ran for 2,832,300 cycles and developed two fractures. The primary fracture occurred at Stiffener 2 at the lower end of the bottom intermittent fillet weld on the centerline side of the stiffener. The crack progressed diagonally upward into panel 2-1 and diagonally downward into panel 2-3 at an angle of 52 deg. The secondary fracture was identical except that it was located at Stiffener 5 and propagated at an angle of 45 deg.

Specimen 58 ran for 4,608,200 cycles and the only fracture was identical to the primary fracture of Specimen 57 with regard to point of initiation, location of stiffener and direction of crack. Figure 18a shows a cross-sectional view of the fracture. Although the stiffener is not shown, the point of initiation can easily be noted from the cresent shape formed where the lowest point of the intermittent weld was fastened to the web.

4. <u>D-Type Stiffener Specimens</u>. The Type D specimen was prepared to test the effect of placing stiffeners on both sides of the web. The stiffener itself is identical to the A-type. Three specimens were tested on a zero to 30 ksi nominal stress range and three specimens were tested at a zero to 24 ksi nominal stress range making a total of 6 D-type specimens.

Specimens 32, 33 and 34 failed at 510,600, 669,800 and 586,800 cycles, respectively, for the zero to 30 ksi range. This averaged 589,100 cycles and agreed quite closely to the single A-type stiffener which averaged 629,800 cycles.

Specimens 47, 48 and 49 failed at 1,129,300, 814,700 and 1,931,800 cycles, respectively, for the zero to 24 ksi range. This averaged 1,291,000 cycles and compared closely to the A-type stiffener at this stress range which averaged 1,314,800 cycles. It was concluded that the effect of putting the stiffeners on one or both sides of the web had a negligible effect on the results.

Specimen 32 had a primary fracture at Stiffener 2 and a secondary fracture at Stiffener 3. Both fractures initiated in a manner similar to the A-type specimen fracture, at the bottom of the fillet weld connecting the stiffeners to the web on the centerline side of the stiffeners. From a careful study of the fracture section it was not possible to determine the exact point of initiation of failure. This specimen was run a considerable number of cycles after failure to study the propagation of the crack. Besides progressing diagonally upward into the web in panel 3-2, the crack extended horizontally along the top of the web-flange fillet weld away from the centerline and continued to Stiffener 3 where it joined the secondary fracture.

Specimens 33 and 34 had practically the same failure characteristics. The primary fractures occurred at Stiffener 2 and secondary fractures developed at Stiffeners 3 and 4. The primary fractures propagated at angles of 56 deg. and 57 deg., respectively. Both secondary fractures were slightly different, however. Specimen 33 initiated a fracture in the usual manner. The crack proceeded diagonally upward for about 1 in. where it stopped. Approximately 1/2 in. from the end of this crack a bit of weld spatter hit the web. At this point another crack started and proceeded diagonally upward. The outward appearance seemed to indicate that this crack jumped a 1/2-in. gap. The secondary fracture on Specimen 34 initiated at the same location as all other cracks but first proceeded upward along the edge of the fillet weld joining the stiffeners to the web for approximately 1/2 in. before it proceeded diagonally into the web. Figure 19c shows the third fracture of Specimen 34 which occurred at Stiffener 4. This cross-sectional view indicates that the crack was initiated by the weld which joined the stiffener on the north side of the beam (left side of the figure) to the web.

Specimen 47 had a primary fracture at Stiffener 2 and a secondary fracture at Stiffener 3. Both cracks initiated at the bottom of the fillet weld joining the north stiffener to the web on the centerline side of the stiffener. Failure 1 propagated diagonally upward at an angle of 49 deg. and Failure 2 angled at 42 deg.

Specimen 48 failed at Stiffener 3, however, two separate points of initiation were noted. One crack occurred at the lower end of the fillet weld which joined the south stiffener to the web on the centerline side of the stiffener. The other crack started approximately 1 in. higher at a small crater in the weld which attached the stiffener on the north side of the beam to the web on the centerline side of the stiffener. The first initiation produced a crack which developed from the second initiation. The two cracks joined and propagated diagonally upward toward the centerline at an angle of 42 deg.

Specimen 49 displayed only one fracture which occurred at Stiffener 4 (see Fig. 19b). A close-up view of Fig. 18d indicates that the fracture initiated in a manner similar to the majority of the fractures of the A and D-type specimens. A cross-sectional view confirmed the fact that the crack initiated at the bottom of the fillet weld which joined the stiffener on the south side of the beam to the web on the centerline side of the stiffener. The crack propagated diagonally upward at an angle of 43 deg. into panel 4-3. It should also be noted that the stiffener on the south side of the beam had been welded about 1/2 in. further down than the stiffener on the north side.

5. E-Type Stiffener Specimens. Eight E-type stiffener specimens were tested; three at a zero to 30 ksi nominal stress range, three at a zero to 24 ksi nominal stress range, one at a zero to 21.5 ksi nominal stress range, and one at a zero to 19 ksi nominal stress range. Type E stiffeners were adopted to study the effect of holding the weld away from the lower portion of the web.

Specimens 16, 17 and 35 were tested on the zero to 30 ksi nominal stress range. Specimen 16 failed at the end of 886,600 cycles at Stiffener 6 with a secondary fracture at Stiffener 7. Both cracks occurred at A-type stiffeners, however.* The failure initiated at the end of the fillet weld which joins the stiffener to the web on the centerline side of the stiffener and propagated diagonally into the panel closest to the centerline. As before, they also progressed horizontally away from the centerline along the top of the web-flange fillet weld.

Specimen 17 failed at Stiffener 4 after 606,000 cycles. The crack initiated at the bottom of the fillet weld, on the centerline side of the stiffener, which joins the stiffener to the web. This point was located 2 in. from the tension flange. The crack propagated diagonally upward into panel 2-4 and downward into panel 4-6 at an angle of 43 deg.

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* See page 9.

Specimen 35 ran 1,070,500 cycles and failed at Stiffener 4. The initiation of the crack occurred with respect to the stiffener in the same general location as Specimen 17. The diagonal angle measured 44 deg.

These three specimens averaged 854,400 cycles and thus, compared to beams without stiffeners, was approximately 78 per cent as efficient. Compared to A-type stiffeners they were 35 per cent better, to B-type stiffeners, 60 per cent better, to C-type, 6 per cent better, and to D-type, 45 per cent better. Of course, these values were computed from relatively few tests. The actual stresses varied from the nominal zero to 30 ksi stress range.

Specimens 50, 51 and 52 were tested on the zero to 24 ksi nominal stress range. They failed at the end of 1,008,600, 1,265,000 and 1,773,800 cycles, respectively. Each specimen had only one failure crack, but the cracks initiated at different stiffeners for each specimen. Specimen 50 failed at Stiffener 3, Specimen 51 at Stiffener 2, and Specimen 52 at Stiffener 5. The points of initiation and the modes of failure were the same as for Specimen 17. The failure angles were measured as 48 deg., 46 deg., and 44 deg., respectively. Figure 19d shows a cross-sectional view of the failure section of Specimen 52. The white chalk mark shows where the fracture initiated.

Specimen 60 ran 3,496,900 cycles. A primary failure occurred at Stiffener 5 and a secondary failure at Stiffener 2. Figure 17c shows the primary fracture which initiated and propagated in the same manner as the previous specimens. The angle that the crack made with the horizontal was measured as 44 deg. The secondary fracture was quite different with respect to the manner in which the crack propagated. The crack initiated at the lower edge of the fillet weld connecting Stiffener 2 to the web at the location which would be expected on the basis of the previously tested specimens. The crack then progressed downward into panel 2-1 and upward into panel 2-3 at an angle of 25 deg. This was the first and only failure to behave in this peculiar manner.

Specimen 59 ran for 5,768,500 cycles on a zero to 19 ksi nominal stress range. Since no drop in load or evidence of failure had been detected, the nominal stress cycle was increased to zero to 24 ksi at which the beam ran an additional 2,345,500 cycles. The primary fracture occurred at Stiffener 5 in a manner identical to the other specimens and propagated diagonally at an angle of 43 deg. Another fracture occurred at the web-flange fillet weld in the tension area of the west support. This crack was attributed to two causes. First, the penetration between the web and the flange in this area was very poor. Secondly, the beam, although supported on rollers at the end of the span, is clamped to the block which houses the bearing area upon which the roller rests. This slight restraint, after a considerable number of cycles, could have helped to initiate the fracture. The same reasoning was used to accept the secondary fracture of Specimen 54 which occurred at Stiffener 6.

6. Other Stiffener Specimens. Three other stiffener specimens were tested in an attempt to see how a change in one of the variables of fastening the stiffener would affect the fracture.

The first specimen was mistakenly prepared by the welder as he welded the C-type stiffeners to both flanges. The specimen was designated as AA-44(0)B + SCX and tested on a zero to 24 ksi nominal stress range. Failure occurred after 1,187,000 cycles. The fracture initiated along the toe of the fillet weld which connected Stiffener 1 to the tension flange. The crack propagated into the flange and also upward for approximately 3/4 of an inch into the web. The maximum stress at the failure section was computed as 25.1 ksi (see Fig. 17b).

The two other specimens were designated as F-type stiffeners. In AA-36(0)B + SF_1 the stiffeners were welded to the compression flange and also continuously down to the mid-depth, or assumed neutral axis, of the beam. There was no weld connecting the stiffener below this point. The failure occurred in the pure moment area in the tension flange 5 in. west of the centerline. The fracture initiated at a slight imperfection on the edge of the flange which seemed to be caused by excess heat during the flame cutting operation. The crack progressed through almost 3/4 of the flange and also straight upward into the web for about one inch.

The last specimen was designated AA-61(0)B + SF_2. The stiffeners were cut off square two inches short of the tension flange and welded only to the web continuously for their entire length of 8 in. Figure 17d shows a close-up of the only fracture which was located at Stiffener 5. The crack initiated at the lower end of the fillet weld connecting the stiffener to the web on the centerline side of the stiffener. The crack propagated diagonally at an angle of 40 deg.

Both F-type specimens were tested on a zero to 30 ksi nominal stress cycle. Specimen 36 failed after 829,500 cycles and Specimen 61 failed after 1,137,800 cycles.

B. Principal Stresses at Failure

After the beams had been tested and measurements had been made at the centerline and failure sections, stresses at various positions in the beam were computed. First, the maximum flexural stress in the extreme fiber was determined at the centerline and at the location in the beam of the primary fracture. Then, the maximum principal stresses were computed at the point of initiation of the primary fractures for all those specimens which did not possess flange failures. The computed failure angle was determined as the plane on which the maximum principal tensile stress acts. This value was compared with the measured angle of failure.

The results are tabulated in Table 8. It is of interest to note that the ratio of the computed angle to the measured or failure angle was always greater than one. The range fell between 1.02 and 1.38 with an average value of 1.33.

C. S-N Curves

Figures 9 to 13 show the S-N curves for the various types of stiffener specimens plotted with the maximum or centerline flexural stress as the ordinate. On the basis of the limited data obtained, it appears that all of the specimens tested on the zero to 30 ksi nominal stress range fail at approximately the same number of cycles. As the weld is held further away from the tension flange, the curves tend to rotate about this point and become slightly flatter. For the B-type stiffener this is not true, presumably because the stiffener is welded to the tension flange. In fact, the A-type stiffener shows a steeper curve which indicates that it may have a lower fatigue life in the lower ranges of stress than the B-type stiffener.

A number of facts should be considered in evaluating the data. First, the number of tests is still limited and the curves could possibly run the other way depending on the scatter band. Secondly, the curves are plotted on the basis of the maximum flexural stress to which the beam was subjected. This stress occurs only in the pure moment region of the span. The various fractures occurred at stiffeners which normally were not in the pure moment area. Most fractures occurred at stiffeners that had flexural stresses which were considerably lower.

In view of this fact, an S-N curve was plotted on the basis of maximum principal tensile stress at the failure section. This curve is shown in Fig. 14. The results indicate a rather well defined scatter band with stresses which range from 12.9 to 34.7 ksi.

An S-N curve has also been plotted in which the maximum bending stress on the extreme fiber at the location of failure is used as the ordinate. The results plotted in this way are shown in Fig. 20. It is apparent from this plot that it is impossible to produce a curve through the plotted points.

A comparison of Fig. 14 and Fig. 20 indicate that the maximum principal stress at the location of failure gives a much better relationship.

D. Metallurgical Studies

Some of the specimens which contained stiffeners were subjected to metallurgical examination to see if there were any metallurgical reasons for the failures occurring as they did. In practically all cases the failure was initiated at a point of stress concentration in the web caused by the termination of the fillet weld which bonds the stiffener to the web.

Whereas the crack propagated at an angle in the panel toward the load point, it propagated along the flange-web fillet weld in the panel away from the load point. A hardness survey across the flange, flange-web fillet weld and the web indicated that there was a change in hardness in the heat affected zone where this latter type of failure occurred.

This change in hardness corresponds to a change in strength and micro-structure. Further examination revealed that there were three separate structures, the unaffected base metal, spheroidized pearlite colonies and martensite. The martensite region is the result of heating the base metal above the A_3, changing the ferrite and carbide to austenite and cooling rapidly to below the A_3. This results in a region of high strength and hardness. When the base metal is heated up close to the A_1, but not above it, the pearlite colonies spheroidize and produce a low strength region compared to the other regions. The fatigue crack occurs along this zone.

IV. SUMMARY OF RESULTS

Although it is evident that the number of specimens tested is inadequate to offer any definite conclusions, a number of indicated generalities can be made from the test data.

The use of two different welding sequences used on the basic beam had little, if any, effect on the fatigue life of the specimen, provided that a good sound weld had been deposited and that reasonable steps were taken to keep distortion to a minimum.

The use of two different stiffener locations had for most specimens, no effect on how or where the fatigue crack occurred. To clarify, no matter where a stiffener was placed in the span, the crack initiated at a point of stress concentration where the stiffener was welded to the basic beam. This point of stress concentration could occur for many reasons. If the stiffener was welded to the tension flange, the most susceptible point was at the toe of the fillet weld joining the two. If the stiffener was welded to the web and not to the tension flange, the most common point of initiation was at the end of the fillet weld joining the web to the stiffener on the tension side of the beam on the centerline side of the stiffener. Stiffeners welded to the web by intermittent fillet welds generally followed this rule, however, two specimens did initiate fractures at the upper ends of the lower intermittent fillet welds. It is possible for initiation to occur at any point on the stiffener-web fillet web, especially if a slight flaw exists, such as a crater due to welding, if the flexural and shearing stress values at the point are relatively high. This is true even if the stiffener is welded continuously to the web and the problem could exist in deeper girders more frequently.

Specimens having stiffeners in which the weld was held back from the tension area of the web could probably exhibit a slightly higher fatigue life.

However, the initiation and mode of failure would probably not be affected greatly unless the stiffener was not welded in the tension area of the beam. One specimen thus fabricated failed in the tension flange similar to a plain beam failure. It should be remembered, however, that although some test specimens were welded to a point two inches from the tension flange, this point was halfway between the neutral axis of the beam and the extreme fiber and any attempt to obtain fatigue life should take this into account.

The problem of welding to the tension flange is still questionable. It appears that welding to the tension flange enhances a flange failure, however, some specimens which were viewed after fracture indicated that a fracture had independently initiated and propagated in the web simultaneously. Also, in the working stress range, the tests showed very little difference in number of cycles to failure. In fact, the results indicated that a specimen not welded to the tension flange could fail sooner than the same specimen which had been welded there.

No logical pattern developed for the various stiffener specimens regarding the particular stiffener in the beam at which failure would most likely occur. It is interesting to note that only two specimens fractured at the centerline stiffener. Both of these were welded to the tension flange. Two other specimens welded to the tension flange failed in the flange at points where no stiffeners were present. All of the stiffener specimens tested, in which the stiffeners were not welded to the tension flange, failed at a stiffener location. The only exception was Type F_1 which was considered a plain beam type failure.

With the exception of one specimen, all of the primary fractures occurred in the tension area of the beam. A few secondary fractures occurred in the compression area of the web but these were attributed to points of stress concentration which could have been indirectly affected after the primary crack had propagated and expanded. No explanation can be given for the peculiar behavior of Specimen 42.

Compression fractures were not uncommon in other parts of the investigation, however, particularly on butt welded specimens. On the basis of those failures and the few stiffener specimens, it was observed that these types of fractures could possibly have only a slight effect on the life of the structure. Tension cracks in the flange produce large deflections. Those fractures which occur in the tension area of the web may also produce objectionable deflections. However, those fractures which develop in the compression area of the web and the flange were observed to have very little effect on the deflection of the beam. In fact, two butt welded specimens had failures completely across the compression flange, but the deflection was so small as to go undetected by the micro-switch which stops the machine when excessive deflection occurs. It was also observed that compression cracks propagate much more slowly after initiation than tension cracks.

After the cracks had initiated, the propagation and eventual failure seemed to follow a general pattern. Flange cracks were fairly straight and perpendicular to the web. Web fractures also progressed in fairly straight lines. With the exception of one secondary crack, all of the web cracks in the tension area proceeded diagonally upward toward the centerline of the beam and diagonally downward away from the centerline. Many of the failures continued downward to the toe of the web-flange fillet weld and then changed direction and proceeded horizontally away from the centerline. Cracks in the compression area of the web followed the same procedure in the opposite sense. They propagated diagonally downward toward the centerline of the beam and diagonally upward toward the web-flange fillet weld.

A comparison was made between the angle that the fracture made with the horizontal and that computed at the point of initiation considering both the shearing stress and the flexural stress. The computed angle was that which the plane of maximum principal compressive stress makes with the horizontal. In all cases the computed angle was larger; the average ratio between the two being 1.33. This indicates that the effect of shear in the beam is a factor which should be considered in a design criterion.

Three specimens which had run a considerable number of cycles and had shown no outward signs of failure were given an increase in stress. Two of these specimens failed after a relatively small number of cycles at the increased stress indicating that even though no noticeable crack was evident, the initiation of the failure had already occurred before the stress was raised. In the other specimen the reverse was true.

S-N curves drawn on the basis of the maximum centerline flexural stress indicated that possibly no endurance limit exists. Plotting the same curve using the maximum principal stress at failure as the ordinate revealed that all the failures fell within a well defined scatter band. It was also noted that the maximum principal tensile stress at failure could be as low as 12.9 ksi.

The S-N curves did indicate the possibility that in the working stress range a specimen whose stiffeners were not welded to the tension flange could fail before a specimen whose stiffeners were welded. On the basis of the limited results at the lower or working stress range, it is not feasible to attempt any other conclusions. It should be noted that no stiffener specimen had a distinct advantage over another. Welding the stiffener to the tension flange should be avoided, however, since it does enhance a flange failure in the tension area for which a sudden failure could result. A web failure would probably exhibit enough deflection to be noticed before complete failure occurs.

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TABLE 1

CHEMICAL COMPOSITION OF STEEL PLATES

Plate Thickness in.	Chemical Content, Per Cent					
	C	Mn	P	S	Si	Cu
3/16	0.23	0.63	0.022	0.031	0.030	0.17
1	0.21	0.60	0.030	0.030	0.053	0.20

TABLE 2

PHYSICAL PROPERTIES OF STEEL PLATES

(8-in. Gage Length Tensile Coupons)

Plate Thickness in.	Yield Strength psi	Ultimate Strength psi	Elongation in 8 in., per cent	Reduction of Area, per cent
3/16	38,800	64,800	29.6	58.0
1	34,600	67,000	28.0	48.6

TABLE 3

DESCRIPTION OF WELDING SEQUENCE A
FOR THE BASIC SECTION

Step No.	Remarks
1	Flame cut the web and flange plates in accordance with the fabrication drawing from the corresponding plate sizes.
2	Assemble the web and flange in the tacking jig.
3	Tack the web and flanges in accordance with the welding procedure.
4	Remove the specimen from the tacking jig and place in the welding stands or on a table for deposition of fillet welds. The specimen should be in an upright position.
5	Deposit the fillet welds on one flange of the specimen in accordance with Fig. 4.
6	Turn beam over and repeat Step 5.

Note: All welds were made with reversed polarity in the flat position and with AWS-ASTM E-7016 electrodes, 5/32 in. in diameter.

TABLE 4

DESCRIPTION OF WELDING SEQUENCE B

FOR THE BASIC SECTION

Step No.	Remarks
1	Flange cut the web and flange plates in accordance with the fabrication drawing from the corresponding plate sizes.
2	Assemble the web and flange in the tacking jig.
3	Tack the web and flanges in accordance with the welding procedure
4	Remove the specimen from the tacking jig and place in the welding stands or on a table for deposition of fillet welds. The specimen should be in an upright position.
5	Deposit the fillet welds on one flange of the specimen in accordance with Fig. 3.
6	Turn beam over and repeat Step 5.

Note: All welds were made with reversed polarity in the flat position and with AWS-ASTM E-7016 electrodes, 5/32 in. in diameter.

TABLE 5

WELDING SEQUENCE A FOR THE ATTACHMENT OF STIFFENERS

Step No.	Welding Sequence	Remarks
1	----	Assemble the required stiffeners on the basic beam designated on the fabrication drawing, by tacking before commencing welding. Each tack should be about 1/2-in. long 3/16-in. fillet weld. However, type "C" stiffeners are to be welded in their final state omitting the tacking step.
2	Stiffener 1	Deposit the fillet welds in the position and order shown in Fig. 5. Note that the welds for type "C" stiffeners have been deposited under Step 1.
3	Stiffeners 2 to 6	In numerical order, carry out Step 2 on Stiffeners 2 to 6.
4	Stiffeners 1a to 6a	Turn beam over and carry out Steps 2 and 3. Note that Stiffeners 1a to 6a are to be tacked in place under Step 1.

Note: All passes are shown in Fig. 5; however, only the passes required by the type of stiffener being welded are to be deposited.

All welds are to be made with reversed polarity, in the flat position and with AWS-ASTM E-7016 electrodes 1/8-in. diameter--125 amp.

TABLE 6

WELDING SEQUENCE B FOR THE ATTACHMENT OF STIFFENERS

Step No.	Welding Sequence	Remarks
1	----	Assemble the required stiffeners on the basic beam, designated on the fabrication drawing, by tacking before commencing welding. Each tack should be about 1/2-in. long 3/16-in. fillet weld. Except that the type "C" stiffeners are to be welded in their final state omitting the tacking step.
2	1 and 1a*	Deposit the fillet welds in the position and order shown in Fig. 7. Note that the welds for type "C" stiffeners have been deposited under Step 1.
3	2 and 2a*	Same as Step 2.
4	3 and 3a*	Same as Step 2.
5	4 and 4a*	Same as Step 2. This sequence to be used on types "A", "B", "D" and "E" stiffeners.
6	5 and 5a*	Same as Step 2. This sequence to be used on type "B" stiffeners.

* Sequences 1a, 2a, 3a, 4a and 5a are to be used only on type "D" stiffeners.

Note: All passes are shown in Fig. 7; however, only the passes required by the type of stiffener being welded are to be deposited.

All welds are to be made with reversed polarity, in the flat position and with AWS-ASTM E-7016 electrodes 1/8-in. diameter--125 amps.

TABLE 7

SUMMARY OF TEST RESULTS

Specimen	Max. Stress[a] in Extreme Fiber ksi	Cycles for Failure 1000	Primary[b] Fracture Location Stiffener	Secondary[b] Fracture Location Stiffener(s)
<u>16-in. Specimens</u>				
AA-27(0)A + SA	30.9	293.9	3	
AA-28(0)A + SA	30.5	695.8	5	2 and 4
AA-37(0)B + SA	29.4	574.9	4	
<u>12-in. Specimens</u>				
AA-12(0)A + SA	30.7	630.7	5	
AA-11(0)A + SA	30.6	712.7	3	
AA-10(0)A + SA	30.6	566.2	3	5
AA-18(0)A + SA	30.0	629.8	5	
AA-38(0)B + SA	24.3	1,182.7	2[c]	2[c] and 3
AA-40(0)B + SA	23.7	1,412.1	3	2 and 4
AA-39(0)B + SA	23.6	1,349.5	3	2[c]
AA-53(0)B + SA	20.3	2,733.1	2	
AA-54(0)B + SA	18.5 24.0	4,955.5[d] 142.4	2	6
AA-29(0)B + SB	31.4	627.8	2	
AA-30(0)B + SB	31.1	446.7	1	
AA-31(0)B + SB	31.0	523.6	1	
AA-43(0)B + SB	25.8	1,271.9	3	
AA-41(0)B + SB	25.3	1,110.3	2	
AA-42(0)B + SB	25.0	4,031.0	2[e]	1[e] and 2[c]
AA-56(0)B + SB	21.1 24.7	5,078.1[d] 153.5	Flange Failure[f] 7 1/2 in. east of centerline	
AA-55(0)B + SB	20.2	4,114.9	Flange Failure[f] 5 1/2 in. east of centerline	

[a] Stress based on section measurements at centerline of test span after failure had occurred.

[b] See Figs. 4 and 6 for stiffener locations.

[c] Fracture of both edges of web.

[d] Specimen did not fail until it ran additional cycles at an increased stress

[e] Fracture in the compression side of the web.

[f] Failure between Stiffeners 1 and 2 in the tension flange.

TABLE 7 (Continued)

SUMMARY OF TEST RESULTS

Specimen	Max. Stress[a] in Extreme Fiber ksi	Cycles for Failure 1000	Primary[b] Fracture Location Stiffener	Secondary[b] Fracture Location Stiffener(s)
12-in. Specimens				
AA-14(0)A + SC	30.0	649.3	3	
AA-15(0)A + SC	29.9	864.2	5	2, 3 and 4
AA-13(0)A + SC	29.5	911.3	5	4
AA-46(0)B + SC	25.3	1,048.7	4	
AA-45(0)B + SC	24.9	1,752.7	4	
AA-44(0)B + SC	24.5	1,902.5	4	
AA-57(0)B + SC	20.0	2,832.3	2	5
AA-58(0)B + SC	19.7	4,608.2	2	
AA-34(0)B + SD	31.6	586.8	2	3 and 4
AA-33(0)B + SD	31.3	669.8	2	3 and 4
AA-32(0)B + SD	31.0	510.6	2	3
AA-49(0)B + SD	24.9	1,931.8	4	
AA-47(0)B + SD	24.9	1,129.3	2	3
AA-48(0)B + SD	24.7	814.7	3	
AA-16(0)A + SE	31.0	886.6	6	7
AA-17(0)A + SE	29.9	606.0	4	
AA-35(0)B + SE	29.8	1,070.5	4	
AA-52(0)B + SE	24.8	1,773.8	5	
AA-51(0)B + SE	24.6	1,265.0	2	
AA-50(0)B + SE	24.5	1,008.6	3	
AA-60(0)B + SE	22.8	3,496.9	5	2
AA-59(0)B + SE	19.7 24.9	5,768.5[d] 2,345.5	5	g
AA-36(0)B + SF_1	29.8	829.5	Flange Failure	
AA-61(0)B + SF_2^h	31.0	1,137.8	5	
AA-44(0)B + SCX[i]	25.1	1,187.0	Flange Failure[j].	

g Failure at fillet weld in tension area over west support.

h Modified F type stiffener, see page 11.

i Same as type C except stiffener is welded to tension flange.

j Failure along fillet weld of Stiffener 1 in tension flange.

TABLE 8

PRINCIPAL STRESS DATA

Specimen	Max. Stress at Extreme Fiber in ksi[a]: Center Line	Max. Stress at Extreme Fiber in ksi[a]: Primary Fracture	Principal Stresses at Primary Fracture in ksi[b]: Max. Tension	Max. Compression	Max. Shear	Computed φ deg.	Measured φ deg.	φ Comp. / φ Meas.
<u>16-in. Specimens</u>								
AA-27(0)A + SA	30.9	30.3	34.7	8.1	21.4	64.2	60	1.07
AA-28(0)A + SA	30.4	16.4	24.3	10.0	17.1	57.4	50	1.15
AA-37(0)B + SA	29.4	16.6	25.7	11.2	18.5	56.6	50	1.13
<u>12-in. Specimens</u>								
AA-12(0)A + SA	30.7	13.2	22.3	11.3	16.8	54.6	52	1.04
AA-11(0)A + SA	30.6	22.5	28.4	9.6	19.0	59.8	58	1.05
AA-10(0)A + SA	30.6	22.3	28.2	9.6	18.9	59.8	55	1.09
AA-18(0)A + SA	30.0	12.9	22.6	11.9	17.2	54.0	52	1.04
AA-38(0)B + SA	24.3	21.6	25.2	7.2	16.2	61.9	52	1.19
AA-40(0)B + SA	23.7	15.8	21.3	8.1	14.7	58.3	50	1.17
AA-39(0)B + SA	23.6	15.8	21.7	8.5	15.1	57.9	48	1.21
AA-53(0)B + SA	20.3	18.1	20.4	5.3	12.8	63.0	55	1.15
AA-54(0)B + SA	18.5 24.0	16.5 21.5	18.7 24.3	4.9 6.4	11.8 15.3	62.8 62.7	56	1.12 1.12
AA-29(0)B + SB	31.4	28.0	32.1	8.7	20.4	62.5	59	1.06
AA-30(0)B + SB	31.1	31.1	Flange Failure.					
AA-31(0)B + SB	31.0	31.0	Flange Failure.					

[a] Stresses based on section measurements after failure had occurred.

[b] Stresses computed at the point of initiation of the crack.

TABLE 8 (Continued)

Specimen	Max. Stress at Extreme Fiber in ksi[a]: Center Line	Max. Stress at Extreme Fiber in ksi[a]: Primary Fracture	Principal Stresses at Primary Fracture in ksi[b]: Max. Tension	Max. Compression	Max. Shear	Computed φ deg.	Measured φ deg.	φ Comp. / φ Meas.
AA-43(0)B + SB	25.8	17.2	22.5	8.2	15.4	58.9	52	1.13
AA-41(0)B + SB	25.3	22.7	25.9	6.9	16.4	62.7	55	1.14
AA-42(0)B + SB	25.0	22.8	25.9	6.8	16.4	62.3	51	1.22
AA-56(0)B + SB	21.1 24.7	20.5 24.0	Flange Failure.					
AA-55(0)B + SB	20.2	20.2	Flange Failure.					
AA-14(0)A + SC	30.0	21.9	21.9	12.8	17.3	52.9	51	1.04
AA-15(0)A + SC	29.9	12.8	24.8	9.9	17.4	51.2	50	1.02
AA-13(0)A + SC	29.5	13.3	22.8	11.7	17.2	54.4	47	1.16
AA-46(0)B + SC	25.3	11.1	17.8	11.3	14.5	52.6	49	1.07
AA-45(0)B + SC	24.9	11.1	18.9	9.6	14.2	54.5	46	1.18
AA-44(0)B + SC	24.5	10.9	17.2	10.9	14.1	51.5	46	1.12
AA-57(0)B + SC	20.0	17.7	17.0	6.7	11.8	57.7	52	1.11
AA-58(0)B + SC	19.7	17.5	16.5	6.3	11.4	58.3	52	1.12
AA-34(0)B + SD	31.6	28.3	32.4	8.8	20.6	62.4	57	1.09
AA-33(0)B + SD	31.3	28.0	32.4	9.1	20.7	62.1	56	1.11
AA-32(0)B + SD	31.0	20.5	27.4	10.3	18.9	58.5	52	1.12
AA-49(0)B + SD	24.9	11.0	18.6	9.5	14.1	54.5	43	1.27
AA-47(0)B + SD	24.9	22.0	23.4	7.8	15.6	59.0	49	1.20
AA-48(0)B + SD	24.7	16.6	22.5	8.7	15.6	58.1	42	1.38

TABLE 8 (Concluded)

Specimen	Max. Stress at Extreme Fiber in ksi[a]		Principal Stresses at Primary Fracture in ksi[b]					φ Comp. / φ Meas.
	Center Line	Primary Fracture	Max. Tension	Max. Compression	Max. Shear	Computed φ deg.	Measured φ deg.	
AA-16(0)A + SE	31.0	8.6	21.5	14.3	17.9	50.8	45	1.13
AA-17(0)A + SE	29.9	13.0	24.1	11.3	17.7	50.2	43	1.17
AA-35(0)B + SE	29.8	13.4	21.8	14.0	17.9	51.3	44	1.17
AA-52(0)B + SE	24.8	5.5	15.6	12.8	14.2	47.8	46	1.04
AA-51(0)B + SE	24.6	21.9	20.7	9.8	15.2	55.4	48	1.15
AA-50(0)B + SE	24.5	16.3	19.5	10.0	14.8	54.4	45	1.21
AA-60(0)B + SE	22.8	5.0	12.9	10.4	11.7	48.1	44	1.09
AA-59(0)B + SE	19.7	4.4	11.4	9.3	10.4	48.1	43	1.12
	24.9	5.5	14.7	12.0	13.3	47.9		1.11
AA-36(0)B + SF_1	29.8	29.8	Flange Failure.					
AA-61(0)B + SF_2	31.0	7.0	20.4	13.5	16.9	47.9	40	1.20
AA-44(0)B + SCX	25.1	25.1	Flange Failure.					

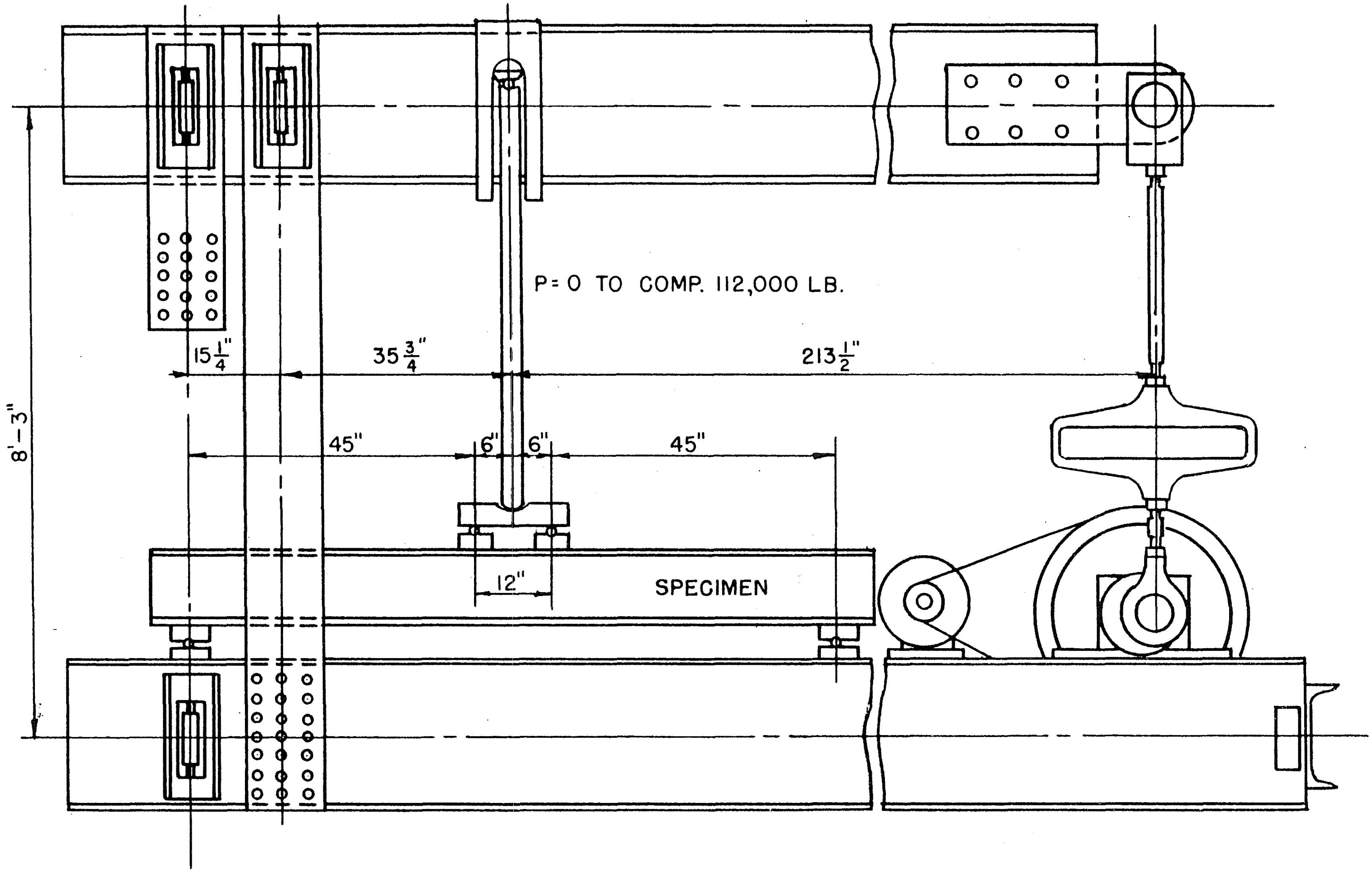
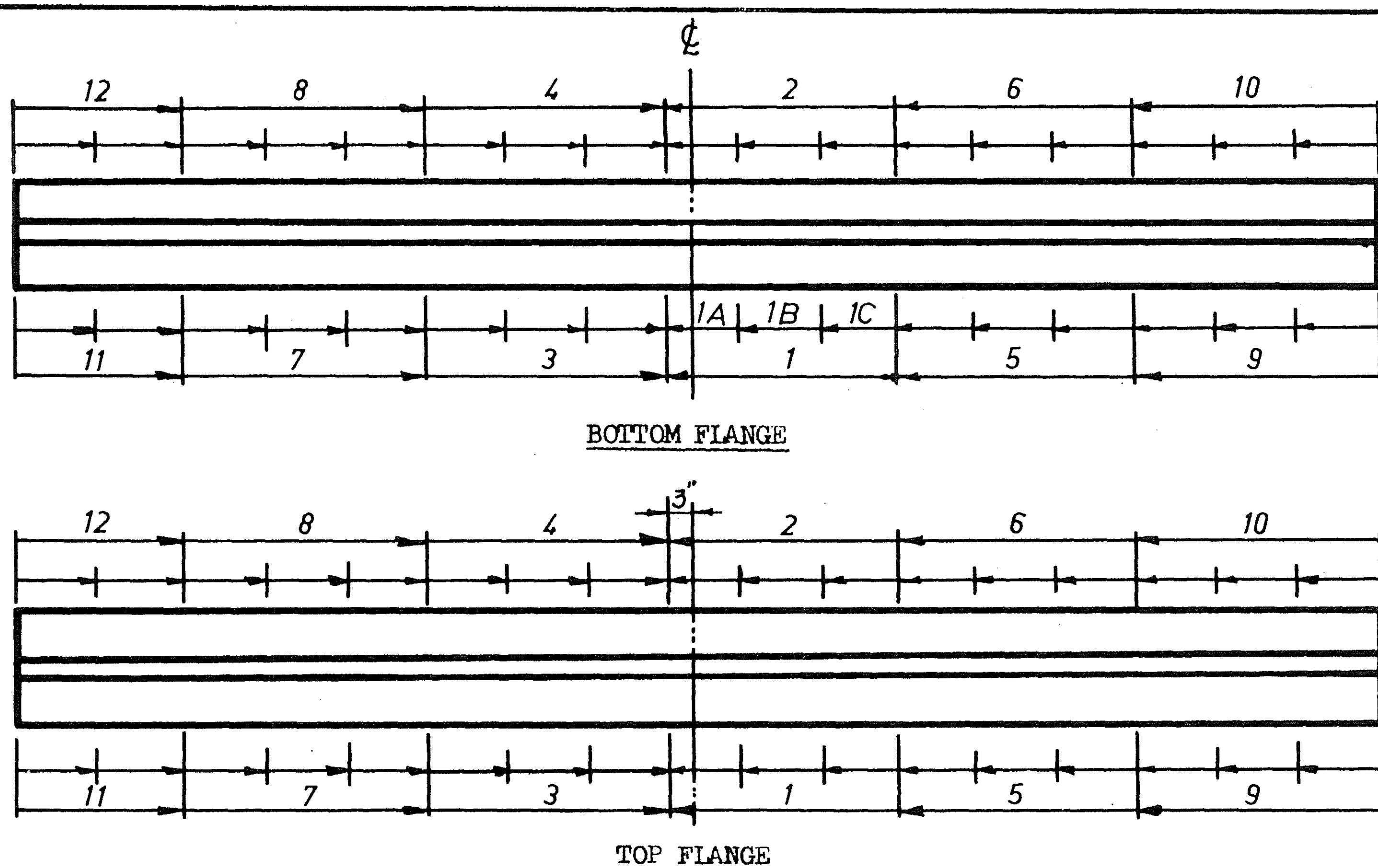


FIG. 1 200,000-LB. WILSON FATIGUE TESTING MACHINE ADAPTED TO TEST FLEXURAL SPECIMENS



WELDING:

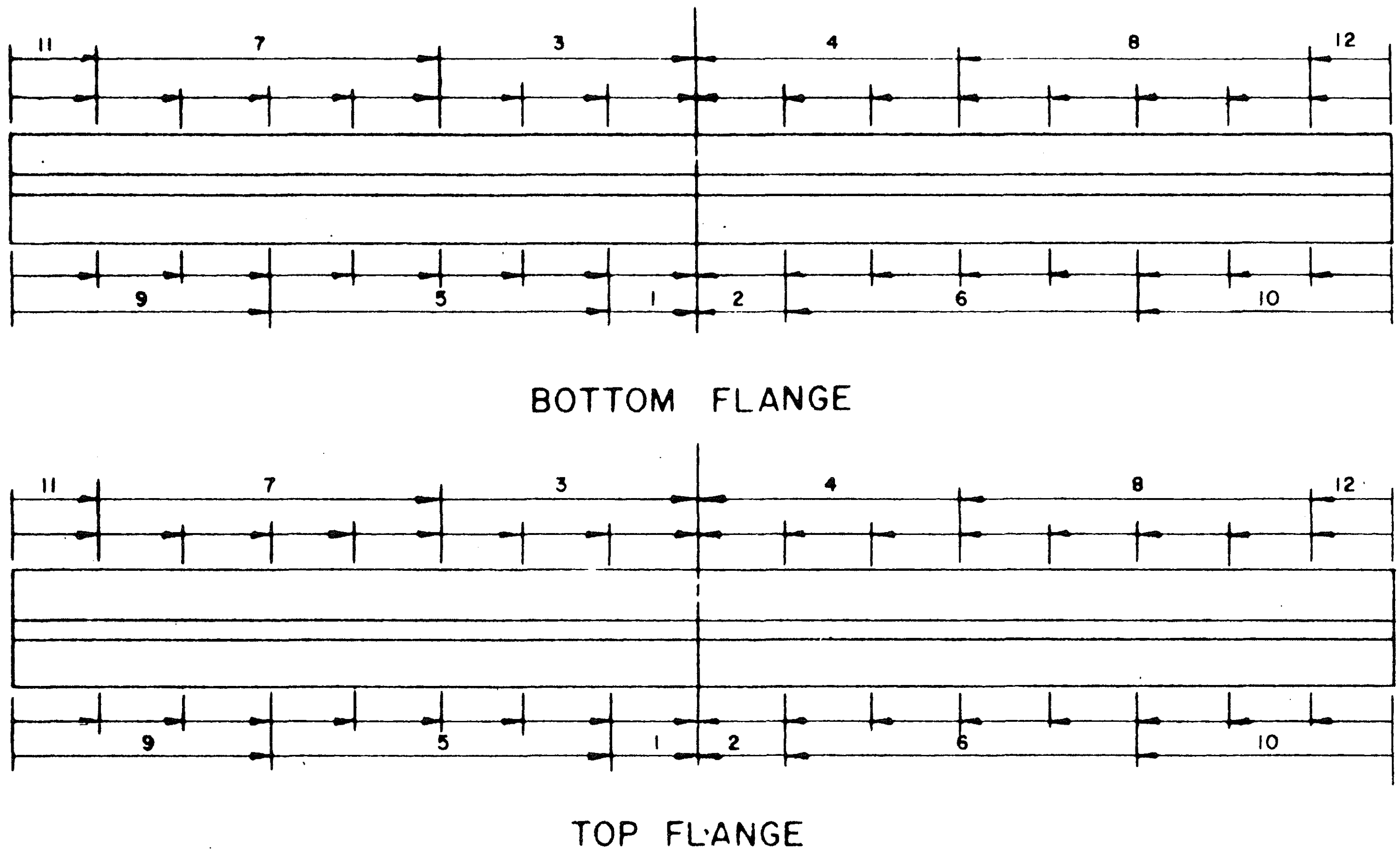
1/4" Fillet Weld, 5/32" dia. E7016 Electrode--175 amps.

NOTE:

Inside arrows indicate the deposition of individual electrodes.

Outside arrows and the numbers indicate the welding sequence.

FIG. 2 WELDING SEQUENCE A FOR THE BASIC SECTION



Welding:

$\frac{1}{4}$" Fillet Weld ; $\frac{5}{32}$" dia. E7016 Electrode — 175 amps

Note:

Inside arrows indicate the deposition of individual electrodes

Outside arrows and the numbers indicate the welding sequence

FIG. 3 WELDING SEQUENCE B FOR THE BASIC SECTION

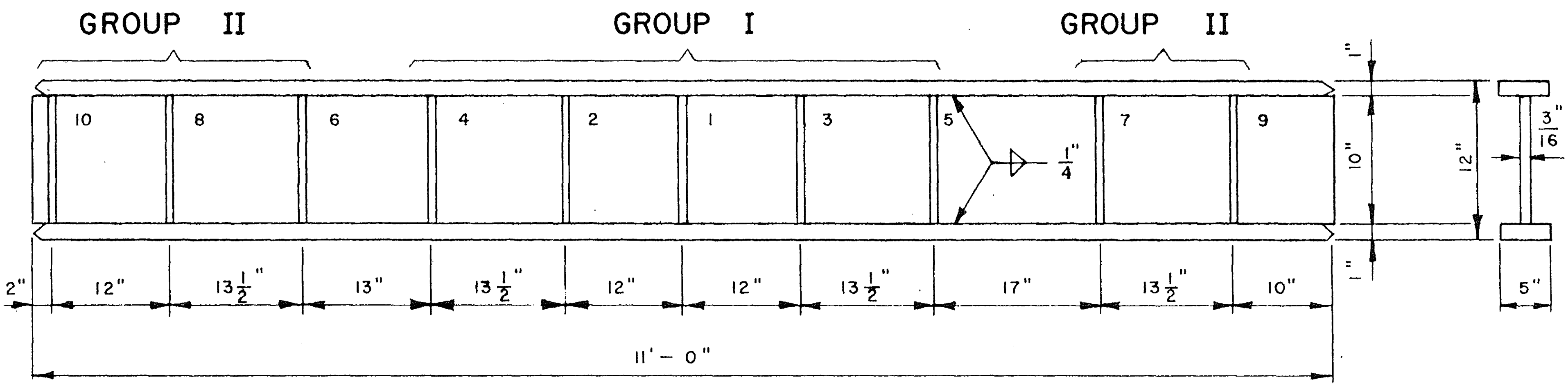
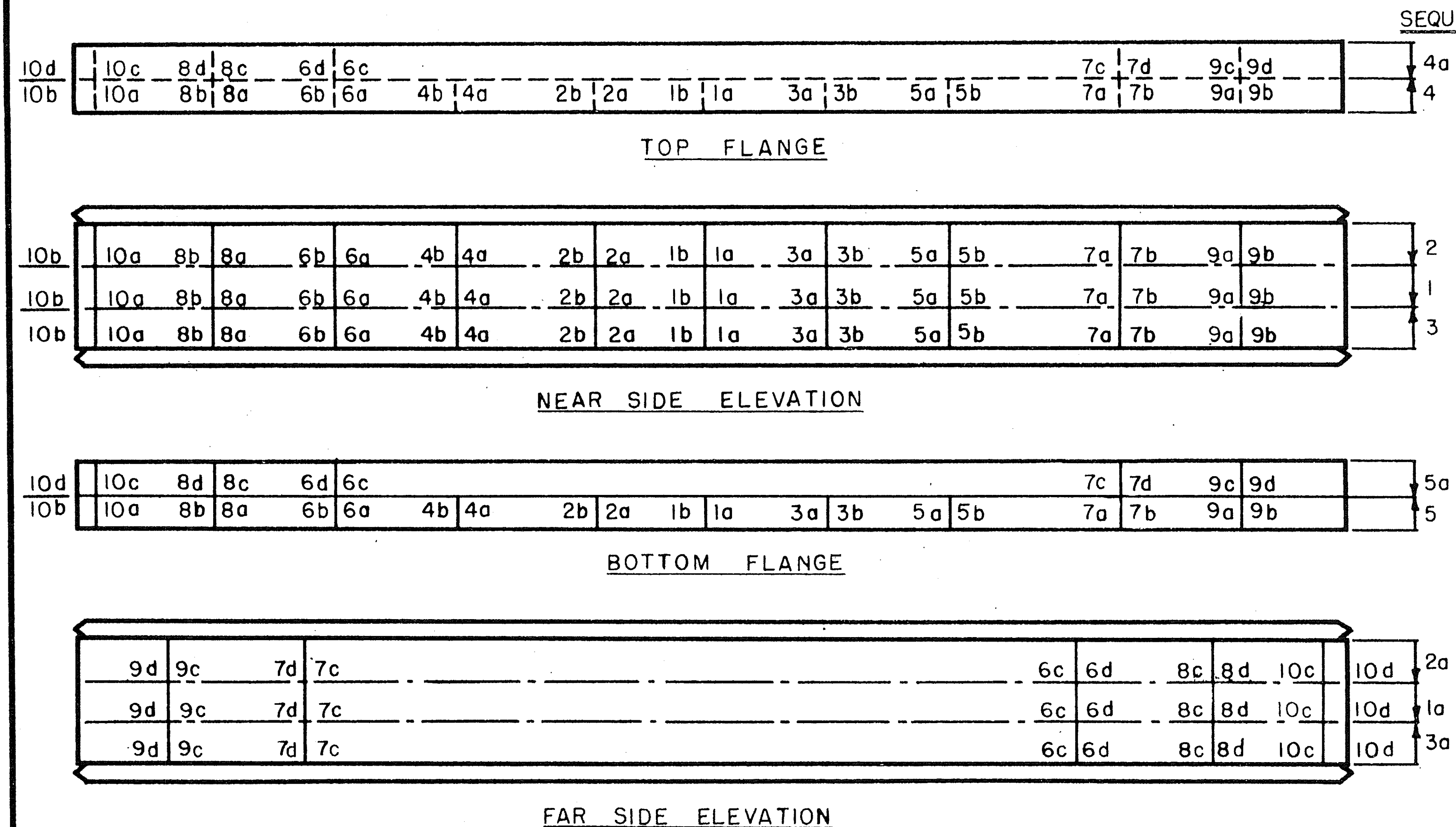


FIG. 4 LOCATION OF STIFFENERS FOR WELDING SEQUENCE A



WELDING: - 3/16" FILLET WELD; 1/8" DIA. E7016 ELECTRODE - 125 AMPS. THE ARROWS INDICATE THE DIRECTION OF DEPOSITION OF INDIVIDUAL PASSES WITHIN EACH WELDING SEQUENCE.

FIG. 5 STIFFENER WELDING SEQUENCE A

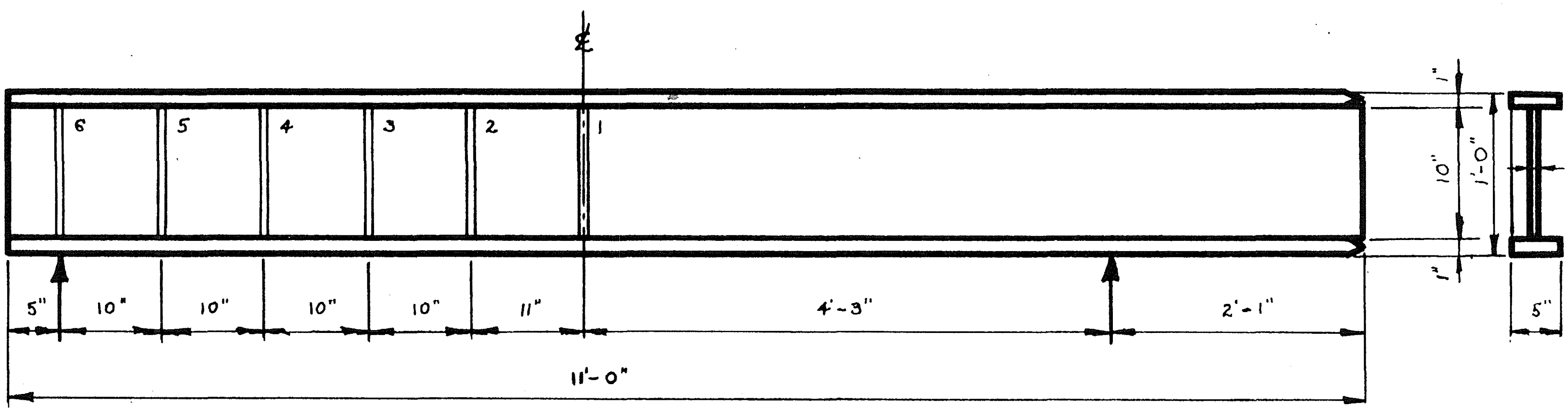
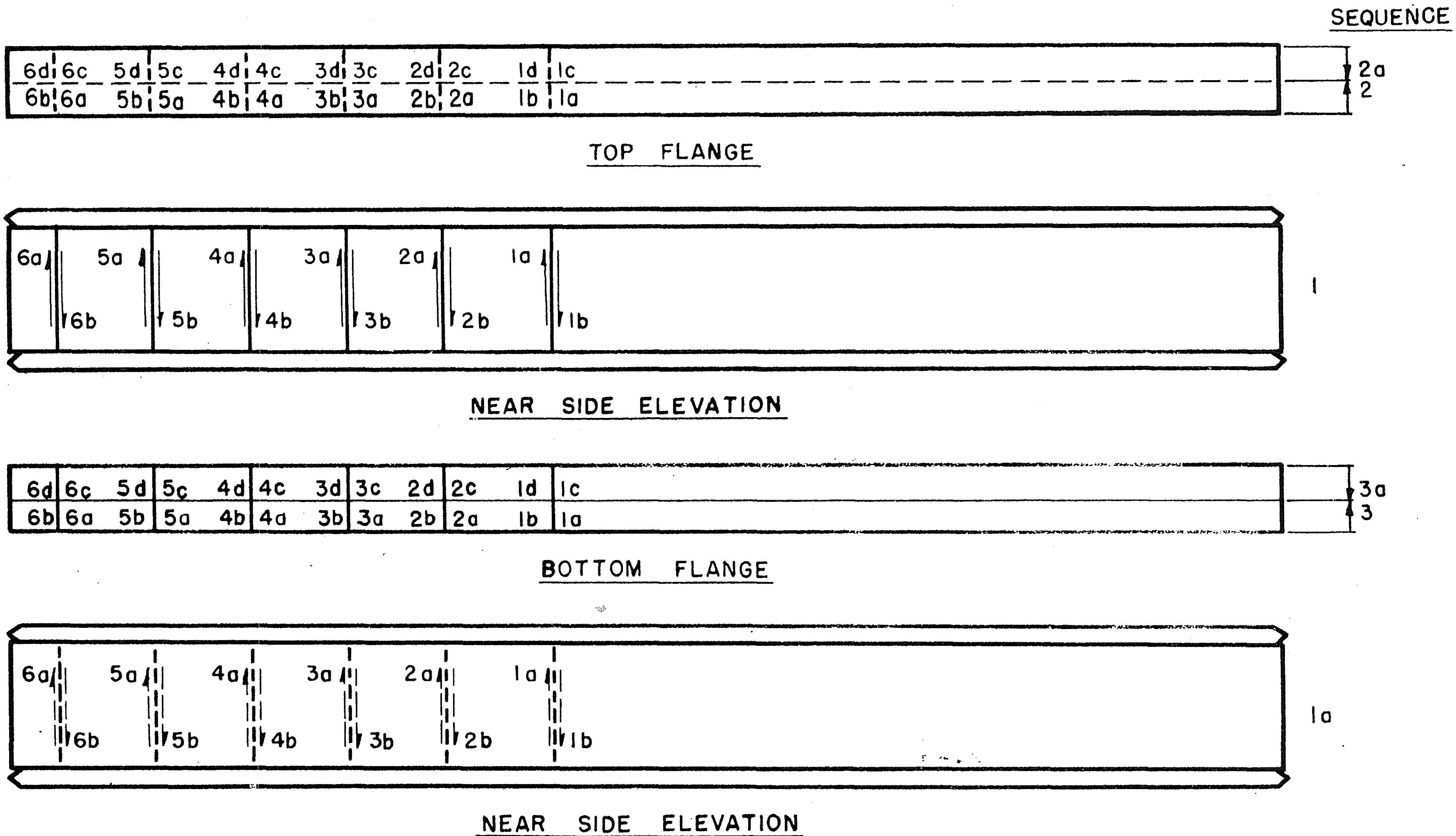


FIG. 6 LOCATION OF STIFFENERS FOR WELDING SEQUENCE B



WELDING:- $3/16$" FILLET WELD; $1/8$" DIA. E7016 ELECTRODE - 125 AMPS. THE ARROWS INDICATE THE DIRECTION OF DEPOSITION OF INDIVIDUAL PASSES WITHIN EACH WELDING SEQUENCE.

FIG. 7 STIFFENER WELDING SEQUENCE B

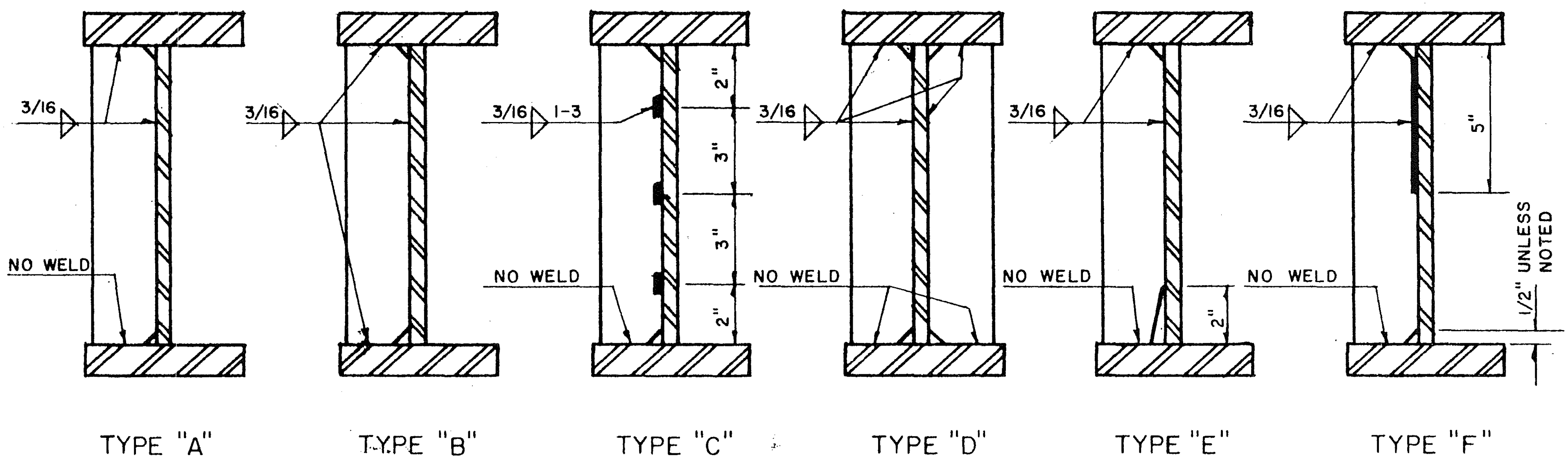


FIG. 8 STIFFENER TYPES

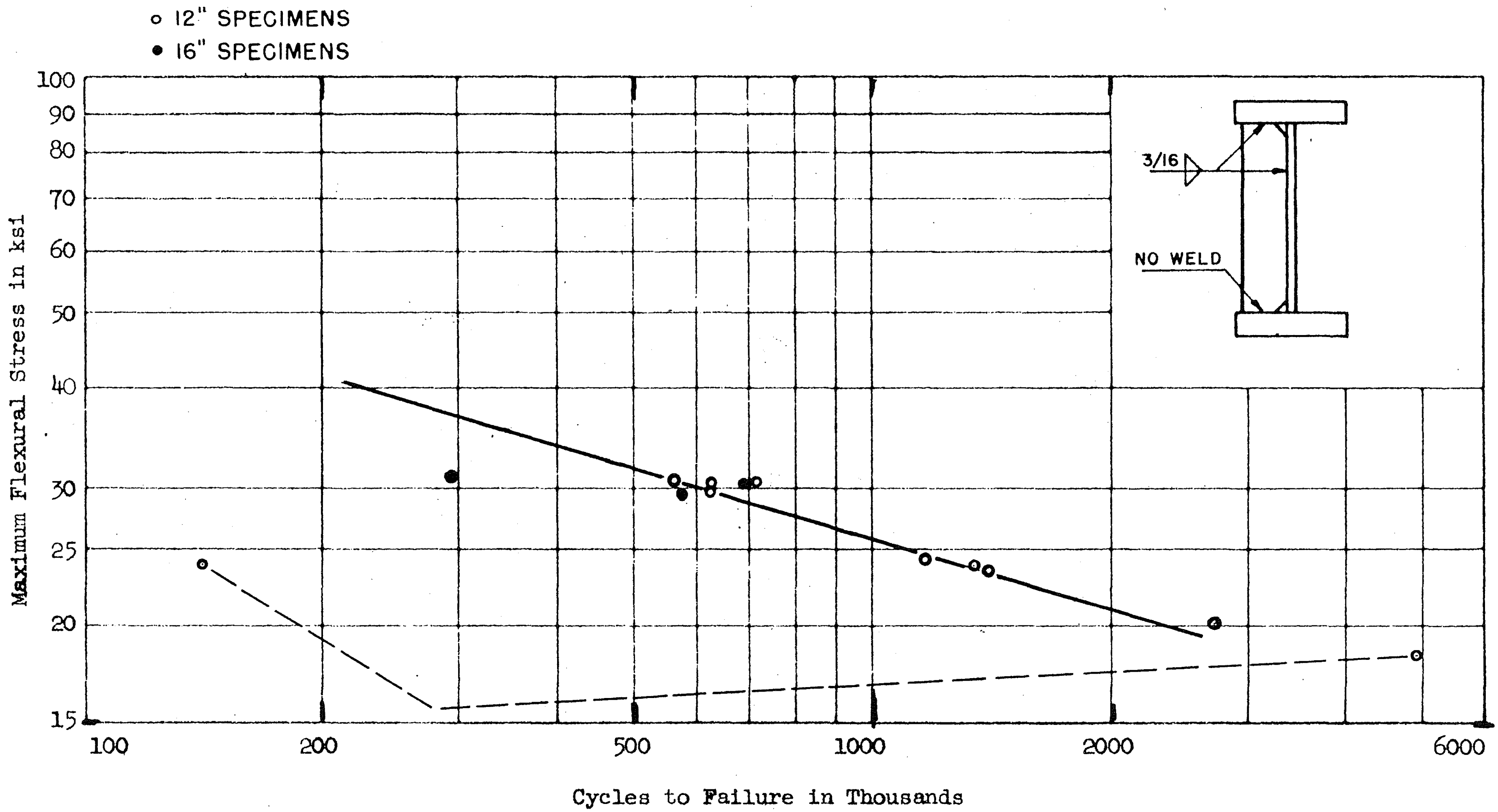


FIG. 9 S-N DIAGRAM FOR STIFFENER TYPE "A"

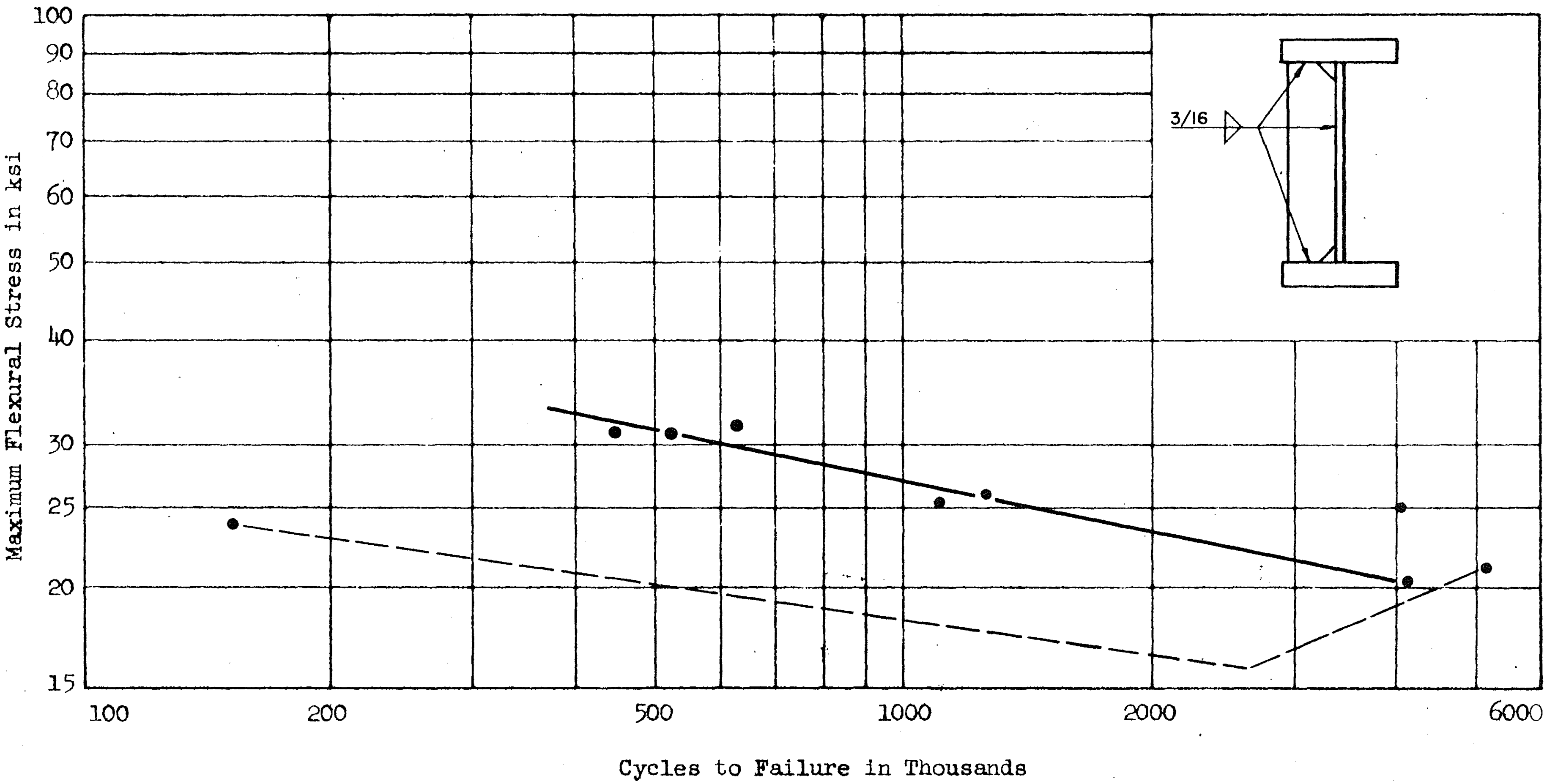


FIG. 10 S-N DIAGRAM FOR STIFFENER TYPE "B"

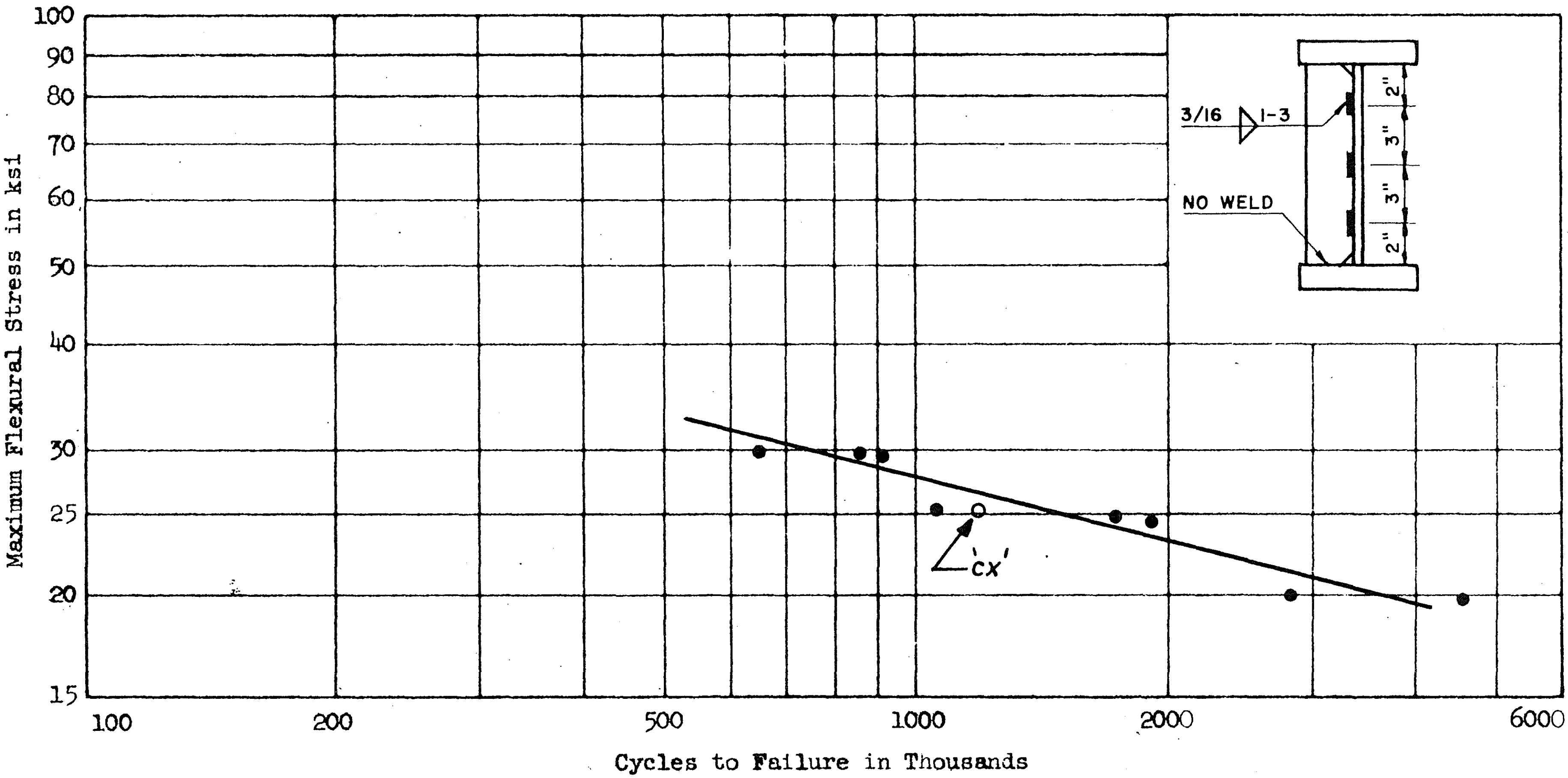


FIG. 11 S-N DIAGRAM FOR STIFFENER TYPE "C"

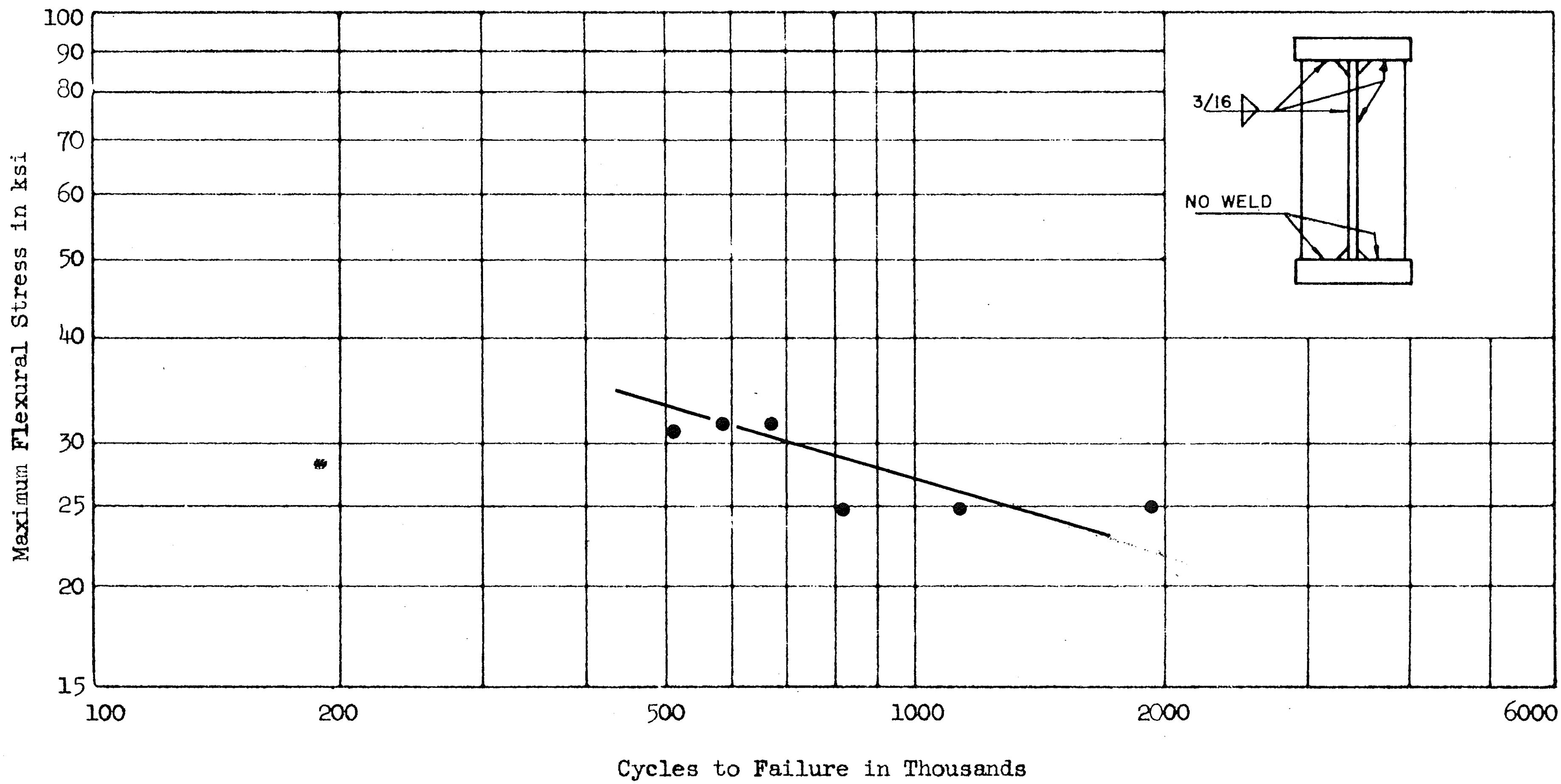


FIG. 12 S-N DIAGRAM FOR STIFFENER TYPE "D"

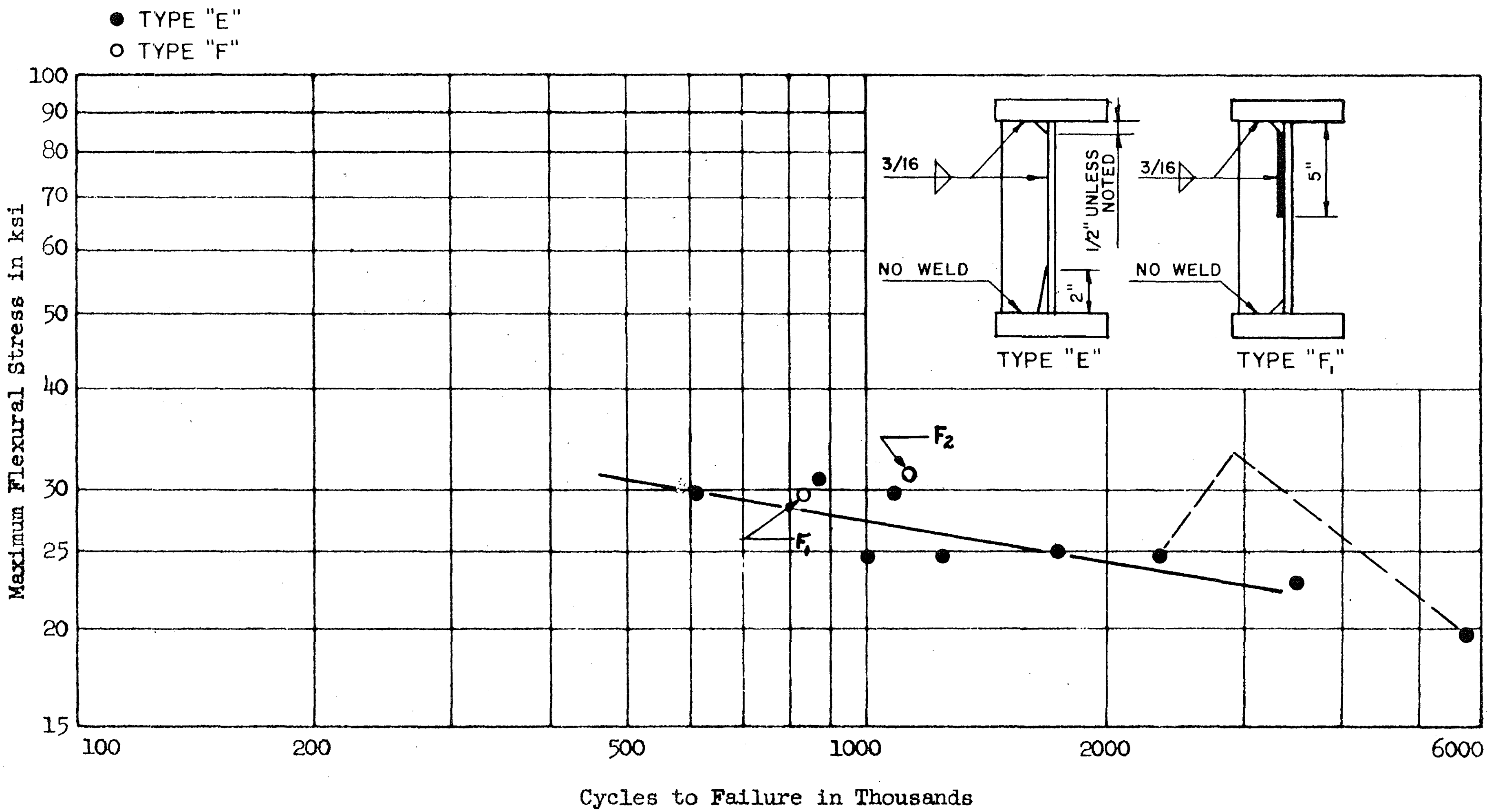


FIG. 13 S-N DIAGRAM FOR STIFFENER TYPE "E" & "F"

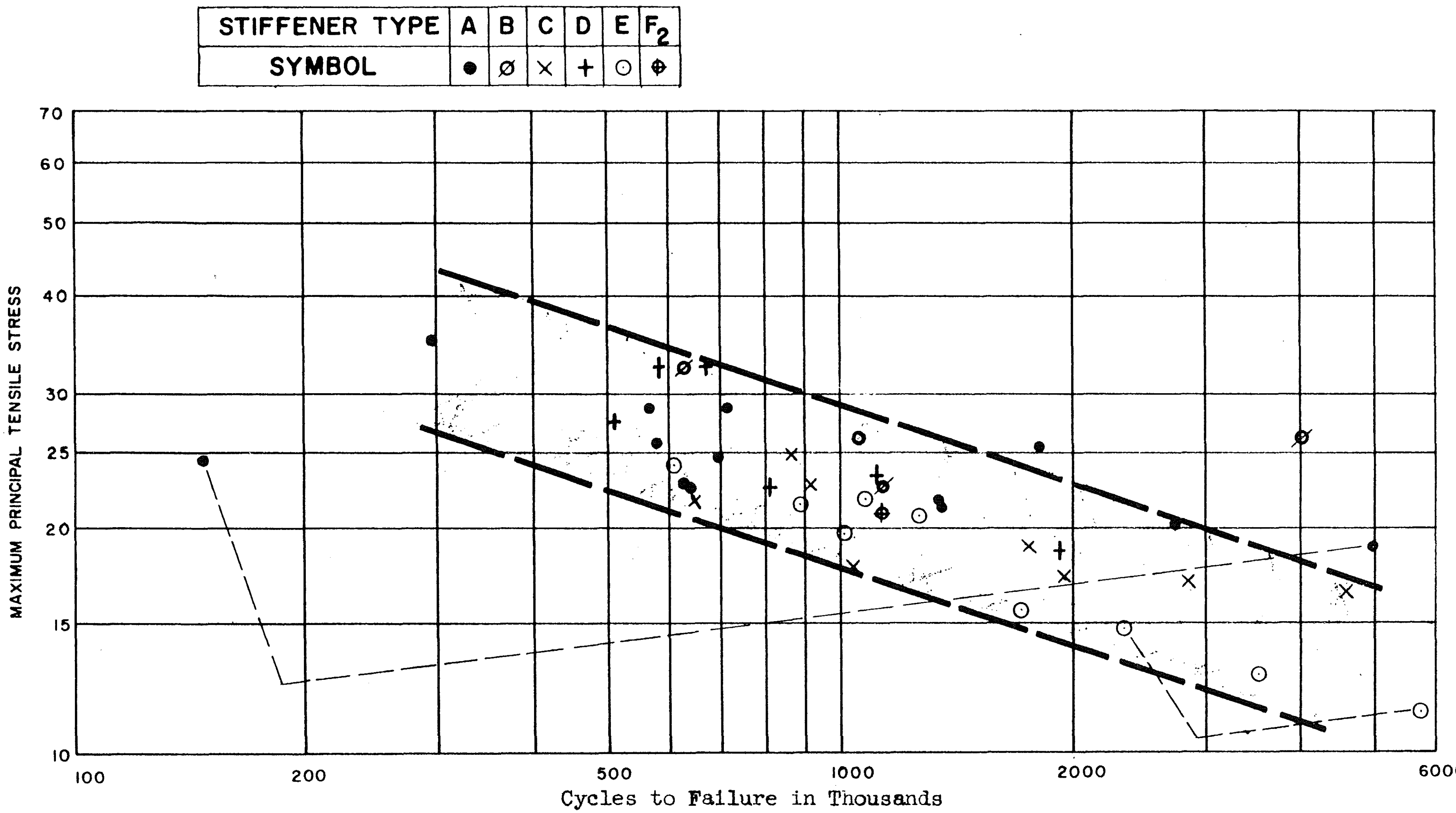
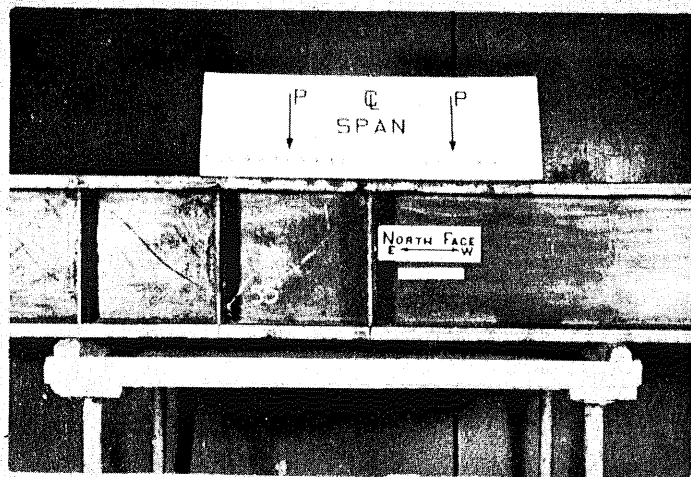
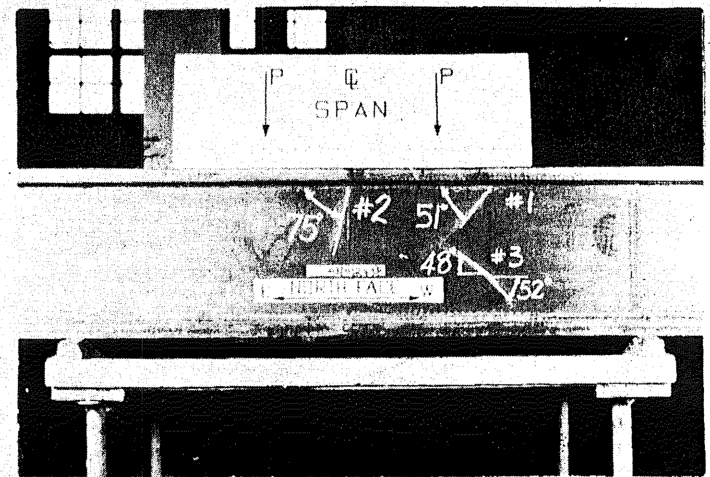


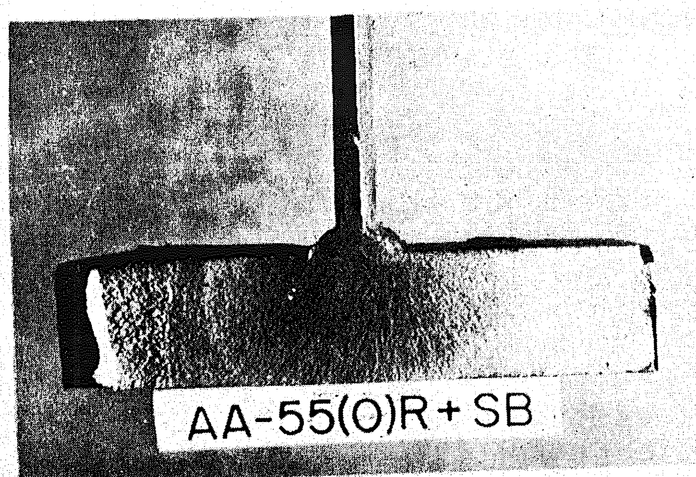
FIG. 14 S-N DIAGRAM FOR MAXIMUM PRINCIPAL TENSILE STRESS AT FAILURE SECTION



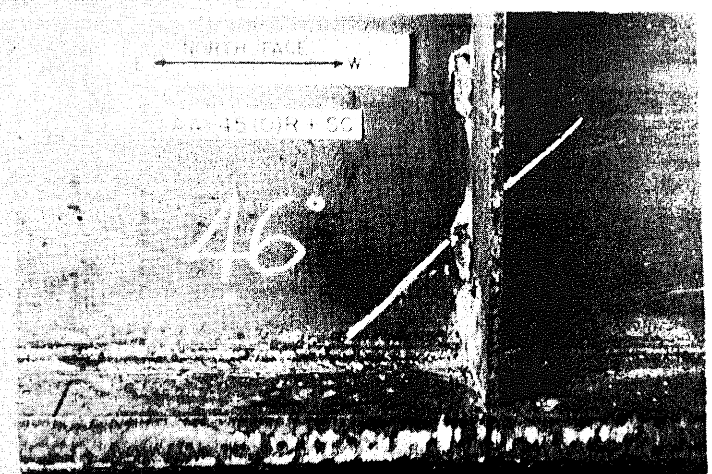
(a)



(b)



(c)



(d)

FIG. 15 TYPICAL FATIGUE FRACTURES OF STIFFENER SPECIMENS

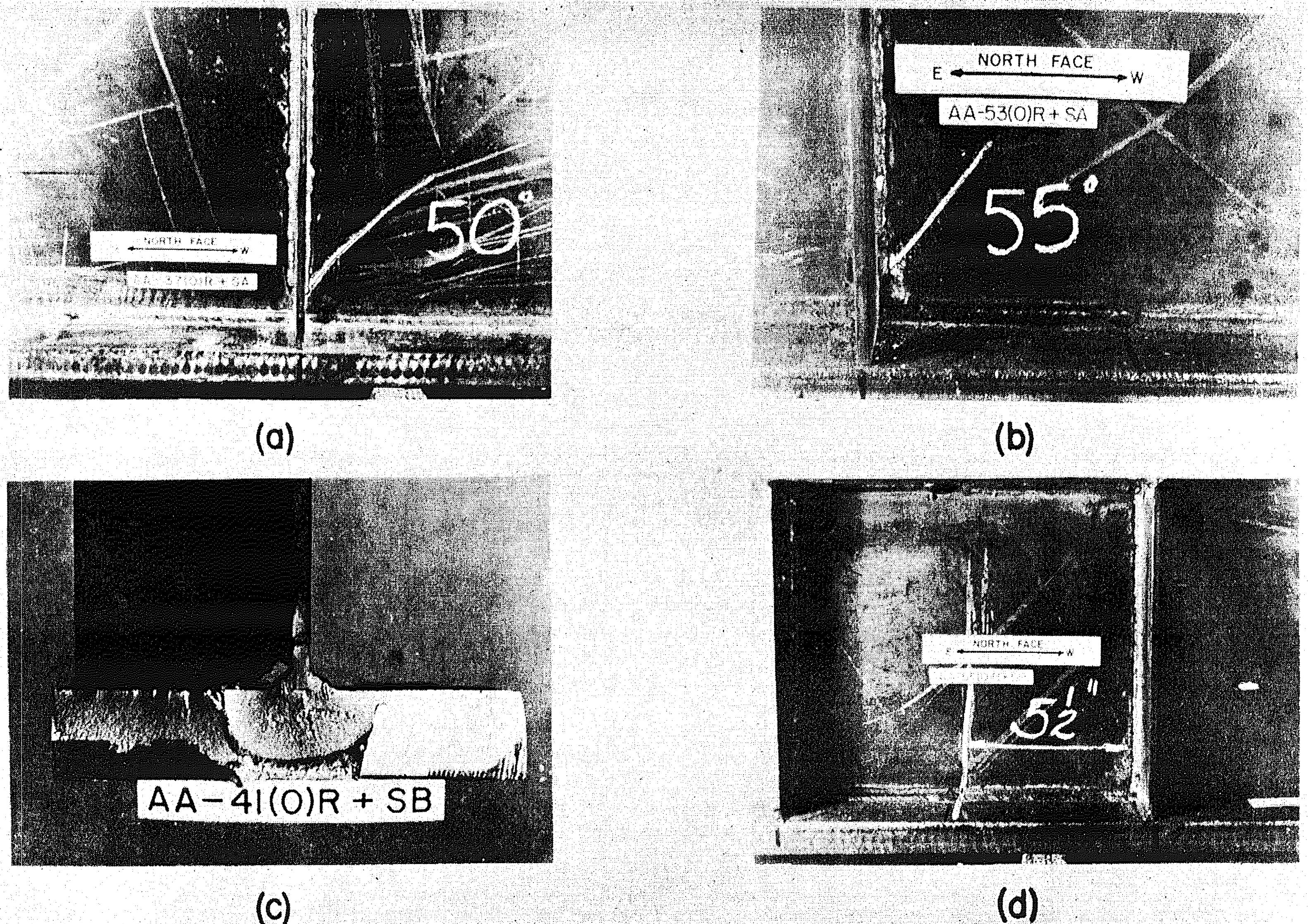


FIG. 16 TYPICAL FATIGUE FRACTURES OF STIFFENER SPECIMENS

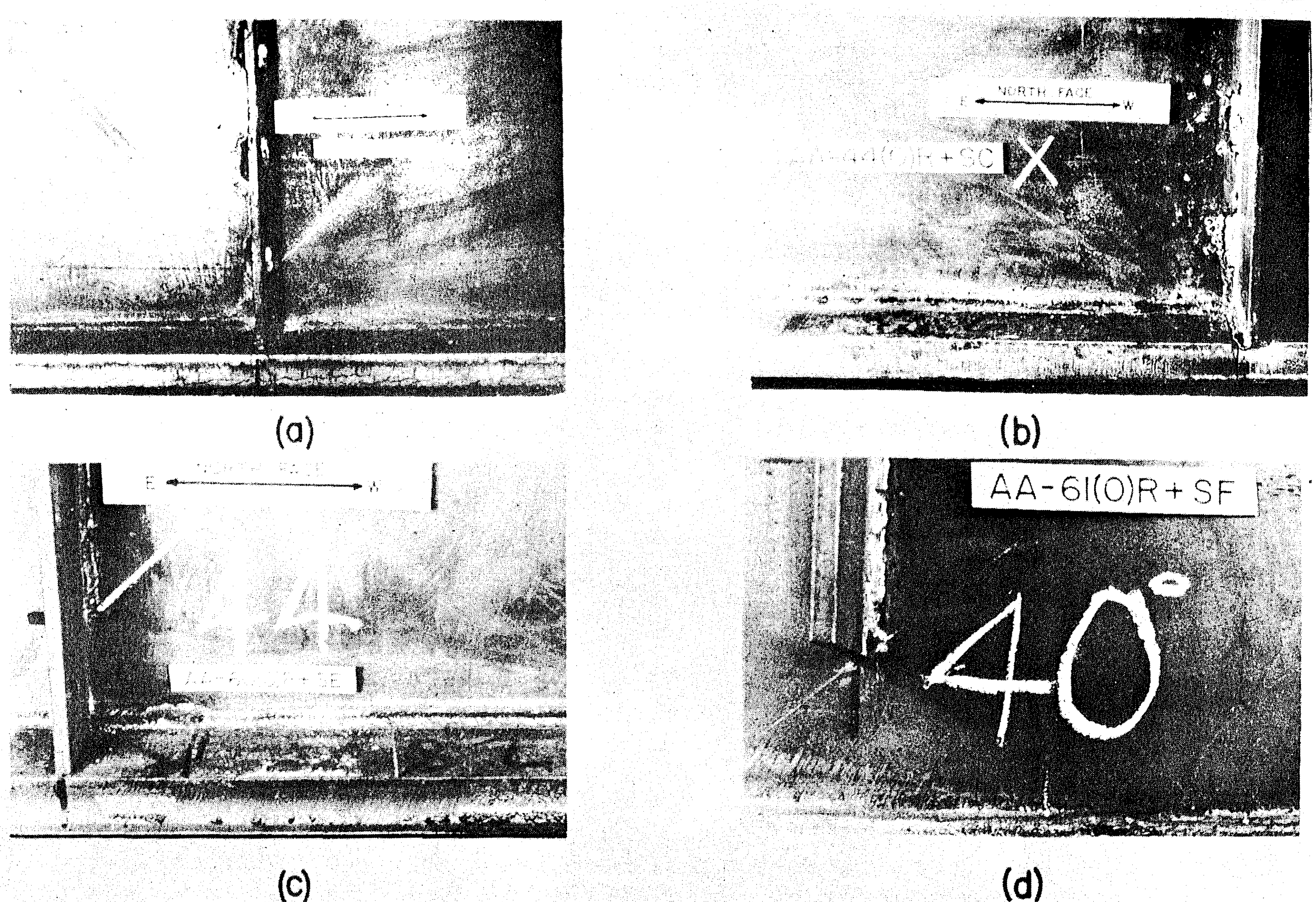


FIG. 17 TYPICAL FATIGUE FRACTURES OF STIFFENER SPECIMENS

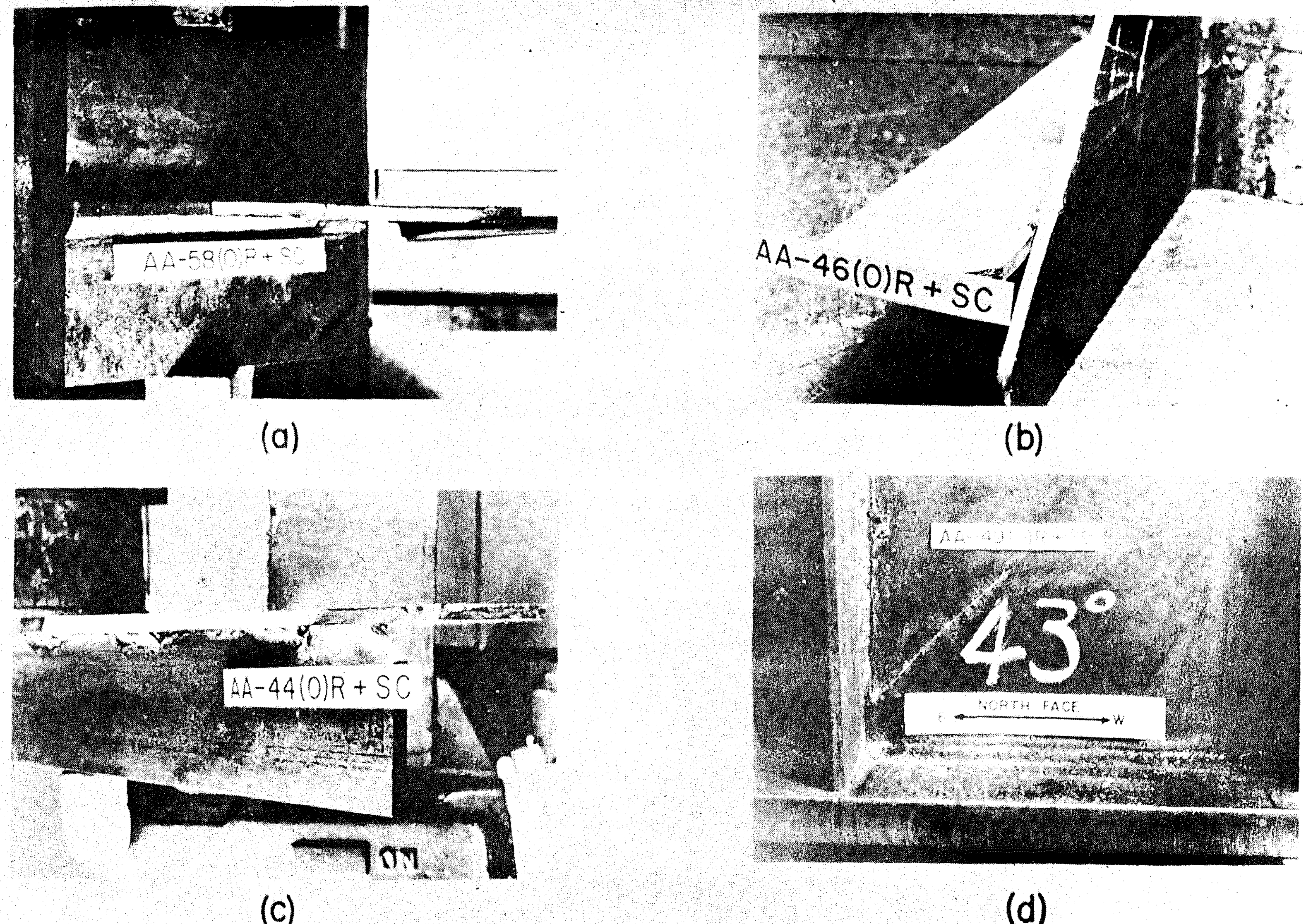


FIG. 18 TYPICAL FATIGUE FRACTURES OF STIFFENER SPECIMENS

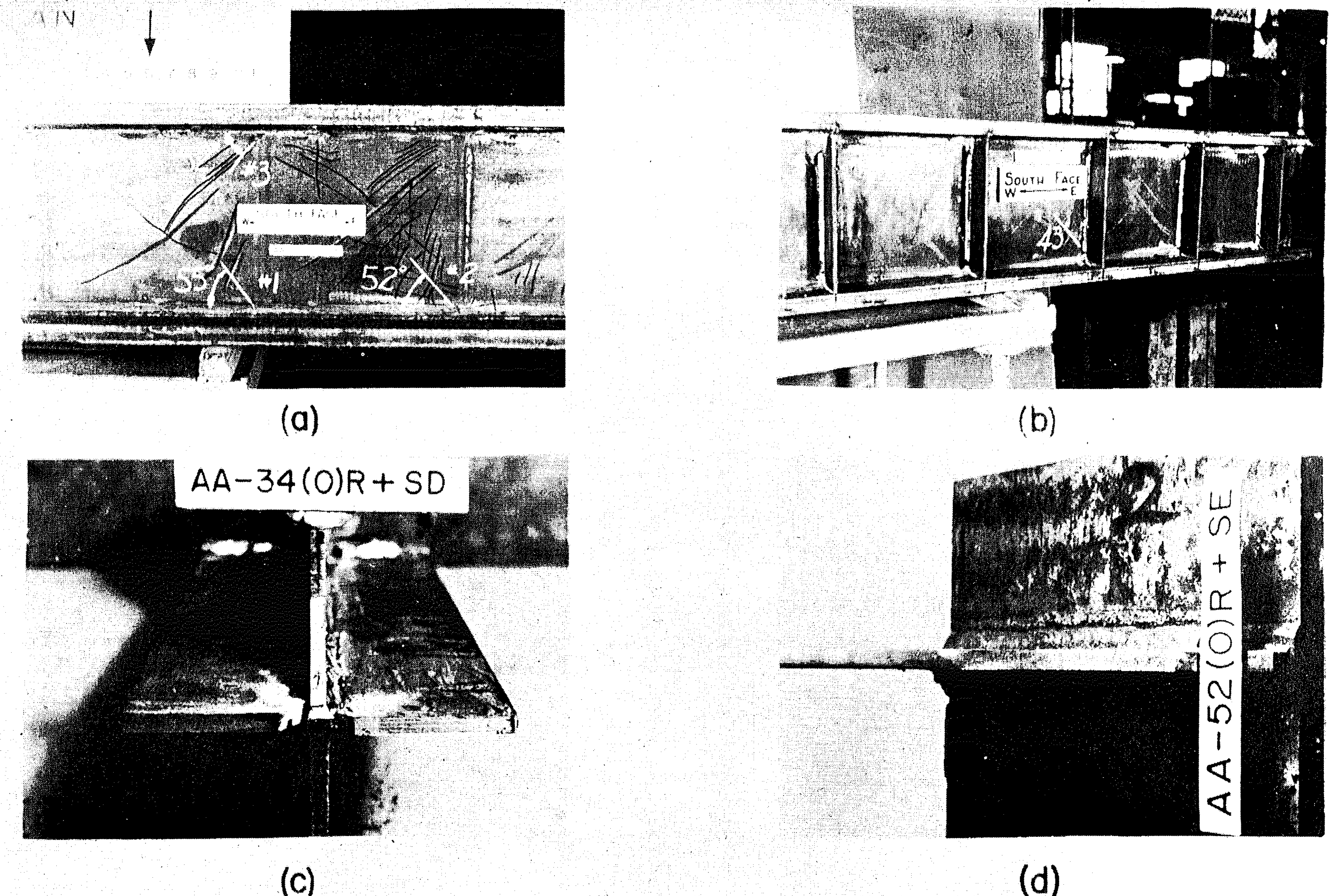


FIG. 19 TYPICAL FATIGUE FRACTURES OF STIFFENER SPECIMENS

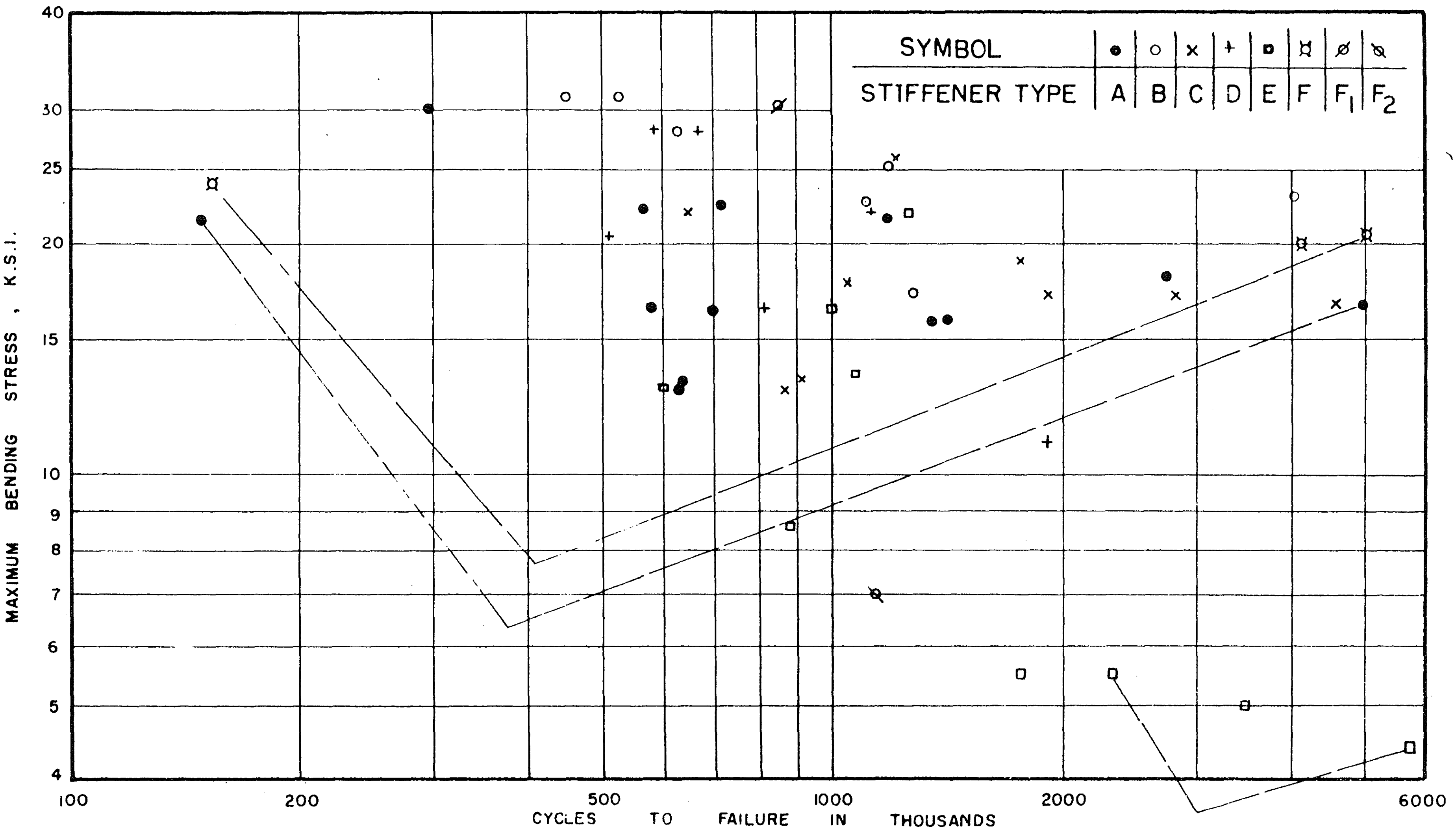


FIG. 20 S-N DIAGRAM FOR MAXIMUM BENDING STRESS AT THE FAILURE SECTION