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BEHAVIOR OF WELDED BUILD-UP BEAMS UNDER REPEATED LOADS

By
W. E. FISHER
J. E. STALLMEYER

Approved by
W. H. MUNSE

UNIVERSITY OF ILLINOIS
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J. E. Stallmeyer

and

W. E. Fisher

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Bureau of Public Roads, Department of Commerce

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I. INTRODUCTION

A. General Summary

The experimental studies described in this report were conducted to determine the behavior of welded flexural members of the type used in bridge construction, to find means of increasing the fatigue life of such welded members, and to develop related information which will advance the art of bridge design. To this end, flexural fatigue tests have been conducted on small all-welded beams fabricated from A-373 steel. Manual arc welding, with E-7016 electrodes and a back-stepping welding procedure, was used in the fabrication of all of the specimens included in this report. Initial studies on this program were conducted on beams without splices. Several field splice configurations were used in the investigation and studies made of the difference in their modes of failure as well as the difference in their fatigue strengths. In addition, the program included fatigue tests on control specimens to determine the fatigue strength of the A-373 steel as-received from the mill and also with butt-welded joints, either parallel or perpendicular to the direction of stress.

The fatigue tests on the beams indicate that the presence of a splice materially reduces the fatigue strength of a welded beam. A difference in fatigue strength is also revealed for the different splice configurations; however, it is necessary to keep in mind the thickness of material used in this investigation.

B. Object and Scope

The increased use in recent years of all-welded girders along with the variety of procedures used by fabricators and designers for making splices has resulted in the existence of a large variety of welded bridge details. Until the present investigation was undertaken there were only a limited number of tests available from which to determine the relative merits of specific details for maximum resistance to repeated loads. In order to evaluate some of the more common details, this investigation on all-welded beams was undertaken.

The purpose of the preliminary phase of the investigation was to study the effect of varying the ratio between the flange thickness and the web thickness. The next phase of the program was conducted on specimens which contained typical butt-welded field splices in order to determine their effect on the flexural fatigue strength of all-welded built-up beams and girders. Four splice types, derived from two basic splice configurations, either with or without cope holes, were investigated while beams without splices and beams with cope holes only were included in the program as control specimens. These tests have been extended to determine the S-N relationships for a number of the splice configurations. These S-N relationships have been determined for fatigue cycles in which the stress varied from a minimum of zero to a maximum tension.

In the future, the program will be extended to include tests on spliced beams under different stress cycles. A program on beams with stiffeners and beams with cover plates is also being undertaken.

C. Acknowledgments

The tests described in this report are a part of an investigation resulting from a cooperative agreement between the Engineering Experiment Station of the University of Illinois and the Department of Commerce, Bureau of Public Roads. Recently the Association of American Railroads has also provided support for the investitation.

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. The research was conducted by W. E. Fisher, Research Associate in Civil Engineering, under the immediate supervision of J. E. Stallmeyer, Associate Professor of Civil Engineering. The Flexural Fatigue program is under the general direction of W. H. Munse, Professor of Civil Engineering. The Fatigue Committee of the Welding Research Council has acted in an advisory capacity for the project.

The initial work on this program was carried out by B. J. Goodal, formerly Research Assistant in Civil Engineering. In addition, the authors wish to express their appreciation to the Civil Engineering Shop personnel for the care and attention they have given to the preparation of the specimens. The metallurgical investigations were conducted by Mr. C. A. Robertson and Mr. R. Falck under the direction of Professor W. H. Bruckner.

II. DESCRIPTION OF TEST SPECIMENS AND TEST PROCEDURE

A. Materials

The original work on this program was conducted on beams fabricated from A-7 steel taken from 6- by 12-ft. plates which were available in the laboratory. The chemical composition, as given by the mill reports, and the physical properties, as obtained from standard flat coupon specimens cut from the parent plates, are given in Tables 1 and 2. All specimens in which this steel was used are designated by a "P".

The remaining work, which constitutes the major portion of this report, was carried out on specimens fabricated from A-373-54T steel which was ordered for use on this program. The chemical composition and physical properties of the materials used 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.

Electrodes conforming to AWS designation E-7016 were used for all manual welds. The welding current was supplied by a 200 ampere DC generator of standard commercial make. After the seal on the electrode container had been broken, the electrodes were stored in an oven to prevent absorption of moisture.

B. Fabrication of Test Specimens

1. Butt-Welded Joints

In order to obtain basic information on the fatigue strength of butt-welded joints in A-373 steel, a series of tests was conducted on a simplified specimen. The specimens used in this investigation are shown in Fig. 3. Nine specimens were tested--three plain plate, three transverse butt joints, and three longitudinal butt joints. The form of the specimens chosen has been used almost exclusively at the University of Illinois in comparing the fatigue strengths of joints in various steels.

A complete description of the welding procedure is contained in a previous report (6)* and need not be repeated here. For both the transverse and longitudinal butt-welded specimens the test weld was prepared first. The two pieces of the test section were machined to provide for a double-V butt weld with an included angle of 60 deg. All passes were deposited in a down-hand horizontal position in a special jig which could be rotated about a horizontal axis. The welding sequence is shown in Fig. 3A.

After completion of the test weld the pullheads, cut from previously tested specimens, were welded to the test section. The test section was then cut to rough form with an oxygen cutting machine, machined to finished dimensions and the edges draw-filed.

Special care was exercised in backchipping and cleaning the passes prior to depositing subsequent passes. Intervals between consecutive passes were not timed. Only sufficient time was allowed to clean the previous pass before the next pass was deposited.

2. Beams Without Splices

The basic section of all beams used in this investigation was uniform throughout the span length. Flange and web plates were cut from stock with a dual-torch oxygen cutting machine. In the case where plates were taken out next to a sheared edge, a strip adjacent to the sheared edge about one inch wide was discarded. A typical layout for one plate of A-373 steel is shown in Fig. 10. The edges of all plates used in the test specimens were flame cut. Plates which had severe notches or other defects, due to cutting

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* Numbers in parentheses refer to the Bibliography.

or handling of the material, were discarded. Plates with minor defects were used, but the severity of such defects was lessened by grinding them to a smooth transition. All slag and burrs on all edges of the plates and mill scale in the region of the weld were removed.

Two procedures have been used for fabrication of the basic section. In the first procedure a flange plate was placed on the flange of an H-beam. Such a section could resist the clamping forces required to align the parts and to bring them into proper contact with each other, without undergoing appreciable deformation. The web plate was then carefully aligned, securely clamped and tack welded to the flange by full size fillet welds spaced about 16 in. apart. The T-section thus formed was turned over, set on the second flange plate, clamped in position and tack welded. All tack welds were cleaned and the specimen was ready for deposition of the web-flange fillet weld.

More recently, the H-beam has been replaced by a jig in which both of the flanges and the web are aligned at the same time and secured in position. The tack welds are then made in accordance with the previous fabrication procedure. Positioning equipment has also been fabricated which permits the beam to be put in any position. This equipment was designed for use with the submerged arc process but works extremely well for the manual procedure also.

Details of the principal fillet welding sequence are given in Fig. 8. This sequence was slightly different from the sequence used in fabricating a number of the earlier specimens of the tests reported herein. The original welding sequence was used for all beams of the "P" series and for some of the earlier specimens of the main series. The two procedures were identical in all but two particulars. In the initial sequence the welder changed location after each deposition of weld. In the principal sequence three electrode lengths were deposited by the back-step method before the welder changed location. Also, the release length, provided at the ends of the member, allowed in the initial sequence, was eliminated in the later members.

In some cases there was visible distortion in the test specimen. Such distortion resulted either from the procedure used for cutting the plates from stock or from the welding sequence. The very early specimens were fabricated from plates which had been cut from stock by means of a single-torch cutting machine. In this case there was considerable distortion of the plates. The use of a dual-torch cutting machine practically eliminated all of this difficulty. The distortion due to welding also varied depending upon the sequence used. Distortion due to welding could be controlled more accurately with the initial welding sequence; however, the principal sequence conforms to the more general shop practice and was therefore adopted.

3. Spliced Beams

Drawings of the splice configurations used in this program are shown in Fig. 7. The two parts of a spliced beam were obtained in two different ways. In one case the two halves were fabricated individually in accordance with the welding procedure outlined for beams without splices. In the second case the spliced beams were fabricated from parts obtained from specimens which had already been tested. This was carried out in the following way.

All specimens were fabricated 2 ft. 6 in. longer than the span on which they were tested. This provided a 1 ft. 3 in. overhang at each end. After failure had occurred, a portion of the beam which contained the fracture was removed. The two remaining pieces were of sufficient length to provide an additional specimen when joined. The overhangs had been subjected to no stress and, therefore, when turned end for end and rewelded, these two pieces provided an additional spliced beam. The ends of all flange plates were beveled with a flame cutting machine for double-V butt joints having an included angle of 60 deg. Since the web material was only 3/16-in. thick, the bevels for the single-V web joints were made with a portable disk grinder.

Two procedures were used in cutting cope holes. In the initial welding sequence, described in Table 3, the holes were cut to full size (3/4-in. radius) before the specimen was assembled. In the principal welding sequence, described in Table 4, a semi-elliptical hole [with 2-in. major axis (flange direction) and 1-in. minor axis] was cut before the specimen was assembled. After the specimen had been assembled and the web splice completed, the semi-elliptical hole was made into a semi-circular hole with a 1-in. radius (see Fig. 9). This removed the ends of the welds in the web splice.

Starting blocks were provided for the butt-welds in the flange. These blocks were removed after the specimen had been completely assembled.

C. Test Procedure

A diagrammatic sketch of the 200,000-lb. Wilson lever type fatigue testing machine used in this investigation is shown in Fig. 1. Photographs of the machines with beams in position are shown in Fig. 2. The mechanical operation of these machines is described in detail in Bulletin No. 377 of the University of Illinois Experiment Station.

Load was applied as two concentrated loads 12 in. apart on a span of 8 ft. 6 in. The two load points were symmetrically placed about the center line. All beams were tested in the as-welded condition. The stress cycle as reported herein was that stress which occurred at the section between the load points, on the extreme fiber. A minimum load was necessary to hold the specimen in position and to maintain the parts of the machine in place. For this reason, the stress cycle, although nominally from zero to a maximum tension, was actually from some small value of tension to a maximum tension. The maximum values were chosen to give a good picture of the S-N relationship in the overstressed portion of the diagram. The total load to be applied was calculated on the basis of the nominal dimension of the section.

After failure had occurred the actual dimensions of the section in the region of failure were measured and the final stress values were calculated. The variation from the theoretical value exceeded 1000 psi only in very rare cases.

D. Specimen Designation

As previously mentioned all specimens of the preliminary test series which was conducted on specimens fabricated from A-7 steel are designated with a "P". The designation system used for all other specimens is such that it contains a complete description of the specimen geometry.

The first part of the designation denotes the splice type of the particular specimen. For specimens without splices the designation is AA. In all other cases the letter corresponds to the particular splice type, a sketch of which is shown in Fig. 7. The number following the letter indicates the number of that particular type of specimen. The following letter or letters within the parentheses indicate the splice type of the original specimen, from which the present specimen was fabricated. In this case the letter "O" indicates that the particular specimen in question was fabricated as an original. The "R" following the parentheses indicates that the specimen has been fabricated with the principal welding sequence.

A few examples should serve to make this system familiar to the reader. For example, the specimen designation D-6 (A-4) R. This designation indicates that this specimen was the sixth of the series which contained the type "D" splice. The original specimen from which this present specimen was fabricated was A-4. This original specimen was the fourth specimen of the series which contained the type "A" splice. The "R" indicates that this specimen, D-6, was fabricated using the principal welding procedure. The fourth specimen of the beams without splices would have the following designation, AA-4 (O) R, where the "O" signifies that this was an original specimen and the "R" that the principal welding sequence was used. If this specimen is rewelded to form the sixth beam of the "E" type splice series, the specimen number would be E-6 (AA-4) R where "R" has the same connotation as before.

The "R" designation applies only to beams which were fabricated using shielded metal-arc welding. If sumberged arc welding had been used in the fabrication of any specimen, this "R" would be replaced by the designation "S". For example, if the tenth specimen of the "AA" series had been fabricated by the submerged arc process its designation would be AA-10(O)S.

The system used to designate all beams is quite versatile and in effect constitutes a "life history" of the test specimens. There is, however, one limitation. The welding sequence employed on the original specimen is not denoted in the designation of the rewelded specimen. The letter which appears after the parentheses signifies the welding procedure that was carried out on the re-welded specimen. The original designation number must be investigated to determine which welding procedure was used on the initial specimen.

III. TEST RESULTS

A. Butt-Welded Joints

The results of the tests, in terms of maximum stress and cycles to failure, are presented in Table 5. In addition to the test data the fatigue strength corresponding to 2,000,000 cycles has been calculated, and the average fatigue strength of each group has been compared to the average fatigue strength of similar specimens in A-7 steel, tested in previous investigations (6).

The fatigue strengths corresponding to failure at 2,000,000 cycles ($f_{2,000,000}$) have been computed from the formula* $f = S(N/n)^k$; where, S is the stress at which the specimen failed after N cycles, n is the number of cycles for which the fatigue strength, f, is desired, and k is an experimental constant equal to the slope of the median line when the S-N (stress-number of cycles for failure) diagram is plotted to a logarithmic scale. Ideally, the value of k should be determined from the results of tests; however, with a limited number of tests and the fact that all specimens in each group had been run on the same cycle (except one longitudinal butt-joint, F-2L), an S-N diagram could not be plotted. Consequently, k values based on the results of the A-7 series were used.

The test results presented in Table 5 indicate that the properties of A-373 steel, both plain plate and butt-welded joints, under fatigue loading are very nearly the same as those for A-7 steel. In the case of the transverse butt joints failure initiated in all cases at the edge of the weld reinforcement within the middle half of the width. The fatigue fracture in

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* See University of Illinois Engineering Experiment Station Bulletin 302, p. 111.

specimen F-2T occurred completely through the parent plate. In the case of F-1T and F-3T about 90 per cent of the fatigue fracture occurred through the parent plate.

Only two of the longitudinal butt joints failed in the test section. Specimen F-2L failed in the transverse butt-weld joining the pullhead to the test section. Since this failure occurred at a life beyond 2,000,000 cycles, no attempt was made to repair the specimen and continue the test. The other failures initiated in the region of the outside pass. In one case this failure occurred at a point where there was a change of electrode. Typical fractures of specimens discussed in this section of the report are shown in Fig. 4.

B. Preliminary Series

1. Beams Without Splices

Four beams without splices were tested with the flange-to-web thickness ratio as the only variable. In three of the specimens this ratio was varied by changing the web thickness and keeping the flange thickness constant. In the fourth specimen (P-7) the flange thickness was also changed. Flange-to-web thickness ratios, based on actual dimensions of the material, varied from 1.0 for specimen P-1 to 5.3 for specimen P-7. Dimensions of the specimens are given in Table 6, and the locations of the fractures are shown on the sketch above the table.

Results of the tests are presented in Table 6. The column headed "Stress in Weld, pli." is the calculated horizontal shear on the throat of the fillet weld, at the point of maximum shear. "Number of Cycles for Failure" as given in the table is the number of cycles registered on the automatic counter at the time the fatigue crack was large enough to allow a sufficient increase in the deflection of the specimen to actuate the micro-switch which stopped the fatigue machine. All stresses are based on nominal dimensions. "Splice Type" refers to the letter designation in Fig. 7.

There is a definite and significant trend in the results of the tests on plain beams. If the life of specimen P-1, with a flange-to-web thickness ratio of 1.0, is used as a basis for comparison, the fatigue lives of specimen P-2, P-6 and P-7, with flange-to-web thickness of 3.1, 4.3 and 5.3, respectively, are 1.24, 2.16 and 2.60 times that of specimen P-1. Certainly, the small number of tests does not permit a generalization but the trend is for specimens to have a longer fatigue life with a greater flange-to-web thickness ratio. This comparison is based on fatigue life and not on fatigue strength.

In addition to the higher fatigue life, another feature observed in the tests on specimens with high flange-to-web thickness ratios was the difference in mode of failure. In all of the specimens, regardless of flange-to-web ratio, fracture initiated at the junction of the web and the flange in the fillet weld at the weld crater caused by a change in electrode. As the test progressed the crack propagated into the flange and the web until failure occurred. In no case was the failure sudden but the rate of propagation was much faster through the flange than through the web.

The initial direction of propagation was different for specimens with low flange-to-web thickness ratio than for specimens with high ratios. In specimen P-1 the crack progressed into the flange first. The rate of crack propagation was quite rapid in this region because of the high stress. Not until the crack had progressed to the extreme fiber of the tension flange did it begin to propagate into the web. In specimens with high flange-to-web thickness ratios (P-2, P-6 and P-7) the initial direction of propagation was into the web. The rate of propagation was somewhat slower in this region because of the smaller nominal stress as the crack progressed toward the neutral axis. When the crack was two or three inches long it began to spread into the flange. Therefore, a larger number of cycles was necessary to complete the failure after a visible crack had appeared for specimens with thin webs than for specimens with thick webs. Visible cracks were observed in all of the specimens prior to failure as defined previously. The fatigue life reported in Table 6 for specimen P-1 is 1.5 per cent higher than the life when a visible crack was first observed. The fatigue lives reported for specimens P-2 and P-7 are 12.2 and 10.8 per cent higher respectively.

All specimens failed in the pure moment region except P-7, which failed 15 in. from the center line. All specimens except P-6 failed in the tension flange. Photographs of typical fractures are shown in Figs. 5 and 6.

In addition to the crack at the junction of the web and flange several small superficial cracks formed at the edge of the tension flange in specimen P-1. However, slight surface irregularities from the flame cutting might have caused surface embrittlement of the steel, thereby causing these cracks to form. These may also have been micro-cracks which opened up during the fatigue test.

Although specimen P-6 failed initially in the compression flange, it is possible that fracture was the result of tensile residual stresses in combination with the applied compressive stresses. For, as the specimen passed through the loading cycle this crack opened even though a nominal compressive stress existed in the top flange throughout the loading cycle. The rate of propagation of this crack was very slow compared to cracks initiating in the tension flange. A minute crack was observed in the fillet weld at a weld crater at the junction of the web and the compression flange at 1,227,000 cycles. After 552,000 additional cycles the crack began to spread through the compression flange. At this time twisting of the specimen could be observed and the crack traversed the compression flange very quickly. A short time later a crack developed in the tension flange, completing the test. There was no appreciable drop-off in load until the crack in the tension flange occurred.

2. Spliced Beams

A description of the six specimens tested in this series and the results of the tests are given in Table 6. The variable studied was the splice. The types of splices studied are given in Fig. 7.

The flange-to-web thickness ratio in this series was 3.1, except for specimen P-6a, for which the ratio was 4.3. It is doubtful that this change in flange-to-web thickness ratio would have any effect on the fatigue life of spliced specimens. In general, the results seem to indicate that the spliced specimen is weaker than the plain specimen. However, specimen P-2a exhibited a slightly greater fatigue resistance than the initial plain beam, specimen P-2. The results of the tests show also that splices made in one plane, without cope holes, are somewhat superior to the other three types tested. Typical photographs of fractures in spliced beams are given in Figs. 5 and 6.

In specimens P-3 and P-4 with splice types A and B, respectively, fracture initiated at the toe of the fillet weld around the cope hole. From there it propagated along the edge of the butt weld into the flange.

Specimen P-5 with splice type "C" failed at a notch cut by the torch due to a blow-out during cutting. This notch acted as a stress concentration and transferred the location of fracture to the edge of the flange. The reported life of the specimen is probably somewhat lower than it would have been without the notch.

Specimens P-2a, P-3a and P-6a were the three specimens that were retested as spliced specimens to investigate the possibility of testing each specimen twice. Splice type D was used in all three specimens. Fracture initiated at the junction of the web and flange in the butt joint. As the tests progressed, the cracks spread into the flange through the heat affected zone or propagated through the weld metal in the butt joint until failure was complete.

C. Principal Series

1. Beams Without Splices

In addition to furnishing the fatigue strength of plain, welded built-up beams, the purpose of this series was to establish a datum to facilitate the comparison of data gathered in the program. A total of nine specimens built up without splices were tested in this study. The three initial specimens of this test series were fabricated with the original welding procedure, Table 4, and the remaining six were prepared using the revised welding sequence, Table 5. Test results are presented in Tables 8 and 9. It should be noted that even though, in some cases, the failure occurs outside the region of pure moment the test stress reported in Table 8 is that which existed in this region, i.e., the maximum stress in the span. Stresses at the location of each fracture and a study of the test results are reported in Table 9. The principal stresses at the primary fracture are shown and the angle between the flange and the minimum principal stress is recorded as the computed φ. The measured φ is the angle between the flange and the fracture which developed in the web.

AA-2(O), AA-3(O), AA-4(O)R, AA-7(O)R, AA-8(O)R

Four of the five specimens which had failures initiating at a change of electrode were tested at a high stress level. AA-2(O), AA-3(O), AA-4(O)R and AA-8(O)R had stress ranges of 0.7 to 29.9 ksi, 0.8 to 30.0 ksi, 0.8 to to 30.2 ksi and 0.5 to 30.8 ksi, respectively. One specimen, AA-7(0)R, was tested at the somewhat lower stress range of 0.4 to 28.8 ksi. The fatigue strength of the five specimens in order of their numerical specimen designation was 1,490,400 cycles, 1,443,400 cycles, 860,700 cycles, 1,539,600 cycles and 805,700 cycles, respectively. With the exception of AA-4(0)R fractures occurred outside the region of pure moment. Specimens AA-2(0) and AA-3(0) were fabricated employing the initial welding sequence and the other three specimens, AA-4(0)R, AA-7(0)R and AA-8(0)R, were fabricated with the principal welding sequence.

Failure of both AA-2(0) and AA-3(0) occurred 9 in. from the center line of the test span. The two specimens were fabricated with the same welding sequence, were tested with the same stress range and had the same fatigue life. In both cases the fractures initiated at a weld crater in the fillet weld. At this point the two weld beads overlap by approximately one inch. In the back-stepping procedure, the welder starts his deposit approximately 9 in. from the nearest weld metal and works toward that previous weld. To secure a full size fillet weld he must overlap a portion of the earlier deposit. Failure occurs at the point where the later deposit just begins to overlap the previous weld. In most cases this is at the end of the crater which is nearer the support. In all future cases this will be called the outside edge of the crater. Due to this back-stepping welding sequence, a stress concentration can be expected to develop at each weld crater.

At a distance of 12 1/4 in. from the center line of specimen AA-7(0)R, a fracture developed. Initiation of the fracture was on the outside edge of a weld crater in the same manner as discussed for specimens AA-2(0) and AA-3(0). A small amount of web rotation, probably caused by flange translation, was recorded; the rotation was of the order ± 1/16 in.

in an 8-in. vertical gage length under full static load. The nature of the loading system of a Wilson type fatigue machine prevents the top flange of the specimen from rotating and no rotation of the bottom flange was noted.

A somewhat different failure pattern developed in specimen AA-8(0)R. Two cracks occurred in the specimen, one initiated at a change of electrode 11 1/2 in. from the center line of the test span and the other crack developed in the edge of the tension flange 4 1/2 in. from the center line. The specimen had progressed to failure before the fractures were noted; therefore, it is not known which fracture developed first or which fracture produced failure. Based on the test results of specimen AA-6(0)R, discussed later, where a crack developed in the web of the beam on one side of the center line before the major fracture initiated on the other side of the center line, the fracture which developed 11 1/2 in. from the center line of the test span probably started first. This fracture will be referred to as the primary fracture and the fracture 4 1/2 in. from the center line will be called the secondary crack. The primary fracture is the larger of the two, covering 75 per cent of the area of the flange, but it occurred at a location of lower stress than the secondary crack which occurred in the maximum flexural stress region. The primary fracture occurred at a weld crater, but unlike the three specimens already discussed, the fracture initiated on the inside edge of the crater nearer to the center line of the test span, not on the outside edge as before. The secondary crack initiated at the edge of the flange and progressed about 40 per cent of the way across the flange at the time of failure.

Fabrication of AA-8(0)R had been altered in the following manner: the web and flanges were placed in the tacking jig in the usual manner; the web being tied down along its entire length. Only the ends of the flanges were held down. The central portion of the flanges was permitted to assume its natural position. The distortion of the specimen's web was held to a minimum by this method of tacking. The initial jigging procedure held both the flanges and the web down in such a manner that all three parts were straight.

Of the five specimens which fractured at a change of electrode, specimen AA-4(O)R was the only one in which this fracture occurred in the "pure moment" region. The crack initiated on the outside edge of the weld crater in the same manner as discussed for AA-2(O) and AA-3(O). Fig. 13 shows a section of the fracture. This section indicates the manner in which the propagation of the crack proceeded. The vertical lines on the section indicate changes in the rate of crack propagation. The coarser grain areas on the edges of the section indicate a high crack propagation rate. After failure, the specimen was allowed to continue running until the fracture had progressed through the entire flange area. An additional 5,200 cycles were required to extend the crack completely through the tension flange. This fact is an indication of the high cracking rate at the outer portions of the flange.

A fracture initiating within a weld pass occurred for one specimen, AA-6(O)R. This beam was tested under a stress range of 0.9 to 29.2 ksi and had a fatigue life of 1,557,900 cycles. The web of the specimen rotated about 1/8 in. in an 8-in. vertical gage length under full static load. A secondary crack, so called because it did not cause failure of the specimen, developed in the web 14 1/2 in. from the center line of the test span. This secondary crack was first noted at a life of 1,442,100 cycles, and the fracture had a length of 2 1/2 in. at 1,533,300 cycles. The primary fracture which developed 15 in. from the center line of the test span, on the opposite side of the center line from the secondary crack, was not detected until failure had occurred. The final inspection of the specimen before failure was at a life of 1,533,300 cycles and failure occurred at 1,557,900 cycles. Therefore, since the primary crack had not initiated or was so small as to be difficult to detect, it can be assumed that the major portion of the primary fracture occurred within 24,600 cycles. The primary crack progressed through the entire thickness of the flange plate and up into the web a distance of 4 in. Closer examination in the region of the secondary fracture revealed that this crack had not propagated into the flange plate.

AA-1(O), AA-8(O)R, AA-9(O)R

Three specimens had failures which initiated at the edge of the tension flange. Specimen AA-8(O)R had a fracture at the edge of the flange that was called a secondary fracture in the previous discussion. All three edge fractures occurred within the pure moment area of the specimens and they all progressed from 40 to 50 per cent of the way through the width of the flange. AA-9(O)R was fabricated with the same jigging procedure as reported in the discussion of specimen AA-8(O)R. The testing stress range of AA-1(O) and AA-9(O)R was 0.7 to 29.5 ksi and 0.4 to 30.6 ksi, respectively. AA-1(O) had a fatigue life of 1,466,600 cycles and AA-9(O)R ran for 847,600 cycles.

AA-5(O)R

The remaining specimen of this test series had what is seemingly a different type of failure. AA-5(O)R fractured in such a manner that the crack remained wholly within the web of the member. The fatigue life of the specimen was 750,800 cycles when tested on a stress range of 0.4 to 29.0 ksi. Fracture initiated just above the outside edge of a weld crater, 21 in. from the center line of the test span. In the same general manner as other failures of this test series, the fracture progressed up into the web. However, the crack did not proceed down into the flange but ran toward the end of the specimen along the top of the fillet weld. As the crack developed, the web "bowed-out" under the forces developed in the web.

As the fracture developed in the web of AA-5(0)R, it progressed in the same general direction as the minimum principal stress at the point of initiation. The minimum principal stress was computed to be a compressive stress in the order of 10.3 ksi. Acting at 90 deg. to the compressive stress was a maximum tensile stress equal to 26.2 ksi; this tensile stress had the effect of "opening up" the fracture as the failure progressed. As the length of the fracture increased the upper portion of the web became in effect a plate loaded on two sides and fixed on one side opposite to a free edge. With the increase in fracture length the critical buckling stress of the fictitious plate was decreased until the maximum compressive stress in the web was reached. The "bowing" of the web was a web buckling failure.

AA-5(0)R had the same general type of fracture as discussed for other specimens of this test series; however, the fracture did not initiate in the flange fillet weld nor did it progress into the flange. Initiation of the fracture was above the fillet weld in the base metal of the web. The portion of the fracture nearer the center line proceeded up into the web at an angle of 45 deg. with the flange; however, following the line of least resistance, the half of the fracture nearer the support ran along the top of the fillet weld.

For the six specimens having all or part of their fracture within the web, the deviation between the computed φ and the measured φ was from 0.7 to 12.9 deg; the average being 7.0 deg.(see Table 9). Specimens AA-5(0)R and AA-8(0)R had deviations of 0.7 and 12.9 deg., respectively. The deviation for the other four specimens was within 3.0 deg. of each other, ranging from 5.6 to 8.6 deg.

The first three specimens were fabricated with the initial welding procedure which required the welder to change his position after every pass had been deposited. The remainder of the specimens were fabricated with the revised welding procedure in which the welder deposits three continuous passes before he changes his position. Therefore, the time between the completion of the last pass at a position and the start of the next pass at the same position is much greater in the revised welding sequence. This increase in time between passes permits greater cooling of the specimen.

The three specimens fabricated with the initial welding sequence had the same fatigue life and were tested under essentially the same stress range. Of the six specimens fabricated with the revised welding sequence, five specimens had fatigue lives which are in the proper order when compared to the stress ranges under which they were tested. The one specimen that did not "line up" in the proper position with the other specimens was AA-5(O)R. The type of failure of this specimen may explain its lack of conformity. The fact that the fracture did not propagate into the flange but remained in the web may have increased the fracture rate. This is, however, probably not the case since in all previous web failures crack propagation was slower in the web area. It is more likely that failure initiated prematurely because of a highly localized stress concentration. This could have resulted from spatter or could be an inherent defect in the plate. Metallurgical examination failed to clarify this question.

Although the difference in fatigue life of the specimens vary by over 800,000 cycles, the fatigue strengths varied by only 1.8 ksi. The average fatigue life, based on specimens AA-1(O) through AA-4(O)R, AA-8(O)R and AA-9(O)R, was 1,152,400 cycles for an average fatigue strength of 30.2 ksi. If AA-5(O)R through AA-7(O)R are used, the fatigue life was 1,282,800 cycles for a fatigue strength of 29.0 ksi.

Professor Wilson (5) tested 12-in. I-beams under fatigue loading and his test results are shown in Fig. 12 with the results of test series "AA". No attempt to pass an average curve through the test results shown has been made. However, if such a curve were passed through the results of series "AA" it would have a k value of approximately 0.05. The results of Professor Wilson's study seem to indicate that the fatigue strength of a built-up welded beam is about 4 ksi lower than that of a rolled member. However, this conclusion is limited by the fact that Professor Wilson tested just three specimens.

2. Spliced Beams

Two basic splice configurations were studied with cope holes introduced into each of the basic configurations to yield four splice types. In addition, several tests were conducted on beams with butt-welded flange splices only and on beams with cope holes only. Details of the splice types are shown in Fig. 7 and all the splice beam test results are included in Table 10. In the following discussion, fractures which initiate at the weld metal-base metal interface of a butt splice in either flange will be referred to as a fracture initiating at the toe of the flange butt splice. After initiation, the fracture traverses the depth of the flange plate passing from the heat-affected zone at the weld metal-base metal interface to base metal and back within the heat-affected zone at the opposite side of the plate; therefore, the fracture is entirely within the base metal of the flange.

a. Series A - Splice Type "A"

The configuration of this test series was a complete splice made in one vertical plane with cope holes in the web to facilitate the deposition of the weld metal in the flange butt joint. Ten specimens were tested under a stress cycle of zero to maximum tension in the extreme fiber of the bottom flange. The maximum tension varied from 20.5 to 31.0 ksi, actual stress based on section measurements after failure had occurred. All specimens in this series were fabricated with A-373 steel. A graphical representation of the test results is given in Fig. 15. Table 10 shows the numerical data of this test series.

In general, the failures occurred in one of three ways. Specimen A-1(AA-1), A-3(AA-3) and A-5(B-4)R failed when a crack was initiated at the toe of the fillet weld around the edge of the cope hole. Specimens A-2(AA-2), A-4(AA-4)R, A-6(B-5)R, A-7(B-6)R and A-10(E-9)R failed either through or at the toe of the flange butt weld. For specimens A-8(AA-7)R and A-9(E-8)R failure initiated in the groove between two parallel face passes of the flange butt splice.

A-1(AA-1), A-3(AA-3), A-5(B-4)R

Of the three specimens which failed at the toe of the fillet weld around the edge of the cope hole, two were tested at a high stress cycle and the third at a low stress cycle. Specimens A-1(AA-1) and A-3(AA-3) were tested on stress cycles of 0.7 to 29.4 ksi and 0.6 to 30.0 ksi and failure occurred at 203,600 and 280,300 cycles, respectively. Specimen A-5(B-4)R failed at 1,310,700 cycles at a stress range of 0.4 to 20.5 ksi.

For specimens A-1(AA-1) and A-3(AA-3) the toe of the fillet weld around the edge of the cope hole was located outside the region of the flange butt weld; therefore, the fracture initiated in base metal and continued its propagation through the flange in base metal. Both the toe of the flange butt weld and the fillet weld around the cope hole were located at the same point in specimen A-5(B-4)R; the fracture initiated at this point and progressed along the toe of the flange butt splice remaining within the base metal of the flange plate. As the flange fracture increased in size a secondary crack developed at the top of the cope hole in all three specimens. The cracks ran along the toe of the web butt splice in the base metal of the web.

A-2(AA-2), A-4(AA-4)R, A-6(B-5)R, A-7(B-6)R, A-10(E-9)R

The specimens composing the second failure type were tested at various stress levels. Specimens A-2(AA-2), A-4(AA-4)R and A-6(B-5)R were tested at stress ranges of 0.6 to 29.9 ksi, 0.6 to 30.2 ksi and 0.6 to 31.0 ksi; failure of the specimens occurred after 175,500, 207,700 and 524,300 cycles, respectively. A-7(B-6)R and A-10(E-9)R failed after 613,900 and 578,600 cycles and had stress ranges of 0.4 to 24.9 ksi and 0.5 to 21.4 ksi, respectively. Specimen A-6(B-5)R should not be included in the test results without corrections due to the fact that the specimen was employed in a static study of the stress distribution of the test specimen and was not tested continuously. The specimen was tested over a period of 20 days and therefore the effect of "down time" cannot be overlooked. Based on studies conducted at the University of Illinois (7) the fatigue life of this specimen would be approximately 268,000 cycles. If the revised fatigue life of the specimen is plotted as shown on Fig. 15, it will "correspond" to the other two tests at the same stress level.

A-2(AA-2) and A-10(E-9)R both had fractures which initiated at the edge of the tension flange within the weld metal of the butt splice. Examination of the fractured sections showed poor root penetration at the edge of the plate. In A-4(AA-4)R, fractures developed at the toe of the butt splice along the lower face of the tension flange. The two fractures joined to form one vertical crack which traversed the entire width of the plate. The fractures in A-6(B-5)R and A-7(B-6)R initiated at the toe of the tension flange butt splice and progressed from the edge of the flange plate along the toe of the butt splice.

A-8(AA-7)R - A-9(E-8)R

Specimens A-8(AA-7)R and A-9(E-8)R were accidentally fabricated somewhat differently. Normally the face pass or last pass of the butt splices was deposited in such a way as to completely span the splice (see the revised welding procedure given in Table 5). In the fabrication of the two specimens of this failure group the face pass was made up of two parallel passes having a groove between them which was not removed before testing, since the testing procedure requires the welding reinforcement to be left on the test specimen. Failure initiated at the junction or groove between the two face passes and propagated through the middle of the butt weld at a considerably reduced number of cycles. Specimens A-8(AA-7)R and A-9(E-8)R were tested on stress ranges of 0.6 to 22.6 ksi and 0.4 to 20.6 ksi; failure initiated at 240,200 and 725,100 cycles, respectively.

The test results are presented in Fig. 15. If an S-N curve is passed through the three points representing the three specimens which had cope hole failures, the fatigue strengths corresponding to failure at 100,000 and 2,000,000 cycles would be 35 ksi and 19 ksi, respectively. For the computation of the fatigue strengths the formula $f = S(N/n)^k$ was used; where S is the stress at which the specimen failed after N cycles, n is the number of cycles for which the fatigue strength, f, is desired, and k is an experimental constant determined from the slope of the median plot on the S-N diagram. The value of k for these three specimens is approximately 0.20.

If the median plot on the S-N diagram is based on the five specimens which had failures initiating at the toe of the tension flange butt splice or within the weld the computed value of k will be 0.28. The fatigue strength corresponding to failure at 100,000 and 2,000,000 cycles for this type of failure would be 38 ksi and 16.5 ksi, respectively.

When the S-N curve is based on the two specimens which had failures in the groove in the face passes of the flange butt splice, the fatigue strength at 100,000 and 2,000,000 cycles will be 25 ksi and 19.4 ksi, respectively. The value of k will be 0.09.

The test results of this series show three types of failures which could occur. The failure initiating at the toe of the fillet weld around the edge of the cope hole was due in part to the stress concentration factor inherent in the cope hole itself. It seems justifiable to conclude that if there were no other stress concentration factors present in the specimen, the failure would initiate at the toe of the fillet weld. The effect of the butt splice in the same or within a short distance of the location of the cope hole concentration point was to reduce the fatigue life of the specimen.

This can be verified by studying the tests conducted on specimens having cope holes only, series F. As is stated in the discussion of the test results for series F specimens, the average fatigue life at a stress of 30.7 ksi was 432,600 cycles. The average fatigue life of those specimens in series "A" which were tested at a nominal stress range of zero to 30 ksi was 227,000 cycles. This average takes into account specimen A-6(B-5)R adjusted for "down time". Comparison of the average fatigue life of these specimens in series "A" with those of series "F" shows the fatigue life of series "A" to be 53 per cent of series "F".

The two specimens which had parallel face passes and which failed when a fracture initiated in the groove between the two passes can be considered as a lower limit. If the reinforcement is not removed after welding, and if the final face pass is composed of two or more parallel passes, the specimen will fail within a minimum number of loading cycles. It seems justifiable to conclude that the fatigue strength could be reduced by simply increasing the stress concentration at the groove.

When all the test results are considered the median plot on the S-N curve produces a value of k = 0.23. The fatigue strength of the test series at 100,000 and 2,000,000 cycles was 35 ksi and 17.5 ksi, respectively. In test series "AA", beams without splices, the average fatigue life for all specimens tested and endurance limit was 29.8 ksi and 1,195,800 cycles. When the fatigue life of the five specimens in series "A" is compared to that of series "AA", the fatigue life of series "A" is about 20 per cent that of series "AA".

The results of test series "C" and "F" have been included on the S-N diagram of Fig. 15; however, this information has not been included in the median plot. Based on a maximum nominal stress of 30 ksi, a comparison of the test results of series "A" with those of series "C" and "F" shows series "A" to have a fatigue life of 35 and 52.5 per cent of series C and F, respectively.

b. Series B - Splice Type "B"

Results of this test series are given in Table 10 and are shown graphically in Fig. 17. The test specimen consisted of a complete joint made with the flange butt splices staggered on either side of the web splice. The web was provided with a cope hole at each flange splice to facilitate the deposition of the weld metal for the butt joint in the flange. Failures of series B specimens occurred in the same general manner as those reported for series A with the exception that failures initiating at the edge of the flange, at the toe of the butt weld, propagated across the flange in the general direction of the toe of the fillet weld around the cope hole. The loading range varied from 0.6 to 30.0 ksi to 0.3 to 19.5 ksi, based on the actual measurements of the fractured section.

B-1(O)R, B-2(O)R, B-3(O)R, B-6(O)R

Four specimens, B-1(O)R, B-2(O)R, B-3(O)R and B-6(O)R, had failures which initiated at the toe of the fillet weld around the cope hole. This type of failure will be referred to as a failure in the cope hole. The stress range and fatigue strength of the four specimens, in numerical order of their specimen designation, are 0.6 to 30.0 ksi, 0.7 to 29.5 ksi, 0.7 to 29.2 ksi and 0.4 to 22.6 ksi and 209,000, 416,800, 367,500 and 528,500 cycles, respectively. After the crack had initiated at the cope hole, it progressed in a vertical plane traversing the flange until the increase in deflection of the specimen had reached 0.05 in. An increase in deflection of 0.05 in. was defined as failure. With the exception of B-6(O)R in which a secondary crack developed, all four specimens were one-crack failures. The secondary crack in B-6(O)R initiated at the edge of the bottom flange at the center line of the butt weld. The crack initiated due to poor root bonding of the weld metal. Initiation and propagation of the primary failure at the cope hole had progressed to the point of failure of the specimen at the time the secondary crack initiated.

B-4(O)R

A somewhat smaller cope hole was provided in specimen B-4(O)R. The toe of the fillet weld around the cope hole was at the same location as the toe of the butt splice in the flange. In the fabrication of the four specimens discussed in the previous paragraph, the toe of the fillet weld at the cope hole was removed from the toe of the butt weld in the flange, and the fracture was initiated in the base metal. When B-4(O)R failed the fracture was not initiated at the cope hole but on the bottom face of the tension flange at the toe of the butt splice. The fracture propagated in a vertical plane through the base metal of the flange and emerged at the toe of the cope hole (see Fig. 18b). B-4(O)R ran for 3,098,300 cycles without producing a fracture at a stress range of 0.3 to 19.5 ksi. At the end of 3,098,300 cycles the stress range was increased from 0.3 to 23.4 ksi. Under the new stress range the specimen continued to run for 57,000 additional cycles before failure occurred. The initial stress range and fatigue life for this specimen are recorded on the S-N diagram (see Fig. 17).

B-5(O)R, B-7(O)R

Fatigue lives of 289,500 cycles and 1,354,300 cycles were recorded for specimens B-5(O)R and B-7(O)R, respectively. Both specimens had the same general type of fracture. The fracture initiated on the bottom face of the tension flange near its edge, at the toe of the butt weld. On the bottom face of the flange the fracture progressed along the toe of the butt joint, but on the top face of the flange the crack propagated through base metal, from the toe of the flange butt splice to the toe of the fillet weld around the edge of the cope hole. The stress concentration at the cope hole seems to have "pulled" the fracture over to it. B-5(O)R and B-7(O)R were tested at stress ranges of 0.2 to 25.6 ksi and 0.6 to 22.3 ksi, respectively.

B-8(O)R

The last specimen of this series is B-8(O)R, and its fatigue life was 952,400 cycles when tested at a stress range of 0.4 to 21.3 ksi. The specimen is similar to specimens B-5(O)R and B-7(O)R in that fracture initiated at the edge of the flange. However, the crack did not initiate at the toe of the butt splice but within the weld metal. As the fracture progressed, it was not "pulled" over to the stress concentration at the cope hole but crossed over the weld metal and followed the toe of the butt splice on both faces of the flange.

The fatigue strength of type "B" splice, obtained from the S-N curve (see Fig. 17), for 100,000 and 2,000,000 cycles, is 32 ksi and 20.5 ksi, respectively. The value of k in Wilson's formula is 0.119. The average test stress and fatigue life of specimens B-1(O)R through B-3(O)R was 29.6 ksi and 331,100 cycles. The fatigue life of series "B" is 24 per cent of series "AA" when specimens which were tested at a nominal stress range of zero to 30 ksi are compared. For series "A", "C" and "F" the same comparison produces the following percentages; 146, 51 and 77, respectively. The results of test series "C" and "F" have been included on the S-N diagram of Fig. 17; however, this information has not been included in the drawing of the median plot on the diagram.

c. <u>Series C - Splice Type "C"</u>

To study the effect of flange butt welded splices on the fatigue strength of structural beams, two specimens were fabricated employing a splice configuration composed of a partial splice. Each flange was made-up of two plates butt-welded together prior to the main fabrication of the specimen. As the specimens were fabricated the butt welds in the flanges were aligned in a vertical plane. A high quality butt-welded flange splice was possible since the problem of welding "through" the web member of the specimen was eliminated.

Both specimens of this test series had failures which initiated at the toe of the tension flange butt weld. The fractures developed near the edge of the flange on its lower face. The fracture traversed the flange width, but the crack did not follow the toe of the butt weld. About 1 in. from the edge of the flange, the fracture veered off into the base metal of the flange so that at the web the crack was one-half inch from the toe of the butt splice. The fatigue life of C-1(O) and C-2(O) was 514,500 and 775,100 cycles. These two specimens were tested at stress ranges of 0.6 to 29.7 ksi and 0.8 to 30 ksi, respectively.

Splice type "C", a shop splice, is considerably stronger than any of the other splices tested. This is not unexpected, since the welds in the flange plates can be made under better conditions and undoubtedly result in higher quality welds. For the two specimens tested, the average test stress was 29.8 ksi and the average fatigue life was 644,800 cycles. Based on the specimens of test series "AA" the fatigue life of splice type "C" is 50 per cent that of the beams without splices. The results of test series "C" have been included on the S-N diagrams for splice types A, B, D and E; however, this information has not been included in the average curves which were plotted.

d. Series D - Splice Type "D"

The splice type employed in series D was of the same general type as that of series A except that the cope hole, which provided for the welding of the flange butt joint of series A, was omitted in the series D specimens. Type D splice was a complete splice made in one vertical plane. Eight specimens employing type D splice were tested under a stress cycle of zero to maximum load. The maximum tension in the extreme fiber of the bottom flange varied from 20.4 ksi to 32.6 ksi. After failure of a specimen had occurred, the fractured section was measured and the actual stresses were computed employing the simple theory of flexural stress. Table 10 shows the numerical values of the test results and a graphical representation is shown in Fig. 19.

D-1(C-1), D-3(F-1)

D-1(C-1) fractured at the center line of the butt splice at 270,900 cycles at a stress range of 0.9 to 32.6 ksi on the extreme fiber. D-3(F-1)R had a stress range of 0.6 to 29.9 ksi and a fatigue life of 342,700 cycles.

Failure occurred on a vertical plane passing through the toe of the butt weld. In fabrication, a change of electrode or crater occurred at the center line of the splice. Of the eight specimens tested in this series, only D-1(C-1) and D-3(F-1)R had craters at the center line of the splice which were clearly distinguishable. In the fabrication of the other six specimens this crater had been wiped out by the welder in completing the splice.

D-2(C-2), D-4(F-2)R, D-5(F-3)R

Three specimens had failures which traversed the width of the flange along the toe of the butt splice. These failures initiated at the edge of the tension flange. The stress ranges were 0.8 to 29.1 ksi, 0.8 to 30.4 ksi and 0.7 to 20.4 ksi for D-2(C-2), D-4(F-2)R and D-5(F-3)R which had fatigue lives of 450,800, 319,000 and 1,027,600 cycles, respectively.

D-8(E-6)R

One specimen had a failure which initiated in base metal outside the region of the tension butt splice. The crack initiated on the bottom face of the flange one-half inch from the toe of the butt weld and propagated through the flange and intersected the top face of the flange at the weld metal-base metal interface of the butt weld. D-8(E-6)R was tested on a stress cycle of 0.6 to 22.5 ksi and had a fatigue life of 1,386,800 cycles.

D-6(E-4)R, D-7(E-5)R

Both D-6(E-4)R and D-7(E-5)R were tested on a stress cycle of 0.4 to 22.7 ksi, and the specimens had a fatigue life of 1,343,700 and 1,054,800 cycles, respectively. A fracture that will be referred to as a secondary crack developed at the center line of the compression flange butt splice in both specimens before failure occurred. Failure was based on an increase in the deflection of 0.05 in. due to cracking in the tension half of the specimen.

At 870,100 cycles a crack was recorded in the compression flange of D-7(E-5)R, and at this time the crack had progressed completely through the flange and down into the web a distance of 2 in. When the compression crack developed, the deflection switch was reset to allow for the required increase in deflection and the test specimen was allowed to continue running until a failure developed in the tension flange. Failure of the tension flange occurred in the base metal at a distance of one-quarter inch from the weld metal-base metal interface of the butt splice. The crack in the tension flange remained in a vertical plane outside the weld metal of the butt splice and was initiated on the lower face of the flange.

For D-6(E-4)R a fracture in the tension flange base metal and the crack in the compression butt splice were recorded at 1,342,300 cycles. The compression crack proceeded completely through the flange and down into the web a distance of 1 in. The fracture in the tension flange progressed through the flange and remained in a vertical plane about one-half inch from the toe of the butt splice.

Both compression cracks initiated in a vertical plane through the center of the compression flange butt splice. Due to the "hammering" effect which the cracks underwent, the point of initiation could not be determined. However, since both cracks initiated somewhere within the center of the butt splice, it seems reasonable to assume that the residual stress present in the compression butt weld after welding was a high magnitude tension stress. A high ordered tension residual stress in the compression flange may produce either a reversal of stress or a complete tension stress cycle in the compression flange under loading. If a complete tension cycle was developed in the compression flange, the range of the cycle would be equal to or greater than that in the tension flange. Since the compression failure initiated and

and propagated completely through the compression flange before the tension flange failure initiated in D-7(E-5)R it is reasonable to assume that the stress range in the compression flange was a reversal. Both fractures in D-6(E-4)R initiated at about the same loading life of the specimen. The stress range in the compression butt splice is assumed to have been a full tension cycle or a reversal cycle in which the compressive stress was of a very low magnitude. Without experimental data relating to the residual stresses in each specimen under consideration, the type of stress range in the compression butt splice is pure speculation. Three specimens had fractures in the compression flange. This is less than 6 per cent of the total number of specimens tested.

The value of k obtained from the S-N diagram of the test results of series D is 0.255 (see Fig. 19). Considering all the test results as a whole, the fatigue strength of a type D splice was 42 ksi and 19.5 ksi at 100,000 and 2,000,000 cycles respectively. The results of test series "C" have been included on the S-N diagram of Fig. 19, but this information has not been included when the median plot through the test data of series "D" was drawn. The average test stress and fatigue life of specimens D-1(C-1) through D-4(F-2)R was 30.5 ksi and 345,800 cycles. The fatigue life of series "D", based on tests conducted at a nominal stress range of zero to 30 ksi, is 30 per cent that of series "AA". For series "C" and "F" the same comparison produces the following percentages, 54 and 80 per cent respectively. Splice type "A" and "D" are in-line splices with and without cope holes. A comparison of these two test series shows that the fatigue life of series "A" is 66 per cent of series "D". On the basis of fatigue strength at 100,000 and 2,000,000 cycles, respectively, splice type "D" is 11.5 and 20.0 per cent stronger.

e. Series E - Splice Type E

Splice type "E" was similar to splice type "B" except that cope holes were not provided in the web of the specimen. The test specimen consisted of a complete joint made with the flange butt welds staggered on either side of the web splice. A total of ten specimens were tested. The test results are shown graphically in Fig. 21, and numerical values are given in Table 10.

E-1(B-1)R, E-2(B-2)R, E-10(B-8)R

Fractures initiated at the toe of the tension butt splice on the edge of the flange in E-1(B-1)R, E-2(B-2)R and E-10(B-8)R. The fractures covered from 40 to 60 per cent of the flange plate. In numerical order of the specimen designation, the beams were tested at stress ranges of 0.7 to 29.9 ksi, 0.7 to 29.3 ksi and 0.4 to 21.4 ksi and had fatigue lives of 396,500, 412,600 and 350,200 cycles, respectively. 45,500 additional cycles were required to produce failure of E-1(B-1)R from the time the fracture was first observed.

E-3(B-3)R

Tested on a stress range of 0.8 to 29.4 ksi, the endurance limit of E-3(B-3)R was 376,900 cycles. The fracture initiated at the edge of the flange within the weld metal of the butt splice at two separate locations; at the root of the butt splice and just above the bottom surface of the flange. Both fractures initiated at locations of poor weld penetration and joined to form a vertical plane which traversed the flange width along the center of the butt weld.

E-4(0)R

A fracture developed on each edge of the tension flange, and was located on opposite toes of the butt splice. After initiation, the larger or primary fracture progressed along the toe of the splice on the bottom face of the flange. On the top face of the flange, the primary fracture turned back into the base metal of the flange; at the web the fracture was one-half inch from the toe of the butt splice. The primary fracture extended over 75 per cent of the area of the flange plate, and the secondary fracture covered an area of 25 per cent of the flange. The secondary failure followed along the toe of the butt splice on both faces of the flange. E-4(O)R was tested at a stress range of 0.5 to 25.5 ksi and had a fatigue life of 800,400 cycles.

E-5(O)R

Two flange fractures, one in each flange of the specimen and one web fracture, developed in E-5(O)R. At 1,526,700 cycles the following two fractures were observed in the specimen (both fractures will be referred to as secondary); a web fracture 14 in. from the center line of the test span and a fracture in the compression flange butt splice (see Fig. 22a). The web fracture occurred on the tension side of the beam at the outer edge of a weld crater. At failure the crack had proceeded into the web for a distance of 2 1/2 in. The angle between the flange and the fracture was 45 deg. The other secondary fracture traversed the compression butt splice at its center line and extended down into the web 3 3/4 in. The initiation of the fracture developed under a reversal stress range, see the discussion of D-6(E-4)R and D-7(E-5)R, and/or fretting corrosion under the loading block. The deflection of the beam was not increased the required 0.05 in. due to two secondary fractures; therefore, the test was continued until the third fracture produced the necessary deflection. The third or primary fracture developed in the base metal of the tension flange 2 1/8 in. from the center line of the test span. Propagation of the primary fracture proceeded to failure in 31,800 cycles after the secondary fractures were observed. Initiation of the fracture occurred at the edge of the flange and traversed 50 per cent of the way through the plate. E-5(O)R was tested at a stress range of 0.4 to 25.6 ksi and had a fatigue life of 1,558,500 cycles.

E-6(O)R, E-7(AA-9)R, E-8(O)R

Three specimens had the same general type of fracture. The fracture initiated at the toe of the tension butt splice and progressed into the base metal of the flange. E-7(AA-9)R and E-8(O)R had fractures which initiated on the bottom face of the flange at its edge. At the time of failure, the fractures had progressed in a vertical direction about 40 per cent of the way through the flange. Testing of E-7(AA-9)R was continued until the fracture had completely traversed the tension flange. Fig. 22 shows a section of the fracture and the change in crack propagation rate is very evident. E-6(O)R had two fractures, the primary one initiated on the top face of the tension flange near one edge. After the primary fracture initiated, it proceeded to traverse the flange in a vertical plane which ran through the base metal of the flange. The crack paralleled the butt splice and remained within one-half inch of it. Before the primary fracture was discovered, a secondary fracture which remained entirely within the web was recorded at a distance of 13 in. from the center line of the test span. At the time the secondary crack was reported, its length was 2 in. and the specimen had been running for 1,756,400 cycles; at failure the fracture was 3 1/4 in. in length and the fatigue life of the beam was 1,919,300 cycles. The crack progressed 1 1/4 in. in 162,900 cycles. The secondary crack developed at a weld crater and investigation of the fractured section showed that the fracture was just entering the flange of the beam. It can be reasoned that had the primary fracture not initiated, the secondary fracture would have proceeded to failure in the same manner as specimens of series "AA". The test data also shows that the major portion of the primary fracture developed in 72,000 cycles and extended through the tension flange and 8 in. up into the web. In numerical order of their specimen designation, the three specimens were tested under the following stress ranges; 0.4 to 25.0, 0.4 to 24.6 and 0.1 to 23.8 ksi and had the following fatigue lives; 1,919,300, 569,100 and 730,400 cycles, respectively.

E-9(0)R

Fabrication of specimen E-9(0)R was varied in that the face passes of the flange butt splice were deposited in two parallel passes having a groove between them in the same manner as discussed for specimens A-8(AA-7)R and A-9(E-8)R. However, unlike the two specimens of series "A" the fracture in E-9(0)R did not initiate in the groove but at the toe of the butt splice on one edge of the flange. The fracture traversed the flange in a vertical plane running along the toe of the weld, and the plane extended 40 per cent of the way through the plate. The specimen was tested on a stress range of 0.6 to 24.4 ksi and had a fatigue life of 723,000 cycles.

Fig. 21 shows the test results graphically and the numerical values are presented in Table 10. All the specimens were fabricated with A-373 steel and the stresses reported herein are based on the section measurements obtained from the fractured sections. The fatigue strength of splice type E, obtained from the S-N curve (see Fig. 21) for 100,000 and 2,000,000 cycles was 42 ksi and 19.5 ksi, respectively. The value of k in Wilson's formula was 0.255. For specimens E-1(B-1)R through E-3(B-3)R, the average test stress and fatigue life was 29.5 ksi and 362,000 cycles. The fatigue life of series "E" is 28 per cent of series "AA" when specimens which were tested under a nominal stress range of zero to 30 ksi are compared. The comparison between series "E" and series "C" and "F" produces the following percentages; 56 and 84 per cent, respectively. Splice type "B" and "E" are staggered splices with and without cope holes. A comparison of these two test series, nominal stress range of zero to 30 ksi, shows that the fatigue life of series "B" is 92 per cent of series "E". As a final comparison, since series "D" and "E" would appear to have a higher fatigue life than series "A" and "B", the fatigue life of series "D" is 95 per cent of series "E". The results of test series "C" havè been included on the S-N diagram of Fig. 21, but this information has not been included when the median plot through the test data of series "E" was drawn.

On the basis of fatigue strength at 100,000 and 2,000,000 cycles, respectively, splice type "E" is 31.2 per cent stronger and 5 per cent weaker.

f. Series F - Splice Type "F"

Generally, the quality of double-V butt joints in the flanges of a beam or girder is comparable to that found in similar joints in plain plates. However, special precautions are often required to insure that the butt weld is sound. The area at the junction of the web and the flange, because of its inaccessibility, is conducive to unsound and imperfect welds.

A method long used in commercial practice to make the area more accessible has been to cut out a small semi-circular hole (cope hole) in the web of the beam immediately above the flange splice. By providing the cope hole it is possible, by projecting the electrode through the hole, to start each weld bead in a region where its ends are accessible for proper cleaning before the adjacent passes are deposited. There can be little doubt that this procedure results in sounder welds. However, there is some question concerning the severity of the stress concentrations created by the cope hole. The purpose of this test series was to evaluate the effect of the cope hole.

The three specimens, F-1(0)R, F-2(0)R and F-3(0)R, were tested under stress ranges of 0.6 to 30.9 ksi, 0.8 to 30.5 ksi and 0.7 to 30.1 ksi and had fatigue lives of 352,800, 502,100 and 442,900 cycles, respectively.

For the three specimens the failures initiated at the toe of the flange fillet weld around the edge of the cope hole. After initiation the fracture progressed in a vertical plane toward the edges of the flange plate. A secondary effect of the flange fracture was a vertical fracture initiating at the top of the cope hole in the web.

For the three specimens tested, the average fatigue life was 432,600 cycles which corresponds to an average test stress of 30.7 ksi. Based on all specimens of test series "AA" the fatigue life of splice type "F" is 37 per cent of the beams without splices. The results of test series "F" have been included on the S-N diagrams for splice types A and B; however, this information has not been included in the average curves which were plotted.

It is possible that the practice of filling the cope hole with base metal and/or weld metal could result in an improvement in the fatigue strength of the specimen, provided that in filling the cope hole other serious stress raisers are not introduced.

IV. METALLURGICAL STUDIES

In order to determine the point of initiation of the fatigue failure more accurately all of the specimens were examined after the test had been completed. Metallurgical studies were carried out on a number of the specimens to detect any particular causes of the failure.

Of the specimens which were fabricated without splices, AA-2(O), AA-4(O)R, AA-5(O)R, AA-7(O)R and AA-8(O)R were examined metallurgically. With the exception of AA-4(O)R all of these specimens failed at the weld crater produced at a point of change of electrode. A hardness survey across this region was carried out on specimen AA-2(O) in a line along the beam. This survey indicated that there was a hardness valley at the point of initiation of the crack. The exact mechanism whereby this hardness valley caused the failure is not known at the present time.

The following discussion of failures is grouped according to splice types. Within each of the splice types there is a further breakdown according to the type of failure. Since in most cases the failures were quite similar the details of the metallurgical examinations will not be repeated here but the general nature of the failures will be discussed.

For splice type A there were three different locations of failure. Two specimens failed at the cope hole in the base material of the flange. These fractures initiated at the toe of the fillet weld. Three specimens failed at the weld metal-base metal interface and two specimens failed because of poor root bonding of the flange butt weld. These last two specimens were A-2(AA-2) and A-8(AA-7)R.

In splice type B all failures, with one exception, occurred at the toe of the fillet weld around the cope hole. One of these specimens, B-6(O)R, also had a secondary failure in the flange butt weld caused by poor root bonding. One specimen, B-5(0)R, failed at the interface.

Both specimens of splice type C failed at the weld metal-base metal interface of the flange butt weld. Nothing unusual was discovered in the initiation or propagation of these fractures.

All specimens of splice type D failed at the weld metal-base metal interface. A hardness survey across the failure in specimen D-2(C-2) revealed that there was an area of high hardness in the heat affected zone of the base metal. This area of high hardness can be interpreted to mean that this region had low ductility compared to other regions where the hardness is lower. This discontinuity in the microstructure of the beam probably acted as a stress raiser and led to an earlier failure than would be expected if the beam had a homogeneous microstructure.

One of the specimens with the type E splice did not fail at the splice but at a weld crater in the fillet weld. Two specimens failed at the interface and two failed because of poor bonding of the root pass. The relative consistency of these test results indicate that all of these three notch conditions are of the same relative magnitude.

All of the specimens with splice type F failed at the edge of the cope hole in a manner similar to those already described.

V. CONCLUSIONS

On the basis of tests performed on beams fabricated from A-7 steel in which the ratio of flange thickness to web thickness was varied, it can be seen that the fatigue life of fabricated beams increases as this ratio is increased. A comparison between these results and those previously obtained on rolled sections (2) reveals that it is possible to fabricate a beam which will have a fatigue strength equal to the rolled section.

This same result is indicated by further tests on beams fabricated from A-373 steel. In these tests of beams without splices it is evident that the point of change of electrode is a point of severe stress concentration. In practically all cases the fatigue fracture initiated at this point.

The composite of test results obtained for spliced beams is shown in Fig. 24. A study of this figure shows that the in-line splice and out-of-line splice have considerably different slopes on the S-N plot. This means that the relative merits of the various splices is different at different stress levels. In addition, for a particular configuration of the splice the use of a cope hole reduces the fatigue strength at all fatigue lives.

In connection with this latter item it is necessary for the web thickness in these beams to be considered. With a web thickness of 3/16 in. it is possible for the welder to get a good flange butt weld without the use of a cope hole. Whether this would be the case for a greater web thickness cannot be determined on the basis of these tests. It would seem that for plate thicknesses normally used in girders a very nominal cope hole would serve the purpose. In this way the hole could be filled very easily in the subsequent welding operations.

All of the splices tested gave fatigue strengths which are sufficient to sustain 2,000,000 cycles of load at stress levels which are currently permitted by the specifications. Poor details or bad welds can, however, reduce the fatigue life to a marked degree for any of the splice configurations.

The static test results indicate that there are considerable residual stresses caused by the welding. These stresses are, however, altered in the first few cycles and at any particular point the load-strain relationship becomes linear.

APPENDIX

I. Introduction

Prior to and during the fatigue test, a series of special studies were run on specimen P-7. The purpose of these tests was to study the effect of welding stresses on the behavior of built-up members, to determine the stress distribution in the member under load, and to detect any redistribution of stresses during the fatigue test prior to failure. This section contains a description of the testing procedure, presentation of typical test results and a short discussion of some of the more interesting phenomena observed.

The fabrication procedure and welding sequence for this specimen conformed to the description given in an earlier section. Specimen P-7, however, had an overall depth of 12 in. as compared to 11 1/2 in. for all previous specimens. The increase in depth was due to the thicker flange material; the web depth was maintained at 10 in.

II. Instrumentation

Thirty-nine SR-4 (thirty type A-7 and three type AR-1, 45 degree rosettes) wire-resistance strain gages were mounted on the specimen. Twenty-one of the A-7 type (twelve on the bottom flange and nine on the top flange) were mounted on the outer face of the flanges, arranged transversely in groups of three. Two were mounted on the inside face of the bottom flange, one on the face of the fillet weld at the junction of the web and tension flange, and six on the web in a vertical row at the center line of the beam. The three rosettes were arranged on a forty-five degree line, starting under one of the load points and sloping toward the support. Positions and reference numbers for all gages are shown in Fig. 25.

Ames dials, for measuring the vertical deflections, were located at the center line and under one of the load points. The buckling tendency of the web was measured in five places. Sanborn continuous strain recording equipment was used to obtain a continuous strain record of the strain gages during the fatigue test.

III. Test Procedure

The specimen was subjected to three static loading cycles, which shall hereafter be referred to as "first run, second run, and third run". A run consisted of loading and unloading the specimen in increments from zero to maximum load and back to zero. The maximum load in each run was 72,300 lb; a value equal to the maximum load in the stress cycle under fatigue loading. Load increments were selected before each run but these were adjusted during the test when it was found desirable. A complete set of readings was taken immediately after each increment of load.

The first two runs were made in an Olson screw-type testing machine having a capacity of 100,000 lb. The third run was made in the fatigue machine, which can be cranked by hand to apply and hold any desired load within its capacity of 112,000 lb. The loading and reaction blocks used in applying the load and to support the member during the fatigue test were also used for the static tests.

The first run had to be interrupted overnight at a load of 50,200 lb. The load was dropped to 2,700 lb. and run back up to 50,200 lb. when the test was resumed in the morning. Otherwise, the runs were un-interrupted except for the time required to take and record the data.

In an endeavor to detect any change in the initial strain distribution in the specimen, zero and maximum strain readings were taken at several stages during the fatigue test on the static strain indicator, and a short continuous dynamic strain record for each gage was obtained on the Sanborn equipment every 100,000 cycles.

IV. General Comments

At no time during the test did the specimen exhibit visual signs of distress. In the first and second run there was a drop-off in load, during reading and recording of the data, as high as 800 lb. (The initial load values were used in plotting the load-strain curves.) This drop-off may be attributed to slip in the machine rather than to the specimen, because in the fatigue machine where drop-off due to the machine was impossible, no drop-off was observed. The light Lueders lines that appeared during welding began to spread further into the web and increase in intensity and number as the load passed 20,000 lb.

Behavior of the SR-4 strain gages was very satisfactory up to two million cycles. Beyond two million cycles some of the gages showed signs of resistance leakage. This was probably due to cracking of the wax and binder, thus allowing moisture to reach the gages and cause shorting with the specimen.

V. Load-Strain Relationships

Load-strain curves were plotted for all the strain gages but only a sufficient number have been included in this report to give a general, yet accurate, picture of the load-strain relationships and strain distribution in the member throughout the tests.

Load-strain relationships for four gages on the extreme fiber of the tension flange are given in Fig. 26. The top half of Fig. 27 gives the load-strain relationships for two gages on the extreme fiber of the compression flange. Location of the gages is given in Fig. 25 and in the small diagram in Figs. 26 and 27. A study of the load-strain relationships for the gages on the two flanges indicates pronounced and significant differences in their behavior, particularly in the first run.

In the first run the load-strain relationships for the gages on the extreme fiber of the tension flange were linear up to a load of 40,000 lb., and agreed very well with the theoretical calculated strains based on a modulus of elasticity of 29 million, as computed from the coupon tests. Beyond 40,000 lb. the strains were not proportional to stress. At maximum load (72,300 lb.) the excess of measured strains over theoretical strains reached 450 microin./in. for gage no. 15. Gages outside of the constant moment region experienced smaller plastic deformations with decreasing values of flexural stress.

The load-strain relationship for the gage on the extreme fiber of the compression flange in the constant moment region (between the loading blocks) was fairly linear throughout the first run. But, measured strains at maximum load were about 100 microin./in. less than the calculated strains. Strain in the extreme fiber outside of the loading blocks, as indicated by gage no. 23, was proportional to load up to a load of 50,000 lb.; beyond this load some plastic straining was evident, and at maximum load measured strains were about 70 microin./in. greater than calculated strains.

The bottom half of Fig. 27 gives the load-strain relationships at two points in the web at the center line of the span, obtained from gages nos. 20 and 25. Of special interest is the fact that gage no. 20 (next to the tension flange) showed no permanent set after the first run and behaved elastically throughout the run, whereas gage no. 25 (next to the compression flange) exhibited considerable plastic behavior and showed a permanent set of 330 microin./in. after the first run. The strains were rather erratic in that there was little correlation between measured and calculated strains.

In the second and third run all load-strain relationships were linear throughout. Strains in the extreme fiber of the tension flange agreed well with calculated strains, while strains in the extreme fiber of the compression flange were consistently about 160 microin./in. less than the calculated strains. Load-strain relationships in the web bore little similarity to calculated strains. Permanent set after the second and third run was negligible.

Fig. 28 gives the strain distribution across the section of the specimen at mid-span. The distribution was rather erratic, particularly in the first run; yet, the results of the second and third run, although unusual, show some consistency. As may be seen from the figure, the distribution was anything but linear, even at small loads. The results indicate a shift of the neutral axis downward about 5/8 in. below the center of gravity of the section. The strains, however, are consistently lower on the extreme fiber of the compression flange.

Fig. 29 gives the transverse distribution of longitudinal strains at the center line in the extreme fiber of the tension and compression flange. During the first run the distribution in the tension flange was uniform up to a load of 30,000 lb. As the load increased, gage no. 15 and 16 began to exhibit an excess of plastic deformation over gage no. 14, thereby disrupting the uniformity. Other than this, the distribution was uniform in both flanges throughout the test. The uniformity of the strain distribution across the flanges is a good indication of the symmetry of loading on the section.

The fact that the load-strain curves obtained from the third run (made in the fatigue machine) agree so well with the load-strain curves from the second run is a good indication that the load applied by the fatigue machine is accurate.

VI. Web Buckling Tendency

The buckling tendency of the web was very small. Maximum deviation from the initial position was 0.009 in. at the center line of the span and over one of the supports. In all cases the web returned to its original position after the load was removed.

VII. Strain Redistribution

The load-strain relationships shown in Fig. 28 indicate a definite readjustment in the strain distribution pattern after the first run. The redistribution can be attributed to the partial relief of residual stresses which took place as the load was applied during the first run. A small amount of redistribution took place in the second run also, but beyond this any redistribution that might have occurred was so small that it could not be detected with the equipment used.

The static strain measurements taken at intervals during the fatigue tests and the continuous strain records taken on the Sanborn equipment indicated no redistribution up to the point where many of the gages showed signs of resistance leakage. However, it is doubtful that the Sanborn equipment would have been able to detect any minor redistribution, even if some had occurred, because of the small scale to which strains are plotted in this type of equipment.

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TABLE 1

CHEMICAL COMPOSITION OF STEEL PLATES

Steel	Plate Thickness in.	Chemical Content, %					
		C	Mn	P	S	Si	Cu
A-7	1/4	0.22	0.32	0.012	0.035	---	---
A-7	3/4	0.28	0.44	0.016	0.029	---	---
A-7	1	0.28	0.44	0.016	0.029	---	---
A-373	3/16	0.23	0.63	0.022	0.031	0.030	0.17
A-373	1	0.21	0.60	0.030	0.030	0.053	0.20

TABLE 2

PHYSICAL PROPERTIES OF STEEL PLATE

(8-in. Gage Length Tensile Coupons)

Steel	Thickness in.	Yield Strength psi	Ultimate Strength psi	Elongation in 8 in. per cent	Reduction of Area per cent
A-7	3/16	44,800	67,800	25.5	52.7
A-7	1/4	37,100	50,700	32.8	66.0
A-7	3/4	35,300	64,600	30.3	51.3
A-7	1	35,000	61,200	34.2	63.7
A-373	3/16	38,800	64,800	29.6	58.0
A-373	1	34,600	67,000	28.0	48.6

TABLE 3

DESCRIPTION OF INITIAL WELDING SEQUENCE

Step No.	Pass No.	Remarks
1A	--	Jig web and flange and clamp
2A	--	Deposit fillet welds
		Start butt splice welds with web in vertical position
1	1	Flange weld - see Fig. 4
2	2	
3	3	
4	4	
5	-	Turn beam over and back-chip pass no. 1 and no. 2
6	5	
7	6	
8	7	
9	8	
10	9	
11	10	
12	--	Turn beam over and complete flange splices
13	11	
14	12	
15	--	Set beam with web in horizontal position
16	13	
17	--	Turn beam over and back-chip pass no. 13
18	14	

Note: All welds were made with reversed polarity, in the flat position and with A.W.S. - A.S.T.M. E7016 electrodes.

TABLE 4

DESCRIPTION OF REVISED WELDING SEQUENCE

Step No.	Pass No.	Remarks
1A	--	Jig web and flange and tack
2A	--	Deposit fillet welds in sequence shown in Fig. 3
		Start butt splice welds with web in horizontal position
1	1	Web weld - see Fig. 5
2	-	Turn beam over and back-chip pass no. 1
3	2	Complete web splice
3a	-	Cut cope holes (only where applicable)
4	-	Set beam with web in vertical position
5	-	Tack run-off blocks to flange (place tacks in grooves only)
6	3	Top flange weld
7	4	
8	5	Bottom flange weld
9	6	
10	-	Turn beam over and back-chip pass no. 3 and no. 5
11	7	
12	8	
13	9	
14	10	
15	11	
16	12	
17	--	Turn beam over and complete splice
18	13	
19	14	
20	--	Cut away run-off blocks and grind edge of flange smooth and flush

Note: All welds were made with reversed polarity, in the flat position and with A.W.S. - A.S.T.M. E7016 electrodes, 5/32 in. diameter.

TABLE 5

RESULTS OF FATIGUE TESTS ON PLAIN PLATE, TRANSVERSE AND LONGITUDINAL BUTT-WELDED SPECIMENS

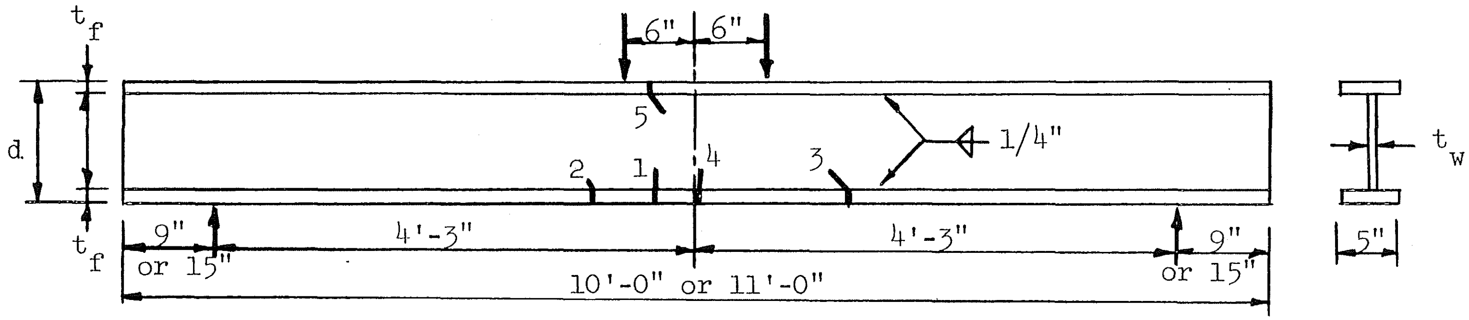
Specimen	Stress	Cycles for Failure	Fatigue Strength*		k
			A-373 Steel	A-7 Steel	
	psi	10^3	$f_{2,000,000}$	$f_{2,000,000}$	
		Plain Plate Specimens			
F-1	36,000	1,046.0	32,100		
F-2	36,000	964.3	31,600		
F-3	36,000	1,751.6	35,200		
		Average	33,000	34,600	0.18
		Transverse Butt-Welded Joints			
F-1T	25,000	859.7	22,400		
F-2T	25,000	978.8	22,800		
F-3T	25,000	882.1	22,400		
		Average	22,500	23,800+	0.13
		Longitudinal Butt-Welded Specimens			
F-1L	27,000	1,623.1	26,200		
F-2L	25,000	3,723.3	25,000+		
F-3L	27,000	3,656.0	27,000+		
		Average	26,100+	26,300	0.13

* Results of tests on A-7 steel taken from Bibliography, Reference 3.

TABLE 6

SPECIMEN DESCRIPTION AND SUMMARY OF TEST RESULTS

OF THE PRELIMINARY SERIES



Specimen	d in.	b in.	t_f in.	t_W in.	$\frac{t_f}{t_W}$	Splice* Type	Max. Stress in Ext. Fiber 1000's psi	Stress in Weld pli	Cycles for Failure 10^3	Location** of Fracture
P-1	11 1/2	5	3/4	3/4	1.0	None	30.0	2440	830.1	1
P-2	11 1/2	5	3/4	1/4	3.1	None	30.0	2340	1,037.3	1
P-6	11 1/2	5	3/4	3/16	4.3	None	30.0	2340	1,793.4	5
P-7	12	5	1	3/16	5.3	None	30.0	3055	2,164.3	3
P-3	11 1/2	5	3/4	1/4	---	A	30.0	2340	350.9	4
P-4	11 1/2	5	3/4	1/4	---	B	30.0	2340	450.7	4
P-5	11 1/2	5	3/4	1/4	---	C	30.0	2340	563.6	2
P-2a	11 1/2	5	3/4	1/4	---	D	30.0	2340	1,357.5	4a
P-3a	11 1/2	5	3/4	1/4	---	D	30.0	2340	571.9	4a
P-6a	11 1/2	5	3/4	3/16	---	D	30.0	2340	767.5	4a
P-7a	12	5	1	3/16	---	D	30.0	3055	459.4	4b

* See Fig. 2 for splice types

** 4 - Toe of fillet weld at edge of cope hole; 4a - Through butt joint; 4b - Along edge of weld reinforcement

TABLE 7

SUMMARY OF FLEXURAL FATIGUE TEST RESULTS

BEAMS WITHOUT SPLICES

Specimen	Max. Flexural Stress* at Extreme Fiber 1000 psi	Cycles for Failure 10^3	Location of Primary Fracture, Distance from Center Line inches
AA-1(0)	29.5	1,466,600	2
AA-2(0)	29.9	1,490,400	9
AA-3(0)	30.0	1,443,400	9
AA-4(0)R	30.2	860,700	3
AA-5(0)R	29.0	750,800	21
AA-6(0)R	29.2	1,557,900	16
AA-7(0)R	28.8	1,539,600	12
AA-8(0)R	30.8	805,700	11 1/2
AA-9(0)R	30.6	847,600	2 1/2

* Stress based on section measurements at center line of test span after failure had occurred.

TABLE 8

PRINCIPAL STRESSES AT PRIMARY FRACTURE

BEAMS WITHOUT SPLICES

Specimen No.	Max. Flexural Stress at Extreme Fiber			Principal Stresses at Primary Fracture*				
	Center Line	Primary Fracture	Secondary Fracture	Maximum Tension ksi	Minimum Compression	Maximum Shear	Computed φ deg.	Measured φ deg.
AA-1(0)	.7 to 29.5	.7 to 29.5	---	Flange Failure				
AA-2(0)	.7 to 29.9	.7 to 27.9	---	30.8	7.6	19.2	63.6	55
AA-3(0)	.7 to 30.0	.7 to 28.0	---	31.0	7.8	19.4	63.4	57
AA-4(0)R	.8 to 30.2	.8 to 30.2	---	Flange Failure				
AA-5(0)R	.4 to 29.0	.3 to 19.3	---	26.2	10.3	18.2	57.9	45
AA-6(0)R	.9 to 29.2	.7 to 22.5	.7 to 23.8	27.8	9.2	18.5	60.2	53.5
AA-7(0)R	.4 to 28.8	.3 to 25.0	---	28.9	8.1	18.5	62.1	55
AA-8(0)R	.5 to 30.8	.4 to 27.0	.5 to 30.8	31.1	8.7	19.9	62.2	60.5
AA-9(0)R	.4 to 30.6	.4 to 30.6	---	Flange Failure				

* Stresses computed at the edge of the web plate.

TABLE 9

SUMMARY OF TEST RESULTS

BEAMS WITH SPLICES

Specimen	Max. Stress in Ext. Fiber 1000 psi	Cycles for Failure 10^3	Location of Fracture
A-1 (AA-1)	29.4	203,600	Cope Hole[c]
A-2 (AA-2)	29.9	175,500	Within the Tension Butt Weld
A-3 (AA-3)	30.0	280,300	Cope Hole
A-4 (AA-4)R	30.2	207,700	Toe of Tension Butt Weld[d]
A-5 (B-4)R	20.5	1,310,700[a]	Cope Hole
A-6 (B-5)R	31.0	524,300	Toe of Tension Butt Weld
A-7 (B-6)R	24.9	613,900	Toe of Tension Butt Weld
A-8 (AA-7)R	22.6	240,200	Within the Tension Butt Weld
A-9 (E-8)R	20.6	725,100	Within the Tension Butt Weld
A-10(E-9)R	21.4	578,600	Toe of Tension Butt Weld
B-1(O)R	30.0	209,000	Cope Hole
B-2(O)R	29.5	416,800	Cope Hole
B-3(O)R	29.2	367,500	Cope Hole
B-4(O)R	19.5	3,098,300[b]	No Fracture
	23.4	57,000[b]	Toe of Tension Butt Weld
B-5(O)R	25.6	289,500	Toe of Tension Butt Weld
B-6(O)R	22.6	528,500	Cope Hole
B-7(O)R	22.3	1,354,300	Toe of Tension Butt Weld
B-8(O)R	21.3	952,400	Within the Tension Butt Weld
C-1(O)	29.7	514,500	Toe of Tension Butt Weld
C-2(O)	30.0	775,100	Toe of Tension Butt Weld
D-1	32.6	270,900	Within the Tension Butt Weld
D-2	29.1	450,800	Toe of Tension Butt Weld
D-3	29.9	342,700	Toe of Tension Butt Weld
D-4	30.4	319,000	Toe of Tension Butt Weld
D-5	20.4	1,027,600	Toe of Tension Butt Weld
D-6	22.7	1,343,700	{Within the Compression Butt Weld Base Metal of Tension Flange
D-7	22.7	1,054,800	{Within the Compression Butt Weld Base Metal of Tension Flange
D-8	22.5	1,386,800	Base Metal of Tension Flange

Note:

[a] Tested discontinuously

[b] Load increased after 3,098,300 cycles

[c] Toe of the web to flange fillet weld at the edge of the cope hole

[d] Weld metal-base metal interface

(Continued on page 61)

TABLE 9 (Continued)

Specimen	Max. Stress in. Ext. Fiber 1000 psi	Cycles for Failure 10^3	Location of Fracture
E-1(B-1)R	29.9	396,500	Toe of Tension Butt Weld
E-2(B-2)R	29.3	412,600	Toe of Tension Butt Weld
E-3(B-3)R	29.4	376,900	Within the Tension Butt Weld
E-4(0)R	25.5	800,400	Toe of Tension Butt Weld
E-5(0)R	25.6	1,558,500	Within the Compression Butt Weld; Base Metal of Tension Flange
E-6(0)R	25.0	1,919,300	Toe of Tension Butt Weld
E-7(AA-9)R	24.6	569,100	Toe of Tension Butt Weld
E-8(0)R	23.8	730,400	Toe of Tension Butt Weld
E-9(0)R	24.4	723,000	Toe of Tension Butt Weld
E-10(B-8)R	21.4	350,200	Toe of Tension Butt Weld
F-1(0)R	30.9	352,800	Cope Hole
F-2(0)R	30.5	502,100	Cope Hole
F-3(0)R	30.1	442,900	Cope Hole

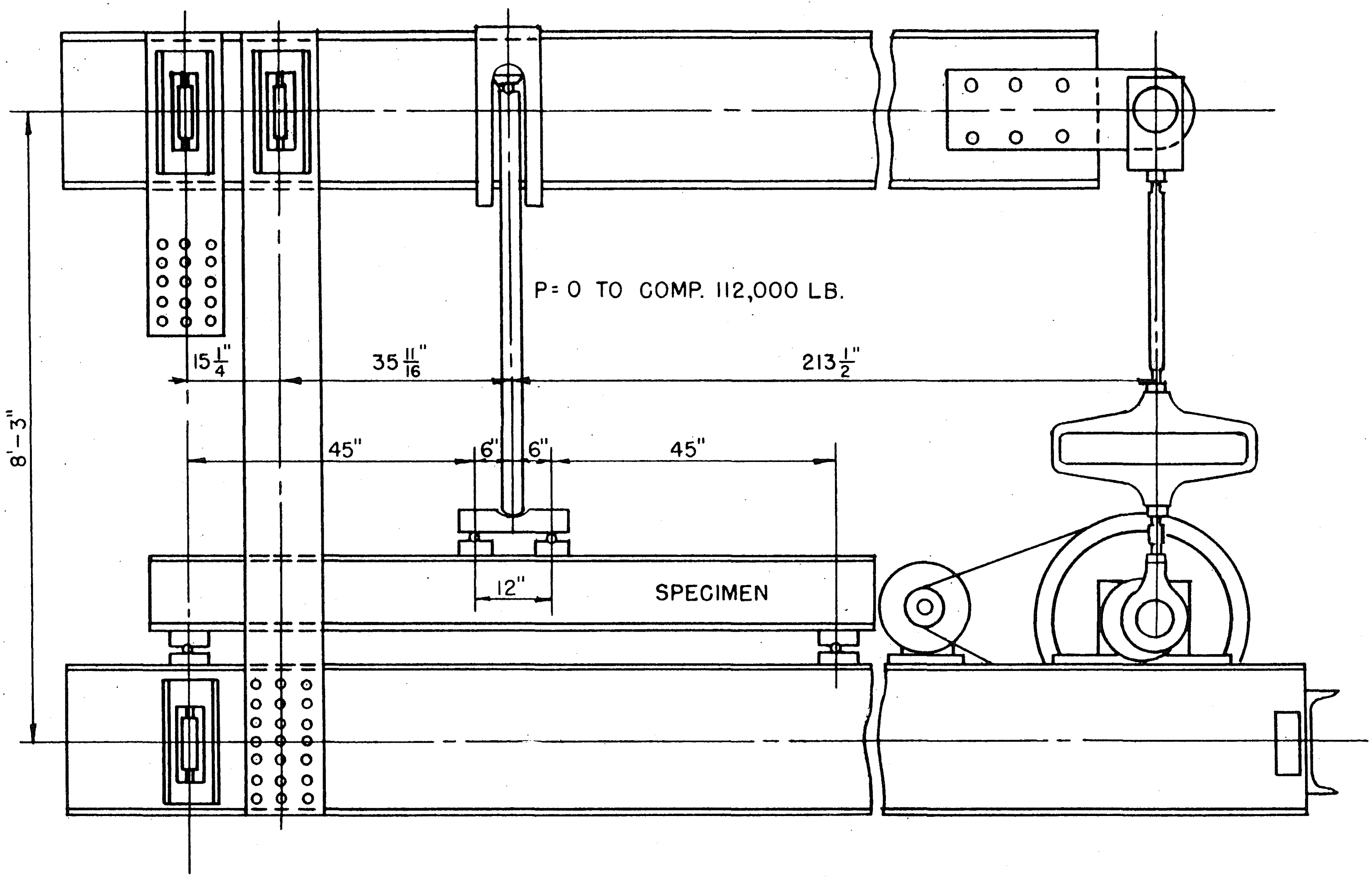
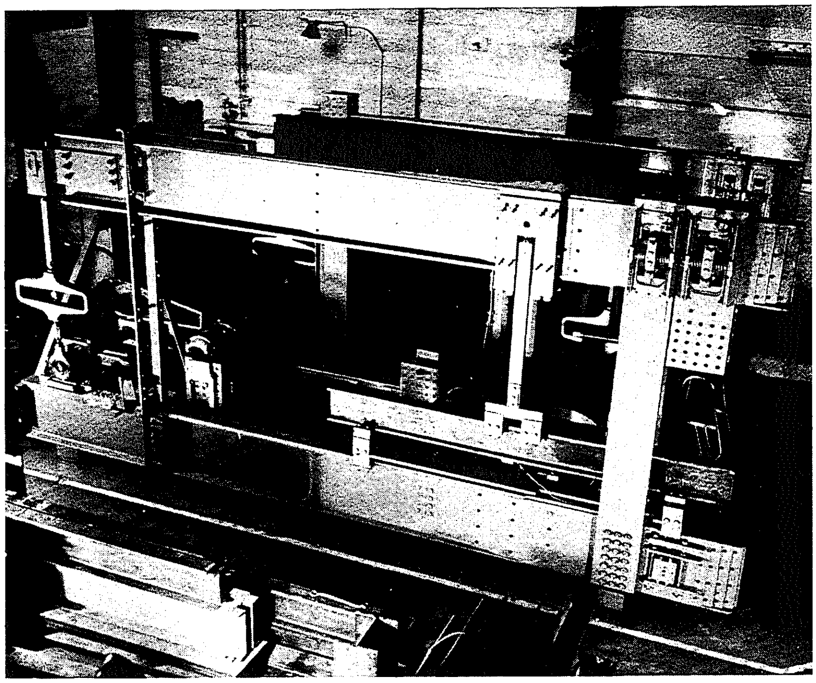


FIG. 1 200,000-LB. WILSON FATIGUE TESTING MACHINE ADAPTED TO TEST FLEXURAL SPECIMENS



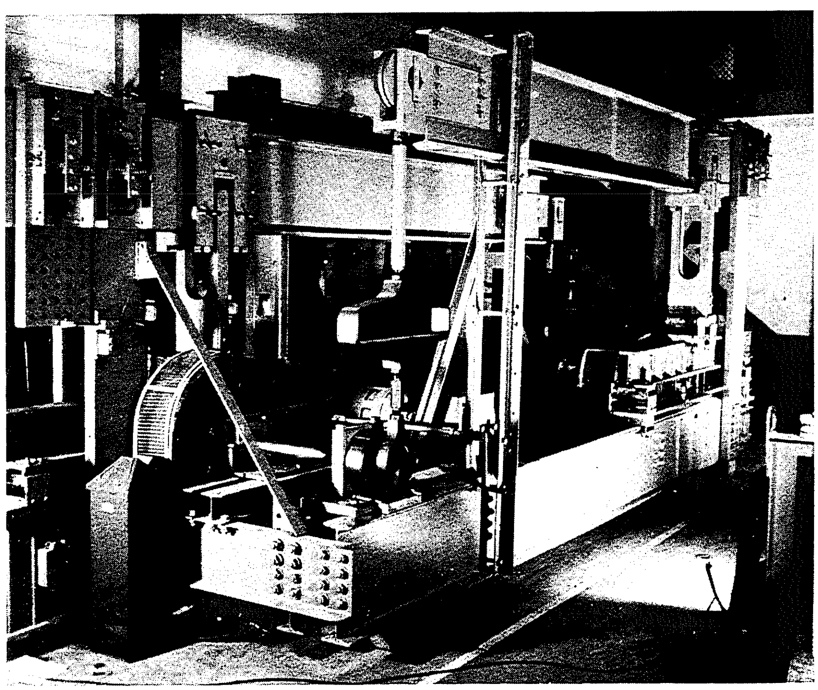
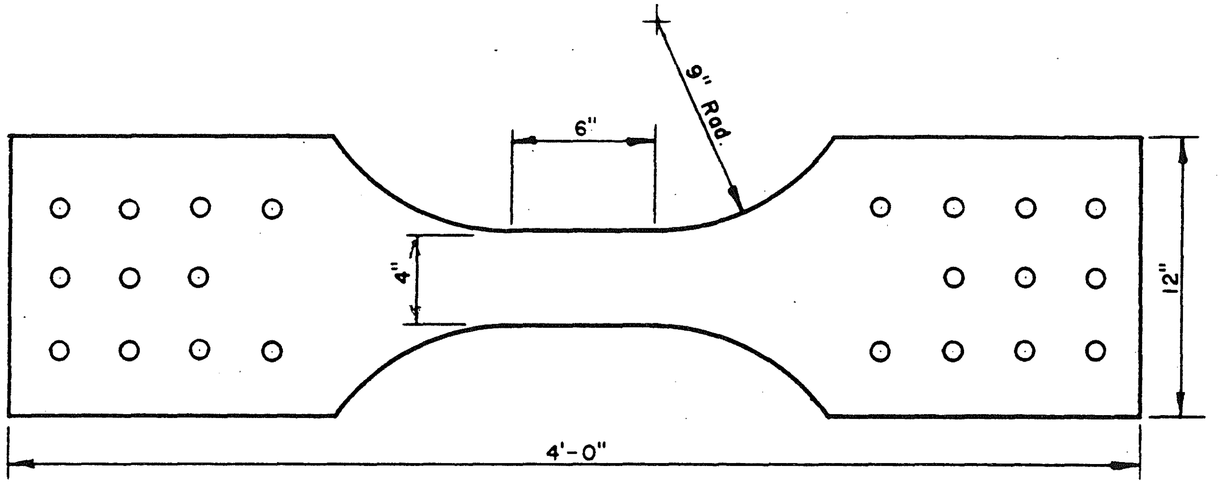
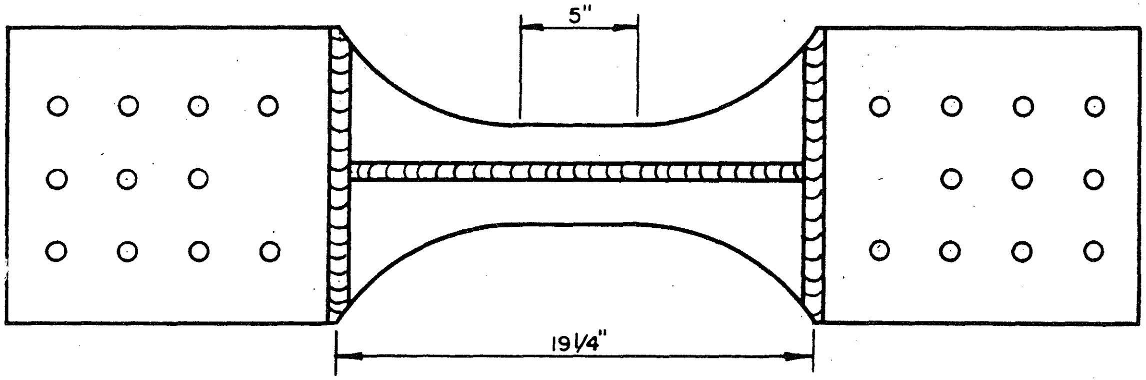


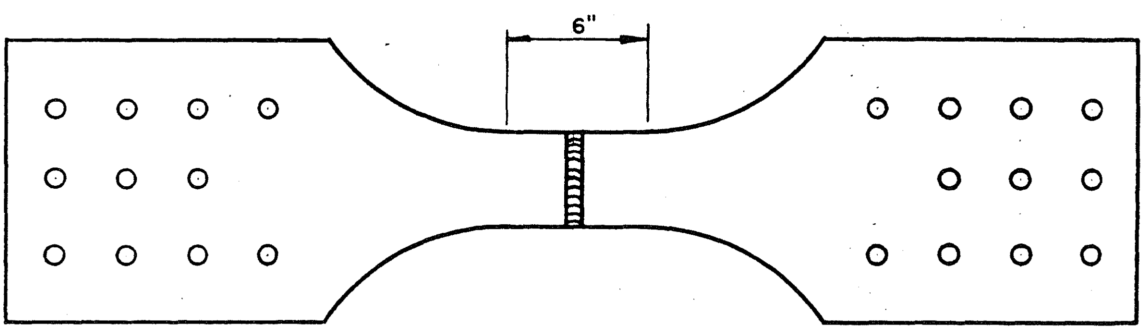
FIG. 2 WILSON FATIGUE TESTING MACHINE



a. PLAIN PLATE

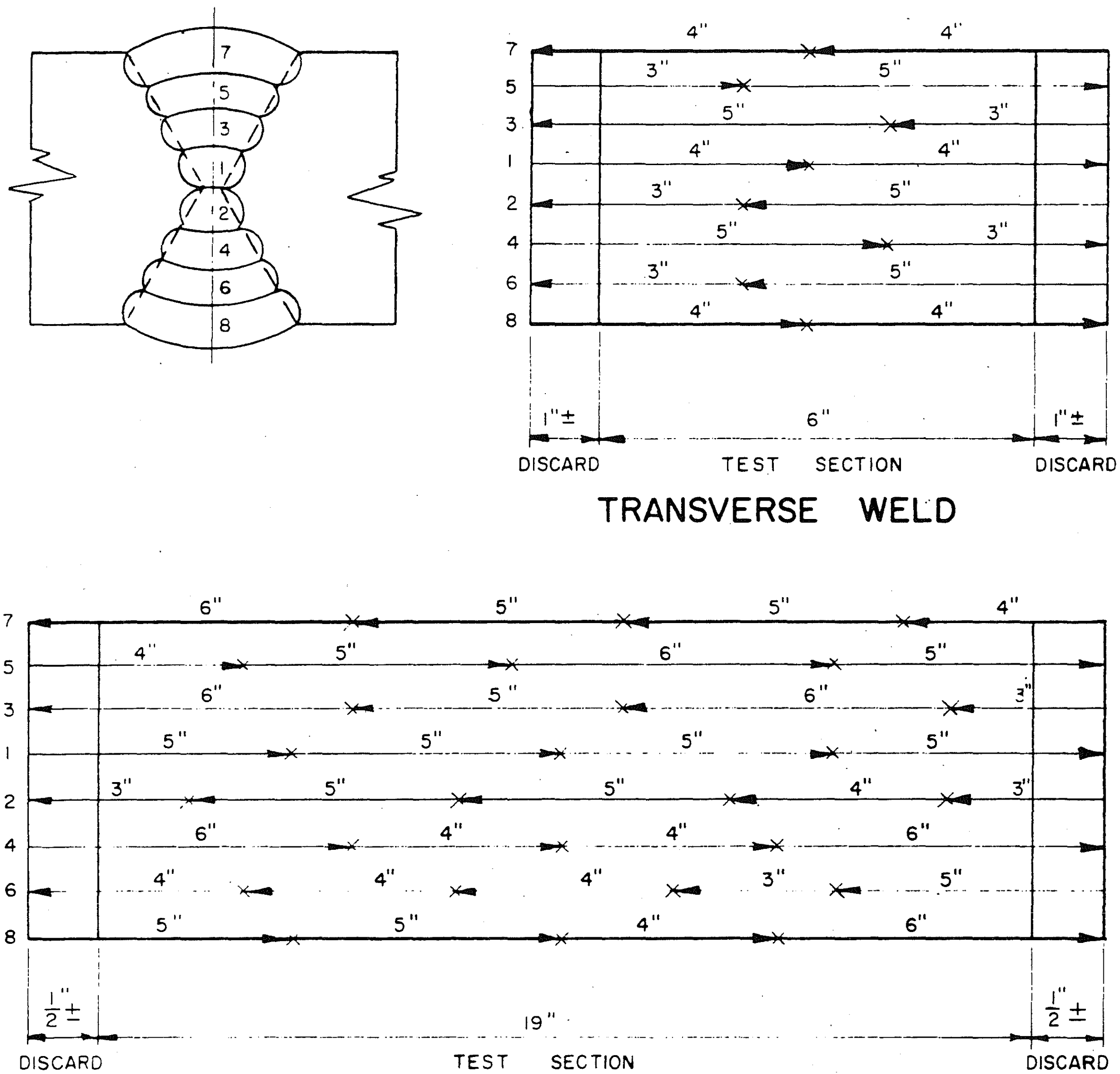


b. LONGITUDINAL BUTT WELD



c. TRANSVERSE BUTT WELD

FIG. 3 DETAILS OF BUTT-WELDED JOINTS

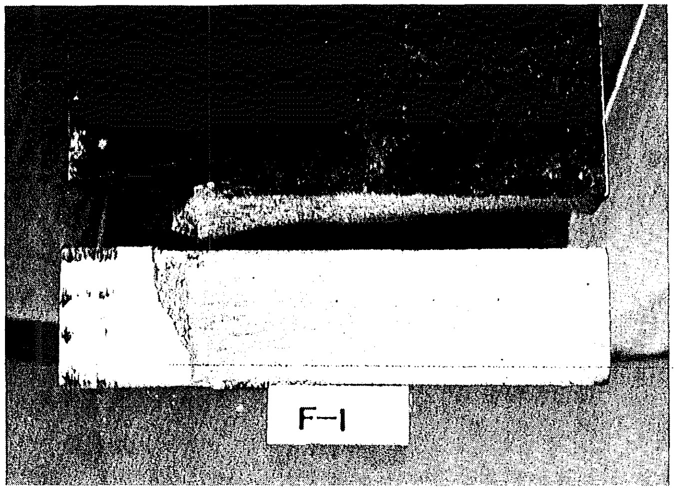


LONGITUDINAL WELD

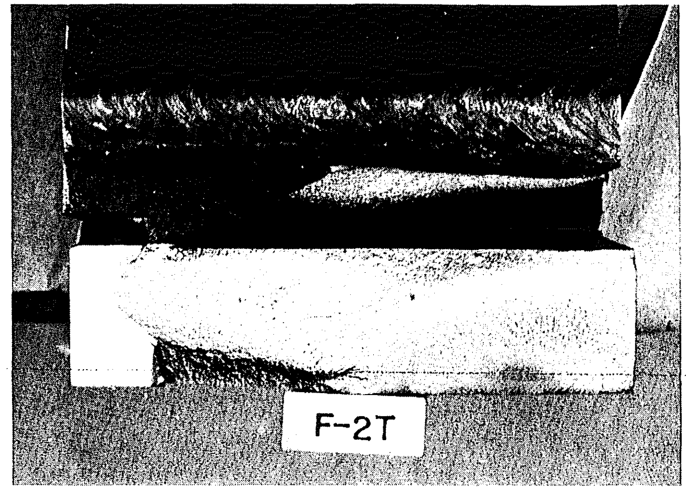
NOTE:

X INDICATES CHANGE OF ELECTRODE
ARROWS INDICATE DIRECTION OF WELDING

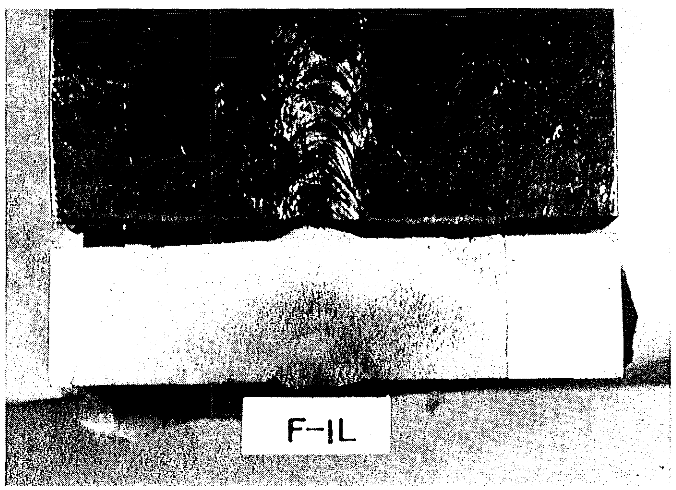
FIG.3A WELDING SEQUENCE FOR LONGITUDINAL AND TRANSVERSE BUTT-WELDED JOINTS



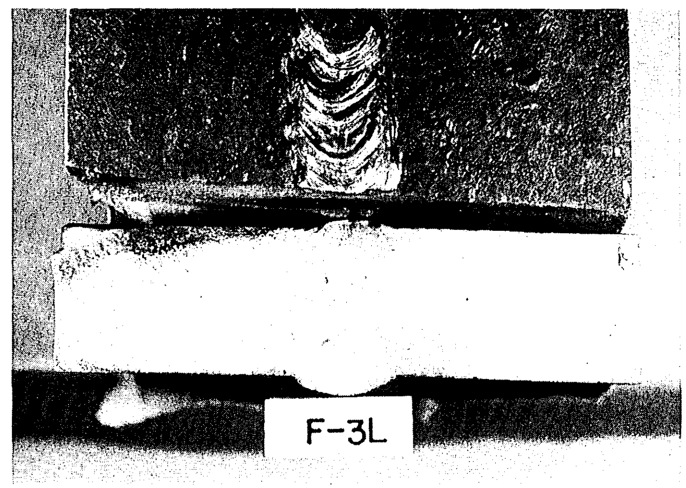
a. PLAIN PLATE SPECIMEN



b. TRANSVERSE BUTT-WELDED SPECIMEN

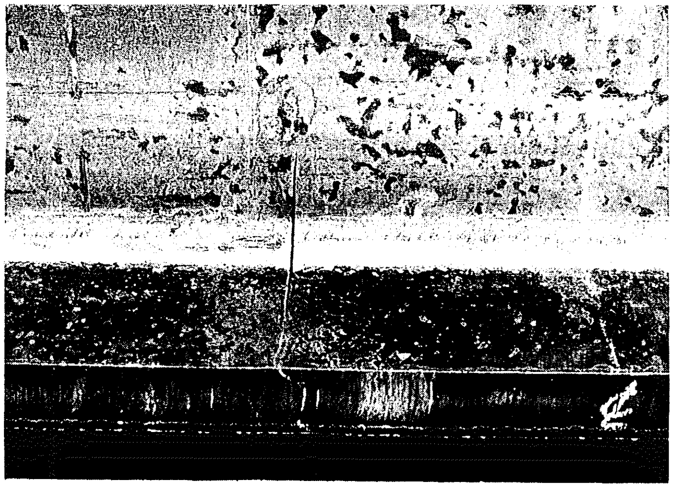


c. LONGITUDINAL BUTT-WELDED SPECIMEN

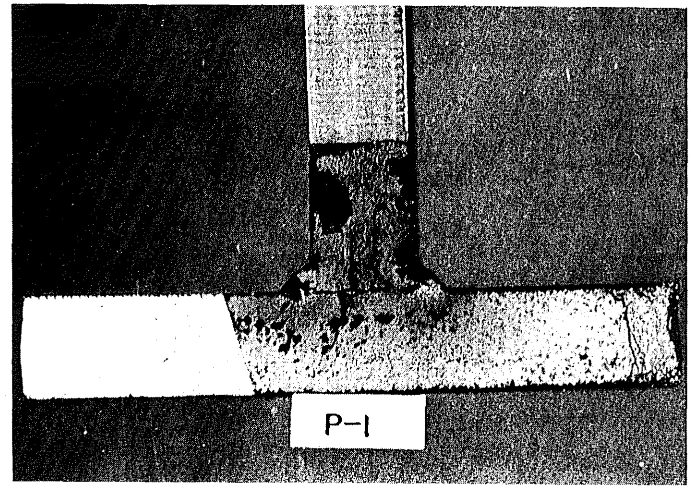


d. LONGITUDINAL BUTT-WELDED SPECIMEN

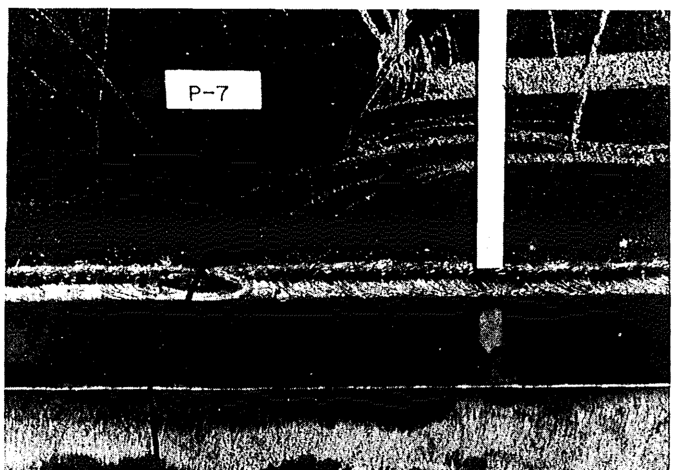
FIG. 4 TYPICAL FRACTURES OF BUTT-WELDED JOINTS



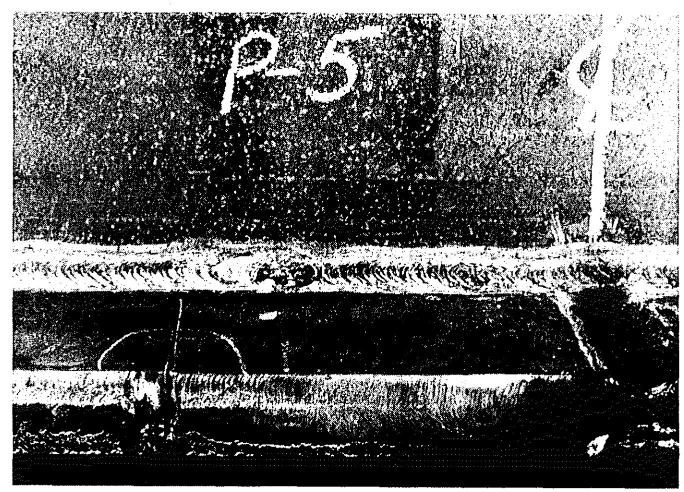
a. SPECIMEN P-1: FAILURE AT CHANGE OF ELECTRODE



b. SPECIMEN P-1: FRACTURED SURFACE

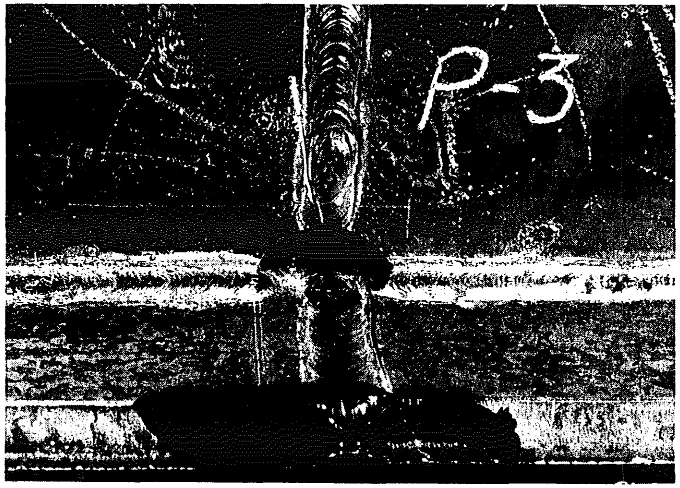


c. SPECIMEN P-7: FAILURE AT CHANGE OF ELECTRODE

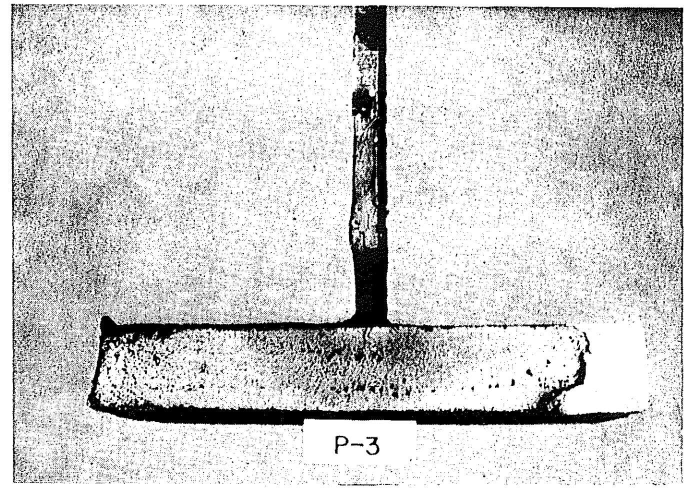


d. SPECIMEN P-5: FAILURE AT EDGE OF TENSION FLANGE

FIG. 5 TYPICAL FRACTURES OF PRELIMINARY SERIES



a. SPECIMEN P-3: FAILURE AT TOE OF FILLET WELD



b. SPECIMEN P-3: FRACTURED SURFACE

c. SPECIMEN P-3a: FAILURE AT TOE OF BUTT WELD

d. SPECIMEN P-2a: FAILURE IN WELD METAL

FIG. 6 TYPICAL FRACTURES OF PRELIMINARY SERIES

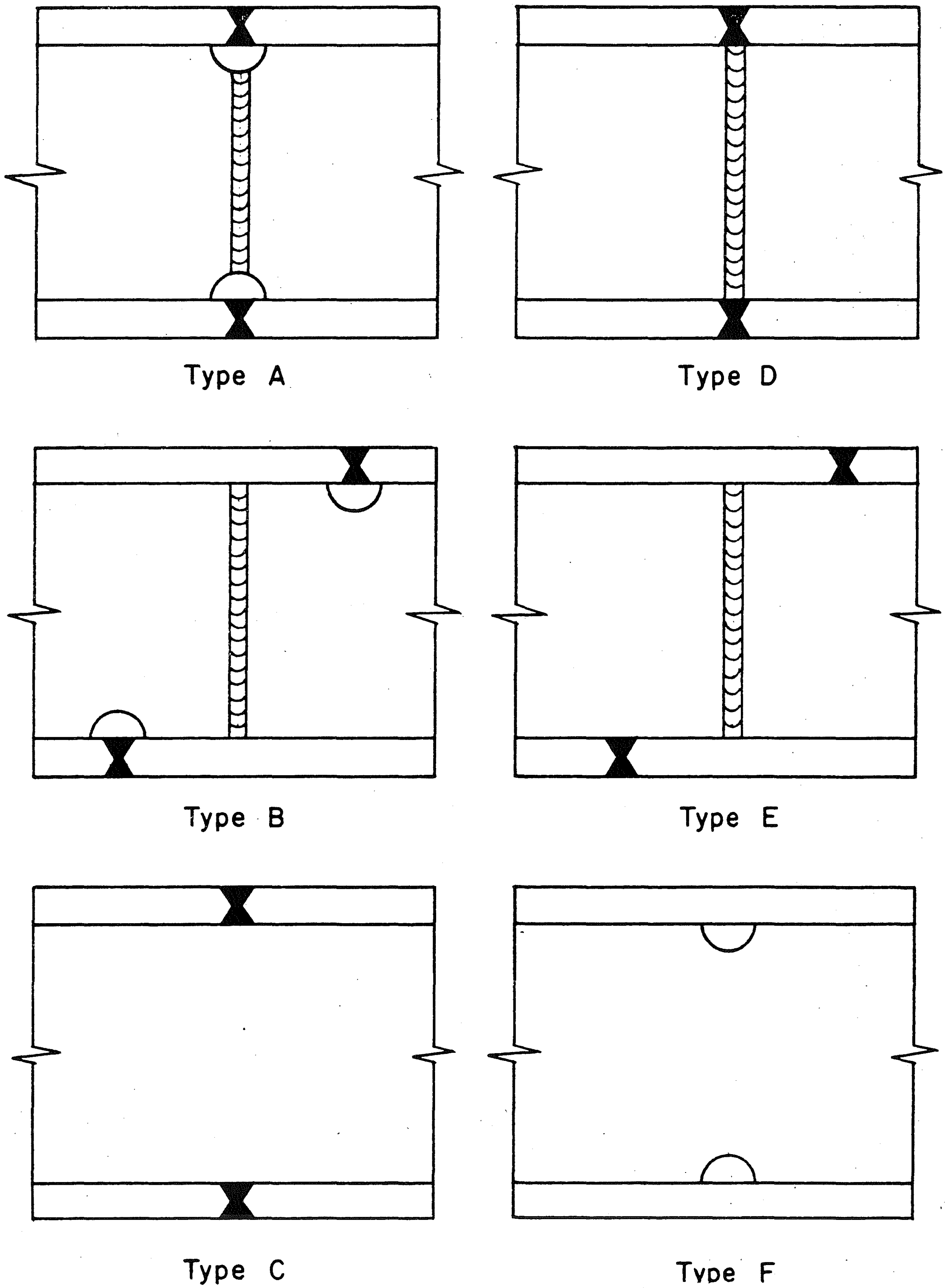
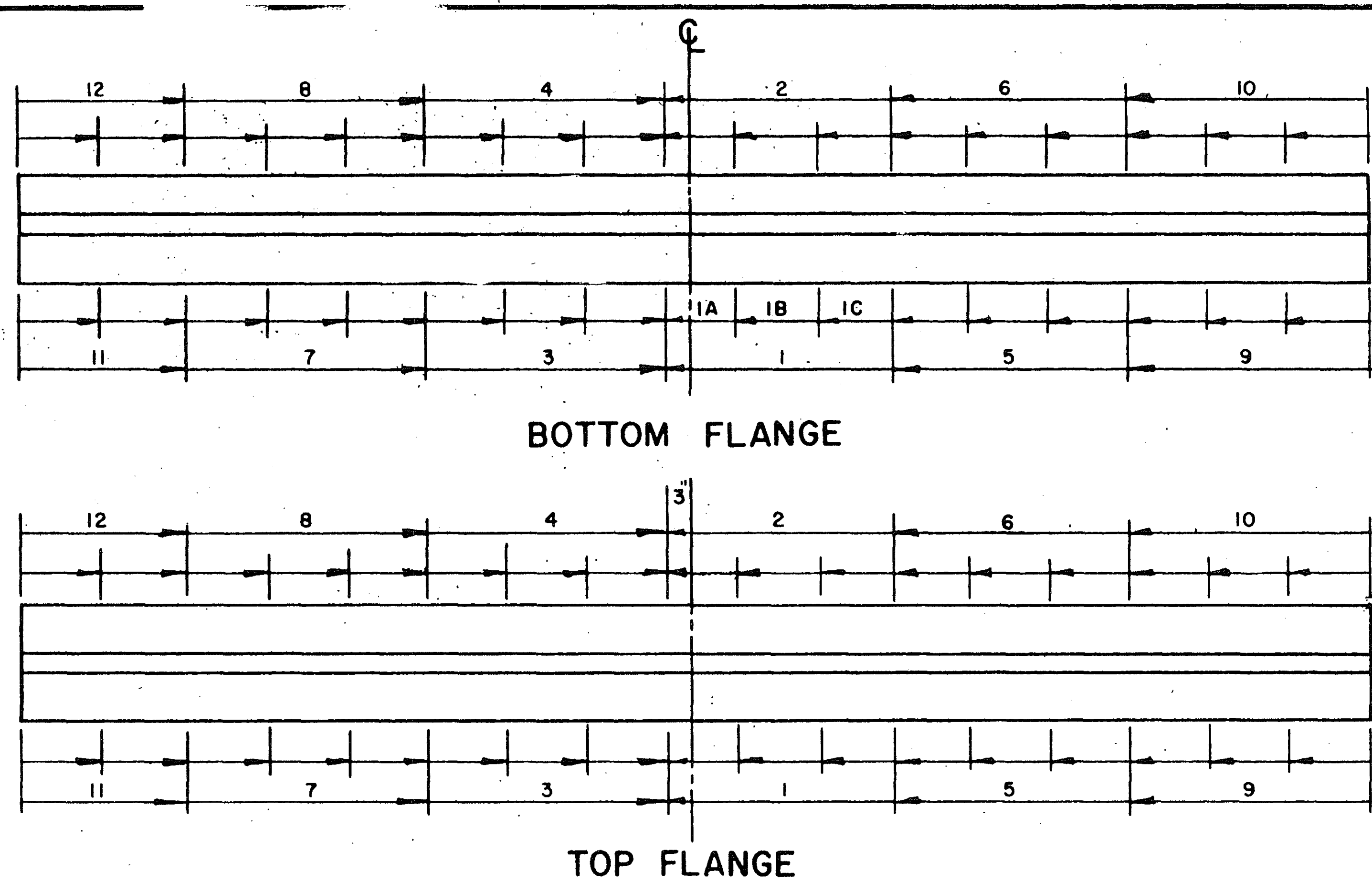


FIG. 7 SPLICE TYPES



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. 8 PRINCIPAL FILLET WELDING SEQUENCE

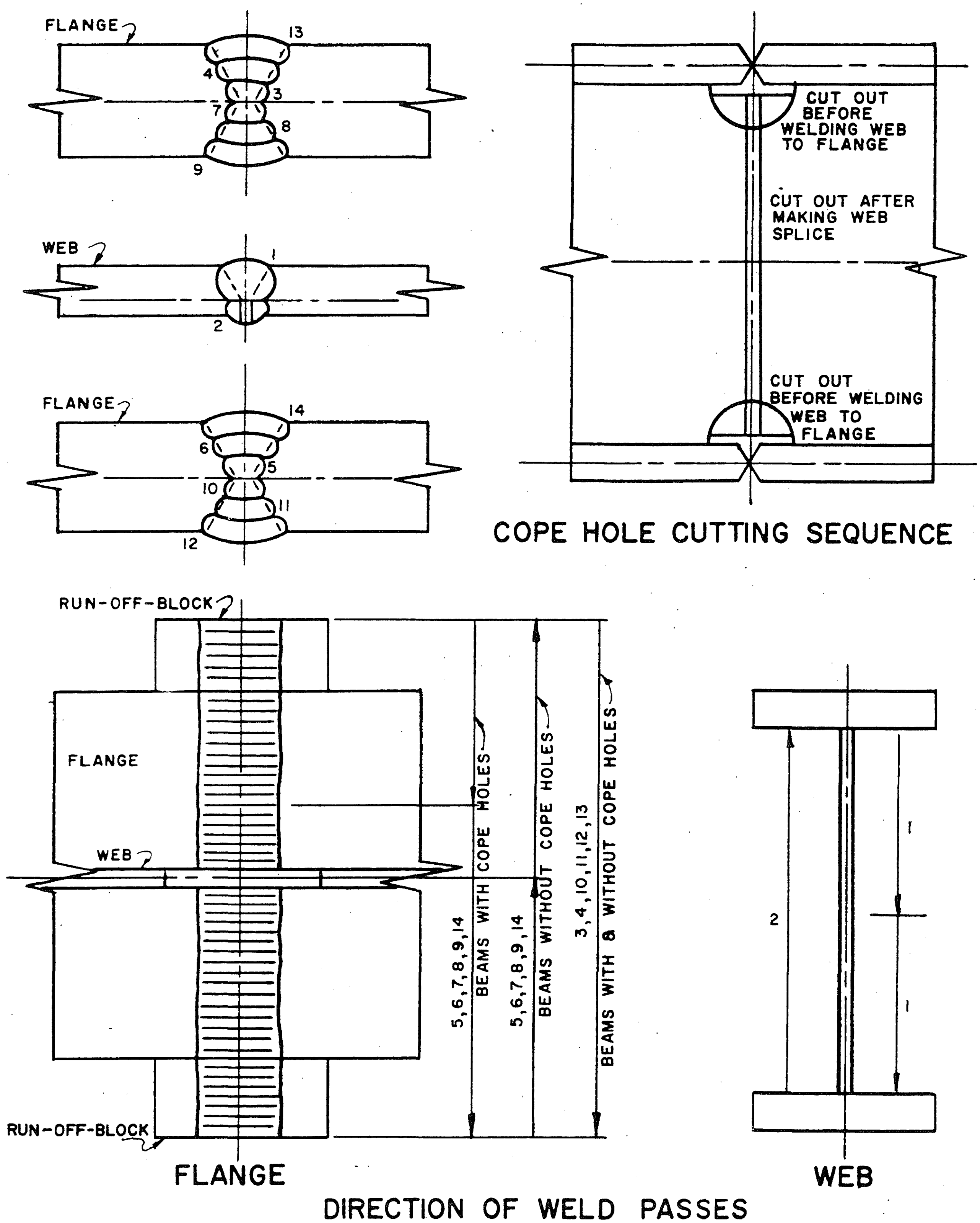


FIG. 9 PRINCIPAL WELDING SEQUENCE FOR BUTT SPLICES

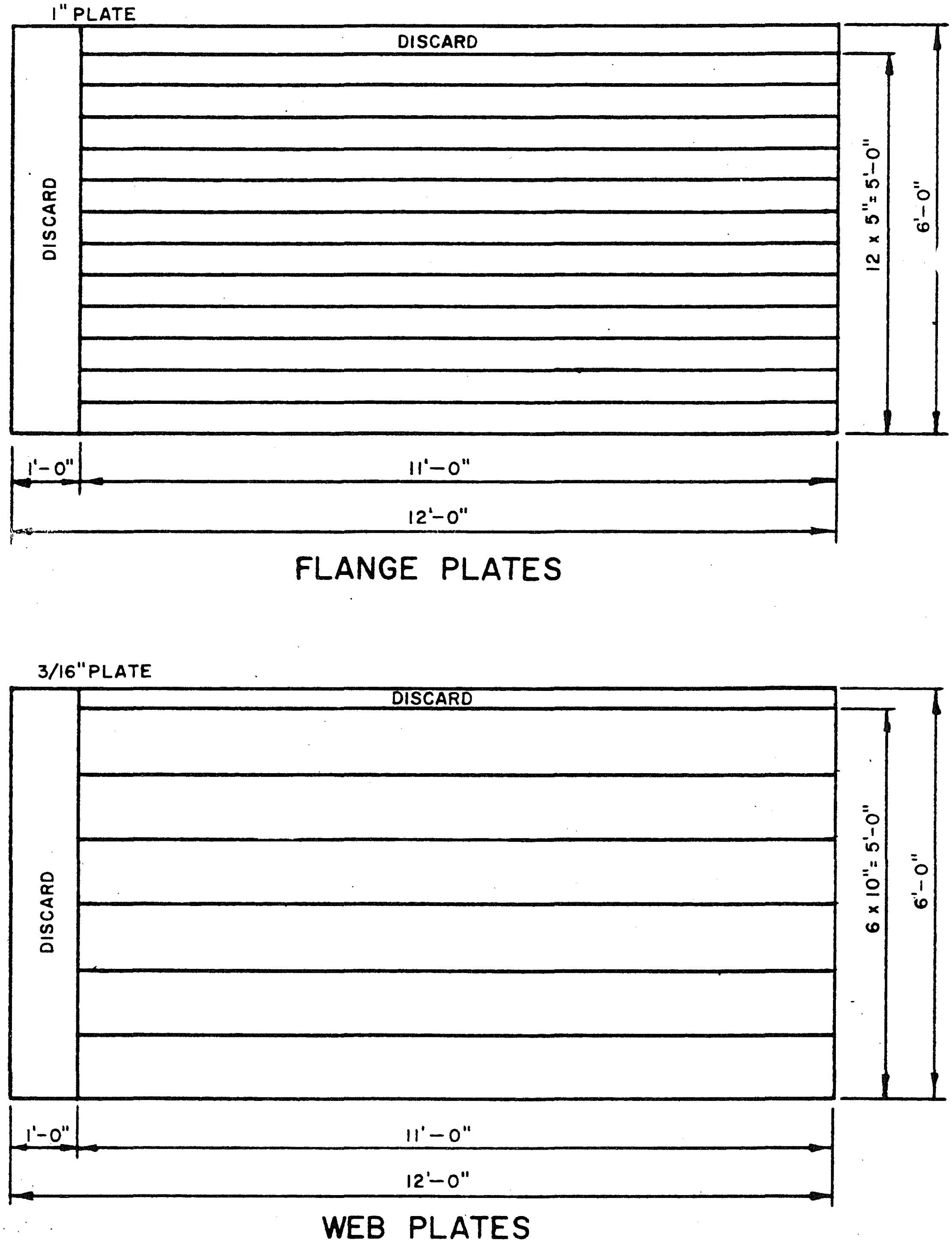
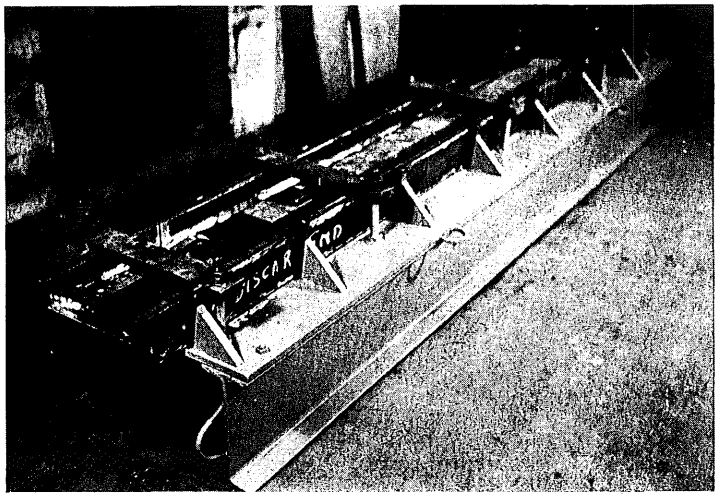
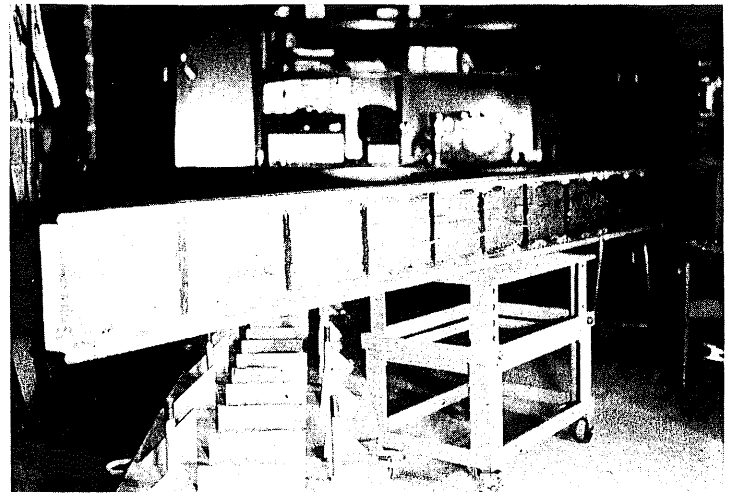


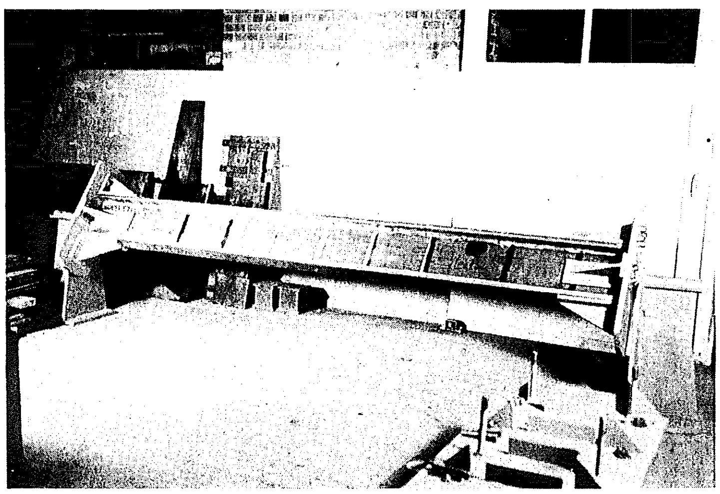
FIG. 10 PARENT PLATE LAYOUTS FOR ASTM A373 STEEL



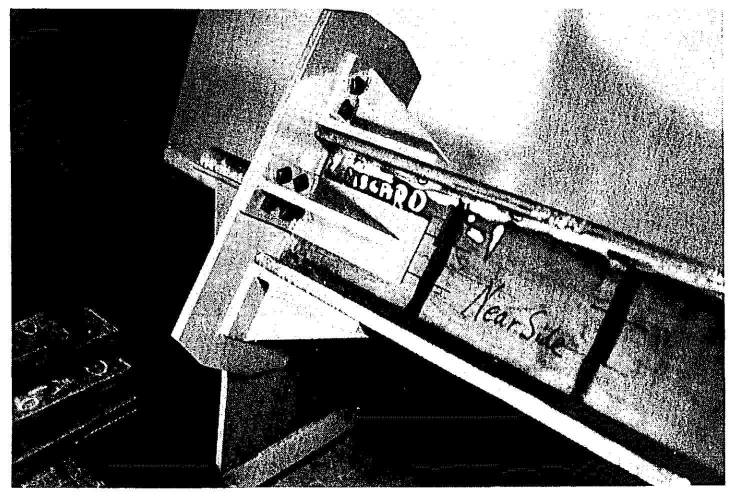
a. SPECIMEN IN TACKING JIG



b. SPECIMEN AFTER TACKING



c. SPECIMEN IN WELDING STANDS FOR DEPOSITION OF FILLET WELDS



d. CLOSE-UP OF WELDING STAND

FIG. 11 FABRICATION OF TYPICAL SPECIMEN

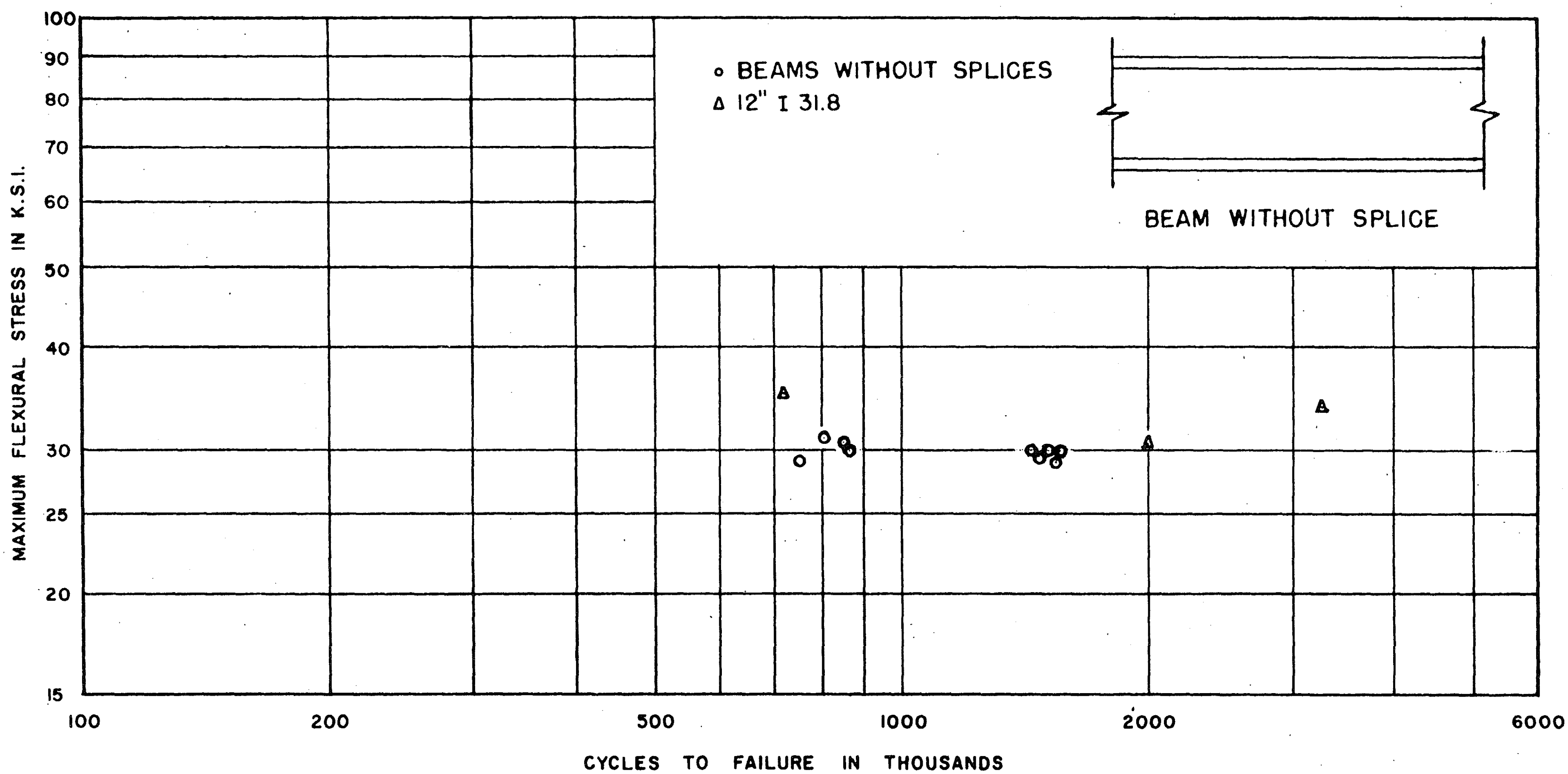
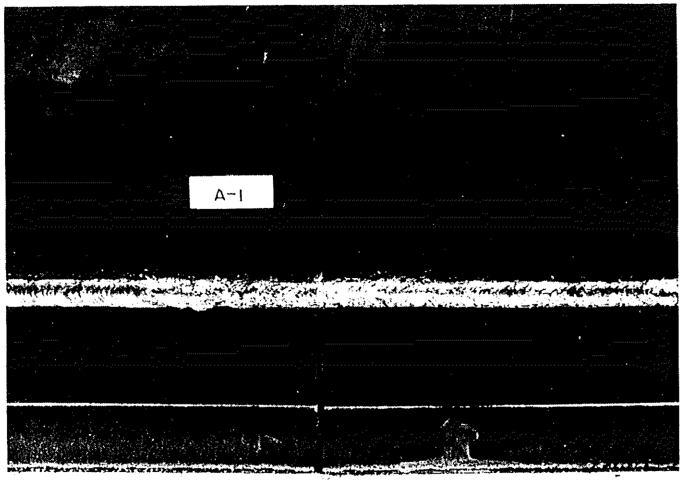
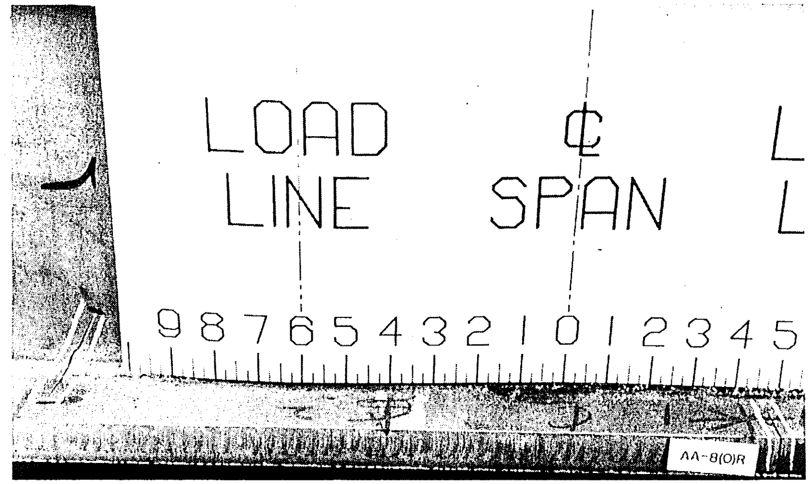


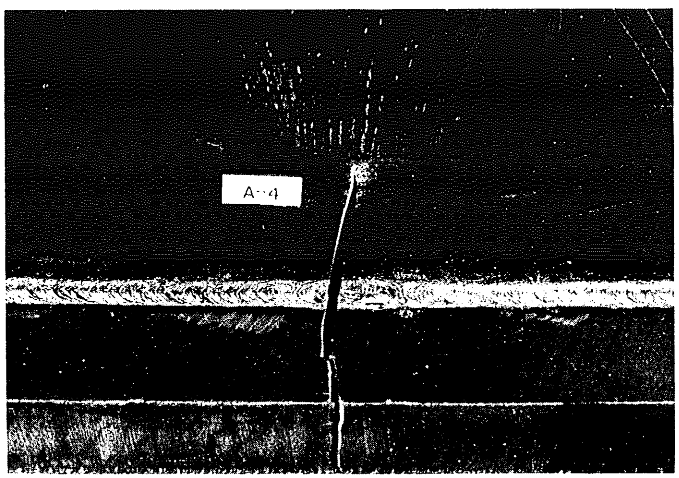
FIG. 12 S-N DIAGRAM FOR BEAMS WITHOUT SPLICES



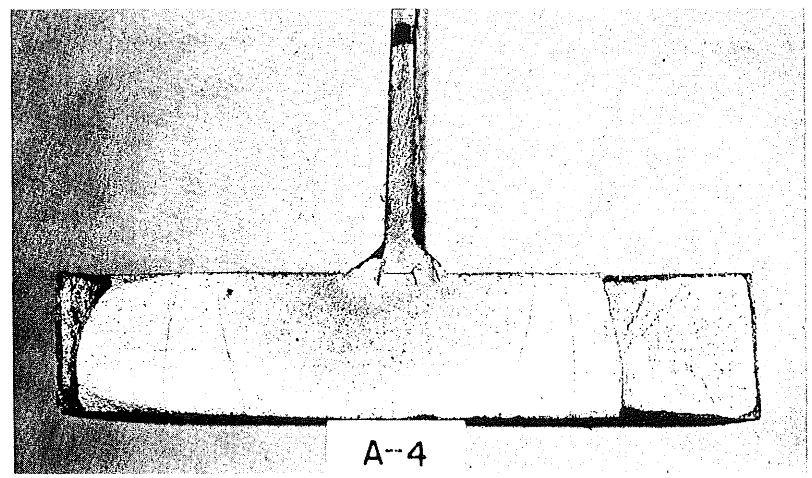
a. SPECIMEN AA-1(O): FAILURE AT EDGE OF TENSION FLANGE



b. SPECIMEN AA-8(O)R: FAILURE AT CHANGE OF ELECTRODE AND AT EDGE OF TENSION FLANGE

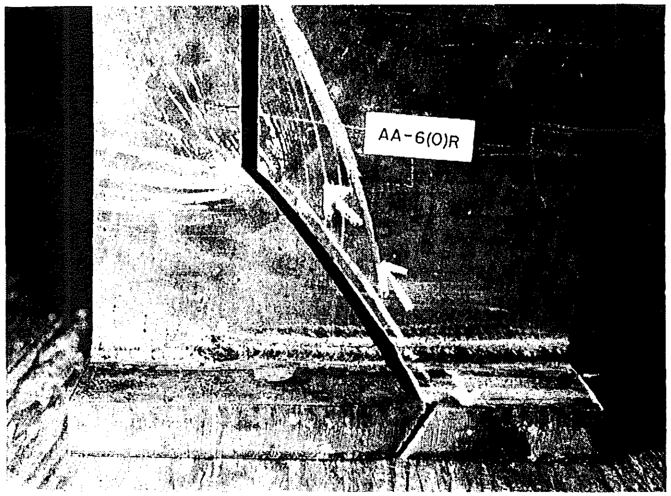


c. SPECIMEN AA-4(O): FAILURE AT CHANGE OF ELECTRODE

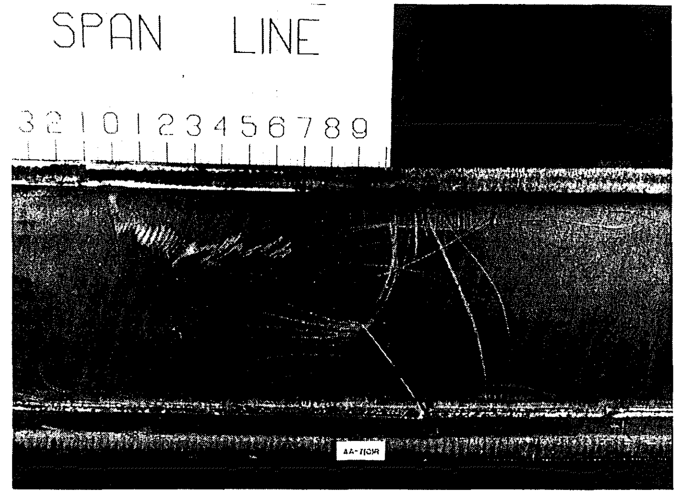


d. SPECIMEN AA-4(O): FRACTURED SURFACE

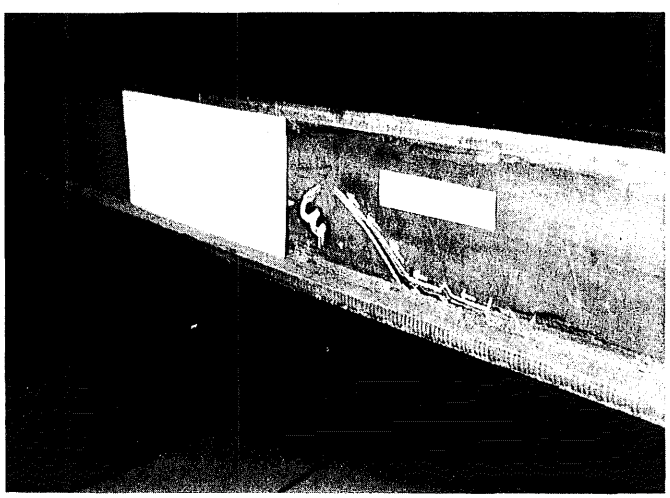
FIG. 13 TYPICAL FATIGUE FRACTURES OF SPECIMENS WITHOUT SPLICES



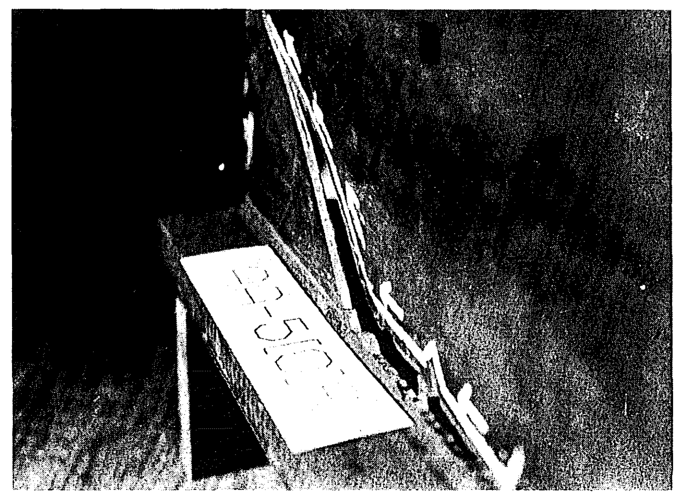
a. SPECIMEN AA-6(O)R: FAILURE IN FILLET WELD



b. SPECIMEN AA-7(O)R: FAILURE AT WELD CRATER



c. SPECIMEN AA-5(O)R: FAILURE IN WEB



d. SPECIMEN AA-5(O)R: CLOSE-UP OF WEB FAILURE

FIG. 14 TYPICAL FATIGUE FRACTURES OF SPECIMENS WITHOUT SPLICES

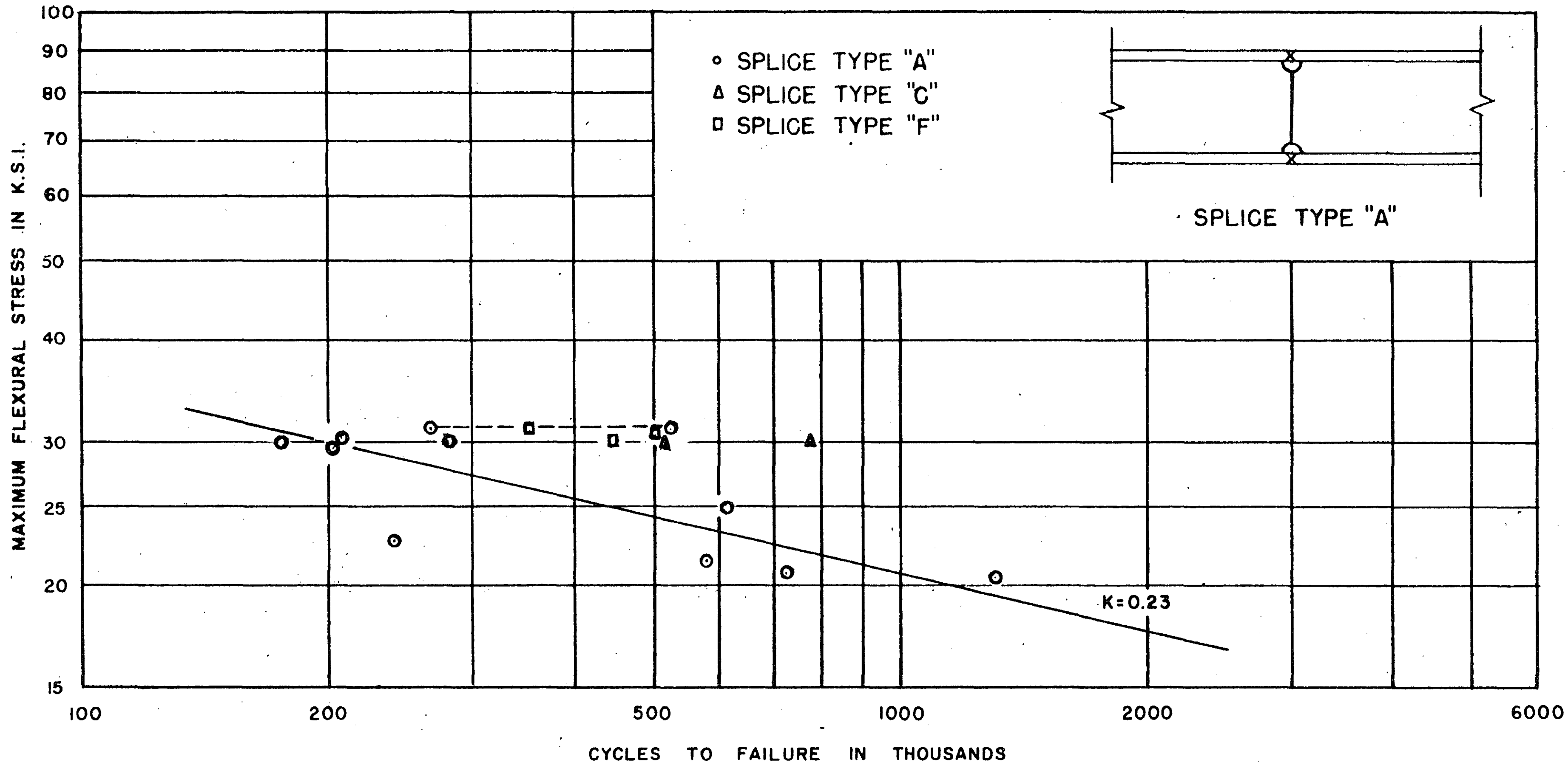
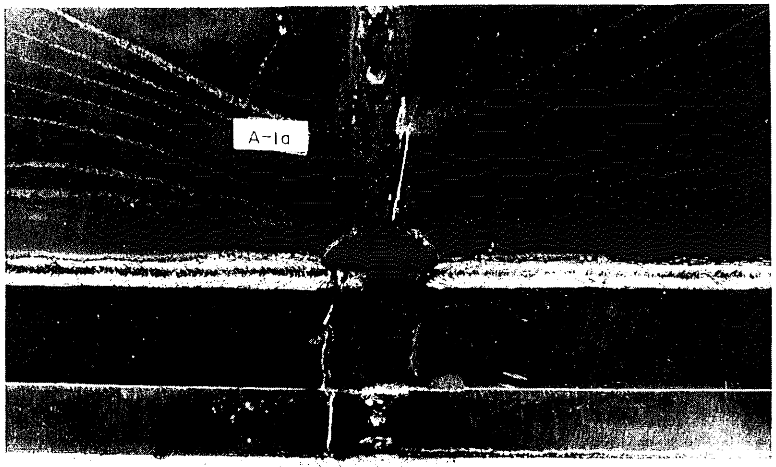
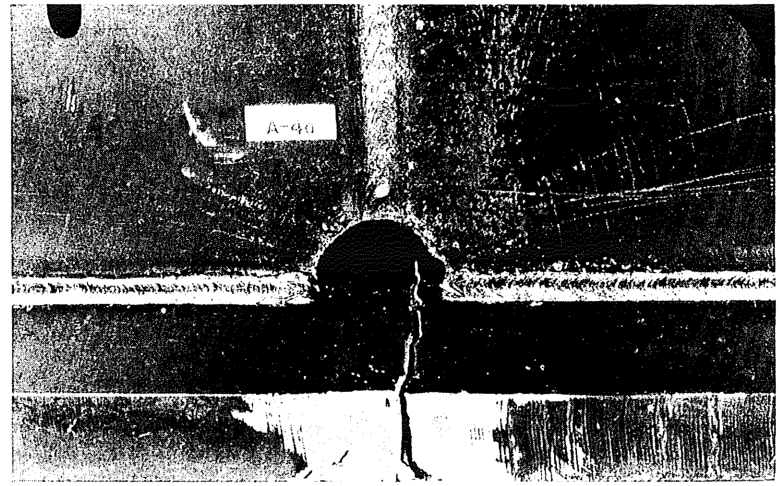


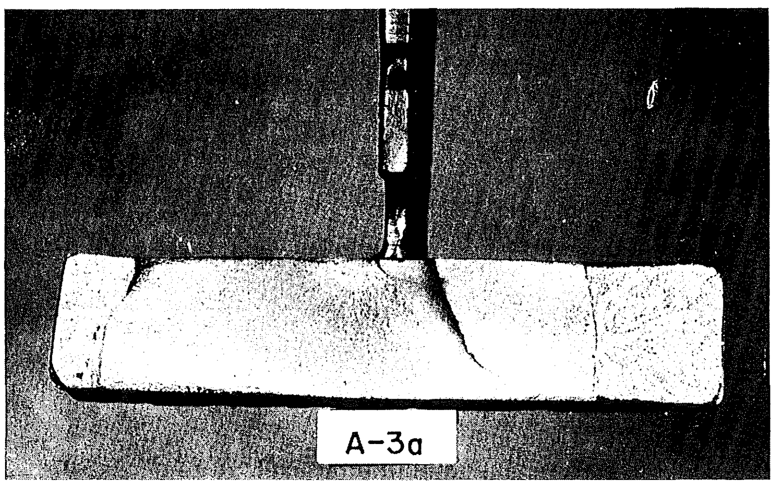
FIG. 15 S-N DIAGRAM FOR SPLICE TYPE "A"



a. SPECIMEN A-1(AA-1): FAILURE AT TOE OF FILLET WELD



b. SPECIMEN A-4(AA-4)R: FAILURE AT TOE OF BUTT WELD



c. SPECIMEN A-3(AA-3): FRACTURED SURFACE

d. SPECIMEN A-9(E-8)R: FAILURE IN BUTT WELD METAL

FIG. 16 TYPICAL FATIGUE FRACTURES OF SPLICE TYPE "A"

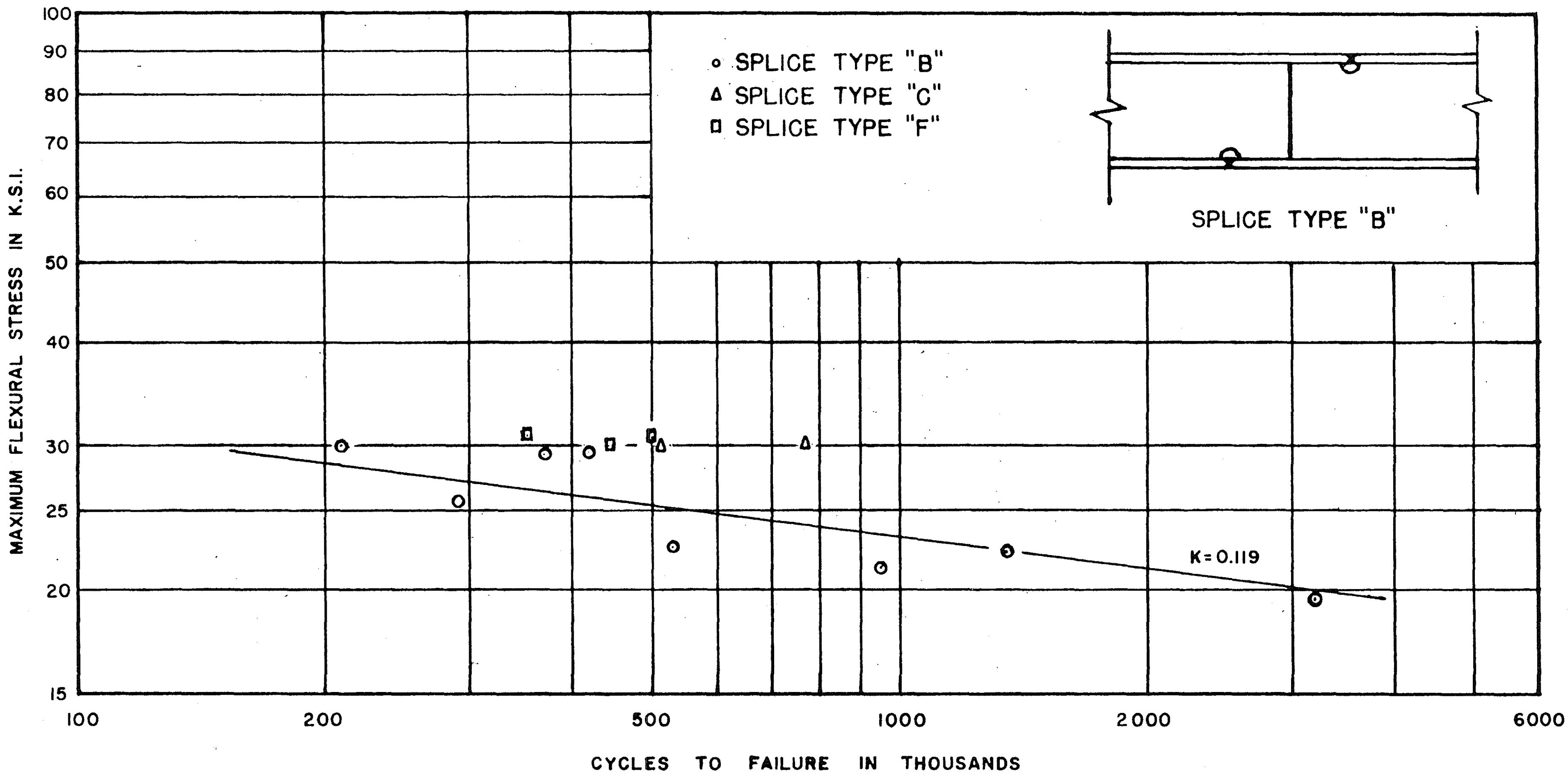
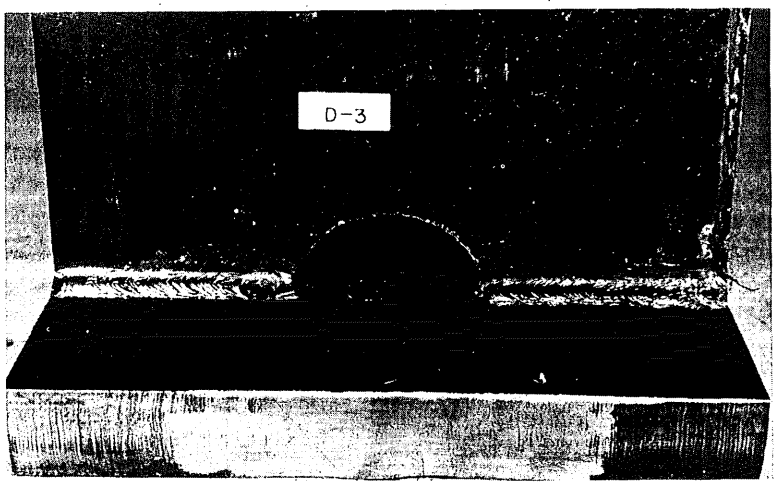
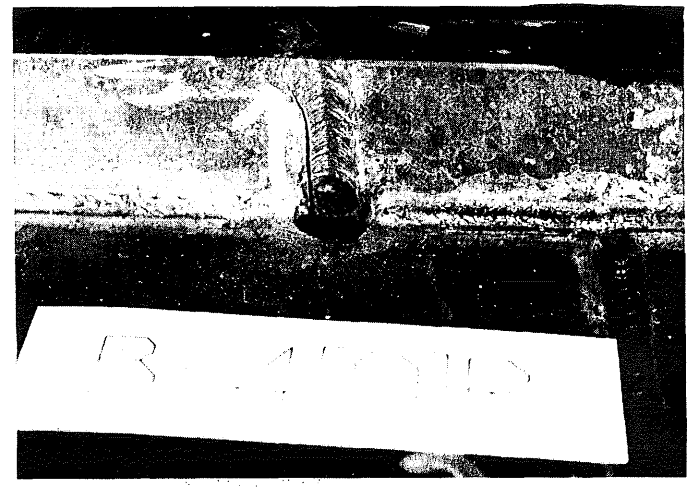


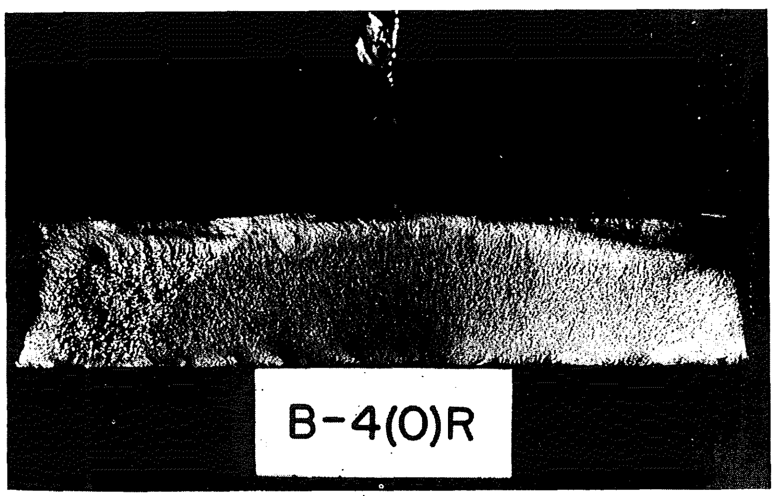
FIG. 17 S-N DIAGRAM FOR SPLICE TYPE "B"



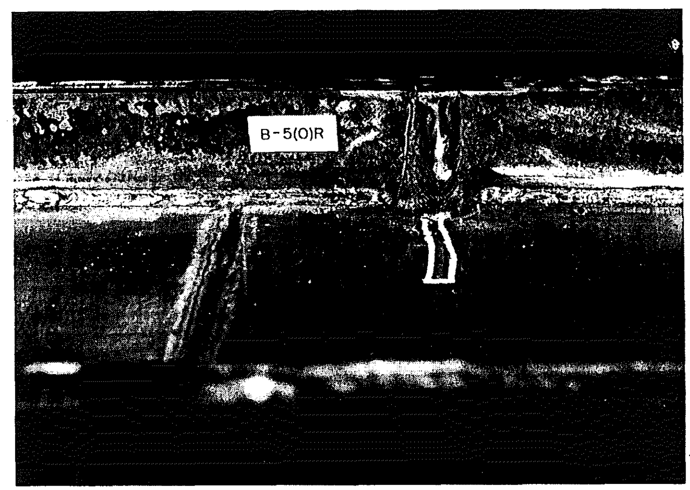
a. SPECIMEN B-3(O)R: FAILURE AT TOE OF FILLET WELD



b. SPECIMEN B-4(O)R: FAILURE IN BUTT WELD



c. SPECIMEN B-4(O)R: FRACTURED SURFACE



d. SPECIMEN B-5(O)R: FAILURE IN BASE METAL

FIG. 18 TYPICAL FATIGUE FRACTURES OF SPLICE TYPE "B"

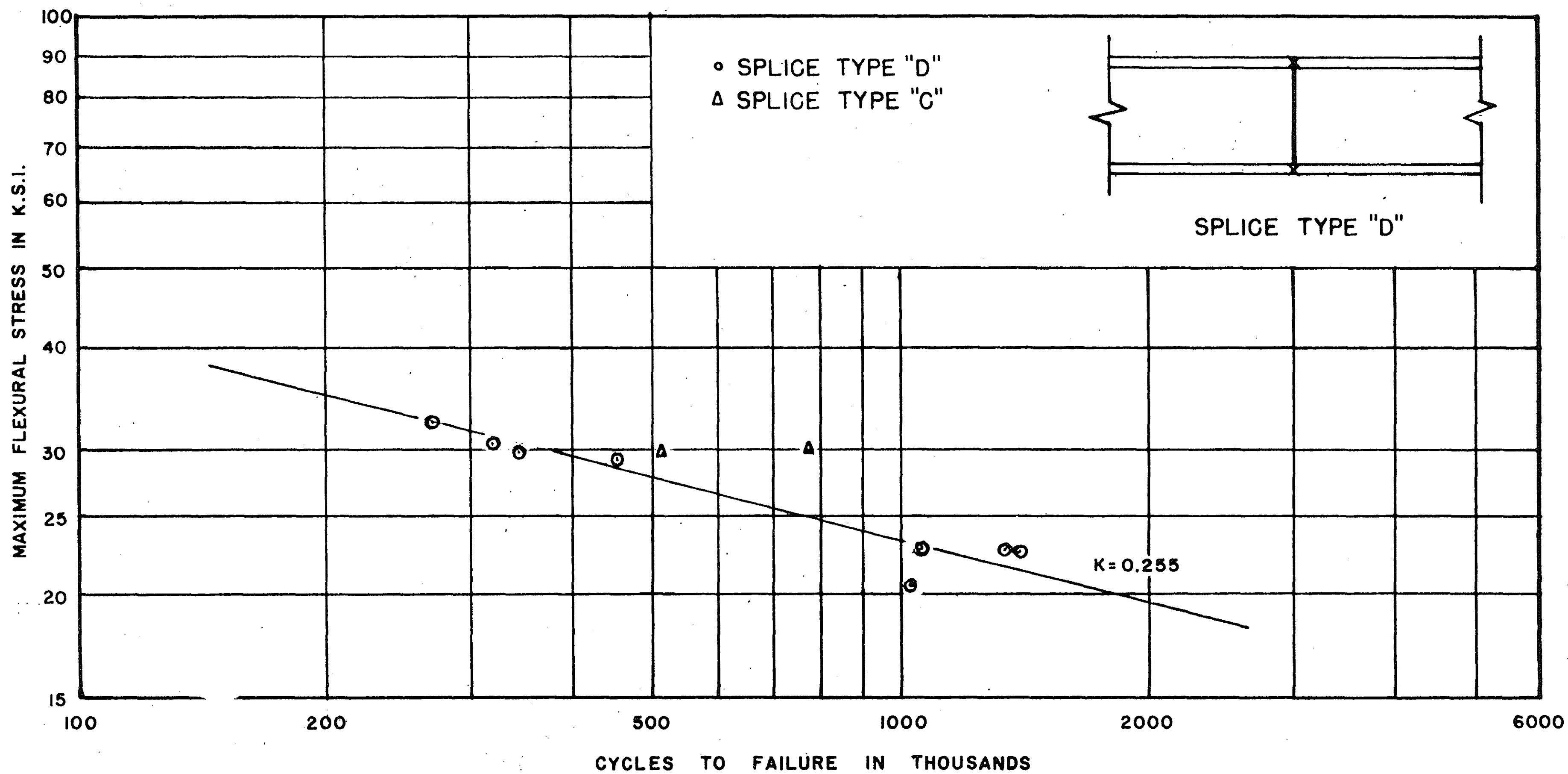
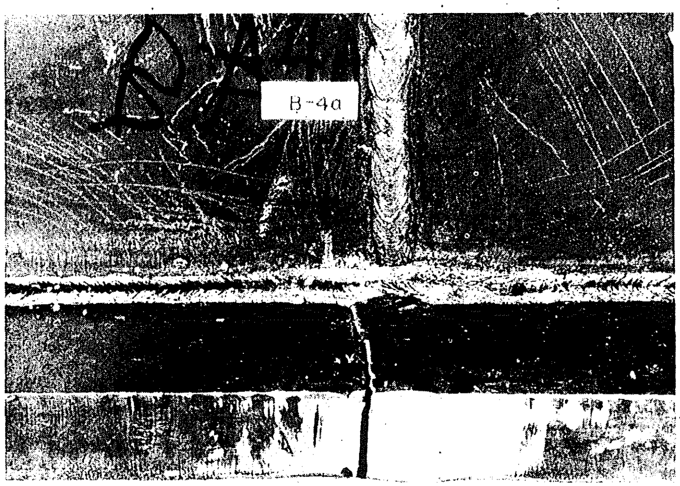
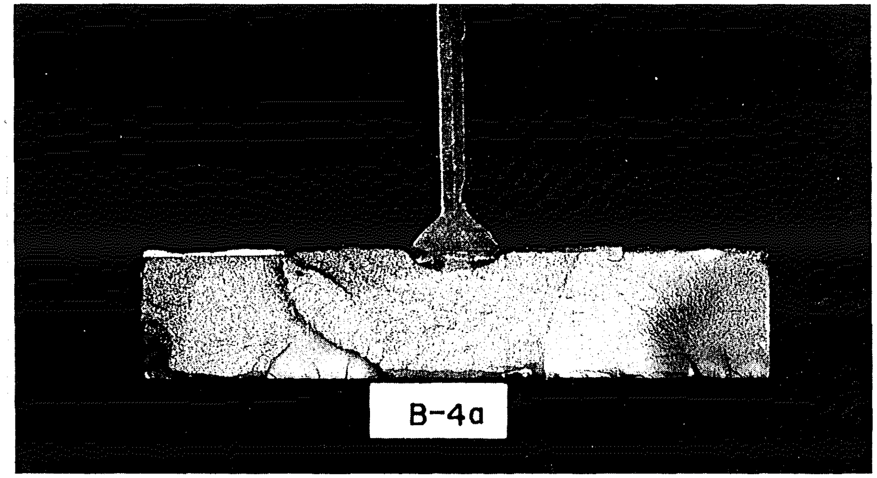


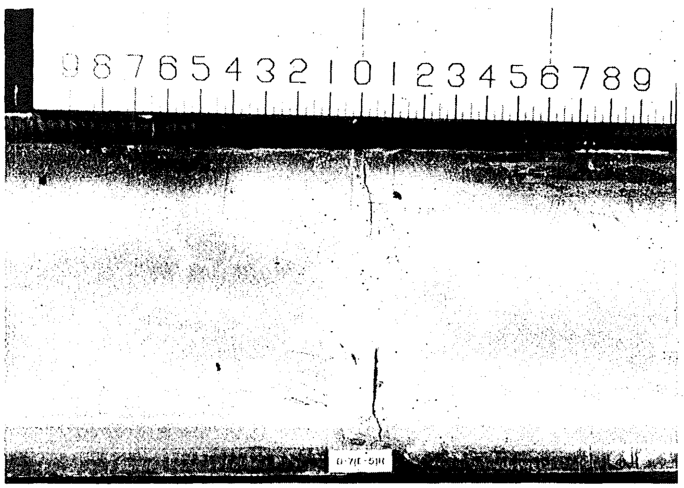
FIG. 19 S-N DIAGRAM FOR SPLICE TYPE "D"



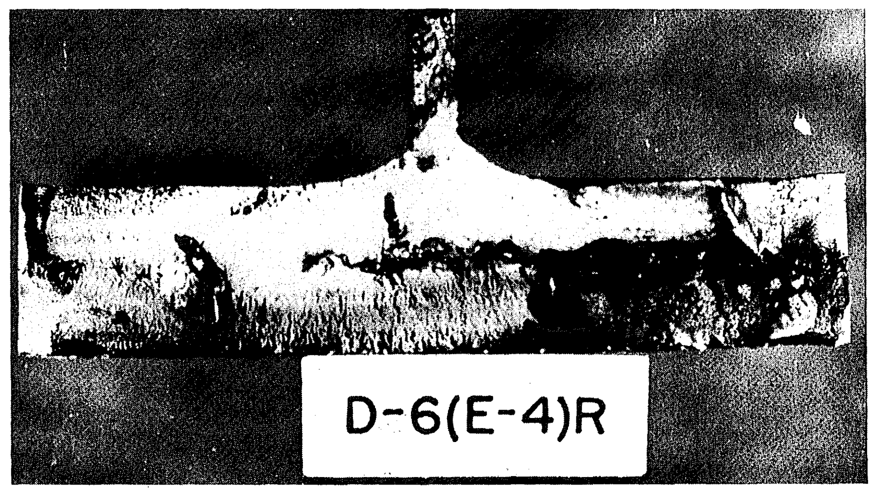
a. SPECIMEN D-4(F-2)R: FAILURE AT TOE OF BUTT WELD



b. SPECIMEN D-4(F-2)R: FRACTURED SURFACE



c. SPECIMEN D-7(E-5)R: FAILURE IN TENSION FLANGE AND COMPRESSION BUTT SPLICE



d. SPECIMEN D-6(E-4)R: FRACTURED SURFACE OF COMPRESSION FLANGE

FIG. 20 TYPICAL FATIGUE FRACTURES OF SPLICE TYPE "D"

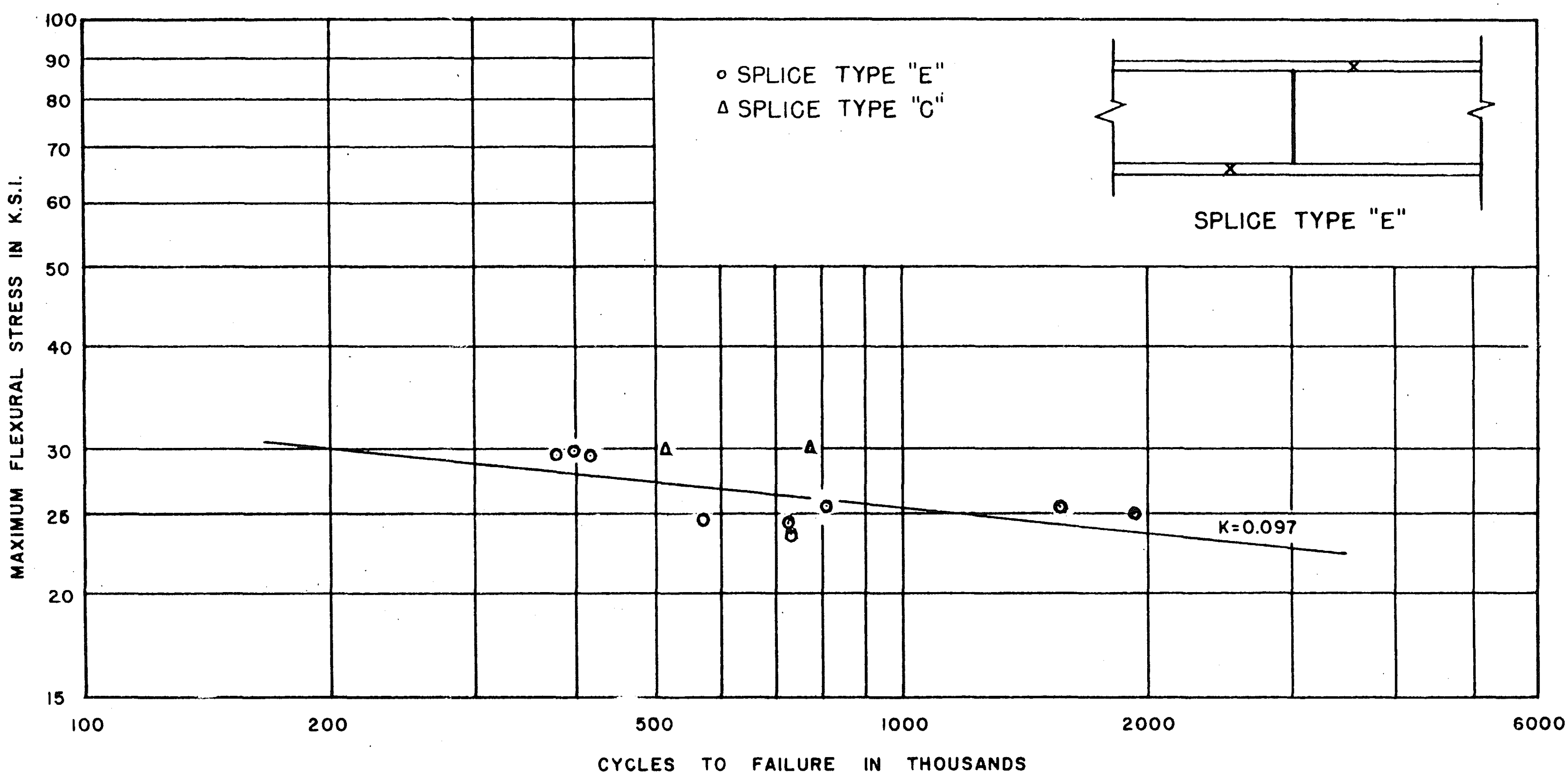
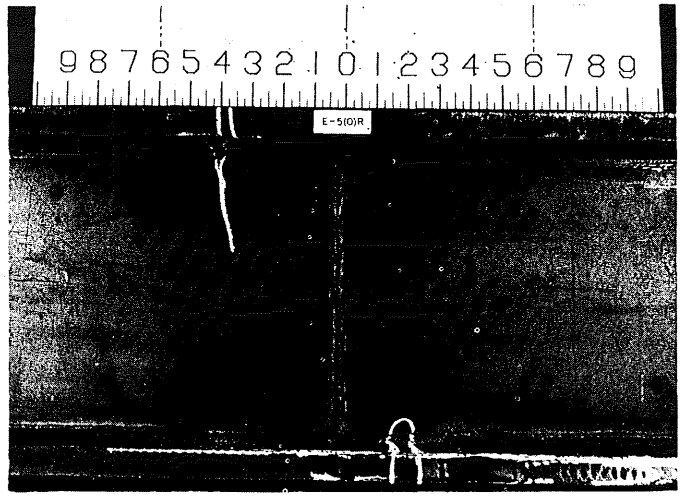
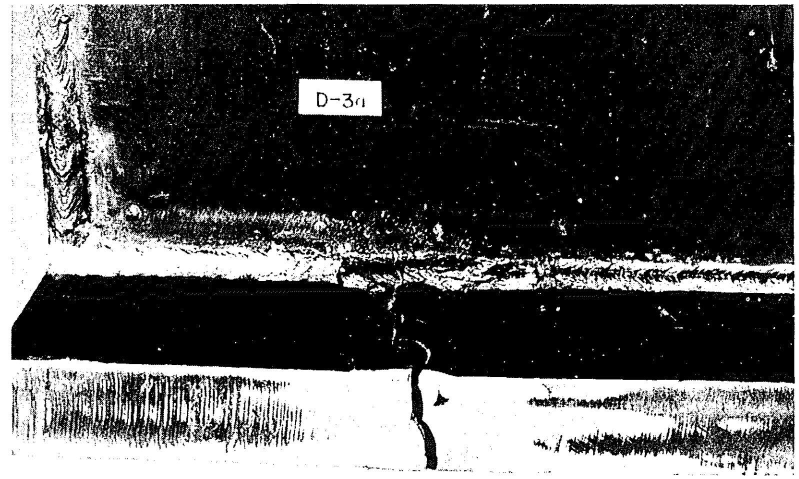


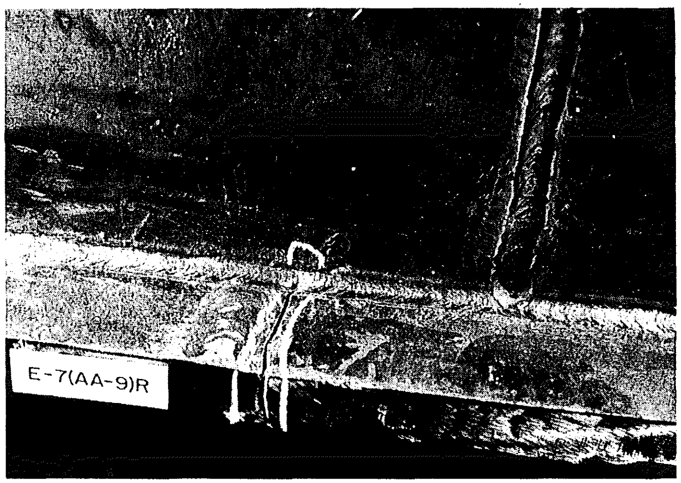
FIG. 21 S-N DIAGRAM FOR SPLICE TYPE "E"



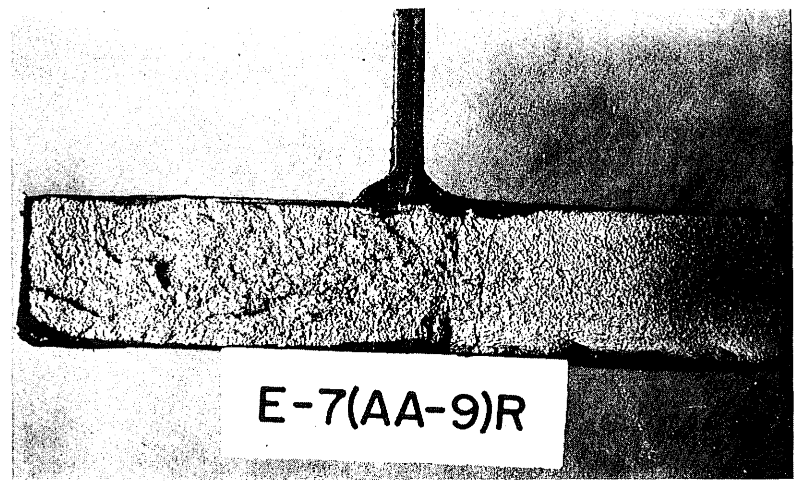
a. SPECIMEN E-5(O)R: FAILURE IN TENSION FLANGE AND COMPRESSION BUTT SPLICE



b. SPECIMEN E-3(B-3)R: FAILURE IN WELD METAL OF TENSION BUTT SPLICE

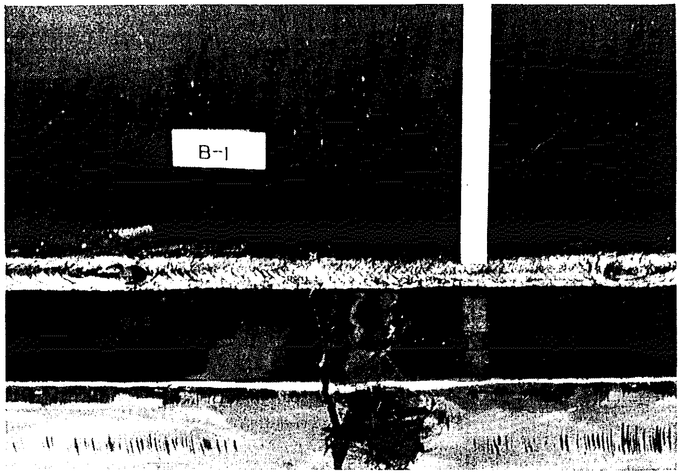


c. SPECIMEN E-7(AA-9)R: FAILURE IN BASE METAL OF TENSION FLANGE

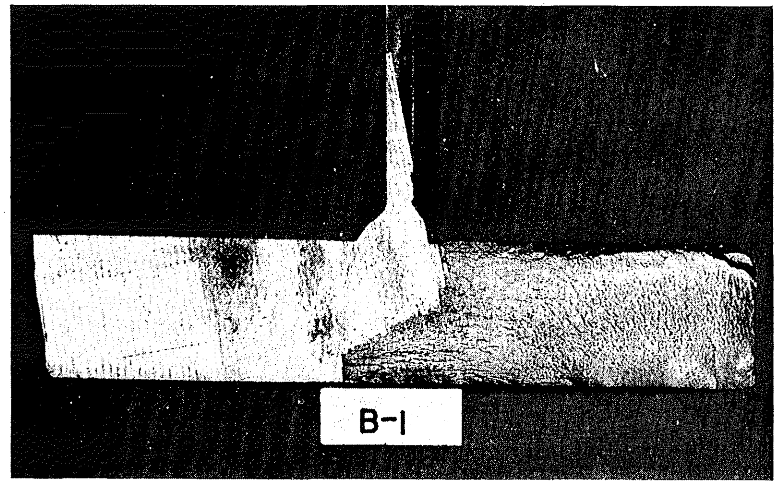


d. SPECIMEN E-7(AA-9)R: FRACTURED SURFACE

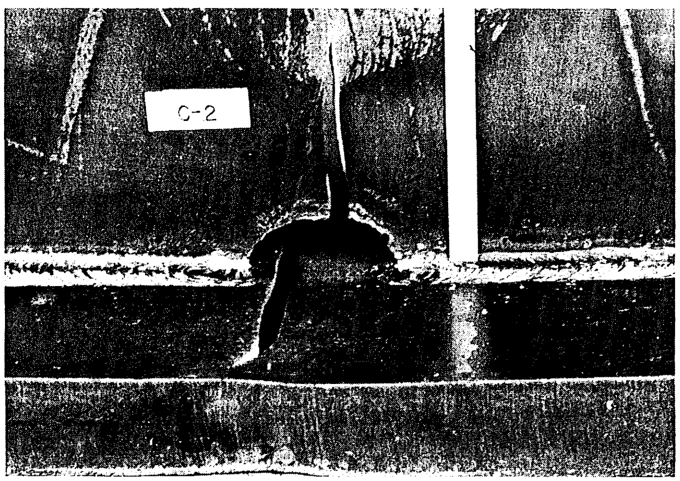
FIG. 22 TYPICAL FATIGUE FRACTURES OF SPLICE TYPE "E"



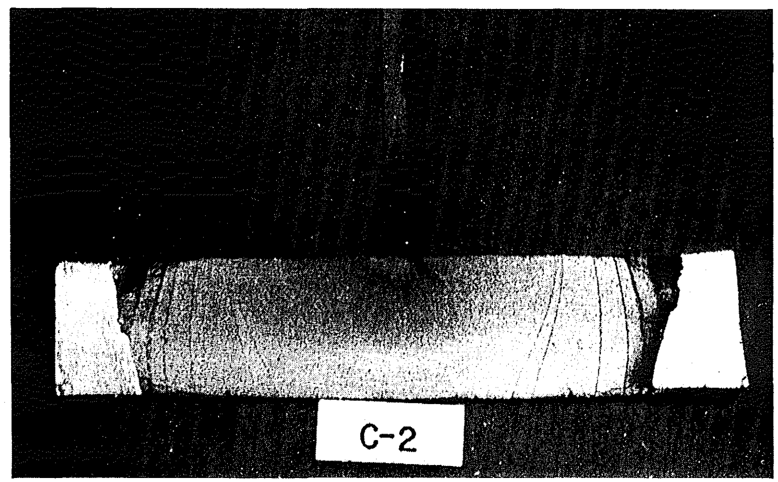
a. SPECIMEN C-1(O) : FAILURE AT TOE OF BUTT WELD



b. SPECIMEN C-1(O) : FRACTURED SURFACE



c. SPECIMEN F-2(O)R : FAILURE AT TOE OF FILLET WELD



d. SPECIMEN F-2(O)R : FRACTURED SURFACE

FIG. 23 TYPICAL FATIGUE FRACTURES OF SPLICE TYPES "C" & "F"

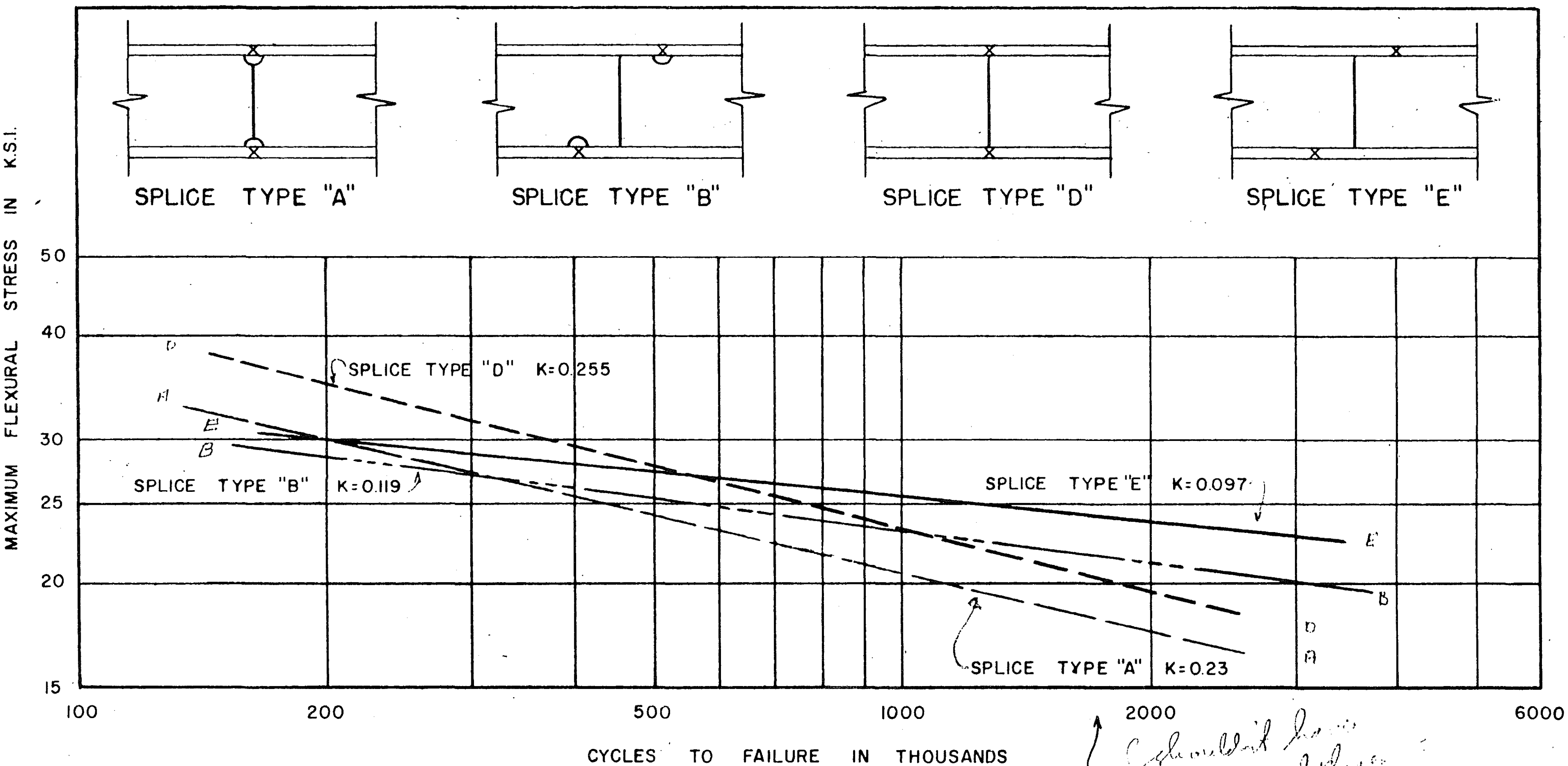


FIG. 24 COMPARISON OF FATIGUE TEST RESULTS

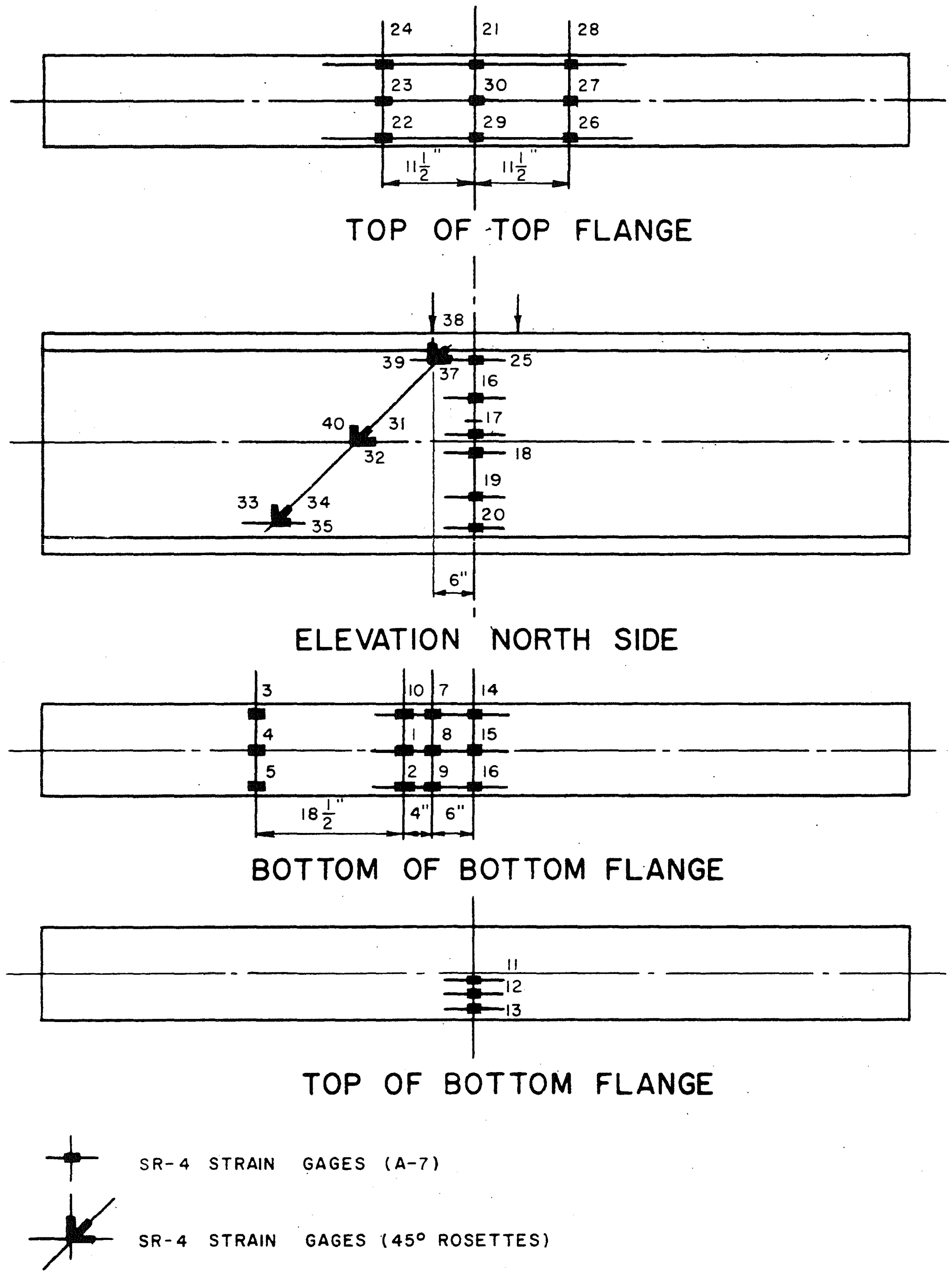


FIG. 25 LOCATION DIAGRAM FOR STRAIN GAGES

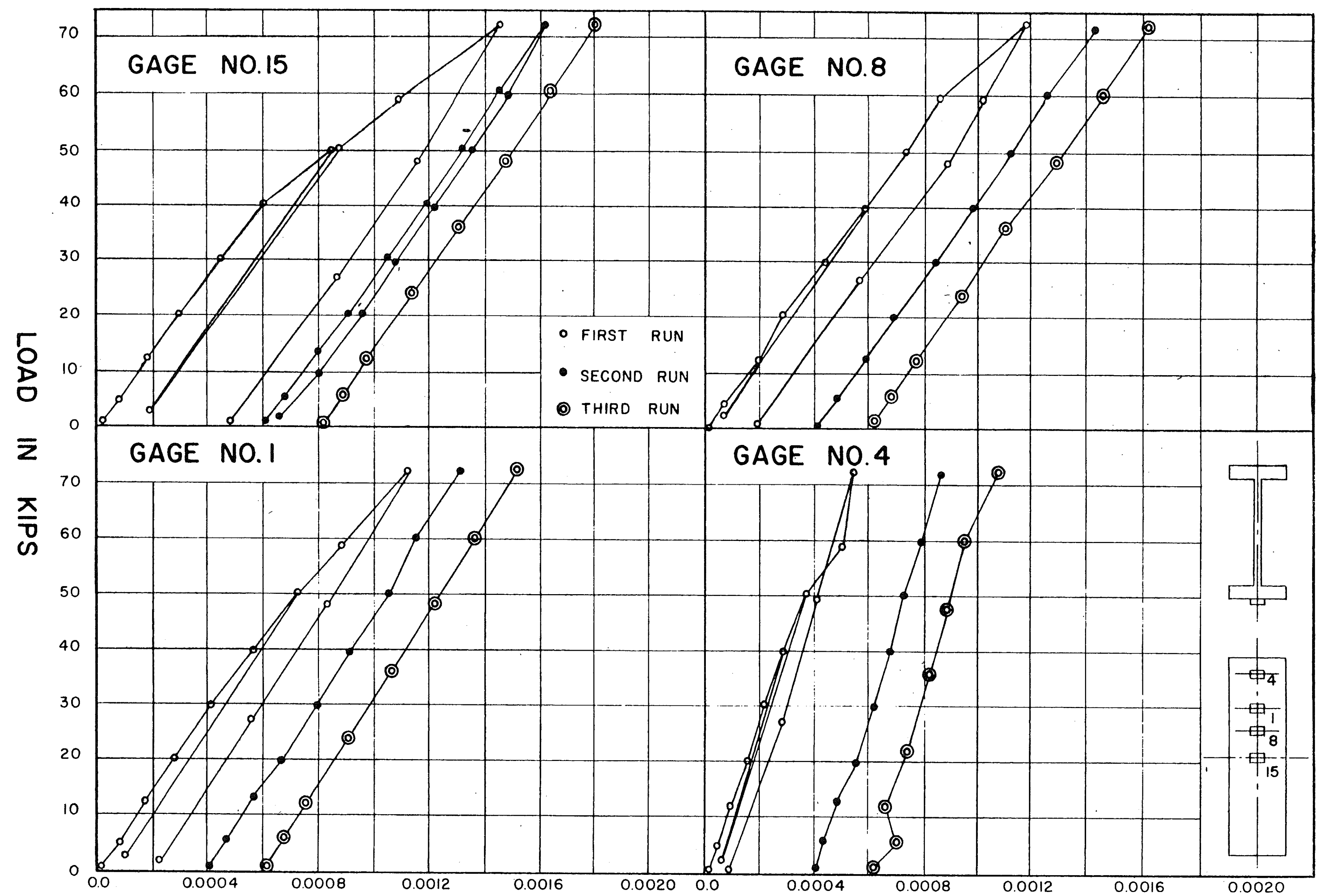


FIG. 26 LONGITUDINAL LOAD STRAIN RELATIONS EXTREME FIBER TENSION FLANGE

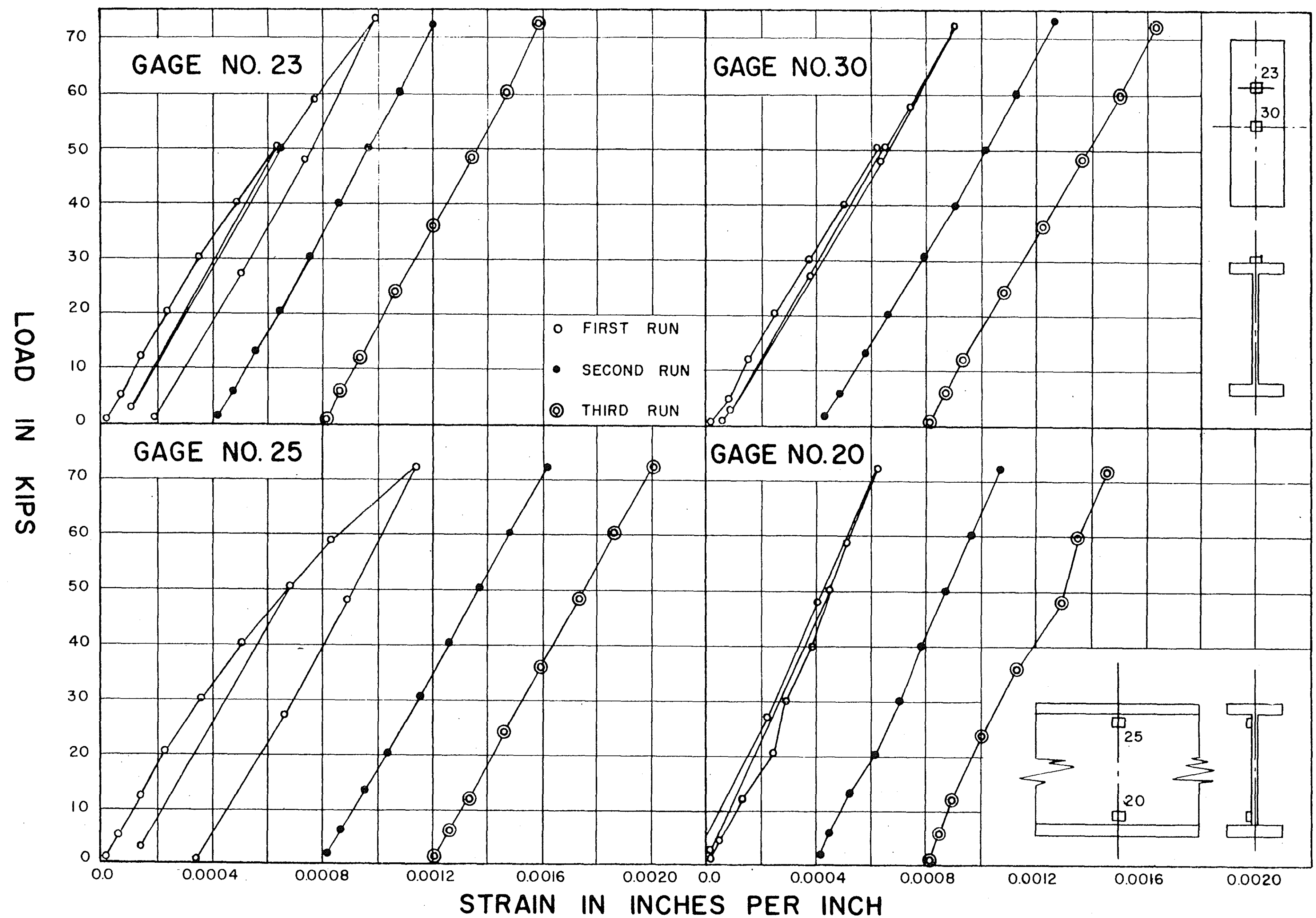


FIG. 27 LONGITUDINAL LOAD STRAIN RELATIONS EXTREME FIBER COMP. FL. & WEB

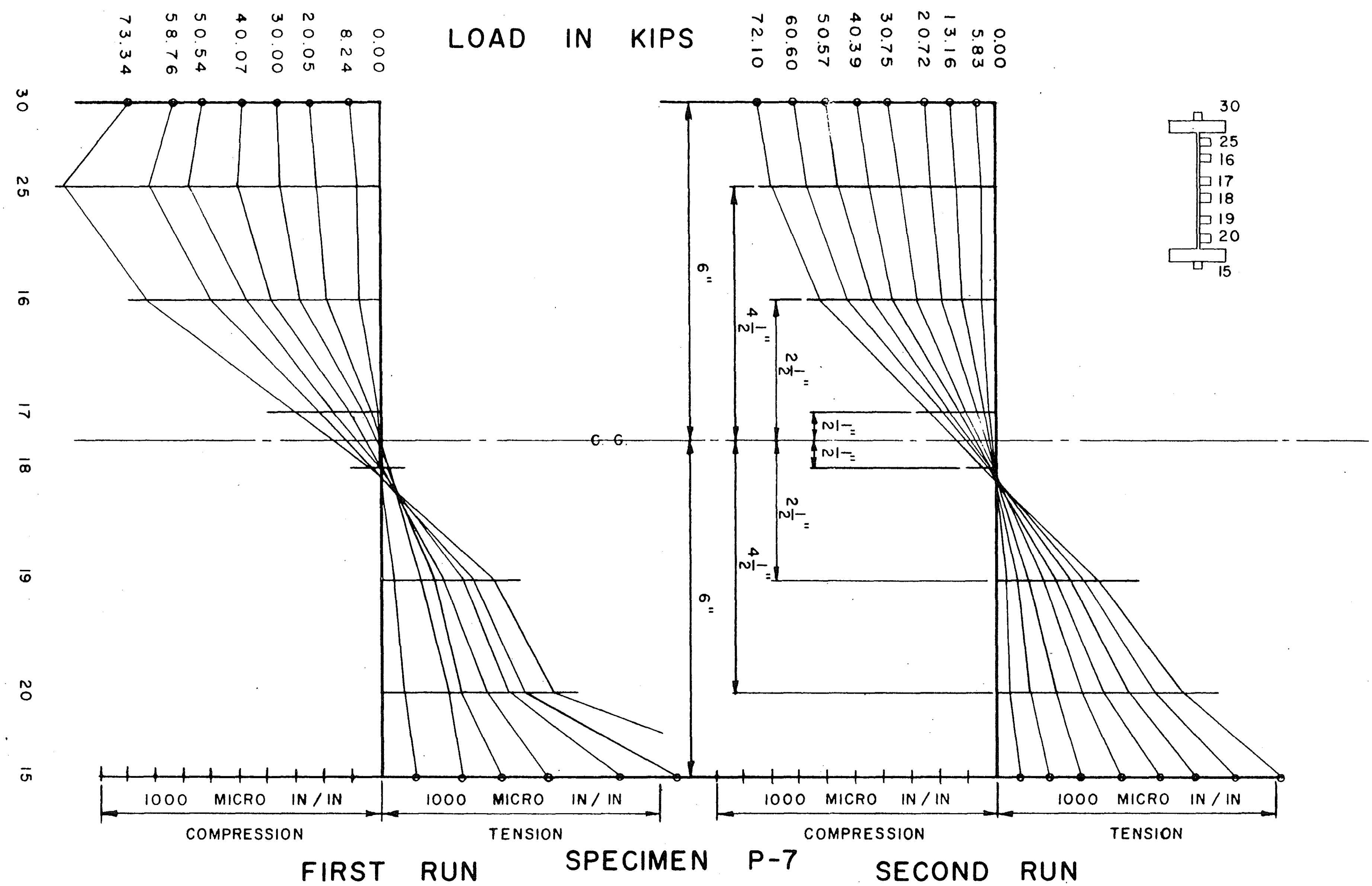


FIG. 28 STRAIN DISTRIBUTION ACROSS SECTION AT CENTER LINE

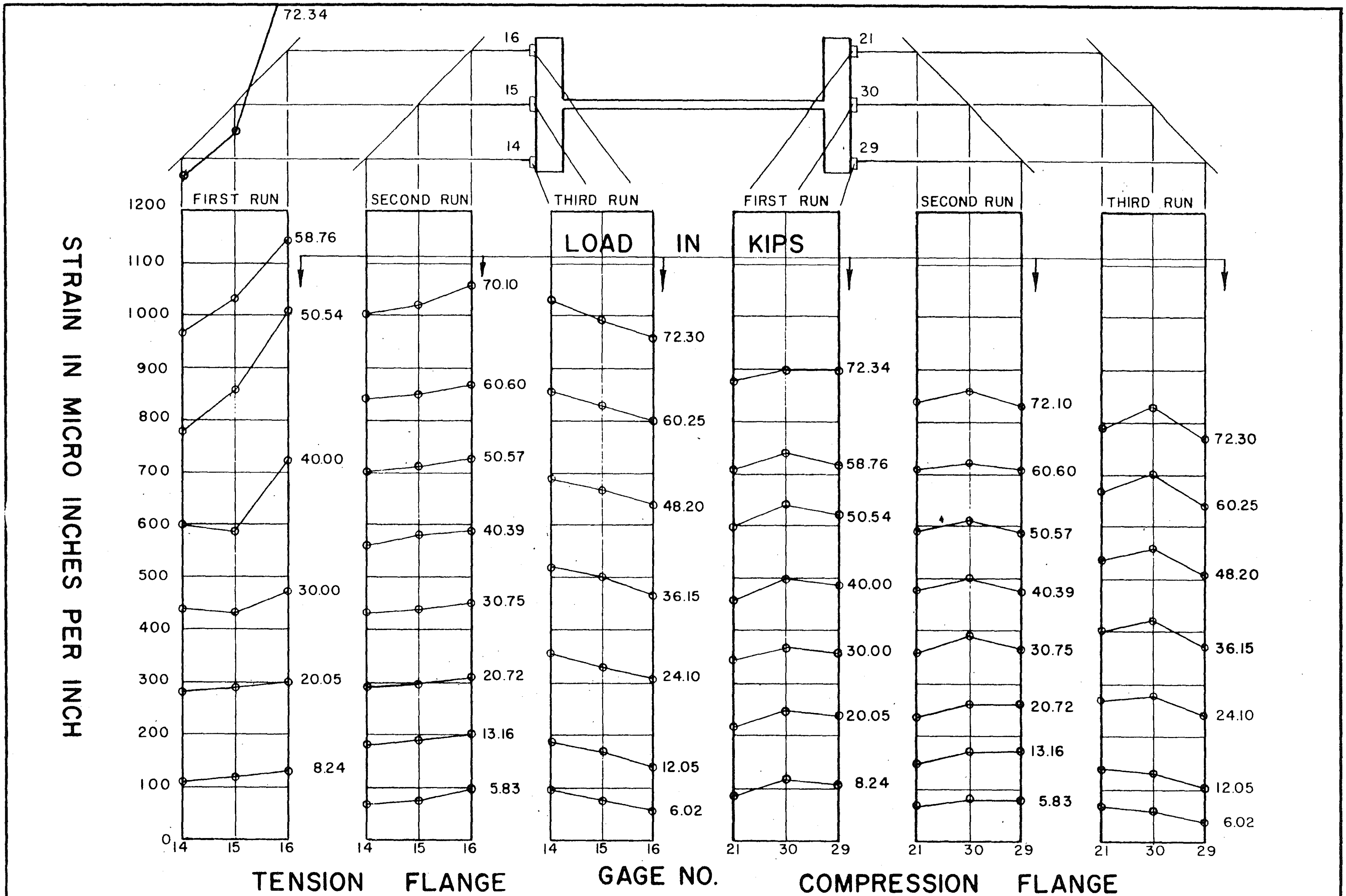


FIG.29 TRANSVERSE STRAIN DISTRIBUTION ACROSS FLANGE AT ℄