CIVIL ENGINEERING STUDIES
STRUCTURAL RESEARCH SERIES NO. 329

EFFECT OF REPEATED LOADS ON THE LOW TEMPERATURE FRACTURE BEHAVIOR OF NOTCHED AND WELDED PLATES

by
W. H. MUNSE
J. P. CANNON
and
J. F. KIEFNER

FINAL REPORT
BUREAU OF SHIPS - DEPARTMENT OF THE NAVY
CONTRACT NOBS 88283
PROJECT SR - 149
SHIP STRUCTURE COMMITTEE

UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS
1 NOVEMBER 1967

EFFECT OF REPEATED LOADS ON THE LOW TEMPERATURE FRACTURE BEHAVIOR OF NOTCHED AND WELDED PLATES

by

W. H. Munse
J. P. Cannon
and
J. F. Kiefner

Final Report

Bureau of Ships - Department of the Navy
Contract NObs 88283
Project SR-149
Ship Structure Committee

University of Illinois
Urbana, Illinois

1 November 1967

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The influence of repeated loadings on the susceptibility of weldments to fracture in a brittle manner is studied for an ABS-Class C steel. The test members have consisted primarily of 12, 24 and 36 in. wide notched-and-welded specimens that, at low temperatures, have been known to provide low-stress brittle fractures.

The repeated loads or loading history are found to affect the fracture behavior of the weldments. In all but one instance the fracture stresses obtained for the notched-and welded wide plates were greater than the stresses to which the members had been subjected during the repeated loadings. Furthermore, the repeated loadings appeared to eliminate the two-stage fractures observed in some of the tests of as-welded specimens. This latter condition is in general desirable, but only if the fracture stress is raised to a high-stress level.

1. INTRODUCTION

1.1 Repeated Loads and Brittle Fracture

Many catastrophic brittle ship failures have been reported to have occurred at low nominal stresses and after the vessels had been in service for a period of time. As a result, it often has been suggested that these brittle fractures might have been related to the repeated loadings to which the vessels had been subjected prior to failure. Although numerous research studies have been conducted to evaluate the many factors that affect brittle fractures, relatively little is known of the effect of repeated loads.

The laboratory tests generally have indicated that high stresses, stresses above the yield strength of a material, are necessary to initiate brittle fractures from fatigue cracks. However, recent investigations (Ref. 1-12) have shown that when high residual stresses, low temperature, and sharp notches are introduced in certain types of laboratory specimens, brittle fractures may be obtained at low levels of applied stress either before or after the members have been subjected to repeated loadings. The investigation reported herein was initiated in January 1963 primarily to evaluate the influence of repeated loadings on the low-temperature fracture behavior of ship-steel (ABS-C) weldments.

In evaluating the relationships between repeated loads and brittle fracture behavior, studies were conducted to obtain information concerning (a) the effect of repeated loads on the susceptibility of weldments to fracture brittlely, (b) the effect of residual stresses on the behavior of weldments at low temperatures, and (c) other possible sources of damage resulting from repeated loadings and their effect on low-stress brittle fracture.

In accordance with the objectives noted above, this study was initially directed toward an evaluation of the most obvious source of damage resulting from repeated loads, a fatigue crack. A program of pilot tests was conducted to study the possibility of fatigue cracks acting as sources of brittle fracture initiation. Plain and welded plate specimens were first subjected to a sufficient number of repeated loads to develop fatigue cracks and then to static loads at low temperatures to determine whether or not low-stress brittle fractures could be initiated from the fatigue cracks. Since these studies did not provide low-stress brittle fractures, the emphasis in the balance of the program was placed on the effect of repeated loadings on the temperature behavior of welded members in which there were no fatigue cracks.

1.2 Acknowledgments

The tests and analysis reported herein were conducted in the Structural Research Laboratory of the Department of Civil Engineering, University of Illinois as a part of the Low-Cycle Fatigue program sponsored by the Ship Structure Committee under the Department of the Navy, Bureau of Ships, Contract NObs 88283. A National Academy of Sciences - National Research Council Project Advisory Committee consisting of Dr. J. M. Frankland, Chairman, Mr. John Bennett, Professor B. J. Lazan,[*] Dr. J. D. Lubahn, and Dr. Dana Young has served in an advisory capacity for this program. The authors wish also to acknowledge the valuable assistance provided by Mr. A. R. Lytle and Mr. R. W. Rumke of the National Academy of Sciences - National Research Council in the administration of this program.

---

[*] Deceased

The authors wish to express their appreciation to Professor V. J. McDonald and his instrumentation staff for their helpful suggestions in many phases of this research, and to Mr. P. G. Little and Dr. S. T. Rolfe for their contributions to the initial stages of the experimental program. Special acknowledgment is due to Mr. D. F. Lange and the mechanics in the Civil Engineering Department's Shop for their excellent workmanship in preparing specimens and maintaining the test equipment used in this program.

2. DESCRIPTION OF INVESTIGATION - PILOT TESTS

2.1 Description of Specimens and Tests

2.1.1. Materials - Three steels were used in the pilot tests to study brittle fracture initiation from fatigue cracks, a rimmed, ABS-class C as-rolled, and HY-80, a high-strength steel. The mechanical properties and chemical composition of these steels are summarized in Table 1.

2.1.2. Plain Plates of Rimmed Steel and HY-80 Steel - Notched plain plate specimens 3/4-in. thick and 10-in. wide were used in the first group of pilot tests on rimmed steel and HY-80 steel. The notch was placed in each of these specimens to provide early crack initiation and consisted of a 5/8-in. drilled hole with 13/16-in. long hacksaw cuts on both sides of the hole, each of which was extended an additional 1/8-in. by a 0.009 in. jeweler's saw cut (See Fig. 1).

The specimens in the first group of pilot tests were first subjected to repeated loads in the 200,000-lb. capacity University of Illinois lever-type fatigue testing machines shown in Fig. 2 at a rate of 180 cycles per minute. In all cases the initial load range applied to these specimens was ±140 kips (±25 ksi based on the original net area). Several of the tests were initiated with the specimens cooled to a low temperature. During the tests the temperature of the specimen increased somewhat; nevertheless, the tests were continued as fatigue cracks initiated and propagated to failure. The initial and final temperature in these tests are reported in Table 2, along with the results of the tests. Complete fracture occurred in the four notched plain plates of rimmed steel at less than 5,000 cycles of loading. In all instances, the failures occurred after cracks approximately 2 1/2-in long had developed from the initial notches. Two of the specimens, R-3A-2 and R-3A-3, failed in a brittle manner at temperatures of -15°F and -17°F. At the time of failure the average fracture stress, the stress on the remaining area (the original area minus the area of the notch and fatigue crack), was approximately +38 ksi. Thus, the failures have been considered to be high-stress brittle fractures.*

The brittle portions of the fractures exhibited rather flat, crystalline surfaces but were noticeably rougher than the portions cracked in fatigue. Specimen R-3A-3 had short branching cracks at the end of the fatigue cracks which are thought to be short brittle cracks that occurred at the time of the final failure.

The two other notched plain plates of rimmed steel failed in a ductile manner at temperatures of +20°F and +107°F and at average fracture stresses of +33 ksi and +38 ksi. The surfaces of these ductile failures appeared dull and fibrous and sloped at an angle of approximately 45° to the plate surfaces. Furthermore, the elongation of the specimens was noticeably greater than that of the specimens that failed in a brittle manner. Thus, although all of the rimmed steel specimens fractured at approximately the same stress level, there was a marked difference in the nature of the fractures and in the amount of deformation in the material at final failure.

Two notched plain plate specimens of HY-80 steel, R-H-1 and R-H-2, were subjected to the same magnitude of repeated loads at temperatures of approximately +75°F and -75°F. These members both failed in a ductile manner after 81,900 and 96,500 cycles of loading respectively. Since, at the time of failure, the fatigue cracks had propagated through about two-thirds

---

* High-stress brittle fractures are considered to be those which initiate at average applied stresses at or above the yield strength of the material.

of the net widths at the time of fracture, the average fracture stress at failure was approximately +85 ksi.

2.1.3. Plain Plates of ABS-Class C Steel - Five pilot tests were conducted at room temperature on 7-in. wide notched plain plate specimens of 3/4-in. thick ABS-class C steel, each containing a centrally located notch. Notches of three different lengths were used in these specimens, all terminating in a jeweler's saw cut (See Fig. 3).

The plates were subjected to repeated loadings corresponding to initial stress ranges of ±33 ksi or 0 to 33 ksi. The presence of the centrally located stress raisers resulted in the early initiation of fatigue cracks. These cracks were permitted to propagate until the total fatigue crack length (original notch not included) was approximately 50% of the gross width. Three of the specimens were then heated 90 minutes at 300°F to accelerate any strain aging that might occur. A fourth specimen, RC-13, had been aged before being subjected to repeated loadings.

All of the fatigue cracked specimens were loaded to failure at temperatures ranging from -25°F to -50°F. Three were subjected to a single axial loading and failed in a brittle manner at a relatively high fracture stress (stress considerably above the yield strength of the material). The two remaining plates were subjected to increasing load in increments of 2.5 ksi and after each increment of loading were struck on the surface near the notch by a hammer which provided a 30 or 50 ft-lb. blow; both exhibited high-stress fractures. The results of the tests are given in Table 3.

2.1.4. Welded Plates of Rimmed Steel - The welded specimens of the pilot study were 7 1/2 in. wide and fabricated from 3/4-in. plates of rimmed steel. The plates were notched with a 0.007-in. jeweler's saw, and then longitudinally butt-welded with E6010 or E7016 electrodes. This notch was chosen because other investigators, using similar notches, had successfully produced low-stress fractures in laboratory studies of welded plates.

The welded plates of rimmed steel were subjected to repeated loadings of ±140 kips(±25 ksi based on the gross area of the specimens) at temperatures ranging from -61°F to +250°F (See Table 4). In six of the seven tests conducted, 3 to 4 in. long cracks had developed before fracture occurred. Four of the specimens failed in a ductile manner at temperatures ranging from +30°F to +250°F and at stresses ranging from 41.7 ksi to 46.0 ksi; whereas, two specimens failed in a brittle manner at stresses of 46.0 and 60.0 ksi, at temperatures of -43°F and +31°F respectively.

The seventh welded plate, Specimen W-1-1, was tested at a temperature of -61°F and failed completely in a brittle manner after a fatigue crack only 1/8 in. long had developed. This failure occurred at a fracture stress of +26.3 ksi.

3. PRINCIPAL TEST PROGRAM

3.1 Description of Specimens and Tests

3.1.1. Material - An ABS-class C as-rolled steel, with mechanical properties and chemical composition as given in Table 1, was used in the principal test program. The 15 ft-lb. Charpy V-notch transition temperature for this material was approximately +5°F as shown in Fig. 6.

3.1.2. Specimens - The principal test specimens were notched and welded plates 3/4-in. thick and either 12, 24, or 36-in. wide, as shown in Fig. 7. They were similar to the notched and welded specimens of the pilot program and consisted of two plates which were notched and then longitudinally butt-welded with E7018 electrodes. In the principal program, however, the notches were machine sawed to a depth of 3/16 in. with a 0.007-in. circular saw. This notching provided a geometry that has been referred to herein as a "Type-A" notch and is illustrated in Fig. 7b.

3.1.3. Test Program - Several types of tests were conducted: axial repeated-load tests, repeated load tests in flexure, and low-temperature tensile fracture tests.

(a) Axial Repeated-Load Tests - Specimens of 12 and 24-in. widths were subjected to repeated axial loads. The stress cycles used for most 12-in. specimens were 0 to -18 ksi, ±18 ksi or ±22 ksi and the number of cycles of repeated loads ranged from one cycle to about 40,000 cycles. Under these conditions fatigue cracks were observed to propagate only in specimens subjected to the complete reversals of loading. In the reversal tests the load was adjusted periodically to maintain the maximum compressive stress on the basis of the original net area and the maximum tensile stress on the basis of the remaining net area.

All repeated load tests on the 24-in. plates were conducted on various tension stress cycles. The maximum stresses applied to the specimens varied from +3.4 ksi to +30 ksi and the number of repeated loads varied from 1 to 11,500, depending upon the desired test conditions.

(b) Repeated Loads in Flexure - Some of the 12-in. wide specimens were loaded in flexure in the manner shown in Fig. 8. Repeated flexural loadings were introduced to produce fatigue damage and crack propagation and yet preserve a V-shaped notch front. The specimens were alternately loaded from one side and then the other until surface cracks of predetermined lengths had been produced. The selected deflections produced nominal surface strains on the order of 2 to 5% at mid-span and required from 3 cycles to 40 cycles to propagate the cracks.

(c) Low-Temperature Tensile Fracture Tests - Each 12, 24, or 36-in. plate, whether subjected to previous loadings or not, was tested statically to failure at a low temperature. Each specimen was prepared for testing by welding it to a set of pullheads that had already been placed in the testing machine. Cooling tanks were then clamped to the surfaces of the test plate, both above and below the notch, and a solution of dry ice and solvent was placed in the tanks to lower the temperature of the specimen to the desired level. Upon reaching the test temperature, the temperature of the specimens was maintained essentially constant for ten to fifteen minutes before being loaded to failure.

3.2 Results of Tests

3.2.1. Non-Cycled Specimens of ABS-Class C Steel

(a) Non-Welded Specimens - Several 12-in. wide specimens were fabricated without being welded longitudinally. The two halves of the specimen were bevelled and notched but left unwelded (See Fig. 7c). The notch geometry in the non-welded plates was essentially the same as that of the welded plates. These non-welded plates were used to study fracture behavior without the presence of residual welding stresses or other variables introduced by welding.

One of the non-welded non-cycled plates, specimen PP-11 (See Table 5), was tested to failure at a temperature of -80°F and failed in a brittle manner at 51.5 ksi. Thus, an applied stress somewhat greater than the yield strength of the material was necessary to initiated failure in the non-welded, notched member of ABS-class C steel tested at a temperature 85°F below the Charpy 15 ft.-lb. transition temperature. A photograph of the fracture surface of this specimen is shown in Fig. 9a. The remaining non-welded plates were subjected to repeated loadings prior to the fracture tests and will be discussed in a later section.

(b) Welded Specimens - Four 12-in. wide non-cycled welded plates with Type - A notches were tested to failure at low temperatures. High-stress brittle fractures occurred in two of the plates tested at temperatures of -46°F and -80°F, while low-stress fractures occurred in the other two plates at temperatures of -80°F and -92°F (See Table 5 and Fig. 10). On the basis of these tests there appears to be a marked strength transition for the 12-in. notched-and-welded plates at about -80°F.

The fractures of the four 12-in. plates, whether at high stress or low stress, were single-stage fractures. That is, the fractures consisted of a single failure which suddenly initiated and propagated completely through the plate. Photographs of the fracture surfaces of a high-stress (WP-2) and a low-stress (WP-5) fracture are shown in Figs. 9b and 9c, respectively.

Six 24-in. and two 36-in. welded plates with Type - A notches were tested at low temperatures, the results of which are presented in

Table 5 and Fig. 10. These plates, tested at temperatures ranging from -70°F to +28°F, exhibited behaviors significantly different from those of the 12-in. plates. Of the 24-in. plates tested two exhibited low-stress single stage fractures at temperatures of -70°F and -21°F, thus indicating that the transition in strength observed at a temperature of -80°F for the 12-in. plates is much higher for the 24-in. plates.

Two 24-in. plates tested at temperatures of -42°F and -2°F and both 36-in. plates tested at temperatures of -2-°F and +28°F exhibited two-stage fracture behavior. That is, fractures which initiated at a low stress, propagated for some distance through the plate, and then arrested, leaving a portion of the plate intact. To fracture the remaining portion of the plate a much higher applied stress was required. The first portions of the two-stage fractures were identified by cracking noises and sometimes on the fracture surface of the specimens by an obvious thumbnail arrest pattern marking on the end of the first stage crack (See Fig. 11a).

The two remaining 24-in. plates tested at temperatures of -38°F and -40°F exhibited high-stress, single-stage fractures. Since two similar 24-in. wide plates had exhibited low-stress fractures at temperatures considerably higher than -40°F, it is thought that these two high-stress fractures were preceded by short, unobserved first-stage cracks which caused the two plates to sustain a high level of stress before fracturing completely.

The low-stress fractures of the 24-in. plates exhibited relatively flat fracture surfaces, just as in the 12-in. plates (See Fig. 11c). However, the high-stress fractures of the 24-in. plates exhibited rouch irregular surfaces (See Fig. 11b), except in the immediate vicinity of the notches, another indication that they might have been two-stage fractures.

3.2.2 Effects of Repeated Loads - ABS-Class C Steel

(a) Non-Welded Specimens - Three 12-in. wide, non-welded plates with Type-B notches were subjected to repeated axial loads to study the effect of repeated loadings on the behavior of notched members that do not contain the residual stresses or other variables introduced by welding. The results of these tests are given in Table 6.

One plate was subjected to a loading sequence selected to produce plastic strains at the notch simulating those resulting from welding. The plate was then loaded to failure at a temperature of -84°F and fractured 50.1 ksi.

The other two plates were subjected to repeated loadings (0 to -18 ksi and ±18 ksi) at room temperature, heated to +300°F for 90 minutes to accelerate any possible strain aging, and then loaded to failure at low temperature. These members fractured at stresses of +50.5 and +52.7 ksi, respectively.

The numbers of cycles and the magnitudes of loadings used for the non-welded plates did not produce visible fatigue cracks nor did they seem to produce a fracture behavior or fracture appearance that differed from that of the non-welded, non-cycled plate discussed earlier. Furthermore, the 90 minute baking at 300°F did not change the behavior of the members.

(b) Welded Specimens Cycled After Welding - Ten 12-in. wide welded plates with Type-A notches were subjected to repeated axial or, in one case, flexural loadings at room temperature and then tested to failure at low temperatures. The number of room temperature loadings ranged from 1 to 28,130 cycles for the nine axially cycled specimens and was 12 cycles for the specimen loaded in flexure. The results of these tests are given in Table 6.

The plate subjected to a single cycle of axial loading from 0 to +38.5 ksi at room temperature, fractured at a stress of +49.2 ksi when tested at a temperature of -43°F. Four of the plates were subjected to 100 cycles and three to 1000 cycles of axial loading, the stress cycles being either 0 to -18 ksi or ±18 ksi. No visible fatigue cracks developed as a result of this larger number of loadings. Upon cooling and testing to failure, it was found that all seven plates developed fracture stresses of yield strength or greater at temperatures ranging from -43°F to -84°F.

Another plate, subjected to 28,130 cycles of axial loading at ±22 ksi, developed a 1.36-in. fatigue crack which severed the weld and propagated into the base plate. When tested at a temperature of -80°F the plate fractured at a net-section stress of 41.6 ksi. Although the plate fractured at a relatively high stress, the fracture stress was somewhat lower than the yield strength of the plate material and the fracture stresses of the other 12-in. plates.

Twelve cycles of repeated flexural loading were applied to one 12-in. specimen. The plate was deflected 1/2-in. in both directions, with the resulting maximum plastic strain being ±2.5%. A fatigue crack resulted from this loading and propagated first into the weld and then into the base metal. This crack measured 1/4-in. at the surface on both sides of the plate. When tested axially at a temperature of -80°F, the plate fractured at a stress of 49.3 ksi, a stress slightly above the yield strength of the material. From an examination of the fracture surface it was evident that the fatigue crack had penetrated to a depth of only 1/16-in; most of the weld was intact and the fatigue crack had not caused any significant reduction in the fracture strength.

The fracture strength of the plate cycled in flexure compares favorably with that of the 12-in. plates subjected to axial cycling.

However, the fracture appearance of this plate differed from that of the axially-cycled and non-cycled 12-in. plates. An irregular fracture surface was obtained, as shown in Fig. 12a. It appears that the plastic strains caused by bending produced a more complex or different fracture behavior in the flexurally cycled specimen than that observed in the axially loaded specimens.

In summary, the results of the tests on cycled and non-cycled 12-in. wide notched-and-welded plates suggest that the repeated loads may have decreased the ease with which the low-stress fracture initiated at a temperature of approximately -80°F. However, since this testing temperature was close to the transition temperature for the members, the variation in behavior observed in the tests may not be too significant.

(c) Specimens Cycled Before Welding - Three 12-in. wide, notched plates were subjected either to axial or flexural repeated loads and then welded. After welding these specimens contained hybrid notches designated as Type-C for the axially cycled specimens and Type-D for the flexurally cycled specimens (see Fig. 7). The results of fracture test on these specimens are presented in the lower portion of Table 6.

Specimen WP-17, welded after cycling in flexure had surface fatigue cracks approximately 1/16-in. long on both surfaces at the tip of each notch. The V-fronts of the notches retained their shape during cycling; however, during welding short cracks propagated outward from the V-notch at the center of the plate, thereby destroying the V-shaped fronts of the notch (see Fig. 12b). When tested axially at a temperature of -85°F, the specimen failed at a stress of +8.7 ksi and thus was a low-stress fracture. The fracture surface was neither as irregular as that of WP-21, a specimen cycled in flexure after welding, nor as flat as the fractures of the 12-in. plates welded before axial cycling.

Specimen WP-20 was subjected to 41 flexural cycles and developed surface cracks approximately 1/32-in. long, but the V-shaped notched fronts in the center of the plate remained intact. The cycled plate was welded and then tested axially at a temperature of -80°F. A two-stage fracture was obtained, the first stage crack initiated at +8.8 ksi and propagated 4 in. The second and final stage initiated at +48.3 ksi, based on the area remaining after the first stage fracture. The low-stress fracture surface was somewhat rougher in appearance than the low-stress fracture surfaces observed in previous tests of 12-in. plates. Nevertheless, the end of the first stage crack, the point of arrest, was evident on the fracture surface.

The plate for Specimen WP-22 with a Type-B notch cut into each outside edge was subjected to 38,000 cycles of axial loading at ±22 ksi. The total length of fatigue crack formed was 0.35 in. However, the crack had propagated farther on one side than on the other. After the application of the repeated loadings, the plate was bevelled on the notched edges and then split down the center; the two bevelled edges were placed adjacent to one another, and the plates then welded longitudinally along the bevelled and notched edges. The specimen was then tested axially to failure at a temperature of -80°F and exhibited a two-stage fracture behavior, the first stage crack initiating at +5.8 ksi and propagating about 4-in. The second stage initiated at +49.4 ksi, based on the area remaining after the first stage fracture. The thumbnail arrest pattern of the first stage was evident on the fracture surface and contrasts markedly with the irregular high-stress fracture surface (See Fig. 12c).

All of the tests of specimens welded after being subjected to repeated loads provided low-stress fractures of either the one-stage or two-stage types. The combination of thermal, strain and fatigue cycling, strain aging, low temperature, and residual stresses appear to have increased the susceptibility of these plates to low-stress fracture initiation.

(d) Twenty-four-inch Wide Specimens - Twenty-two 24-in. wide welded plates with Type-A notches were axially cycled from 0-to-tension at room temperature and then tested to failure at a temperature of approximately -40°F. The temperature of -40°F was selected on the basis of previous tests on non-cycled, twenty-four-inch wide notched-and-welded specimens, a number of which exhibited low-stress fracture initiation at or above this temperature. In eleven of the tests, the maximum stress in the stress cycle was selected equal to 10, 20 or 30 ksi. In the remaining tests, the plastic strains observed in the vicinity of the notches during the first cycle of loading were used to establish the magnitude of the repeated loads. In most instances, whether stress controlled or strain controlled, strains were observed at a number of locations in the specimens and used to evaluate the behavior of the members. The results of these tests are summarized in Table 7.

(i) Results of Tests. Of the 8 plates subjected to "Stress-controlled" cycles of 0 to +10 ksi, two exhibited high stress single-stage fractures at stresses of +43.8 ksi and +50.7 ksi, and six plates exhibited low stress single-stage fractures at stresses ranging from +6.8 ksi to +26.5 ksi. The plate subjected to a stress cycle of 0 to +20 ksi failed at +41 ksi and the plates subjected to repeated maximum stresses of +30 ksi fractured at +31.2 ksi and +46.5 ksi. In the case of the "strain-controlled" tests, failures were found to occur at or above yield point strength of the material in 8 cases and at low stress levels in 3 instances, all being single-stage fractures.

In all but one instance the fracture stresses for the 24-inch wide plates were greater than the stresses to which the members had been previously subjected at room temperature. However, in the case of Specimen WP-28, a member subjected to 50 room temperature stress cycles of 0 to 10.0 ksi, failure occurred at a stress of +6.8 ksi.

The relationship between the repeated-load stresses and the fracture stress is shown in Fig. 13. Although many of the specimens failed at stresses only slightly greater than the cyclic stress, a number of the specimens withstood a stress significantly higher when tested to failure at low temperature. Thus, the fracture stress for these notched and welded members is apparently affected by not only the previous stress history, but also other factors.

It is suspected that two-stage fracturing may have been involved in many of the high-stress fractures. However, this type of fracturing was not observed either audibly or visibly in the cycling or fracture tests. Thus, the room temperature loadings appear to have precluded the 2-stage fractures observed in previous non-cycled tests, unless the room temperature repeated loading produced unobserved first stage cracking in those specimens that sustained the high fracture stresses. Specimen WP-32, which was loaded to +37.3 ksi at a temperature of -40°F and then unloaded, exhibited small cracks at the notch on the surface of the weld. Similar cracking, although not observed, probably occurred in the other plates during the low-stress cyclic loadings. If such cracks had been present, they would account for the unexpected high-stress fractures obtained in so many of the plates subjected to small cyclic loadings.

Low stress fractures in the 24-inch wide plates subjected to repeated loads exhibited relatively flat and fairly smooth fracture surfaces, while the high stress fractures were rough and irregular. This behavior is typical of behavior observed in many other brittle fracture studies conducted in recent years. Typical fracture surfaces of two 24-inch specimens are shown in Fig. 14.

During most of the tests measurements were made of the total elongation over the full length of the test section. This total elongation to failure for the various test members is given in Table 7 and is in excellent agreement with the elongation that would be obtained in an ordinary tensile coupon test.

(ii) Strain Measurements. To evaluate the deformations in the vicinity of the notch of the notched-and-welded specimens, strain gages were mounted near the notches of a number of the specimens as shown in Fig. 15. These gages were then monitored during the application of the repeated loads. The resulting data indicate the existence of plastic strains (See Table 7) at certain of the gage locations; however, the strains on the interior of the material and at other locations can be expected to differ markedly, some strains being greater and some possibly smaller.

The largest plastic strains were recorded on the weld side of the notch, the region of maximum residual stress and also the region having the largest stress concentration. For a nominal plate stress of 10 ksi, the plastic strains in this notch region were generally on the order of 2000 micro-inches per inch (a strain concentration of approximately 6); on the base plate side of the notch the plastic strains were in the neighborhood of only 500 micro-inches per inch.

Strains indicated by the gages on the centerline of the weld appeared to remain essentially elastic during cycling to 10 ksi; the large plastic strains appear to be confined to regions close to the notch. Typical plots of applied stress versus the repeated-load strains for the various gage locations are shown in Fig. 16. It is evident that yielding initiates almost immediately at the tips of the weld notches (gages 2 and 4). Furthermore, from the strain gage data obtained in the tests it was readily evident that the residual stresses as well as the fracture behavior of supposedly identical specimens differed markedly, possibly as a result of minor differences in the welding procedures or techniques, undetected pre-cracking in the specimens, to minor differences in geometry at the root of the notches, and to differences in the material properties resulting from the welding.

Slight differences in the notch geometry of the specimens were observed despite the careful control of specimen fabrication. Non-uniform distortions of the plates during welding resulted in small changes in the gap between the plates, and thus, a change in length of the notch. It was thought that this variation in notch geometry might account for the variations in behavior observed in the tests. However, studies of the notch geometry of the specimens did not reveal any consistent relationship between the notch geometry, the variations in plastic strains, or the fracture behavior.

(iii) Mechanical Property Changes. Consideration was given also the effect of the fabrication and repeated loadings on the tensile properties of the material. Miniature coupon specimens were cut from various locations near the notch of a specimen and tensile tests conducted on the material (See Fig. 17). Here it may be seen that near the notch the yield strength and the ultimate tensile strength of the material increased while the ductility decreased, apparently the result of the thermal and strain cycles to which the material had been subjected by the welding.

In related studies Kiefner and Munse(13) found that notched bend specimens of ABS-Class C steel which had been subjected to an axial prestraining at temperatures in the range of 300° to 800°F cracked at loads as low as 87 percent of the "yield load" when tested at temperatures between -80° to +80°F. Furthermore, some of the specimens exhibited cracking during the axial prestraining at a temperature in the range of 300° to 600°F. Thus, the properties as well as the cracking sensitivity of this steel appear to be related to the thermal and strain cycling to which the material is subjected.(13,14)

(iv) Stress Concentrations. From the measurement of strains on the surface of the test plates the notching of the notched-and-welded specimens is known to provide a severe local stress condition and consequently to be responsible, at least in part, for the low-stress fracturing of the test members. However, the magnitude of the internal stress, or strain, concentration at the tip of the notch has until recently not been known. A recent study by Cannon and Munse(15) has shown that a strain concentration on the order of 13 may exist near the tip of the notch, and that severe constraint also exists in this same general area. The introduction of this strain concentration in a region of high constraint and of high residual stresses,(16) in combination with an applied stress of 8 to 10 ksi, can easily account for a stress at the notch equaling the theoretical critical fracture stress reported in the literature.(17) Furthermore, since these conditions exist in a region of the material that has been subjected to a thermal and strain cycling, and may have relatively low notch toughness, a condition is provided which would appear to be highly condusive to the initiation of low-stress brittle fractures.

4. SUMMARY OF RESULTS AND CONCLUSIONS

A variety of tests have been included in this program to evaluate the effect of repeated loadings on the susceptibility of ABS-Class C steel weldments to fracture in a brittle manner, a question that is of great concern to the ship industry.(18) The results of these tests in combination with related supporting data help to define the importance of the many parameters that affect the low-temperature low-stress fracture behavior of ship-steel weldments and, in particular, the behavior of ABS-Class C steel weldments. In addition, they provide an evaluation of some of the phenomenological aspects of low-stress brittle fracture in weldments.

4.1 Summary of Results

The studies reported herein were conducted primarily on members fabricated from ABS-Class C steel; however, in pilot studies some evaluations were made also on a rimmed steel and HY-80, a quenched and tempered high strength steel. Some of the evaluations were made on plain notched plates, although most of the studies were conducted on notched and welded specimens.

In the preliminary or pilot studies on 7 to 10 in. wide plain notched plates of rimmed steel with fatigue cracks of considerable length, only high-stress fractures* were obtained at temperatures as low as -50°F. However, the tests of 7 1/2 in. wide notched-and-welded plates suggest that low-stress (below the yield strength of the material) fractures may occur when both repeated loadings and welding are combined, but only when tested at very low temperatures

---

* Fractures at average applied stresses at or above the yield strength of the material.

The principal program of this investigation was conducted on specimens 12, 24 or 36 in. wide and fabricated of ABS-Class C steel. Briefly the results of these tests may be summarized as follows:

(a) 12-in. wide plain notched plates (no weld) failed at high stresses at temperatures as much as 85°F below the 15 ft-lb. Charpy V-notch transition temperature.

(b) 12-in. wide notched-and-welded specimens exhibited a transition to low-stress fractures at a temperature of -80°F. (Approximately 85°F below the Charpy transition temperature.)

(c) 12-in. wide specimens, whether plain notched or notched-and-welded showed no detrimental effect from cyclic loadings.

(d) 24-in. wide notched-and-welded plates gave low-stress single-stage fractures at temperatures as high as -21°F. Two-stage fractures were obtained at temperatures as high as +2°F.

(e) 24-in. wide notched-and-welded specimens which were cycled and then tested to failure at -40°F indicate that their behavior is affected by the stress history to which the member is subjected. The room temperature cycling precluded two-stage fracturing.

(f) 36-in. wide notched-and-welded specimens exhibited two-stage fractures at temperatures as high as +38°F.

Where comparisons are possible, it appears that the width of the notched-and-welded members had an effect on the ease with which brittle fractures were initiated, both for single-stage and two-stage low-stress fractures; the wider the specimen, the higher the temperature at which a particular type of fracture initiated.

In addition to the above fracture data, strain measurements on the welds of the notched-and-welded specimens indicated that yield point residual stresses existed in the welds of some of the notched-and-welded plates. This is verified by Nordell and Hall.(16) However, these residual stresses are believed to vary considerably from one specimen to the next.

4.2 Conclusions

Based on the results of the tests on ABS-Class C steel reported herein and on the recent related studies,(13, 15) one must conclude that repeated loadings will affect the susceptibility of a notched-and-welded member to fracture in a brittle manner at low stresses. In all but one instance, the fracture stresses obtained for the notched-and-welded wide plates were greater than the stresses to which the members had been subjected during the repeated load tests, a conclusion arrived at by others also.(19,20) The repeated loadings, in general, also changed many of the low temperature failures from a two-stage "low-stress/high-stress" condition to a single-stage fracture condition. Such a condition is in general desirable, but only if the resulting fracture stress is raised to a high-stress level. Repeated loads of relatively low magnitudes may result in single-stage low-stress brittle fractures, an undesirable condition.

In the notched-and-welded members, low-stress fractures apparently occur as a result of the introduction of very high strain concentrations in a region of high constraint and high residual stresses, and in material that has an increased crack sensitivity due to thermal and strain cycling during welding. This condition has resulted in either single-stage or two-stage fractures in the members at low temperatures. It further appears that the temperatures at which the low-stress fractures occur, increase with an increase in the width of the members. However, the data are not sufficient to quantitatively define the temperature and stress levels necessary for each type of failure or its relationship to the specimen size.

5. REFERENCES

1. A. A. Wells, "Brittle Fracture Strength of Welded Steel Plates - Tests on Five Further Steels," British Welding Journal, August 1961.
2. W. J. Hall, W. J. Nordell, and W. H. Munse, "Studies of Welding Procedures," Welding Journal, November 1962.
3. A. A. Wells and F. M. Burdekin, "Effects of Thermal Stress Relief and Stress Relieving Conditions on the Fracture of Notched and Welded Wide Plates," British Welding Journal, May 1963.
4. C. C. Woodley, F. M. Burdekin, and A. A. Wells, "Mild Steel for Pressure Equipment at Sub-Zero Temperature," British Welding Journal, March 1964.
5. W. J. Nordell and W. J. Hall, "Two Stage Fracturing in Welded Mild Steel Plates, Welding Journal, March 1965.
6. W. J. Hall, J. R. Joshi, and W. H. Munse, "Studies of Welding Procedures - Part II," Welding Journal, April 1965.
7. F. M. Burdekin, and A. A. Wells, "Wide Plate Tests on a Mn Cr Mo V Steel," British Welding Journal, February 1966.
8. C. C. Woodley, F. M. Burdekin, and A. A. Wells, "Electroslag Welded Wide Plate Tests on 3 in. Thick Mild Steel," British Welding Journal, March 1966.
9. H. Kihara, K. Iida and E. Fujii, "Brittle Fracture Strength of Welded and Notched Wide Plates Subjected to Prior Cyclic Loading, IIW Document No. XIII 460-67, April 1966.
10. K. Iida and H. Inoue, "Low Cycle Fatigue Behavior of Welded and Notched Wide Plate of Mild and High Strength Steels," IIW Document No. XIII-429-66, April 1966.
11. W. J. Hall and A. D. Chamberlain, "Studies of Welding Procedures - Phase III," Welding Journal, May 1966.
12. C. C. Woodley and F. M. Burdekin, "Wide Plate Tests on Two Electroslag Welded Steels," British Welding Journal, June 1966.
13. J. F. Kiefner and W. H. Munse, "Influence of Thermal and Strain Cycling on Fracture Susceptibility of Mild Steel," Civil Engineering Studies, Structural Research Series No. 319, Urbana, Illinois, February 1967
14. F. M. Burdekin, "Effects of Thermal Straining During Welding on the Fracture Toughness of a Mild Steel," British Welding Journal, Vol. 14, February 1967.
15. J. P. Cannon and W. H. Munse, "Evaluation of Flow and Fracture Propensity of Notched Steel Plates by Means of a Photoelastic Model", Civil Engineering Studies, Structural Research Series No. 314, Urbana, Illinois, August 1966.

16. W. J. Nordell and W. J. Hall, "Two Stage Fracturing in Welded Mild Steel plates, Welding Journal, Vol. 43, No. 3, March 1965.

17. R. N. Wright, W. J. Hall, S. W. Terry, W. J. Nordell, and G. R. Erhard, "Studies of Some Brittle Fracture Concepts", Ship Structure Committee Report, SSC-170, September 1965.

18. Georg Vedelar, " To What Extent Do Brittle Fracture and Fatigue Interest Ship-Builders Today?", Sveiseteknikk, June 1962.

19. K. Iida and H. Inoue, "Low Cycle Fatigue Behavior of Welded and Notched Wide Plate of Mild and High Strength Steels", IIW Document XIII-429-66, April 1966.

20. H. Kihara, K. Iida and E. Fujii, "Brittle Fracture Strength of Welded and Notched Wide Plate Subjected to Prior Cyclic Loading," IIW Document XIII-460-67, April 1966.

TABLE 1 SUMMARY OF MATERIAL PROPERTIES

(A) Tensile Test Data (Standard ASTM 0.505-in. Diameter)*

Steel	Temperature (°F)	Yield Stress (ksi)	Ultimate Strength (ksi)	Elongation in 2-in. %	Reduction of Area %
Rimmed	+78	34.7	68.1	36.0	58.0
HY-80	+78	80.2	94.8	24.3	68.2
ABS - C	+78	39.4	70.6	35.2	60.0
ABS - C	-40	43.5	76.0	35.0	60.0
ABS - C†	+78	40.1	70.6	33.5	61.6
ABS - C†	-40	44.6	80.9	34.5	62.4

(B) Chemical Analysis - Percent (Mill Reports)

Steel	C	Mn	P	S	Si	Cu	Mo	Cr	Ni	Al
Rimmed	.18	.42	.013	.031	.02	.23	-	.07	.14	.003
HY-80	.16	.33	.021	.019	.26	-	.48	1.61	2.68	-
ABS - C	.24	.69	.022	.030	.20	.22	-	.08	.15	.034

* (All specimens taken parallel to direction of rolling - each value an average of two tests.)

† Aged (90 min. at 300°F).

TABLE 2

SUMMARY OF TEST RESULTS ON 10-IN. WIDE PLATES WITH 2 1/2-IN. CENTRALLY LOCATED NOTCHES

Specimen Number	No. of Cycles	Initial Testing Temperature, °F	Temp. at Time of Failure (°F)	Fatigue Load (kips)	Fatigue Crack Length at Failure (in.)	Fracture Stress(1) (ksi)	Type of Failure
			(Rimmed Steel)				
R-3A-1	4,100	0	+20	±121.5*	2.62	+33	Ductile
R-3A-2	4,850	+78	-17	±140	2.60	+37**	Brittle
R-3A-3	4,600	-42	-15	±140	2.70	+38	Brittle
R-3A-4	3,000	+78	+107	±140	2.59	+38	Ductile
			(HY-80 Steel)				
R-H-1	81,900	+75	+80	±140	5.50	+93	Ductile
R-H-2	96,500	-75	-70	±140	5.00	+75	Ductile

* The first 4,000 cycles were applied at a load of ±140 kips (±25 ksi on the original net area).

** The first 200 cycles were applied with the specimen at a temperature of +78°F (1/16" long fatigue cracks had developed). The specimen was then cooled to a temperature of -30°F to continue the test.

(1) Fracture stress is based on the net section of the cracked specimen.

TABLE 3

BRITTLE FRACTURE TESTS ON ABS-C AS-ROLLED PLATE SPECIMENS

Specimen	Length of Initial Saw Cut (in.) (See Fig. 3)	Stress History† (Repeated Loads at Room Temperature)	Fatigue Crack Length (in.)(2)	Static Test Temp. (°F)	Impact (ft-lb)	Fracture Stress(3) (ksi)
RC-2	2	± 33 ksi N = 36,530	3.45	-25	None	68.5
RC-3	3/4	± 33 ksi N = 34,750	4.23	-25	None	49.5
RC-6	2	± 33 ksi N = 16,680	3.50	-25	None	61.5
RC-7(1)	3/4	0 to + 33 ksi N = 130,665	3.65	-36	30	58
RC-13	3/8	± 33 ksi N = 26,450	3.46	-50	50	55

† Nominal stress on original net area - Constant load employed during repeated load tests.

(1) This specimen not artifically aged. All others aged 90 minutes at 300°F. Specimen RC-2, RC-3, and RC-4, aged after fatigue test, and specimen RC-13, aged before fatigue test.

(2) Fatigue crack length at the time of static test.

(3) Fracture stress is based on the net section of the cracked specimen.

TABLE 4

RESULTS FROM TESTS OF NOTCHED-AND-WELDED PLATES TESTED UNDER COMPLETE REVERSAL OF STRESS

(Rimmed Steel)

Specimen Number	Initial Testing Temperature, °F	Temp. at Time of Failure (°F)	Fatigue Load (kips)	No. of Cycles	Total Crack Length at Failure*	Fracture Stress(4) (ksi)	Final Failure
			E7016 Welds				
W-1-4	+72	+250	±140	14,000	3.35	+45.2	Ductile
W-1-7	-20	+ 31	±140	23,700(1)	4.375	+60.0	Brittle
W-1-8	-18	+ 55	±140	20,900	3.50	+46.0	Ductile
			E6010 Welds				
W-1-6	+72	+250	±140	6,400(2)	3.20	+43.6	Ductile
W-1-5	-20	+ 30	±140	25,000(3)	3.00	+41.7	Ductile
W-1-1	-55	- 61	±140	13,700	0.50*	+26.3	Brittle
W-1-2	-30	- 40	±140	22,300	3.50	+46.0	Brittle

* Includes length of crack (from tip to tip of fatigue cracks - extending through the weld) except for that of W-1-1 which is actual fatigue crack length plus the original notch (weld not included) since in this instance the weld did not appear to have cracked.

(1) First 2,400 cycles applied at +72°F with stress range from -16 to +21 ksi.

(2) Slag inclusion at notch caused very early initiation of fatigue crack.

(3) Fatigue crack initiated at slag inclusion 2 in. below the saw cut.

(4) Fracture stress is based on the net section of the cracked specimen.

TABLE 5

SUMMARY OF RESULTS - NOTCHED-AND-WELDED AND NON-WELDED SPECIMENS TESTED TO FAILURE WITHOUT PREVIOUS LOADINGS

(ABS-Class C Steel)

Specimen Number	Width (in.)	Temperature (°F)	Fracture Stress (ksi)(3)
WP-2	12	-46	56.7
WP-5	12	-80	13.3
PP-11(2)	12	-80	51.5
WP-15	12	-80	56.7
WP-16	12	-92	18.0
WP-18	24	-70	6.0
WP-19	24	-42	4.6/49.5(1)
WP-24	24	-21	17.9
WP-25	24	- 2	4.0/52.3
WP-43	24	-40	47.0
WP-44	24	-38	44.0
WP-26	36	-20	5.0/37.0
WP-27	36	+28	5.4/54.2

(1) Denotes PRIMARY/SECONDARY stresses of a two-stage fracture.

(2) Notched specimen, not welded.

(3) Fracture stress is based on the net section of the specimen.

TABLE 6

SUMMARY OF RESULTS - 12-in. WIDE, NOTCHED-AND-WELDED AND NON-WELDED SPECIMENS SUBJECTED TO REPEATED LOADS

(ABS-Class C Steel)

Specimen Number	Room Temperature Cycling		Low Temperature Static Test	
	Stress Range (ksi)	Number of Cycles	Temperature (°F)	Fracture Stress (ksi)
(A) Notched Non-Welded Specimens				
PP-12	Variable cycles Min=-20 ksi, Max=+20 ksi	6	-84	50.1
PP-13*	0 to -18	109	-80	50.5
PP-14*	±18	100	-84	52.7
(B) Specimens Welded Before Cycling				
WP-1	0 to +38.5	1	-43	49.2
WP-3*	0 to -18	120	-43	48.9
WP-4*	±18	102	-40	50.0
WP-6*	0 to -18	1,000	-80	43.6
WP-7*	±18	1,000	-80	57.2(1)
WP-8	0 to -18	1,000	-84	52.0
WP-9	0 to -18	100	-84	58.9
WP-10	±18	100	-82	52.3
WP-23	±22	28,130	-80	41.6(4)
WP-21	2.5% strain in flexure	12	-80	49.3
(C) Specimens Welded After Cycling				
WP-17	5.0% strain in flexure	3	-85	8.7(2)
WP-20	2.3% strain in flexure	41	-80	8.8/48.3(3)
WP-22	±22	38,000	-80	5.8/49.4

(1) Shear failure in pullhead bolt line.
(2) Fabricated and tested perpendicular to rolling direction.
(3) Denotes PRIMARY/SECONDARY stresses of a two-stage fracture.
(4) A 1.36-in. Fatigue crack existed at the time of the fracture test.

* Specimen artificially aged after being subjected to repeated loads. (Held at 300°F for 90 minutes to accelerate aging).

TABLE 7

RESULTS OF TESTS AT -40°F ON 24-IN. WIDE, NOTCHED AND WELDED SPECIMENS SUBJECTED TO REPEATED AXIAL LOADS

(ABS-Class C Steel)

Specimen Number	Room Temperature Cycling			Low Temperature Static Test (-40°F)	
	Stress Cycle (ksi)	Number of Cycles	Max. Plastic Strain (microinches per inch)	Fracture Stress (ksi)	Total Elongation(2) at failure, (%)
WP-28	0 to +10	50	1,710	6.8	0.020
WP-29	0 to +9.5	1	1,040	12.7	0.026
WP-30	0 to +30	1	-	31.2	-
WP-31	0 to +10	1	-	11.0	-
WP-32	0 to +10	100	-	50.7(1)	-
WP-33	0 to +30	100	-	46.5	-
WP-34	0 to +10	200	3,297	15.6	0.020
WP-35	0 to +10	10	-	12.5	0.026
WP-36	0 to +10	50	2,980	43.8	0.256
WP-37	0 to +10	100	1,700	13.8	0.51
WP-38	0 to +10	1	2,110	26.5	0.064
WP-39	0 to +6	1	2,070	52.8	0.640
WP-40	0 to +4.95	1	4,515	43.5	0.208
WP-41	0 to +12.65	1	2,470	53.3	-
WP-42	0 to +9.6	10,000	3,325	45.3	-
WP-45	0 to +6	1	340	45.6	0.281
WP-46	0 to +8.2	1	260	39.0	0.140
WP-47	0 to +20	1	-	41.0	0.130
WP-48	0 to +9.2	1	1,420	12.7	0.042
WP-49	0 to +5	11,500	630	52.0	1.275
WP-50	0 to +3.44	10,600	2,450	9.4	0.020
WP-51	0 to +6.9	1	1,700	43.8	0.695

(1) WP-32 received one additional cycle at 37.3 ksi before being tested to failure.

(2) Gage length for elongation measurements was about 2-in. longer than the specimen length because of mountings on the pullheads.

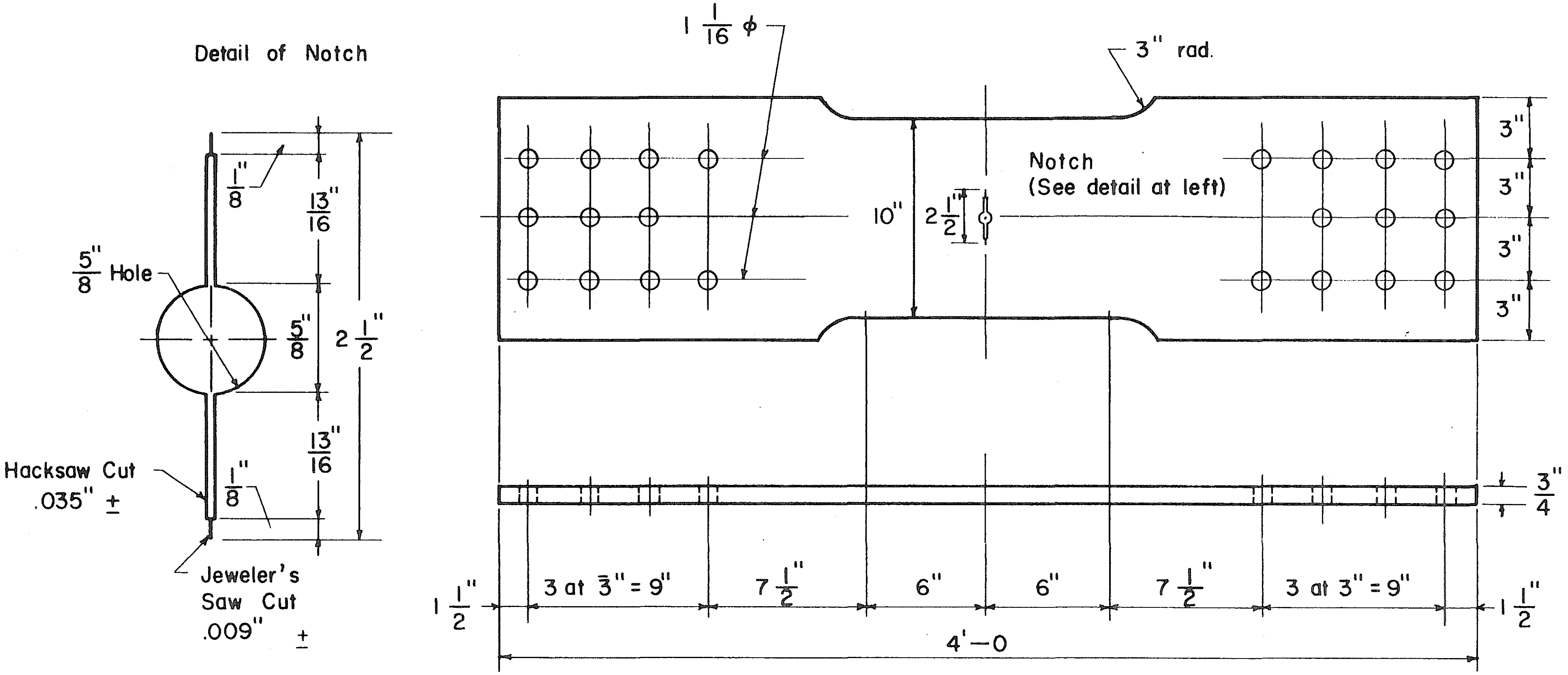


FIG. 1 DETAILS OF PLAIN PLATE SPECIMENS OF RIMMED AND HY-80 STEELS

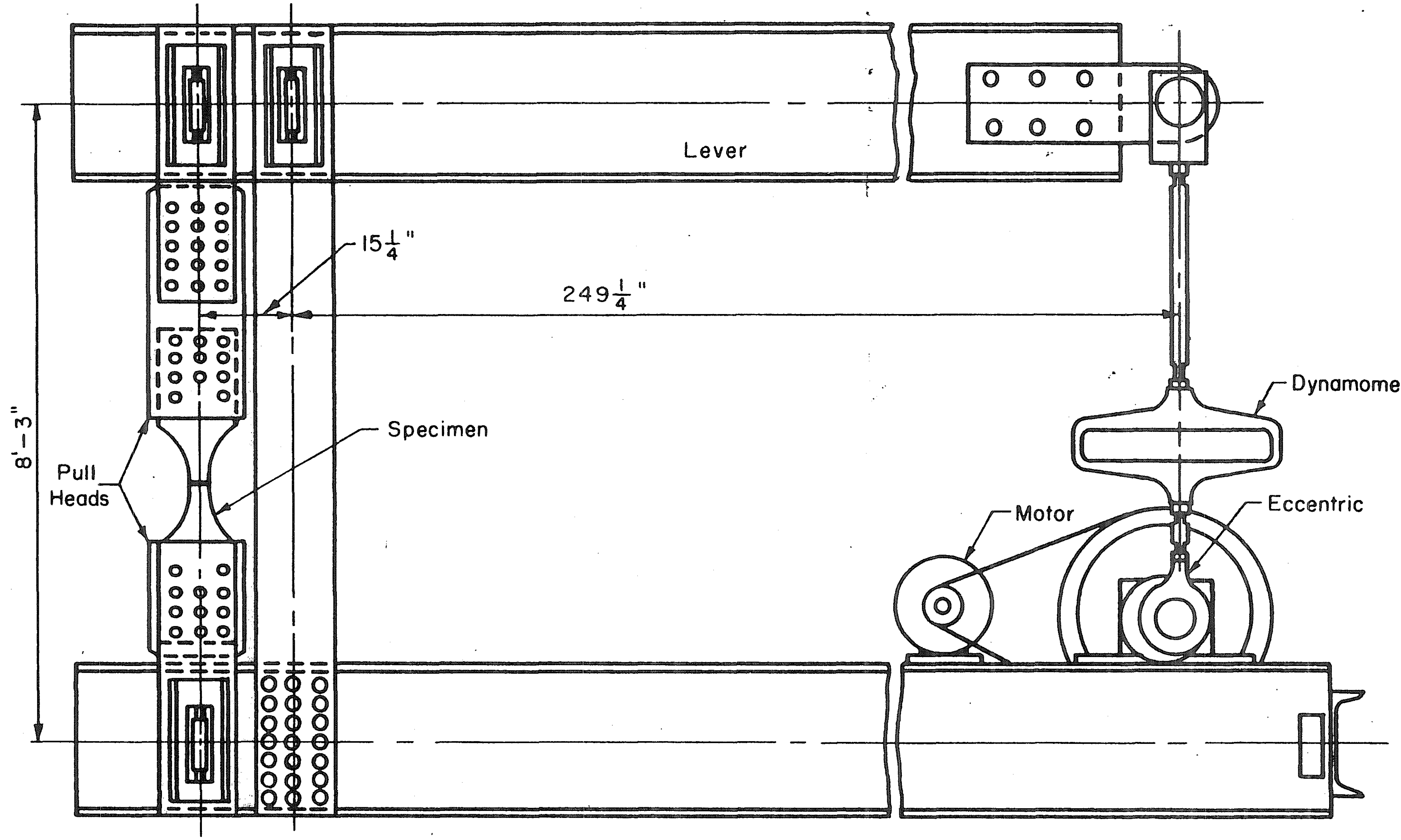
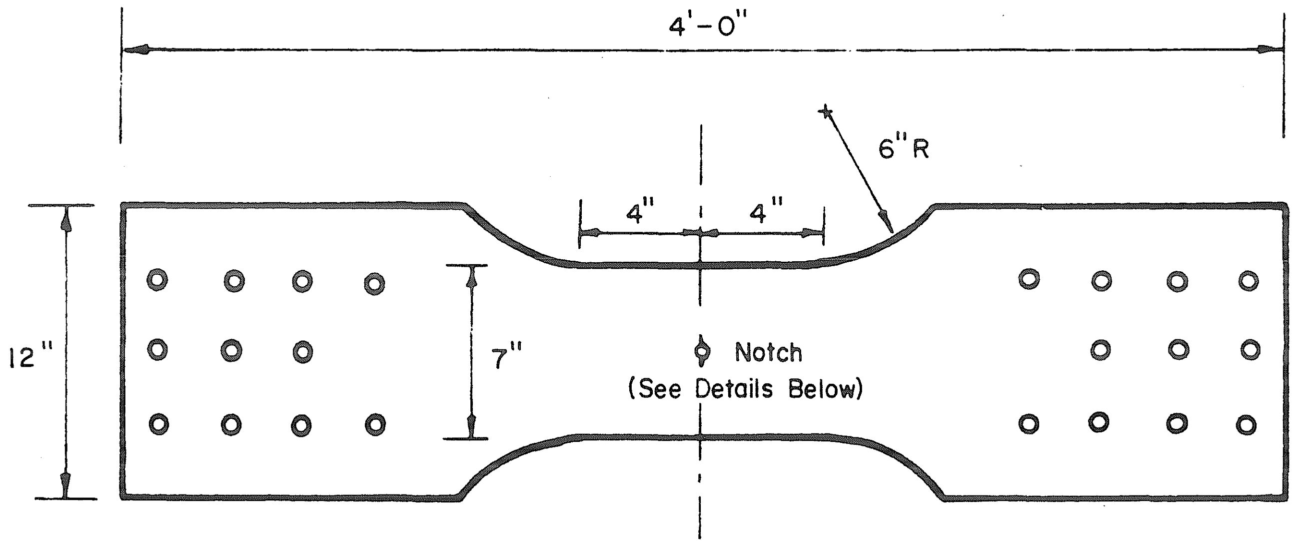
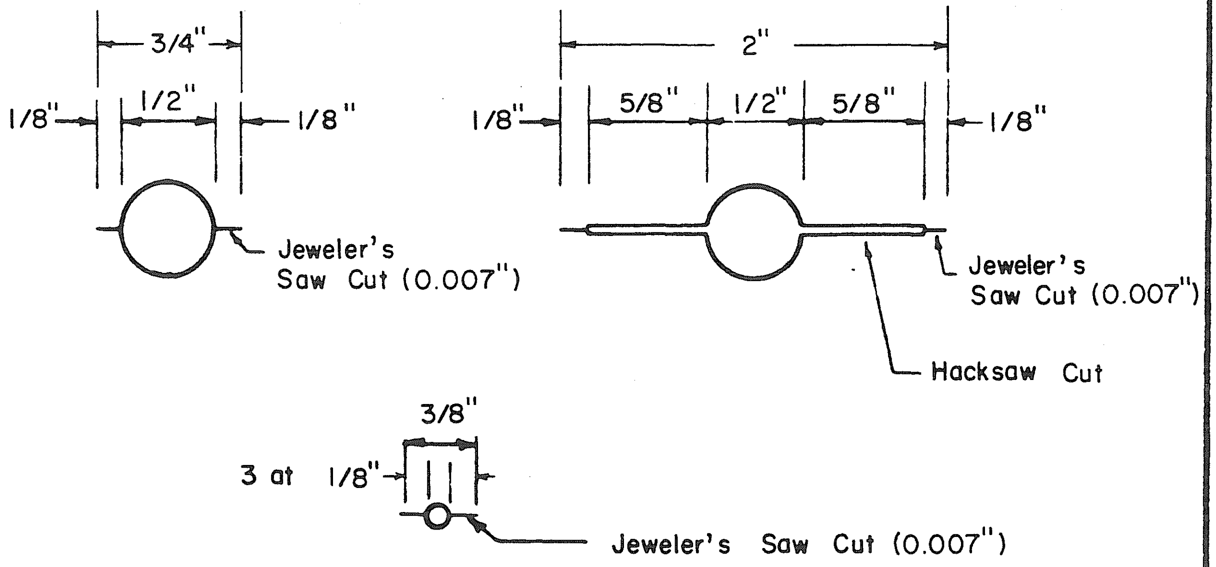


FIG. 2 ILLINOIS 200,000 LB FATIGUE MACHINE

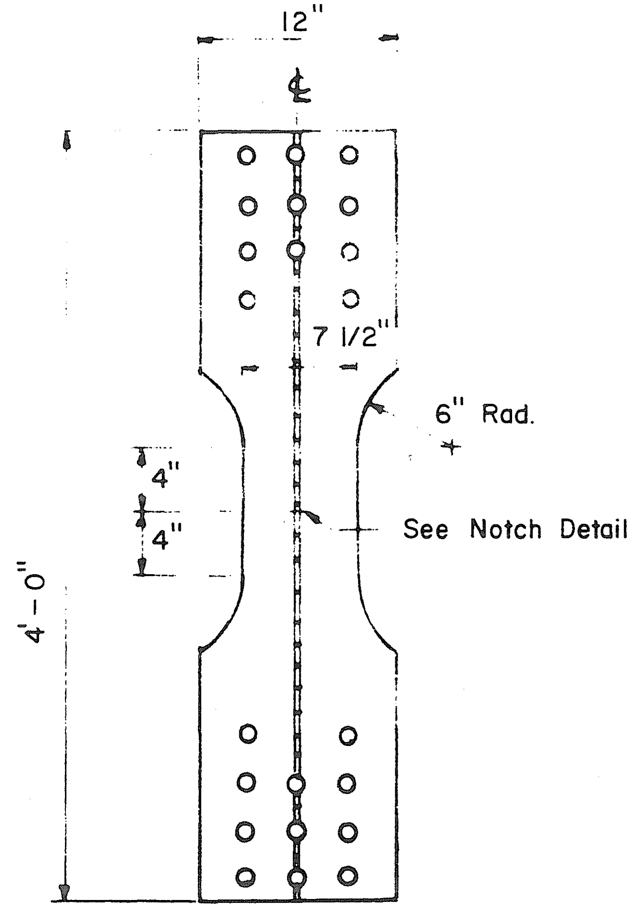


(a) Specimen Layout

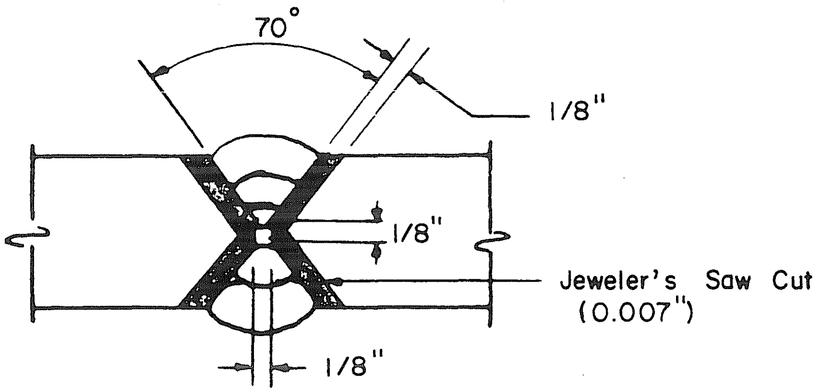


(b) Notch Details

FIG. 3 SPECIMEN DETAILS FOR FLAT PLATE TESTS OF ABS CLASS C STEEL

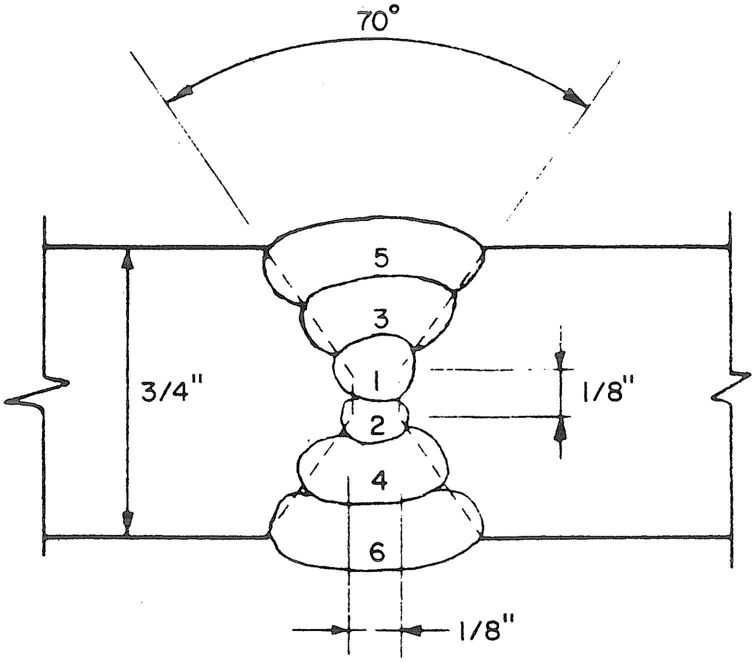


(a) Test Specimen



(b) Notch Details

FIG. 4 DETAILS OF NOTCHED AND WELDED SPECIMENS OF RIMMED STEEL



For all welded plates

Pass No.	Electrode Dia., in.	Arc Speed in./min.	Amps.	Volts
1	5/32	6	140	20
2	5/32	7	170	20
3-6	3/16	5	220	20

Note: Interpass Temperature — 100 deg. F

Electrodes:

for Rimmed Steel	E7016 or E6010
for ABS class C	E7018

FIG. 5 WELDING PROCEDURE AND DETAILS

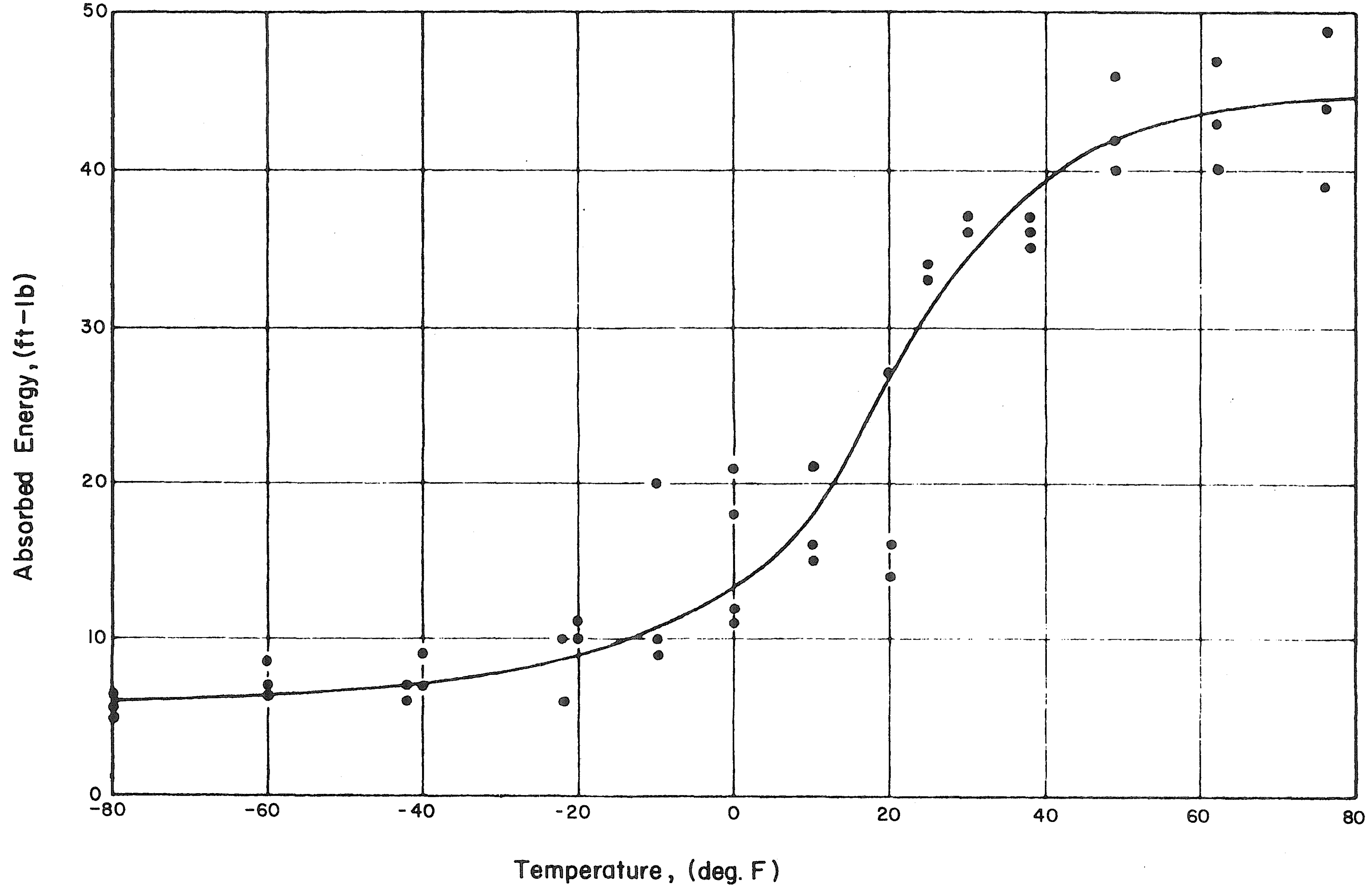
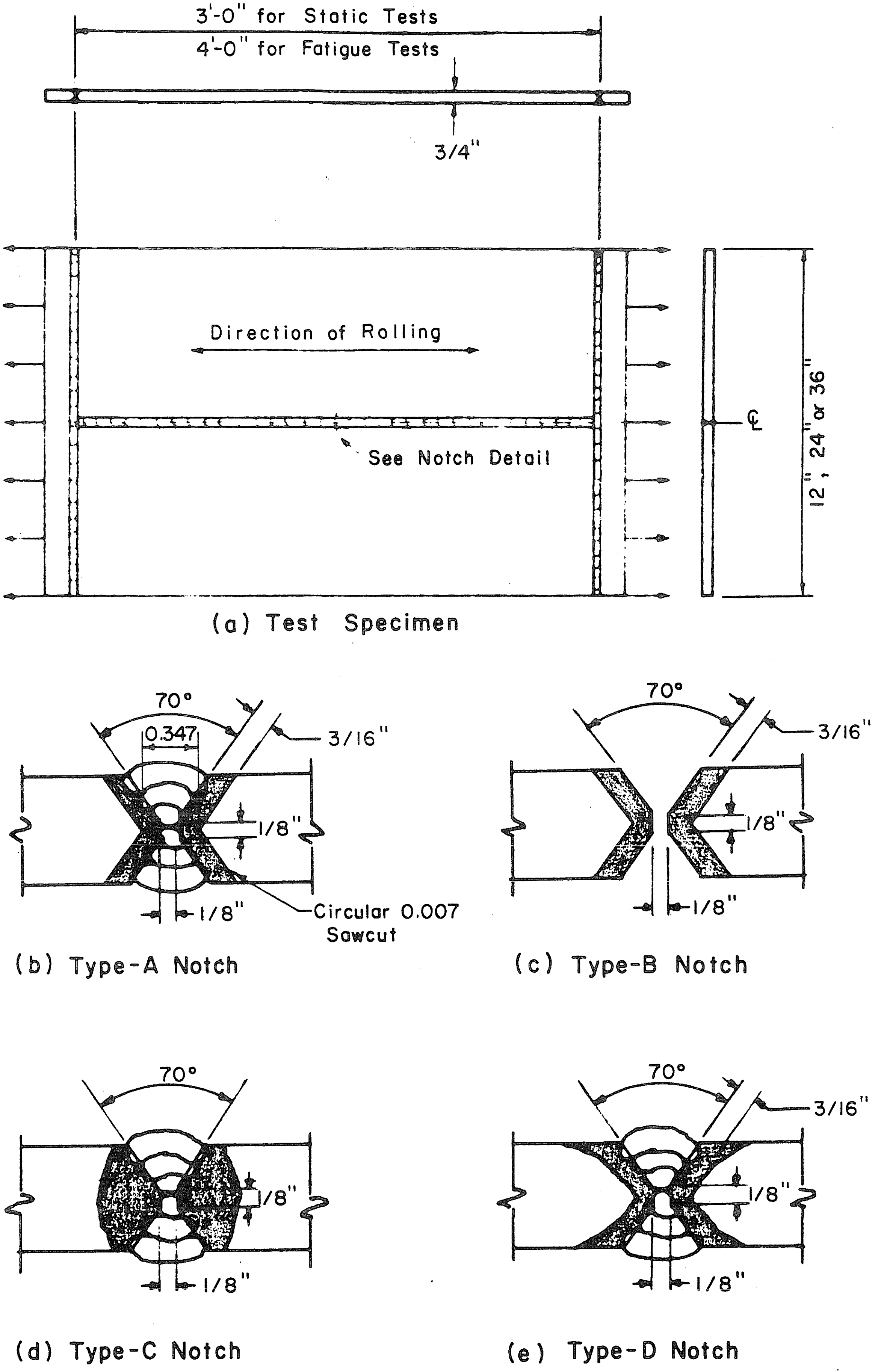


FIG. 6 RESULTS OF CHARPY V-NOTCH IMPACT TESTS FOR ABS CLASS C STEEL



(a) Test Specimen

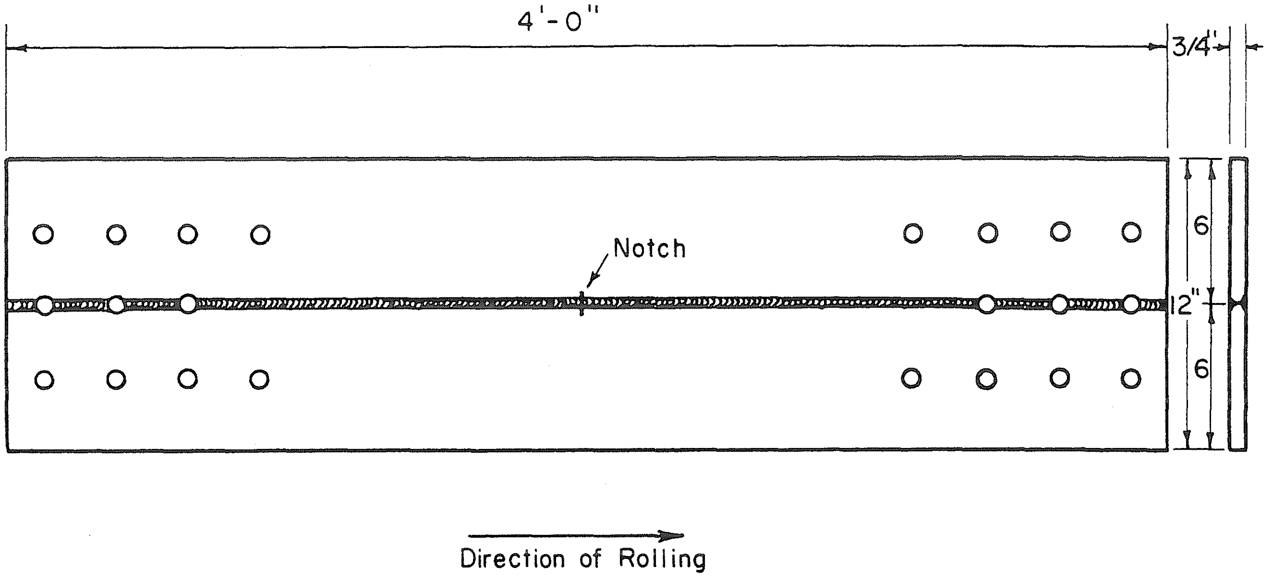
(b) Type-A Notch

(c) Type-B Notch

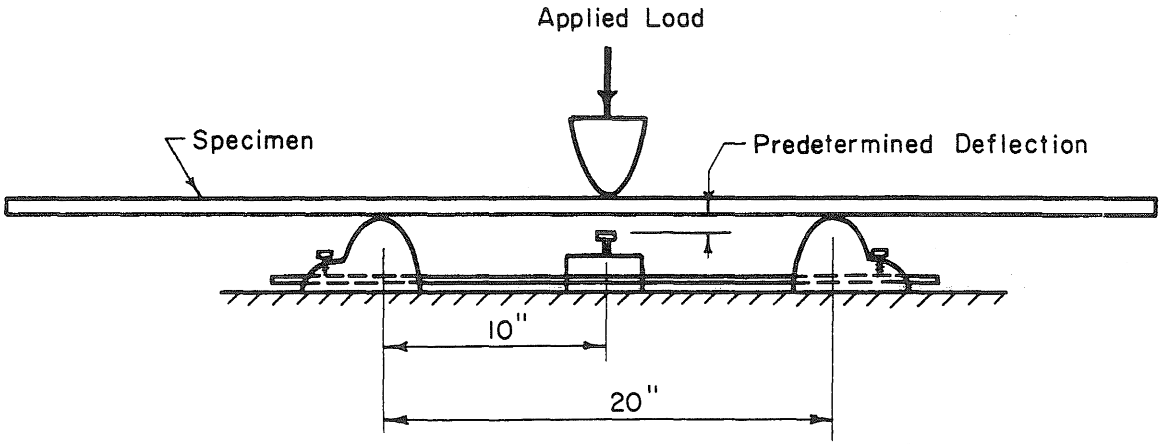
(d) Type-C Notch

(e) Type-D Notch

FIG. 7 SPECIMEN AND NOTCH DETAIL FOR SPECIMENS USED IN PRINCIPAL PROGRAM

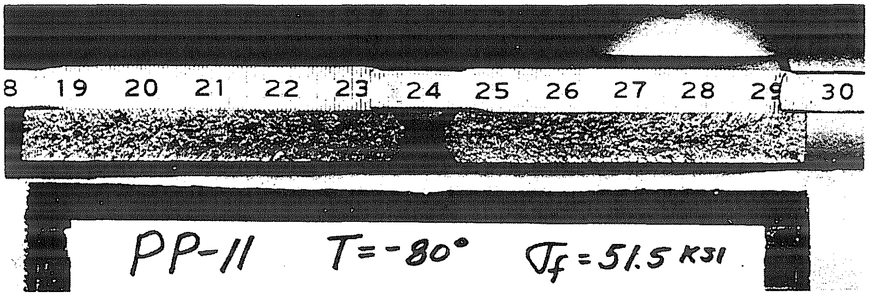


(a) Specimen

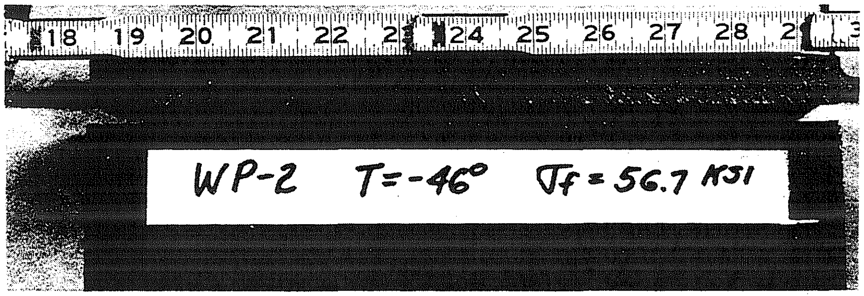


(b) Loading Conditions

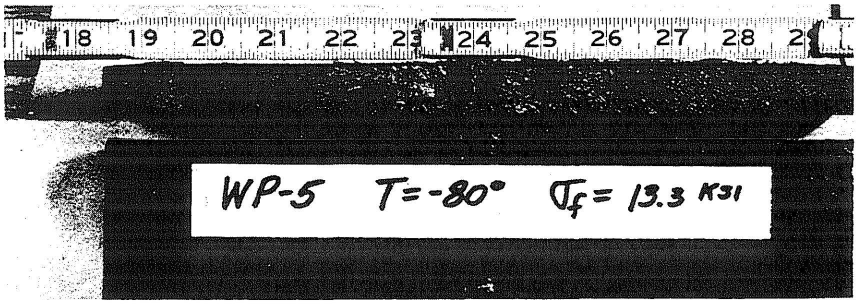
FIG. 8 LOADING CONDITIONS AND SPECIMEN FOR FLEXURAL CYCLING



(a) Specimen PP-11
Plain Plate with Type-B Notch



(b) Specimen WP-2
High Stress Fracture



(c) Specimen WP-5
Low Stress Fracture

FIG. 9 PHOTOGRAPHS OF 12-IN. NON-CYCLED SPECIMENS

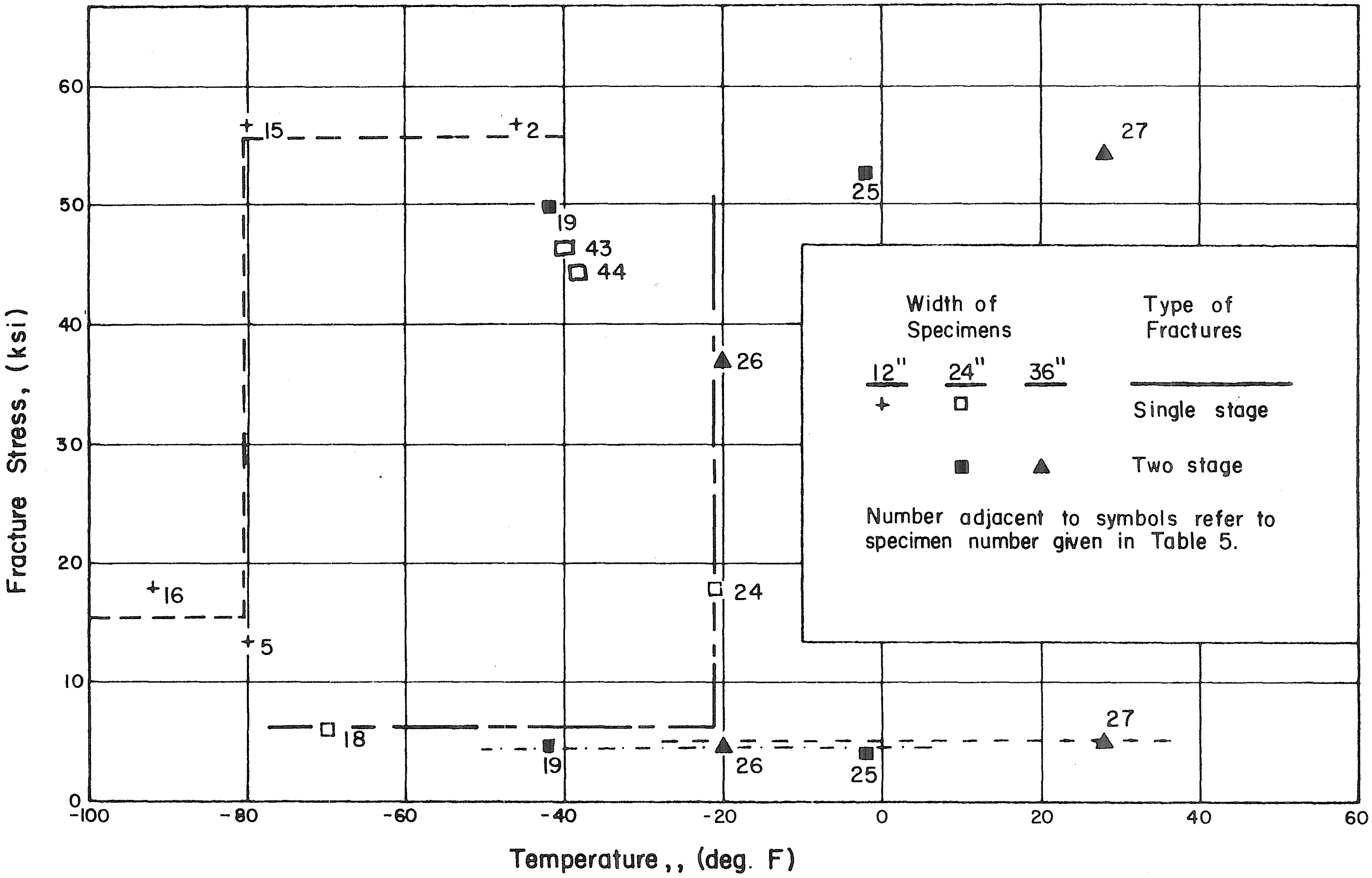
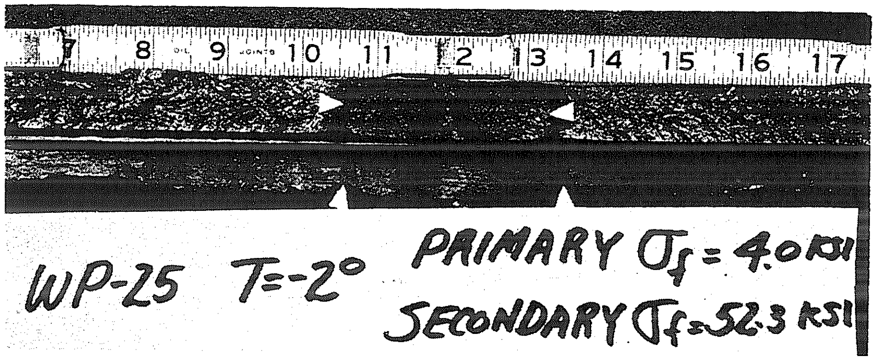
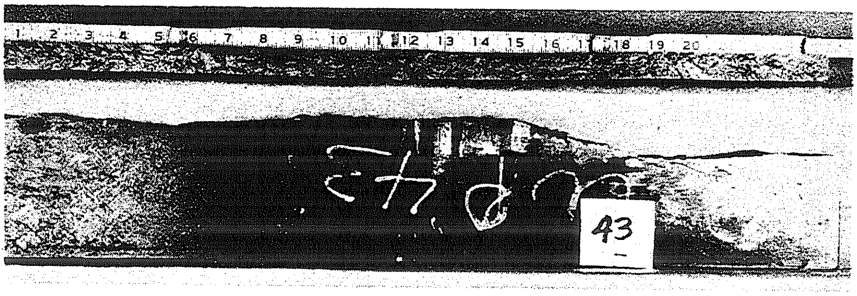


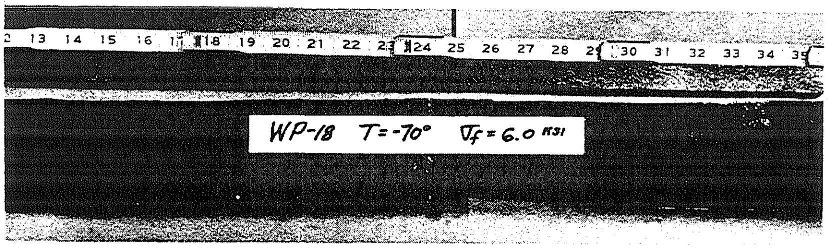
FIG. 10 RESULTS OF TESTS ON NON-CYCLED, WELDED AND NOTCHED SPECIMENS OF 12-IN., 24-IN., AND 36-IN. WIDTHS



(a) Specimen WP-25
Two-Stage Fracture

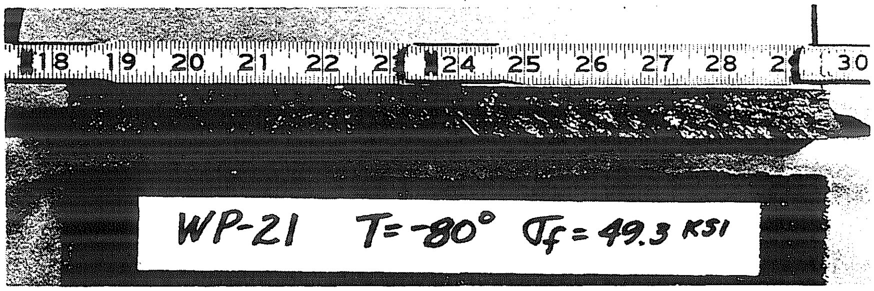


(b) Specimen WP-43
Single-Stage High Stress Fracture

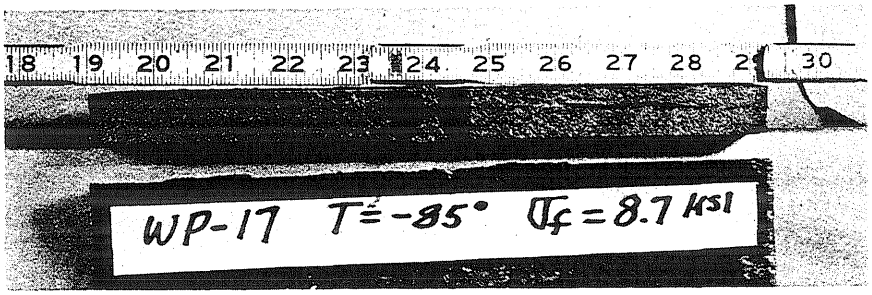


(c) Specimen WP-18
Single-Stage Low Stress Fracture

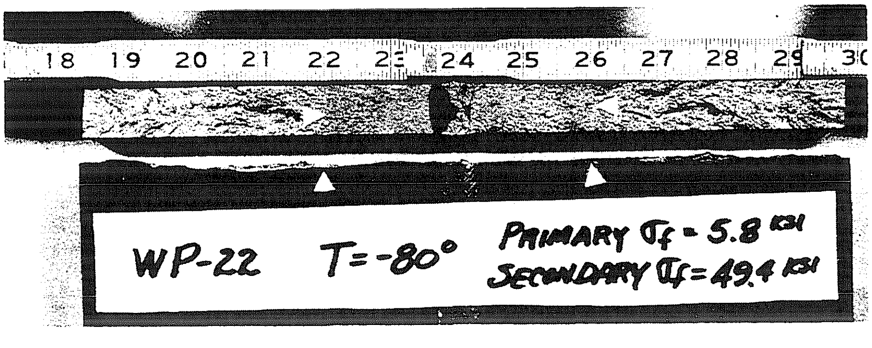
FIG. 11 PHOTOGRAPHS OF 24-IN. NON-CYCLED SPECIMENS



(a) Specimen WP-21
Cycled in Flexure after Welding, Single-Stage High Stress Fracture



(b) Specimen WP-17
Cycled in Flexure before Welding, Single-Stage Low Stress Fracture



(c) Specimen WP-22
Axially Cycled before Welding, Two-Stage Fracture

FIG. 12 PHOTOGRAPHS OF 12-IN. PLATES SUBJECTED TO REPEATED LOADS

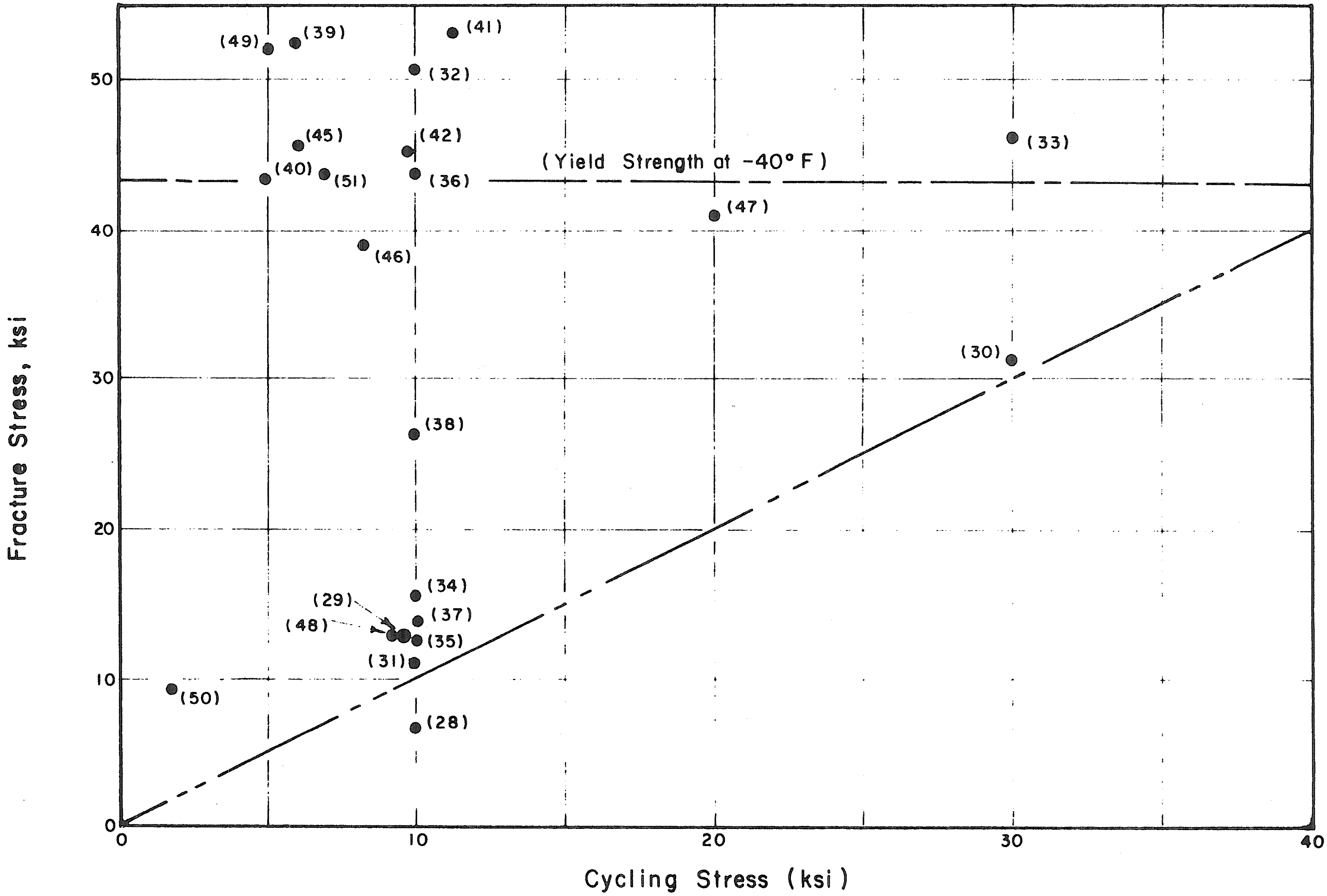
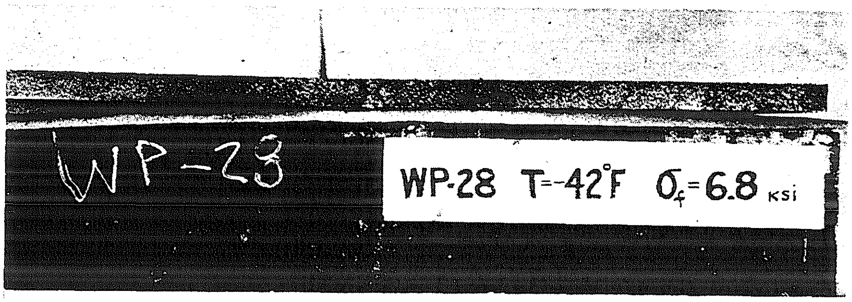
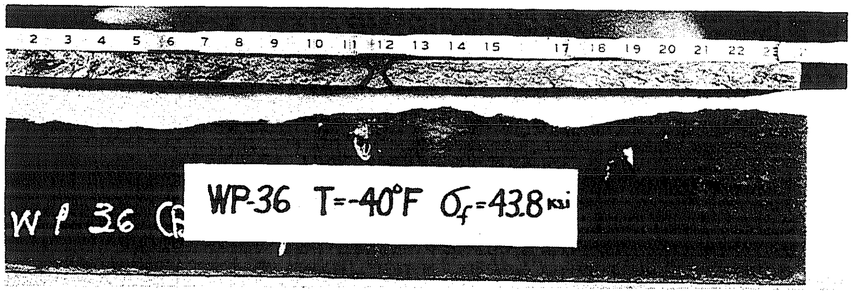


FIG. 13 FRACTURE STRESS vs. CYCLING STRESS FOR 24-IN. WELDED AND NOTCHED PLATES



(a) Specimen WP-28
Low Stress Fracture



(b) Specimen WP-36
High Stress Fracture

FIG. 14 FRACTURE SURFACES OF 24-IN. SPECIMENS SUBJECTED TO REPEATED LOADS BEFORE TESTING TO FAILURE.

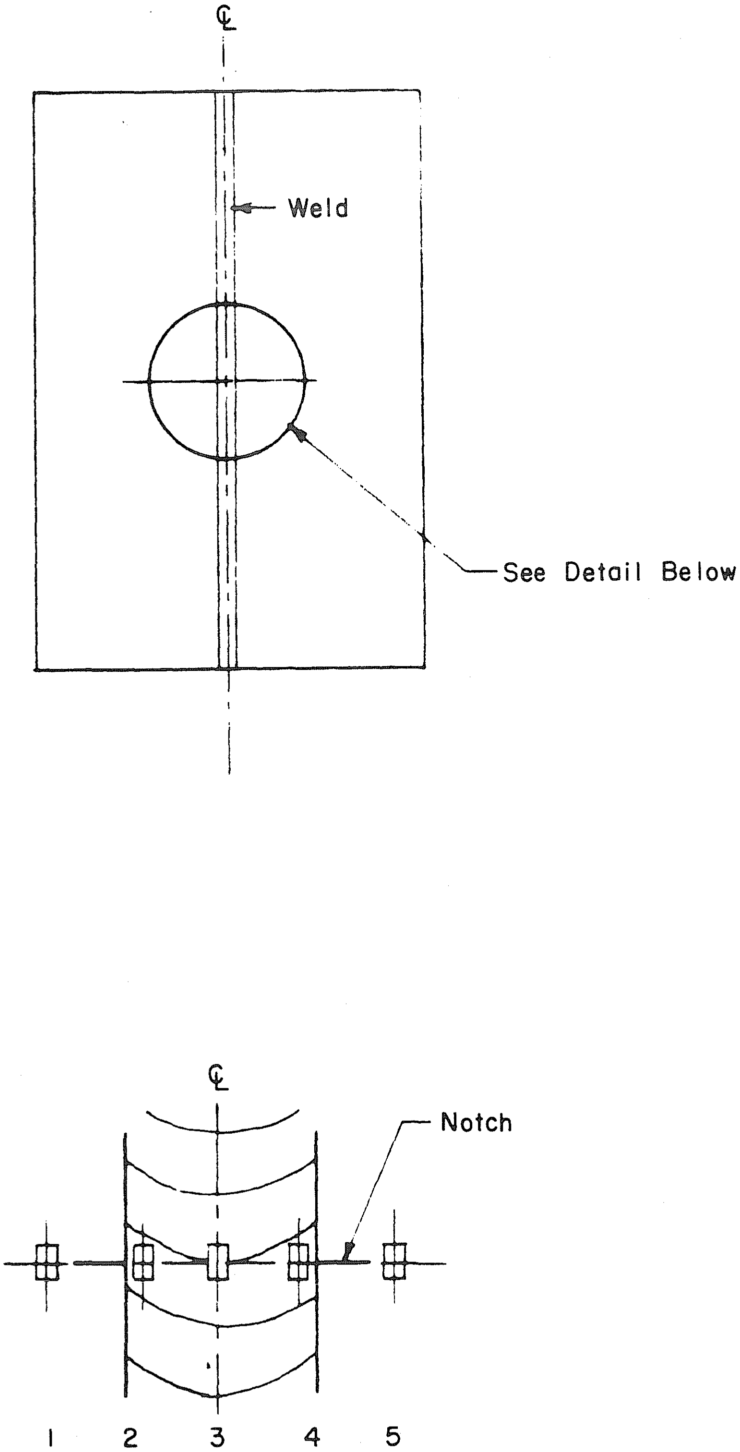
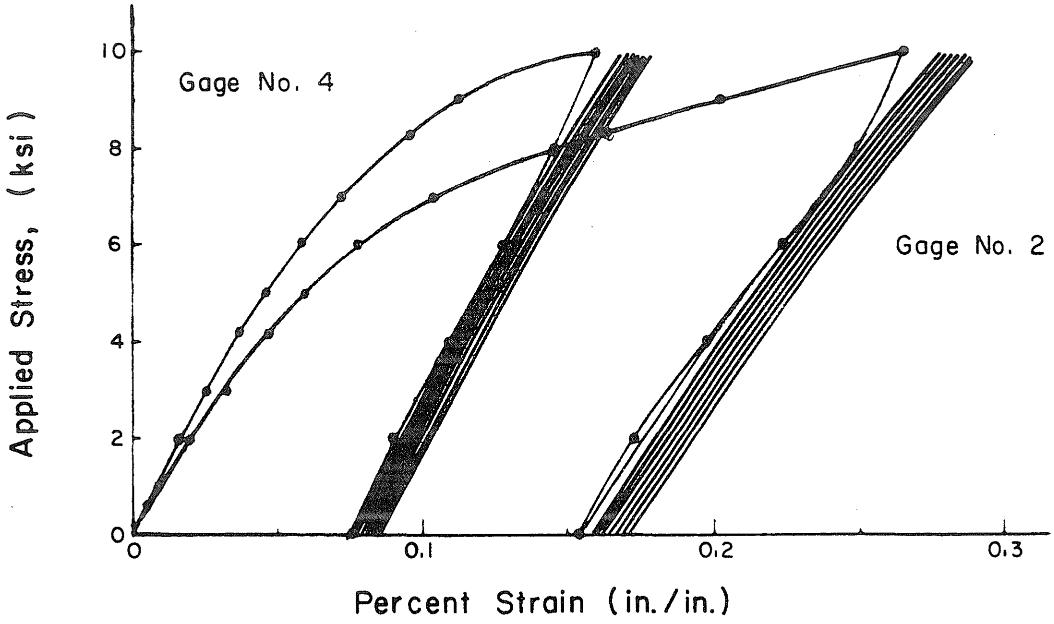


FIG. 15 DETAILS OF STRAIN GAGE LOCATIONS FOR 24-IN. WIDE, WELDED PLATES



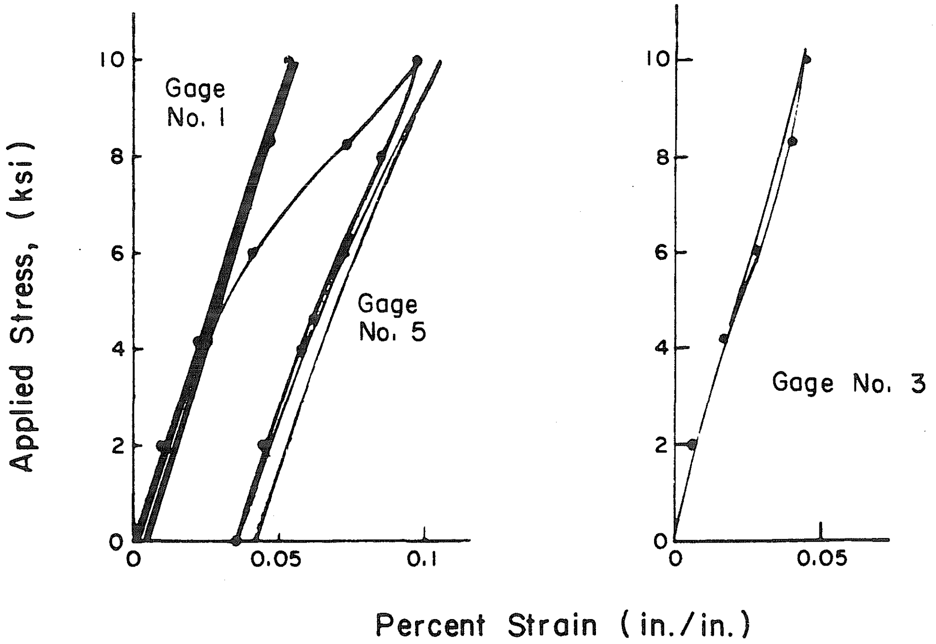
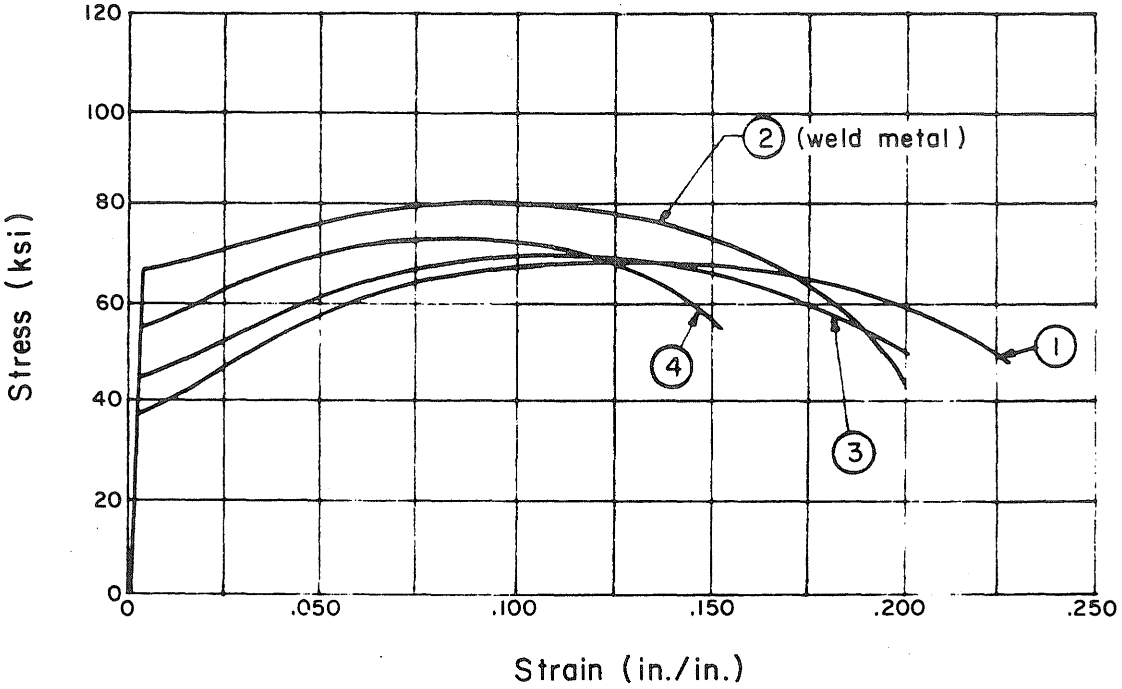
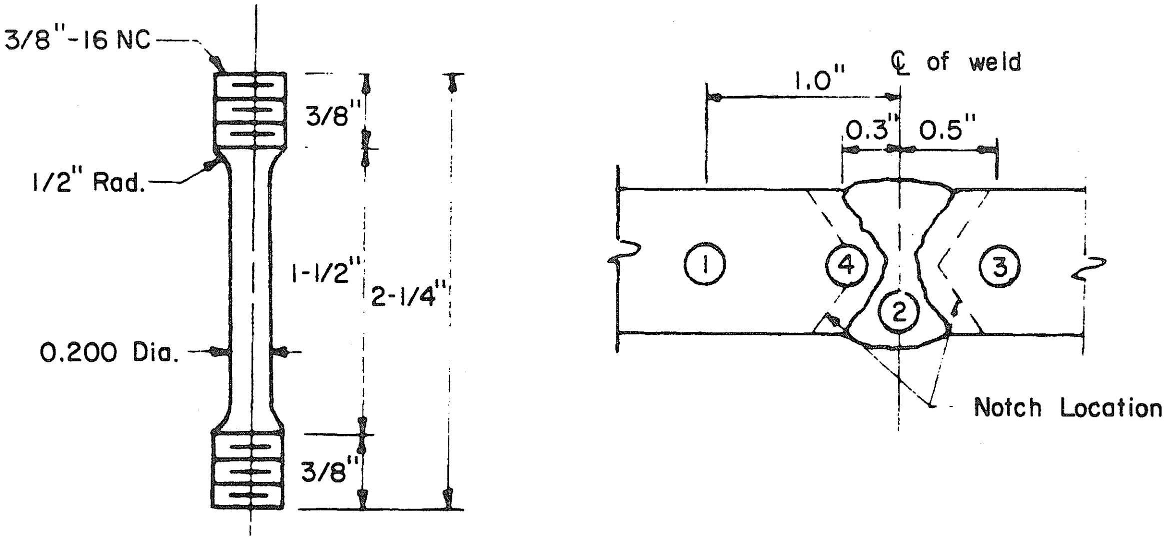


FIG. 16 APPLIED STRESS vs. PERCENT STRAIN FOR 50 CYCLES OF LOADING AS INDICATED BY STRAIN GAGE MEASUREMENTS ON SPECIMEN WP-28



Stress vs. Strain Curves for the Tensile Specimens



Tensile Specimen

Details of Specimen Location

FIG. 17 MATERIAL PROPERTY VARIATIONS IN THE VICINITY OF THE NOTCH