SSC-188

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

SHIP STRUCTURE COMMITTEE

October 1968

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October 1968

Dear Sir:

For many years the hypothesis has been considered that cracks may well be generated from a few cycles of loading while under high stresses. To explore this theory, a study was undertaken at the University of Illinois. Herewith is a copy of the final report from that study entitled *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.

This report is being distributed to individuals and groups associated with or interested in the work of the Ship Structure Committee. Comments concerning this report are solicited.

Sincerely,

D. B. Henderson

D. B. Henderson
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC - 188

Final Report

on

Project SR - 149

"Low-Cycle Fatigue"

to the

Ship Structure Committee

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

by

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Department of the Navy
Naval Ship Engineering Center
Contract Nobs 88283

U. S. Coast Guard Headquarters
Washington, D. C.

October 1968

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.

CONTENTS

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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 affected by 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, i.e. 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 on a broader scale the influence of repeated loadings on the low-temperature fracture behavior of one particular steel, namely ABS-C, ship-steel weldments. Two other steels were introduced for comparison purposes.

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 low-stress brittle fracture (b) the effect of residual stresses on the behavior of weldments at low temperatures (c) other possible effects of repeated loadings.

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. Since these specimens did not develop low-stress brittle fractures, the emphasis in the balance of the program was placed on studying the effect of repeated loadings on the low 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 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.

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. PILOT TEST PROGRAM

In order to provide some preliminary information on the behavior of centrally notched and fatigued cracked specimens when subjected to various combinations of repeated and static loading history and temperature, several pilot test series were run. The results of these pilot tests were to guide the character of the test in the principal program.

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 steel, ABS-class C as rolled, and HY-80, a heat treated high-strength steel. The mechanical properties and chemical compositions of these steels are summarized in Table 1.

* Deceased

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 Composition - 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).

2.1.2 Plain Plates of Rimmed Steel and HY-80 Steel:- Notched plain plate tensile specimens 3/4- in. thick, 10-in. wide X 48" long were used in the first series of pilot tests on rimmed steel and HY-80 steel. The notch, see Figure 1, was placed in each of these specimens to provide early crack initiation and consisted of a 5/8-in. diameter 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. Total length of the notch was 2½".

The specimens in this series were first subjected to repeated cyclic 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 results of the tests. The test results were judged on the basis of temperature at fracture.

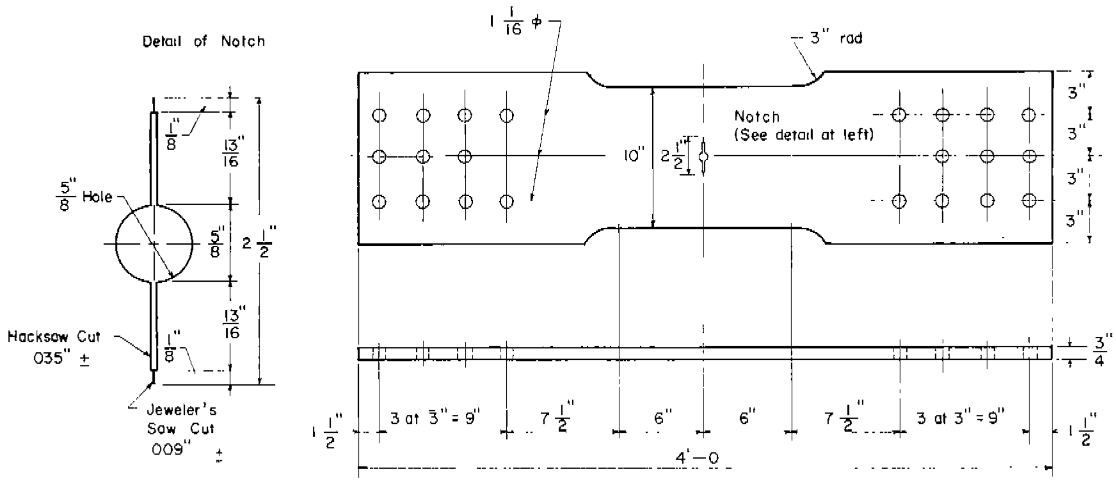


Fig. 1 Details Of Plain Plate Specimens Of Rimmed And HY-80 Steels.

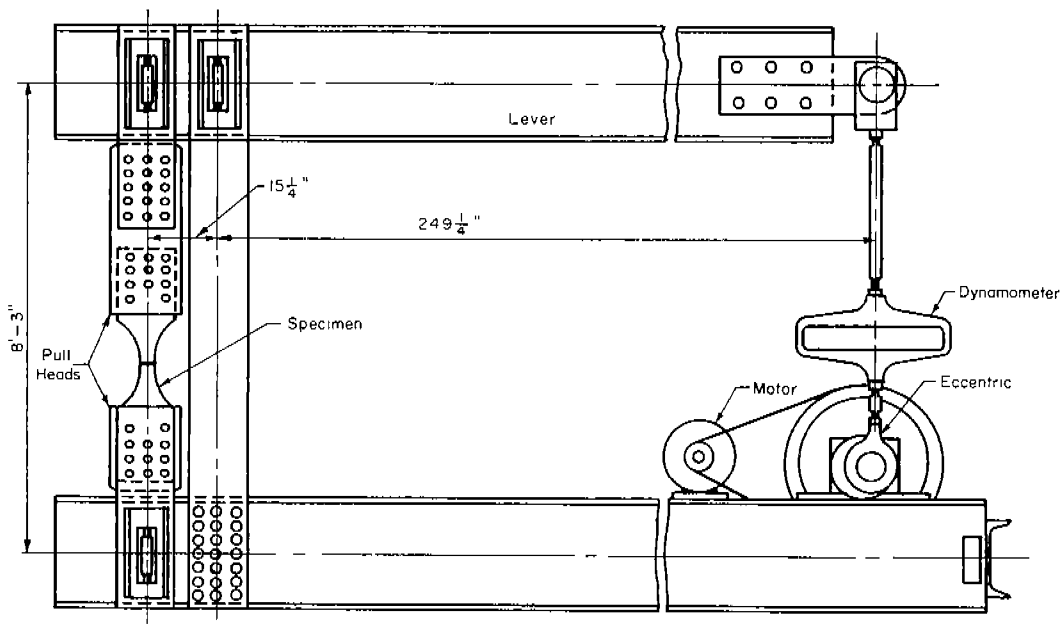


Fig. 2 Illinois 200,000 LB Fatigue Machine.

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.

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 the initial notch had been extended by approximately 2 1/2-in. Two of the specimens, R-3A-2 and R-3A-3, tested at -15°F and -17°F, failed in a brittle manner. Two others tested at +20°F and + 107°F failed in a ductile mode. At the time of failure the average fracture stress was approximately +38 ksi for all specimens. Thus, the failures have been classified as high-stress fractures.*

The brittle 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 surfaces of the ductile failures appeared dull and fibrous and sloped at an angle of approximately 45° to the plate surfaces. Furthermore, the elongation of these specimens was noticeably greater than that of the specimens that failed in 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 depending on the temperature at which failure occurred.

This series included two specimens of HY-80 steel, R-H-1 and R-H-2, subjected to the same magnitude of cyclic loads at temperatures of approximately +75° and -75°F. Both failed

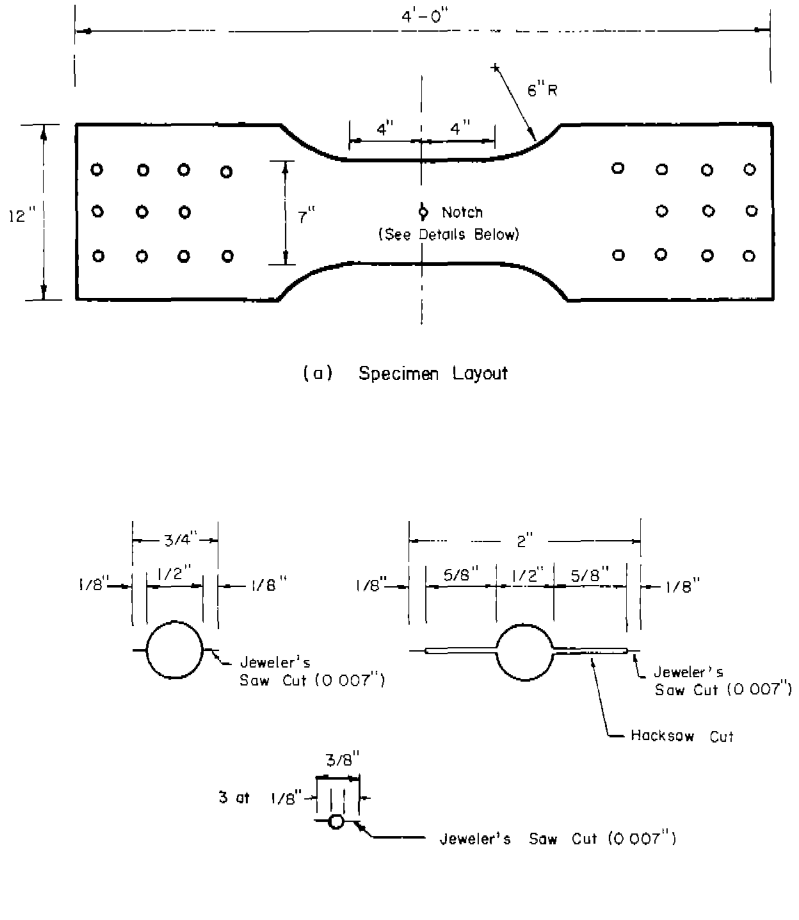
* High-stress brittle fractures are considered to be those which initiate at average applied stresses at or above the yield strength of the material.

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 of the net widths, the average fracture stress at failure was approximately 85 kips.

2.1.3. Plain Plates of ABS-Class C Steel:- The second series of pilot tests embrace five 7-in. wide notched plain plate specimens of 3/4 -in. thick ABS-class C steel, each containing a centrally located notch and tested at room temperature. Notches of three different lengths were used in these specimens. The design of the specimen and the notch variations are shown in Fig. 3.

The specimens 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, was aged before being subjected to repeated loadings.

All of the fatigue cracked specimens were then tensile tested to failure at temperatures ranging from -20°F to -50°F. Three were subjected to a single axial loading and failed in a brittle manner at a relatively high fracture stress. The two remaining plates were subjected to increasing load in increments of 2.5 ksi and, after each increment of loading and while under load, were struck on the surface near the notch by a hammer which



(a) Specimen Layout

(b) Notch Details

Fig. 3 Specimen Details For Flat Plate Tests Of ABS Class C Steel.

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, Specimens RC-2, RC-3, and RC-6, aged after repeated loading and specimen RC-13, aged before repeated loading.

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

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

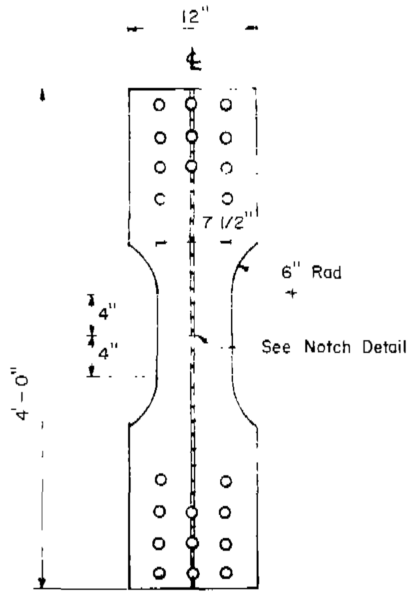
provided a 30 or 50 ft.-lb. blow; both also exhibited high-stress brittle fractures. The results of the tests are given in Table 3.

2.1.4. Welded plates of Rimmed Steel:- The third series of pilot tests embraced seven welded specimens fabricated from 3/4-in. plates of rimmed steel. The design of the specimen and notch and the welding procedures are given in Fig. 4 and 5. The notch shown in Fig. 4 was chosen because other investigators, using similar notches, had successfully produced low-stress fractures in laboratory studies of welded plates.

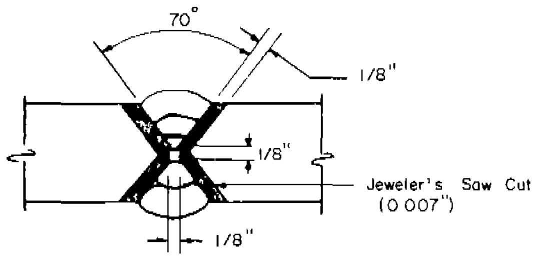
The specimens were subjected to cyclic loading of ± 140 kips (± 25 ksi based on the gross area of the specimens) at temperatures ranging from -61°F to + 250°F. The temperatures rose during testing and test results were judged by the temperature at the time of failure. The testing conditions and test results are given in Table 4.

In six of the seven tests 3 to 4 in. long fatigue cracks had developed before final 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 and thus appeared to be more nearly a low-stress brittle fracture.



(a) Test Specimen



(b) Notch Details

Fig. 4 Details Of Notched And Welded Specimens Of Rimmed Steel.

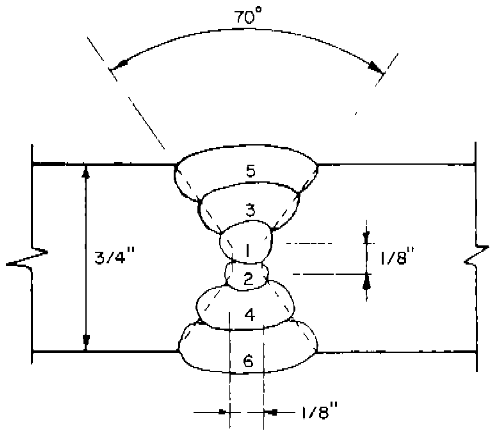
The principal observation that can be made from these pilot runs was that low-stress brittle fracture was not developed in 7" and 10" wide unwelded carbon steel plates even after severe fatigue cracking and at testing temperatures down to -50°F. (in HY-80 steel down to -75°F). Brittle appearing fractures were developed on a number of tests but the load at fracture was high, ie., above the normal yield strength of the plate. One notched welded specimen of rimmed steel tested at -61°F developed a low-stress brittle fracture.

It was concluded from these pilot tests that the subsequent testing should be on a wider specimens and at lower temperatures.

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 all tests in the principal test program. The 15 ft-lb. Charpy V-notch transition temperature for this material was



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.

approximately +5 F as shown in Fig. 6.

3.1.2. Specimens: - The 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 third series specimens of the pilot program except in width and in the manner of creating the notch prior to welding. 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:- The testing program involved two steps; introduction of fatigue and testing to failure. Fatigue was developed by repeated loading either axially or in flexure. Final testing to failure was carried out by normal low-temperature tensile testing.

(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

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.

or ± Ksi or ± 22 Ksi and the number of cycles of repeated loads ranged from one cycle to about 40,000 cycles. 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.

The axial repeated load tests on the 24-in. plates were conducted on various zero-to-tension stress cycles only. 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.

(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-sharped notch crack 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

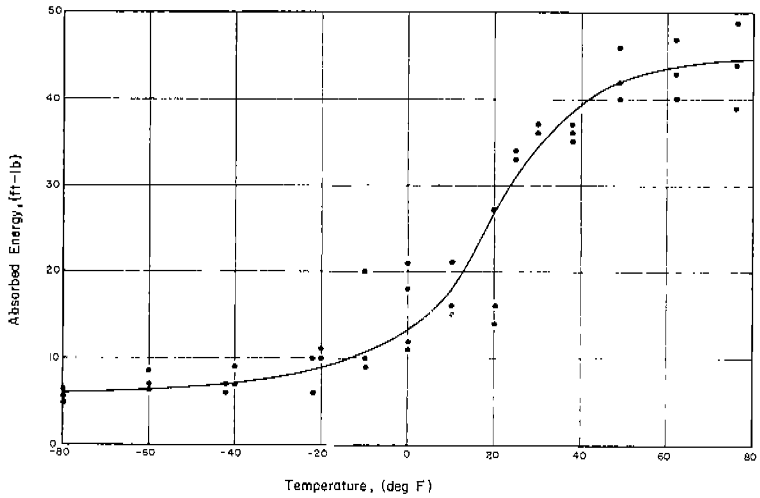


Fig. 6 Results of Charpy V-Notch Impact Tests For ABS Class C Steel.

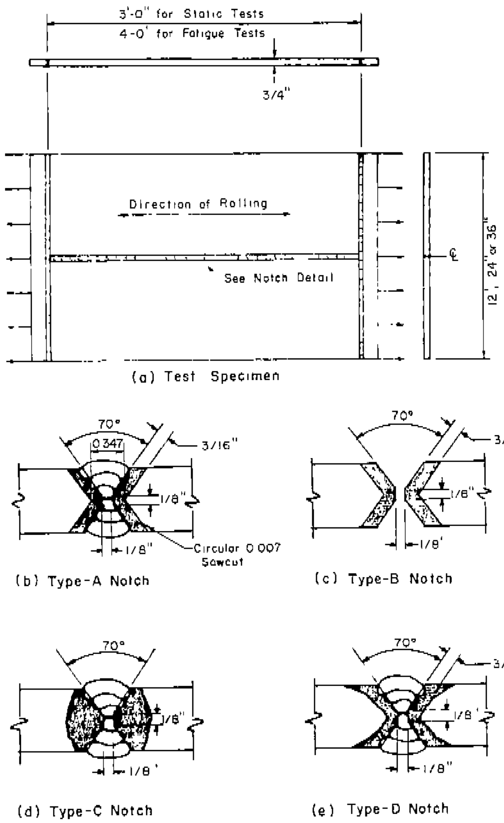
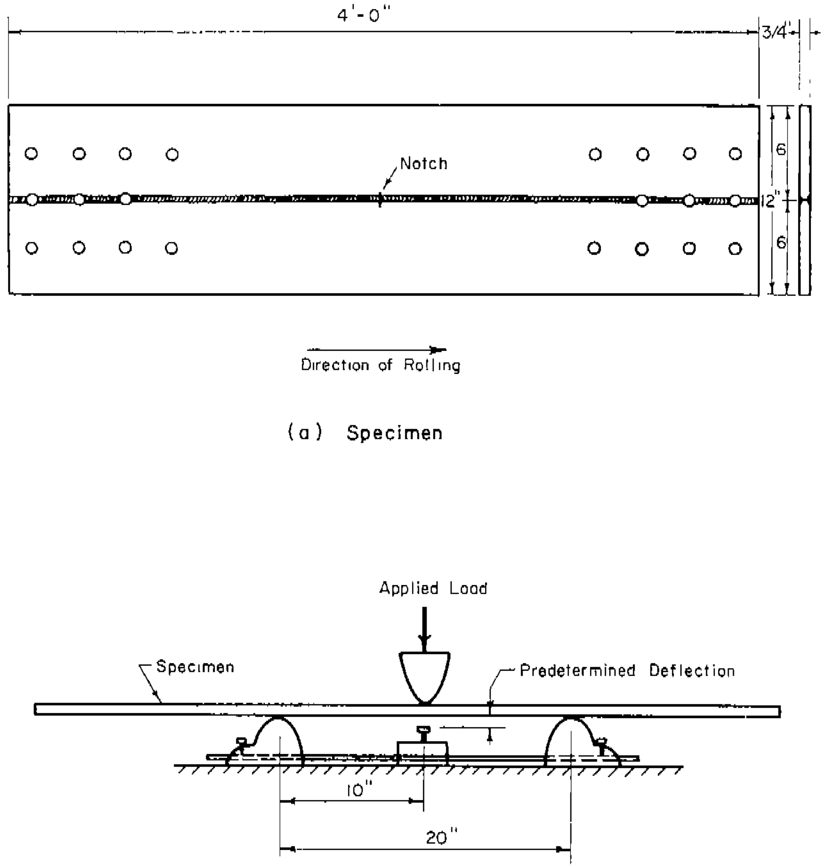


Fig. 7 Specimen And Notch Detail For Specimens Used
In Principal Program.



(b) Loading Conditions

Fig. 8 Loading Conditions And Specimen For Flexural Cycling.

the order of 2 to 5% at mid-span and required from 3 cycles to 40 cycles to propagate the cracks.

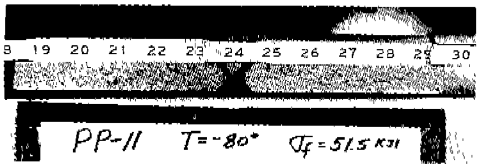
(C) Low-Temperature Tensile Test to Fracture:- Each 12, 24, or 36-in. plate, whether subjected to previous loadings or not, was tested statically to failure at a low temperature. Each specimen was prepared for testing by welding it to a set of pullheads that had already been placed in the testing machine. 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

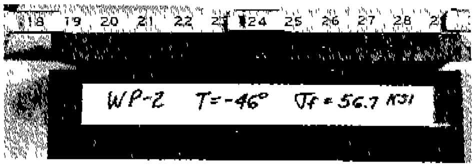
3.3 Non-Cycled Specimen

(a) Non-Welded Specimens: - In order to provide a base line free from the effects of residual stress, one set of 12-in. wide specimens was bevelled, and notched but left unwelded (See Fig. 7c).

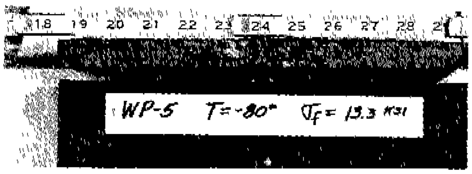
This specimen PP-11 (See Table 5), was tested to failure at a temperature of -80°F and failed in a brittle manner at 51.5 ksi. Thus, an applied stress somewhat greater than the yield strength of the material was necessary to initiate failure in notched ABS-class C steel tested at a temperature 85°F below the Charpy 15 ft.-lb. transition temperature. A photograph of the fracture surface of this specimen is shown in Fig. 9a.



(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.

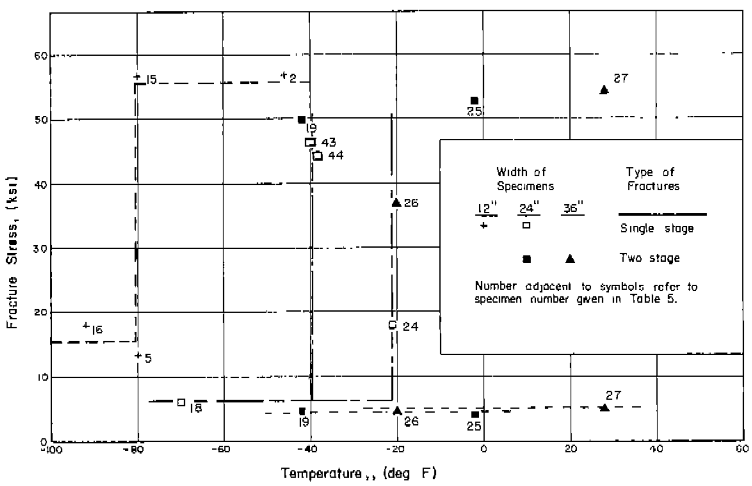


Fig. 10 Results Of Tests On Non-Cycled, Welded And Notched Specimens Of 12-In., 24-In., And 36-In. Widths.

TABLE 5

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

(ABS-Class C Steel)

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

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

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

(b) Welded Specimens:- Four 12-in. wide welded specimens with Type-A notches were tested to failure at low temperatures with test results shown in Table 5. High-stress brittle fractures occurred in two of the specimens 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. On the basis of a plot of these tests (Fig. 10) there appears to be a marked strength transition for the 12-in. notched-and welded plates at about -80°F.

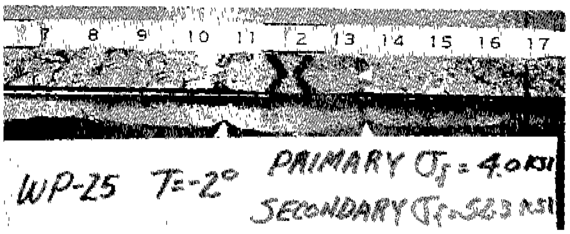
The fractures of the four 12-in. plates, whether at high stress or low stress, were single-stage fractures; that is, the fractures consisted of a single failure which suddenly initiated and propagated completely through the plate Photographs of the fracture surfaces of a high-stress (WP-2) and a low-stress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

Six 24-in. and two 36-in. welded specimens with Type-A notches were also 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, two exhibited low-stress single stage fractures at temperatures of -70°F and -21°F. Two 24-in. plates tested at temperatures of -42°F and -2°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.

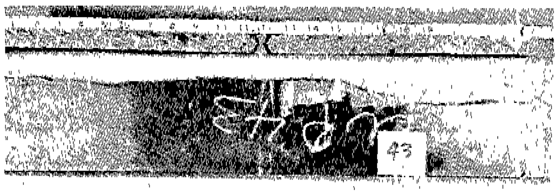
To fracture the remaining portion of the plate a much higher applied stress was required. The first portions of the two-stage fractures were identified by cracking noises and sometimes on the fracture surface of the specimens by an obvious thumbnail arrest pattern marking on the end of the first stage 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. Both 36 in. wide specimens tested at temperatures of -2°F and 28°F exhibited two stage fracture behavior. From a plot of these data it would seem that the strength transition temperature rose with increasing widths being about -80 F for 12", 20°to-40°F for 24", and somewhat higher for 36" wide specimen.

3.2.2. Effects of Repeated Loads - 12" Wide Specimens

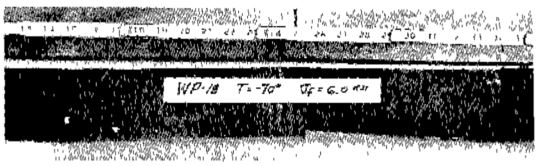
(a) Non-Welded Specimens:- Three 12-in.



(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.

TABLE 6

SUMMARY OF RESULTS - 12-in. WIDE, WELDED AND NON-WELDED NOTCHED 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) Notched Welded Specimens				
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) Notched Welded Specimens Strained Before Welding				
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).

wide, non-welded plates with Type - B notches were subjected to repeated axial loads to study the effects of residual stresses or other variables introduced by welding. The results of these tests are given in Table 6 and compare with axial specimen PP-11, see Table 5.

One specimen (PP-12) was subjected to a loading sequence selected to produce plastic strains at the notch simulating those resulting from welding. This straining of course was cold, hence, did not completely duplicate welding straining. The plate was then loaded to failure at a temperature of -84° and fractured at 50.1 ksi.

The other two specimens 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 -80 F. These members fractured at stresses of +50.5 and +52.7 ksi, respectively.

Neither the numbers of cycles, the aging treatment, or the magnitudes of loadings developed in these test produced visible fatigue cracks nor did they produce a fracture behavior or fracture appearance that differed from that of the, non-cycled plate PP-11, repeated loading under these conditions therefore did not seem to be detrimental.

(b) Welded Specimens:- Ten 12-in. wide welded plates with Type-A notches were subjected to repeated axial or, in one case, flexural loading 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.

One specimen subjected to a single cycle of axial loading from 0 to +38.5 ksi, fractured at a stress of +49.2 ksi when tested at a temperature of -43°F. Four specimens 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 crossed 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.

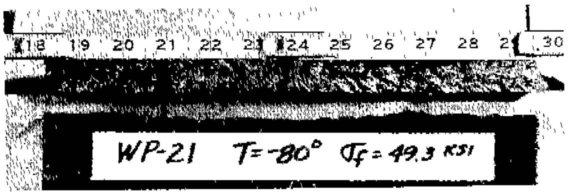
Twelve cycles of repeated flexural loading were applied to one 12-in. specimen. The plate was deflected 1/2-in. in both directions, with the resulting maximum plastic strain being ± 2.5%. A fatigue crack resulted from this loading and propagated first into the weld and then into the base metal. This 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.

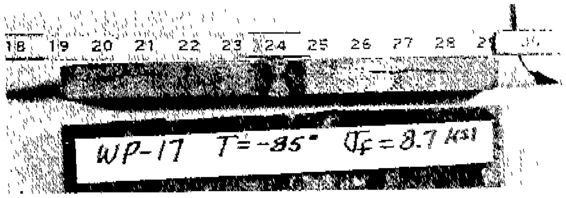
In summary, the results of the tests on cycled and non-cycled 12-in. wide notched-and welded plates, Tables 5 and 6, suggest that the repeated loads lowered the strength transition temperature of these specimens. In the uncycled condition 2 low-stress failures out of 4 tests occurred at -80°F but in the cycled condition no low stress failures occurred out of 7 tests at that temperature.

(c) Specimens Cycled Before Welding:- To get some indication of the effect of cycling before welding, three 12-in. wide, notched plates were subjected either to axial or flexural repeated loads and then welded. There were therefore comparable to specimens PP-12, 13, and 14, but with subsequent welding. 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 tests on these specimens are presented in the lower portion of Table 6.

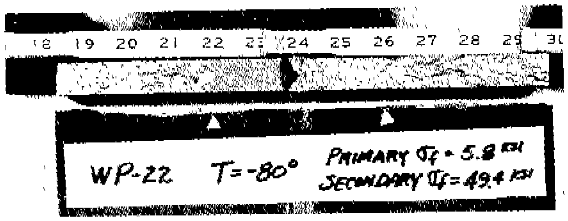
In Specimen WP-17, surface cracks approximately 1/16-in. long developed during the 3 cycles of loading on both surfaces at the tip of each notch. The V-fronts of the notches retained their shape during cycling; however, during welding short cracks propagated outward from the V-notch at the center of the plate, thereby destroying the V-shaped fronts of the notch (See Fig. 12b). When tested axially at



(a) 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.

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 fractured at +48.3 ksi. 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 from which Specimen WP-22 was prepared, had a Type-B notch cut into each outside edge and was subjected to 38,000 cycles of axial loading at $\pm$ 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. The plate was then bevelled on the notched edges and split down the center; the two bevelled edges were placed adjacent and welded longitudinally along the bevelled and notched edges. The specimen was 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, at the testing temperature of -80° to -85°F. It is worthy of note that all three specimens had developed appreciable cracking as compared to specimens in the previous notch welded series.

3.2.3 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, as approximating the strength transition of those specimens. 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 measured 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.

(a) Results of Tests:- Two of the eight 24" wide specimens, subjected to "Stress-controlled" cycles of 0 to +10 ksi, 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. These results, 6 low-stress failures out of 10 tests, quite clearly confirm the previous tests on non-cycled specimens that a strength transition exists in 24" wide welded and notched specimens at about -40°F. There is however, less evidence that the cycling was beneficial, as had been the case with the 12" wide specimens. The choice of testing temperature at -40°F may have been critical in this. In the case of the "strain-controlled" tests, high stress failures occurred in 8 cases and low stress failure in 3 instances, all being single-stage fractures.

In all but one instance the fracture stresses for the 24-in wide plates were greater than the stresses to which the members had been previously subjected at room temperature.

The relationship between the repeated-load stresses and the fracture stress at -40°F 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. There seemed to be good indications that submitting the notched specimens to cyclic loading of higher than 10 ksi at room temperature, which was above the transition temperature, was benificial in testing at -40°F. This improvement is in the same direction as as found for the 12" wide specimen.

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. 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, may have 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. Typical fracture surfaces of two 24-inch specimens are shown in Fig. 14.

(b) 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 the Fig. 15. These gages were then monitored during the application of the repeated loads. The resulting data indicate the existence and amount 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.

The largest plastic strains were recorded on the weld side of the notch. For a nominal plate stress of 10 ksi, the plastic strains in this region were generally on the order of 2000 micro-inches per inch (a strain concentra-

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 at failure, (%)[(2)]
WP-28	0 to +10	50	1,710	6.8	0.020
WP-31	0 to +10	1	-	11.0	-
WP-32	0 to +10	100	-	50.7[(1)]	-
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-47	0 to +20	1	-	41.0	0.130
WP-30	0 to +30	1	-	31.2	-
WP-33	0 to +30	100	-	46.5	-
WP-50	0 to +3.44	10,600	2,450	9.4	0.020
WP-40	0 to +4.95	1	4,515	43.5	0.208
WP-49	0 to +5	11,500	630	52.0	1.275
WP-39	0 to +6	1	2,070	52.8	0.640
WP-45	0 to +6	1	340	45.6	0.281
WP-51	0 to +6.9	1	1,700	43.8	0.695
WP-46	0 to +8.2	1	260	39.0	0.140
WP-48	0 to +9.2	1	1,420	12.7	0.042
WP-29	0 to +9.5	1	1,040	12.7	0.026
WP-42	0 to +9.6	10,000	3,325	45.3	-
WP-41	0 to +12.65	1	2,470	53.3	-

(1) WP-32 received one additional loading of 37.3 ksi at -40°F 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.

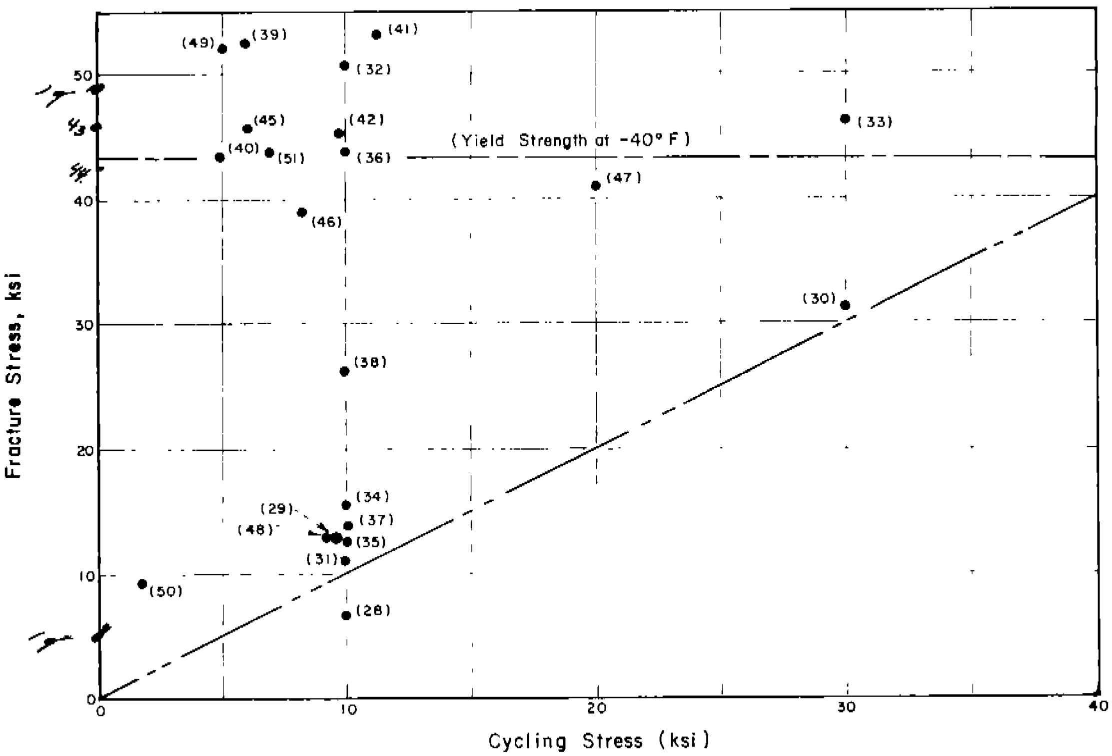


Fig. 13 Fracture Stress vs. Cycling Stress For 24-In. Welded And Notched Plates.

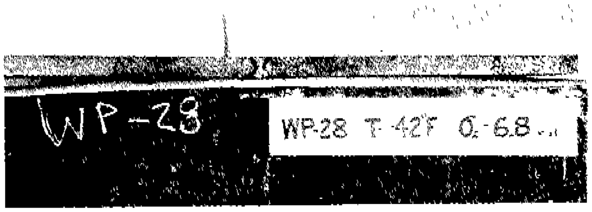
tion of approximately 6); on the base plate side of the notch the plastic strains were in the neighborhood of only 500 micro-inches per inch.

Strains indicated by the gages on the centerline of the weld appeared to remain essentially elastic during cycling to 10 ksi. 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.)

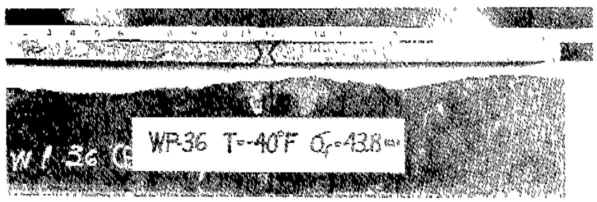
Slight differences in the notch geometry of the specimens were observed despite the careful control of specimen fabrication, but studies of the notch geometry of the specimens did not reveal any consistent relationship between this slight variation in notch geometry, the variations in plastic strains, or the fracture behavior.

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. Futhermore, some of the specimens exhibited cracking during the axial prestraining at a temperature 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]

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 shipbuilding 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



(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.

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.

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.

In the pilot studies on 7 and 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. It was concluded from the pilot tests that the subsequent testing should be on a wider specimen and at low temperatures.

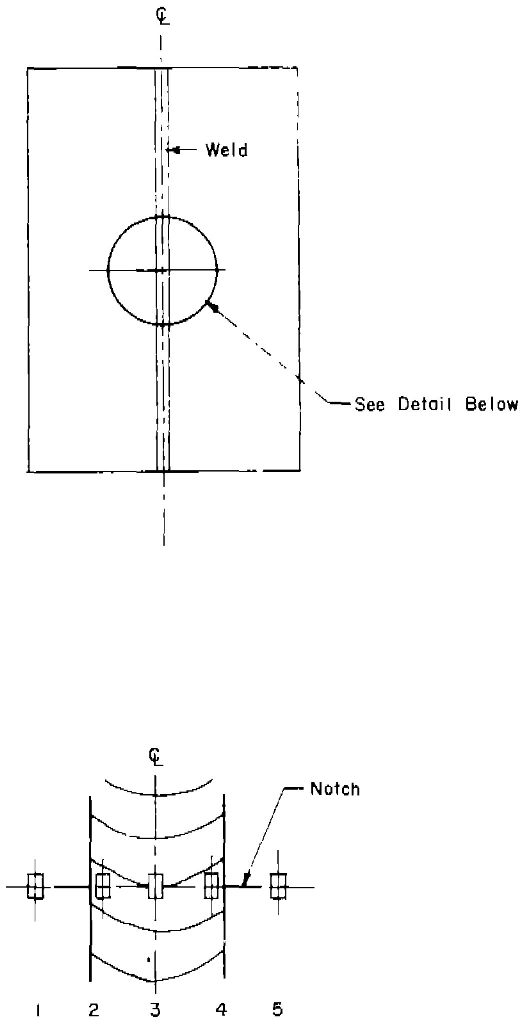


Fig. 15 Details Of Strain Gage Locations For 24-In. Wide, Welded Plates.

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

(a) A 12-in. wide plain notched unwelded plate failed at high stress at -80°F, a temperature 85°F below the 15 ft-lb. Charpy V-notch transition temperature.

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

(c) Tests on 12 -in. wide notched-and welded specimens indicated some benefit in strength transition from cyclic loadings.

(d) 24-in. wide notched-and-welded plates exhibited a strength transition to low-stress single-stage fractures at a temperature of about 40°F.

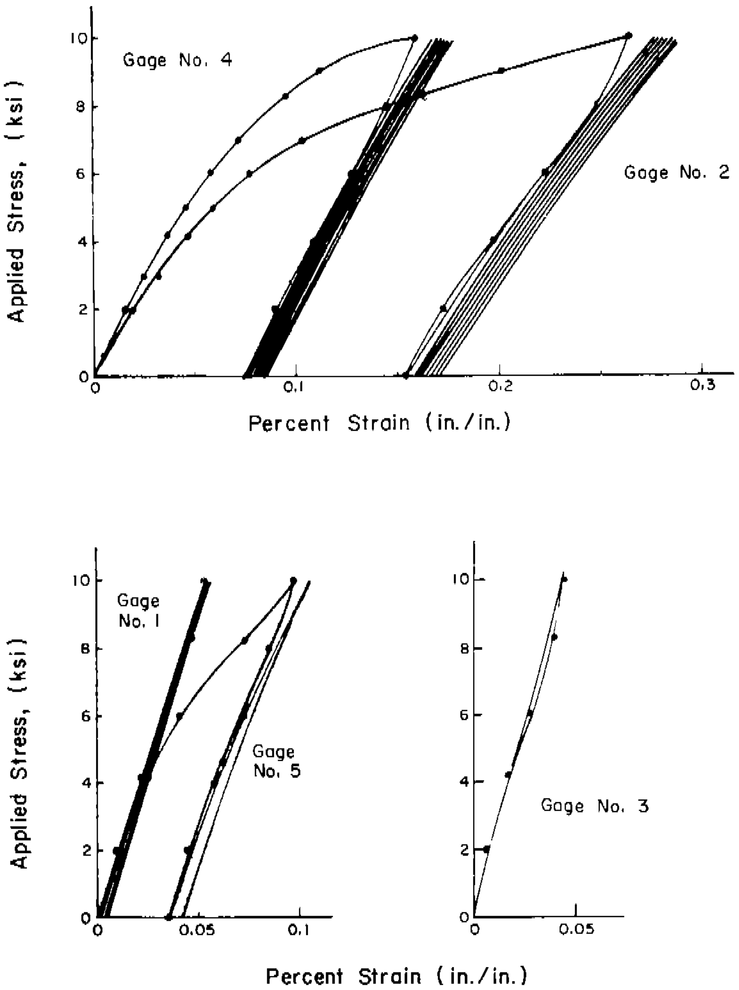


Fig. 16 Applied Stress vs. Percent Strain For 50 Cycles Of Loading As Indicated By Strain Gage Measurements On Specimen WP-28.

Evidence of the benefit or lack thereof from cycling was less clear than for the 12" wide specimen, due possibly to the limit in testing temperature (all fracture tests of cycled specimens were conducted at -40°F)

(e) 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. To benefit adequately from repeated loadings, it appears these loadings must be of sufficient magnitude to overstress the members. (See also Reference 21).

(f) There was some further evidence from studies of the amount and distribution of plastic strain around then notches that significant straining above the transition temperature was beneficial to low temperature testing.

(g) The width of the notched-and welded members had an effect on the ease with which brittle fractures were initiated, the wider the specimen, the higher the temperature at which a particular type of fracture initiated.

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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.

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