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BRITTLE FRACTURE PROPAGATION STUDIES

SSC-148

BY

F. F. VIDEON, F. W. BARTON AND W. J. HALL

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20 August 1963

Dear Sir

As part of its research program directed toward the improvement of hull structures of ships, the Ship Structure Committee has been sponsoring a brittle-fracture mechanics study at the University of Illinois.

Herewith is the First Progress Report on the low-velocity phase, SSC-148, Brittle Fracture Propagation Studies, by F. F. Videon, F. W. Barton, and W. J. Hall.

This project was conducted under the advisory guidance of the Committee on Ship Structural Design of the National Academy of Sciences-National Research Council.

This report is being distributed to the individuals and agencies associated with the project, and to those interested in the Ship Structure Committee program. Questions or comments regarding this report would be appreciated and should be sent to the Secretary, Ship Structure Committee.

Sincerely yours,

T. J. Fabik
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-148

First Progress Report
of
Project SR-155
"Low-Velocity Fracture"

to the

Ship Structure Committee

BRITTLE FRACTURE PROPAGATION STUDIES

by

F. F. Videon
F. W. Barton
and
W. J. Hall

University of Illinois
Urbana, Illinois

under

Department of the Navy
Bureau of Ships Contract NObs-65790

Washington, D. C.
U. S.Department of Commerce, Office of Technical Services
20 August 1963

ABSTRACT

This investigation was undertaken to study low-velocity brittle fracture in wide steel plates. The detailed results of two tests of 6-ft-wide prestressed steel plates are presented along with pertinent observations from tests of similar specimens conducted as one of the last phases of Project SR-137. Also, results of nineteen tests of 2-ft-wide centrally notched plates, a majority of which had a longitudinal butt weld are presented.

In 6-ft-wide prestressed plates, the residual stress field (longitudinal tensile stresses at the edges of the plate balanced by compressive stresses throughout the central portion) made initiation possible with no external applied stress, and had a significant effect on the fracture propagation. Fracture speeds were high (4000-6000 fps) near the edges of the plates and decreased rapidly to as low as 165 fps as the fracture propagated into the region of compressive stresses. In the low-speed regions the magnitude and extent of the dynamic strain field associated with the crack tip was considerably less than had been recorded in earlier tests (Project SR-137) of high-speed fractures in plain plates.

For the 2-ft-wide centrally notched and welded plates in which the fractures were initiated statically, fracture speeds as high as 5000 fps were recorded in the zone of high residual tensile stresses near the weld; the speed apparently stabilized at about 1800 fps after the fractures had propagated out of the high tensile stress field. The dynamic strain field associated with the intermediate-speed fractures (1800 fps) were roughly commensurate with that which would be expected for this fracture-velocity level. The fracture initiation observations indicated that the tensile residual stress alone was not sufficient to insure low-applied-stress fracture initiation; also, metallurgical effects associated with high-heat input during welding are not necessary in all cases for low-stress initiation. Indications are that strain cycling of the material in the notch region arising from welding may play an important role in the initiation of brittle fractures.

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NOMENCLATURE

The following terms are commonly used throughout the text:

Dynamic Strain Gage - Strain gage whose signal is monitored with respect to time on an oscilloscope during the fracture test; this same gage also may be used for static monitoring before and after the test.

Static Strain Gage - Strain gage used only to monitor the static strain level.

Component Strain Gage - One of the three individual strain gages of the rectangular strain rosette.

Crack Detector - A single wire strain gage located on the plate surface perpendicular to the expected fracture path and intended to be broken by the fracture. A measure of the fracture speed and crack tip location may be obtained from a knowledge of the distance between detectors and the time interval corresponding to the breaking of adjacent detectors.

Initiation Edge - In Part A, the edge of the specimen at which the brittle fracture is initiated. In Part B, fracture was initiated from a central-notch.

Notch Line - In Part A, an imaginary straight line connecting the fracture initiation notches on opposite edges of the plate specimen. In Part B, an imaginary transverse line passing through the initiation notch.

Base Strain - For any gage, the strain corresponding to the applied test load plus the initial residual strain, with due regard for sign.

Zero Strain Level - In Part A, the reference condition of zero strain corresponding to the as-rolled, slotted, but prewelded state. In Part B, the reference condition of zero strain level corresponding to the as-rolled, notched, beveled but prewelded state.

PART A. LOW-VELOCITY-FRACTURE STUDIES IN WIDE STEEL PLATES

INTRODUCTION

Object and Background

The series of tests described in this part of the report was conducted to evaluate the parameters associated with low-velocity brittle-fracture propagation in 6-ft-wide steel plates. The study consisted of running the fracture through a field of compressive residual stress and making measurements of surface strains and fracture speeds during the crack propagation.

The earlier pilot studies of low-velocity fracture propagation made as a part of Project SR-137 have been reported in References 1 and 2. Other recent work at the University of Illinois leading up to the present investigation is reported in References 3 through 7. Although the preliminary studies[1-2] provided considerable strain and speed data, measurements which would permit the determination of principal strains near the propagating fracture front were lacking. The results from two plate tests undertaken to supply the desired information are presented herein. In addition, the salient observations from the earlier 6-ft-wide prestressed plate tests are incorporated in order to provide as complete an analysis as possible. At the time this study was undertaken, to the authors' knowledge, there had been no wide-plate investigations devoted to study of the effect of a residual stress field on fracture propagation. There had been several studies involving fracture toughness of welded plates (involving residual stress as one of the variables) in Great Britain, Japan, and the United States, and a summary of much of this work is presented in Reference 8. Other work concerning studies of residual stress and fracture have appeared recently.[9-10-11] For the most part the work reported in the latter papers are "go" or "no go" tests but in Reference 10 the authors reported that the fracture path more or less traversed the plate at right angles to the direction of principal stresses arising from the residual stress system prior to the time the fracture started--an observation which also was made in the early stages of the present investigation. However, in the referenced work no measurements were made of the change in the residual stress system or other fracture characteristics during the time the fracture was propagating.

Scope

The study was undertaken to determine the effect of residual tensile stress on initiation and propagation and at the same time allow a study of the behavior of the propagating fracture through both tensile and compressive residual stress regions. Earlier work on 2-ft-wide specimens[5] indicated that welding of tapered slots cut in each edge of the specimen was the most satisfactory method for obtaining the desired residual stress pattern. This procedure, described briefly in a later section of this report, was adopted in preparation of all specimens in this investigation.

Two brittle-fracture tests of 6-ft-wide plates containing a residual stress field were conducted as a part of this particular study. For identification purposes the specimens are hereafter designated as Tests 49 and 50 to conform to the numbering of tests conducted as a part of the recent brittle-fracture mechanics program at the University of Illinois (SSC Projects SR-137 and SR-155). The plates were instrumented with strain gages and crack speed detectors to provide information about their behavior during propagation. The detailed results on Tests 49 and 50 are presented herein; for purposes of completeness, the analysis and discussion are based not only on the results of Tests 49 and 50 but also on pertinent observations from the earlier Tests 42 through 48.[1-2]

DESCRIPTION OF SPECIMENS, INSTRUMENTATION AND TEST PROCEDURE

Material Properties

The plate specimens used in this investigation were prepared from 3/4-in. semikilled steel plate. The mechanical, chemical and Charpy V-notch data for this material were obtained during the course of an earlier investigation and the average values are presented in Fig. 1.

Fabrication and Procedure

The plate specimens used in this investigation were 72-in. wide, 3/4-in. thick and 54-in. long. The net width of each specimen along the notch line was approximately 2 1/4 in. less than the gross width as a result of the notches cut in each edge of the specimen. These notches were used for the notch-wedge-impact method of fracture initiation which has been described previously.[3]

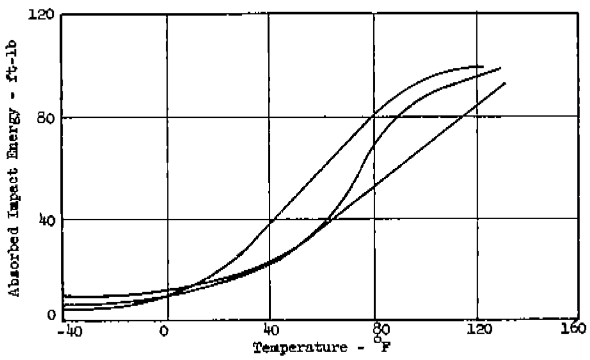
TENSILE TEST DATA

Yield		Maximum		Percent Elongation		Percent Reduction	
L*	T*	L	T	L	T	L	T
33.8	34.0	61.8	61.8	40.7	39.1	66.9	61.0

*L = Longitudinal
T = Transverse

CHECK ANALYSIS

C	Mn	P	S	Si	Cu	Ni	Al
0.19	0.74	0.019	0.028	0.055	0.02	Trace	0.03



Charpy V-Notch Curves

FIG. 1. MATERIAL PROPERTIES.

The general preparation of each test specimen was similar and consisted of sawing tapered slots to the desired dimensions, welding these slots to produce the residual stress pattern in the plate, and finally cutting the edge notches used in crack initiation.

Four tapered slots, two per edge, were cut in each plate. The location and dimensions of the slots were identical for Tests 49 and 50 as shown in the sketches of these specimens in Fig. 2 and 3. The depth of all four slots was the same and their locations were symmetrical with respect to the longitudinal center line and the transverse notch line.

The welding procedure employed was similar for both specimens and the typical sequence was as follows. Welding initially began at a point 4-in. from the tip of one slot and proceeded to the tip. This 4-in. length was welded with alternating passes on opposite faces of the plate. For the particular dimensions of the slot and specimen, a total of six passes was required to completely close the slot. This same procedure was then followed on similarly located 4-in. segments of the remaining three slots. Four-inch lengths were chosen so that one electrode would last for a complete pass; E7016 electrodes were used throughout. All four slots were then welded again in the same manner, this time beginning at a point 8-in. from the tip of the slot and proceeding to the previously completed weld. The remainder of the slot length was welded following the same procedure. This particular welding technique was planned to keep bending to a minimum by the symmetrical placing of the weld metal and yet to produce maximum contraction at the edges of the plate.

Measurements of Residual Strains

The residual strains in the plate specimens, resulting from the prestressing procedure, were measured by means of Baldwin SR-4 strain gages and were checked in some cases by a 6-in. Berry mechanical gage. SR-4 gages were placed back-to-back at selected points. Longitudinal and transverse strain measurements were made across the notch line as well as at selected points above the notch line. The instrumentation layout for Tests 49 and 50 is shown in Fig. 2 and 3.

Initial strain readings from all gages were taken after the tapered slots had been sawed

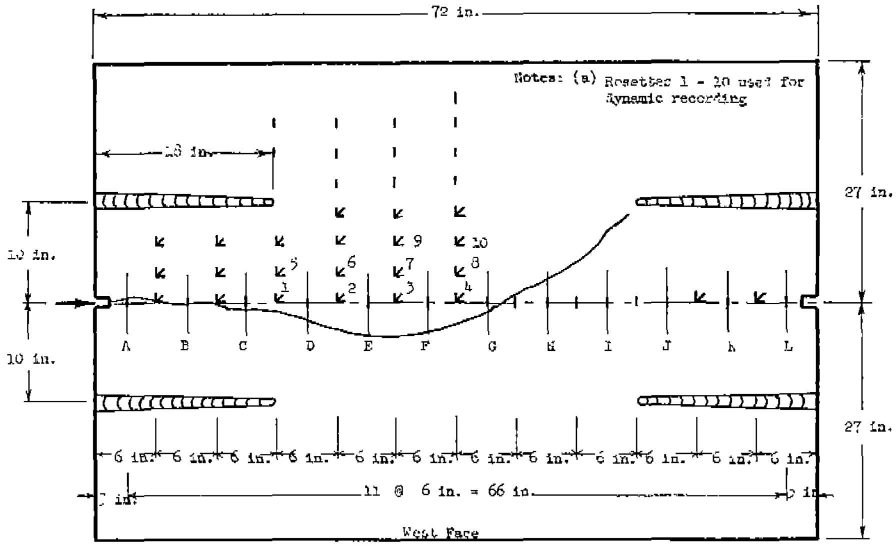


FIG. 2. INSTRUMENTATION LAYOUT AND SLOT CONFIGURATION - TEST 49.

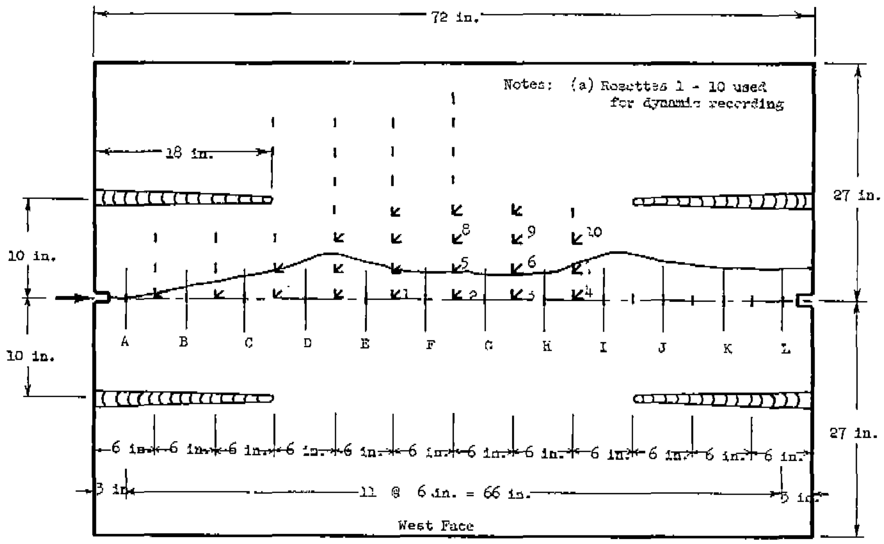


FIG. 3. INSTRUMENTATION LAYOUT AND SLOT CONFIGURATION - TEST 50.

and with the specimen in an unrestrained condition. These strain readings established the zero strain level, and all other strains were referenced to this prewelded state. After the specimen had been prestressed by welding the tapered slots, the final static strain readings were taken at room temperature.

Dynamic Instrumentation

Thirty-four channels of cathode-ray oscilloscope recording instrumentation were used for recording dynamic strains; Baldwin SR-4 Type A7 strain gages and Type AR7 strain rosettes (both types 1/4-in.gage length) were used to measure the dynamic strains.

Crack speeds were measured by using a system of surface crack detectors which broke as the fracture traversed the plate; these crack detectors consisted of Baldwin SR-4 Type A9 strain gages (6-in. gage length). The breaking of a crack detector opened an electrical circuit and fed a step change in voltage to the recording channel. From a knowledge of the distance measured along the crack between detectors and the elapsed time between successive interruptions of the circuit, the average fracture speed could be computed. The fracture speed also could be obtained by noting the elapsed time between peaking of successive SR-4 strain gages at a fixed distance from the fracture path.

Data Reduction

Reduction of the strain data recorded on 35mm strip film was facilitated by the utilization of a decimal converter and the University of Illinois high-speed digital computer, the ILLIAC. A brief summary of the data reduction procedure is given below.

The 35mm film strips were enlarged and timing marks were scaled on the enlargements. Each individual trace had timing interruptions to insure timing synchronization of all traces. With the aid of the decimal converter, values of gage strain versus time were simultaneously plotted on an X-Y plotter and typed in tabular form. In Tests 49 and 50, in which strain rosettes were used, the strain-time data also were punched on IBM cards; these data were subsequently transferred from the IBM cards to punched paper tape and processed through the ILLIAC which computed values of the principal strains. The ILLIAC results consisted of tabulated principal strain data, as well as scaled oscilloscope displays of component gage and principal strain traces which were photographed for later enlargement and processing.

Test Procedure

The test procedure used for these tests consisted of cooling the specimen (with crushed dry ice) to the desired test temperature, applying the test load if an external stress was to be employed, and initiating the fracture by means of an impact produced by driving a wedge into a notch in the edge of the plate. A more detailed description of the cooling technique and the notch-wedge-impact method of initiation may be found in earlier publications.[3-4]

BRITTLE-FRACTURE TESTS AND RESULTS

General

Brittle-fracture tests were conducted on two specimens containing a residual strain field produced by the welding of the tapered slots.

Although the magnitude of the measured residual strains varied slightly for the specimens, the overall patterns were similar for both plates. The highest residual strains were produced at the edges of the plates and reached yield magnitude for a distance of a few inches in from each edge. As a result of these high tensile strains at the edges of the specimens, it has been demonstrated[1-2] that it was possible to initiate fractures with no externally applied load.

A nominal stress of 3000 psi was applied in Tests 49 and 50 to keep the plates taut in the machine and to obtain a fracture that would traverse the entire plate or at least a major portion of the plate before arresting; this loading also reduced bending to a limited extent.

Fractures were successfully initiated in Tests 49 and 50. In Test 50 the fracture propagated across the entire width of the plate and in Test 49, the fracture arrested in the compressive strain region after traversing a major portion of the plate width. The results of Tests 49 and 50 are presented in detail herein. A tabulated summary of the test conditions and fracture details for these tests and Tests 43-48 are presented in Table 1.

Test 49

Tests 49 and 50 were designed primarily to provide information regarding the principal strain behavior in the specimens during fracture propagation, and to provide additional information about the type of residual strain pattern resulting from welding of the tapered slots. The major portion of the instrumentation, including all gages used for dynamic recording, was located on the west face of the specimen, and in all subsequent discussion regarding the residual strain field and the dynamic strain records, it should be kept in mind that these readings were taken from one side of the plate only.

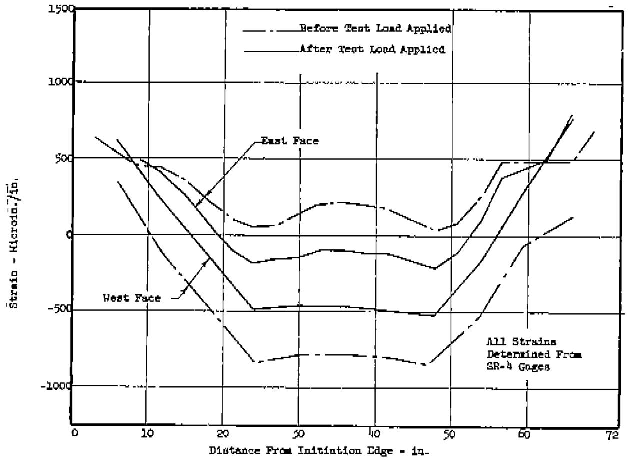
The average longitudinal residual strain across the notch line at the test load is presented in Fig. 4 (a). As may be noted from this plot, the average residual compressive strain (back-to-back strain gage readings) across the central 24 in. of the specimen was approximately -300 microin./in. The longitudinal and transverse residual strain distributions at selected points on the west plate face are shown in Fig. 4 (b) and 4 (c). It will be observed from these plots that both the longitudinal and transverse strains along and away from the notch line are quite uniform throughout the central portion of the specimen. Thus, it appears that the residual compressive strain field through which the fracture propagated was of fairly constant magnitude.

This specimen was tested at an applied stress of 3000 psi, at a temperature of -10 F using the standard notch-wedge-impact initiation technique. An external applied stress was utilized in an attempt to obtain a fracture

TABLE 1. SUMMARY OF SIX-FOOT-WIDE PRESTRESSED PLATE TEST.

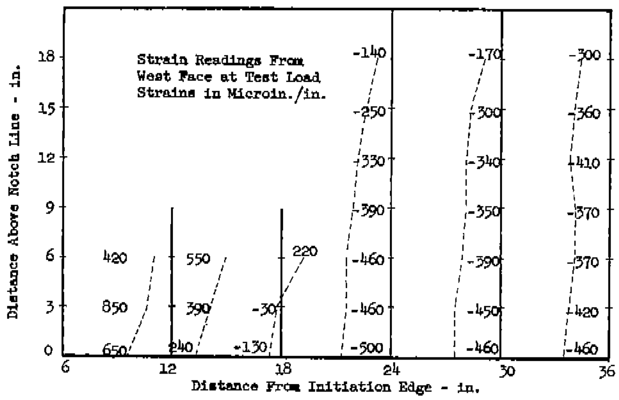
All specimens were 3/4 in. thick by 6-ft wide, semikilled steel plates.

Test No.	Average Net Applied Stress (psi)	Test Temp. (°F)	Specimen Description	Average Speeds High - Low (fps)	Remarks
43	0	-12	48 in. plate length; 18 in. tapered slots, 6 in. above and below notch line; welded and tested in vertical position on laboratory floor, with ends of plate unrestrained	not measured	Fracture propagated approximately 56 in. before arresting
44	0	-12	36 in. plate length; plain plate - no welding; tested in vertical position on laboratory floor, with ends of plate unrestrained	not measured	First shot, no fracture; second shot, fracture propagated approximately 19 in. into plate
45	3000	-20	60 in. plate length; 18 in. tapered slots, 6 in. above and below notch line; specimen welded to pull plates in machine before slots were welded	5500 - 100	Fracture propagated completely across specimen
46	3000	0	48 in. plate length; 20 in. tapered slots, 6 in. above and below notch line; specimen welded to pull plates in machine before slots were welded	4500 - 50	Fracture propagated completely across specimen
47	0	-8	60 in. plate length; 20 in. tapered slots, 6 in. above and below notch line; specimen clamped to pull plates in machine before slots were welded	3800 - 250	Fracture propagated approximately 25 in. before arresting
48	0	0	60 in. plate length; 20 in. tapered slots, 6 in. above and below notch line; specimen clamped to pull plates in machine before slots were welded	4150 - 50	Fracture propagated approximately 36 in. before arresting
49	3000	-10	54 in. plate length; 18 in. tapered slots, 10 in. above and below notch line; specimen welded to pull plates in machine before slots were welded	5650 - 150	Fracture propagated approximately 52 in. before arresting
50	3000	-10	54 in. plate length; 18 in. tapered slots, 10 in. above and below notch line; specimen clamped to pull plate in machine before slots were welded	6400 - 330	Fracture propagated completely across plate



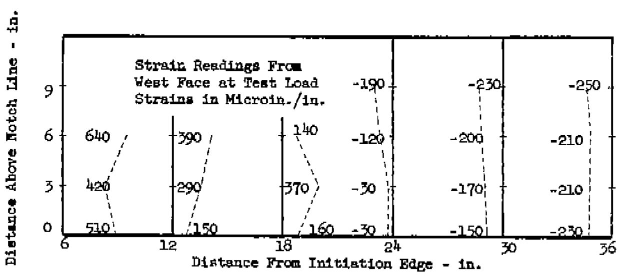
(a) Longitudinal Strain Along Notch Line

FIG. 4a. RESIDUAL STRAIN DISTRIBUTION - TEST 49.



(b) Longitudinal Strain at Selected Points on Plate Surface

FIG. 4b. RESIDUAL STRAIN DISTRIBUTION - TEST 49.



(c) Transverse Strain at Selected Points on Plate Surface

FIG. 4c. RESIDUAL STRAIN DISTRIBUTION - TEST 49.

that would propagate through the region of the specimen where the dynamic strain readings were to be taken. On the basis of previous tests, it was felt that 3000 psi would be sufficient to insure complete fracture. The fracture, did not completely traverse the plate, but did travel through the instrumented region, arresting approximately 52 in. from the initiation edge. A photograph of the fracture and a close-up of the area of arrest are shown in Fig. 5. Note that the fracture curved sharply upward before arresting, apparently traveling normal to the direction of maximum principal stress.

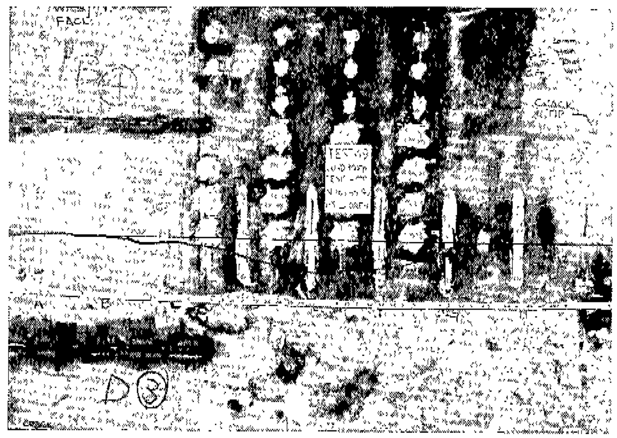


FIG. 5a. FRACTURE PATH - TEST 49.

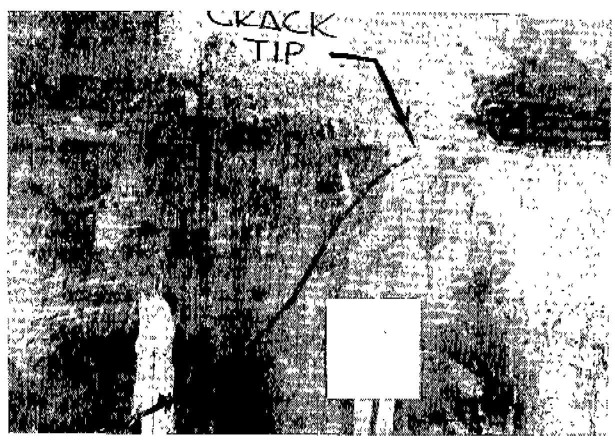


FIG. 5b. FRACTURE PATH - TEST 49. (Closeup of Arrest Area)

The instrumentation layout and crack path are shown in the sketch in Fig. 2 and the strain-time records obtained from ten of the rosette gages are shown in Fig. 6. Also included in the latter plots are the computed principal strains and maximum shear strains for each gage point during fracture propagation.

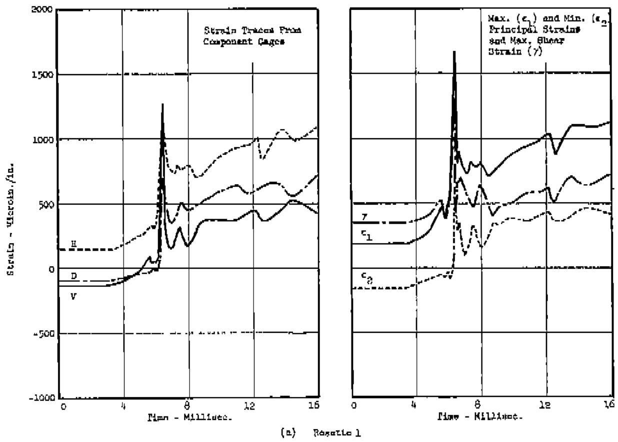


FIG. 6a. STRAIN-TIME RECORDS - TEST 49.

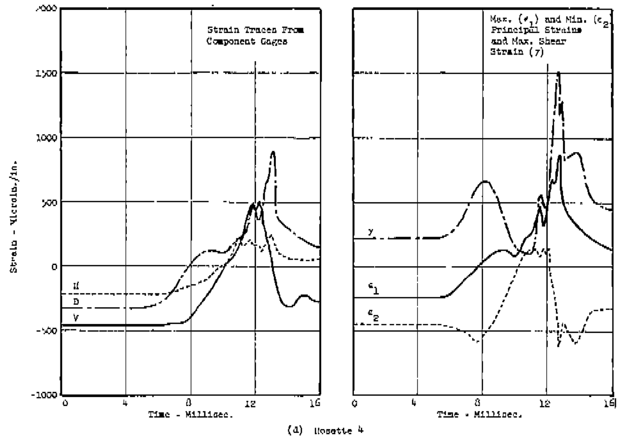


FIG. 6d. STRAIN-TIME RECORDS - TEST 49.

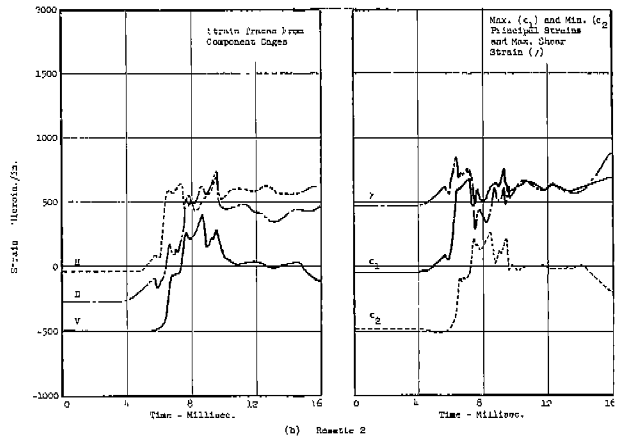


FIG. 6b. STRAIN-TIME RECORDS - TEST 49.

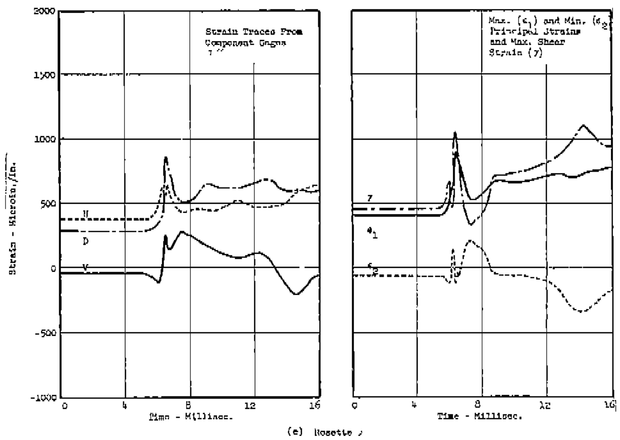


FIG. 6e. STRAIN-TIME RECORDS - TEST 49.

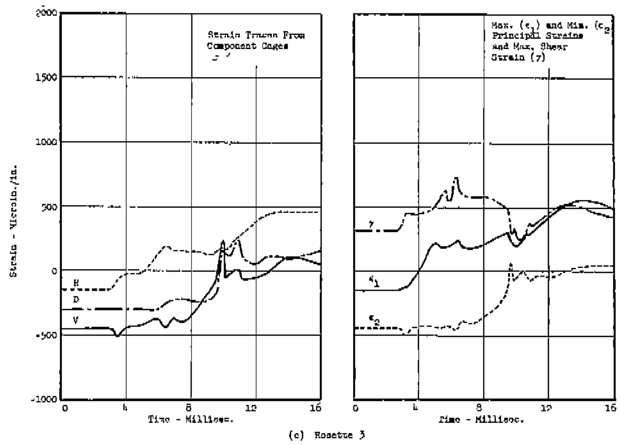


FIG. 6c. STRAIN-TIME RECORDS - TEST 49.

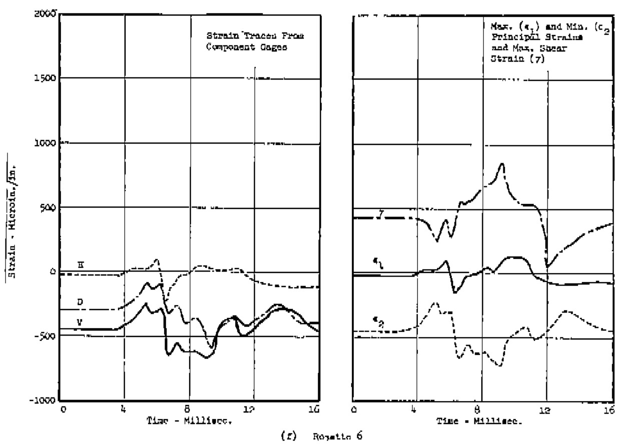


FIG. 6f. STRAIN-TIME RECORDS - TEST 49.

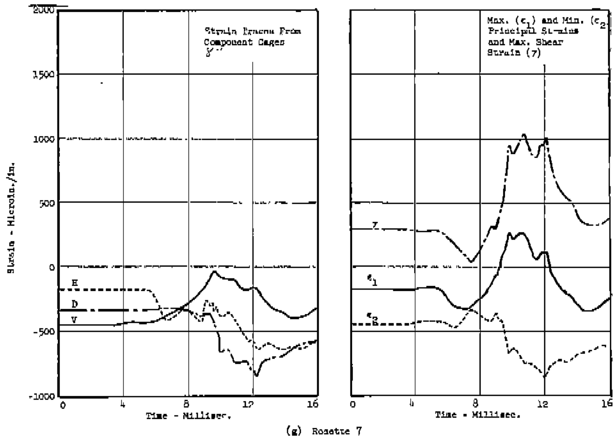


FIG. 6g. STRAIN-TIME RECORDS - TEST 49.

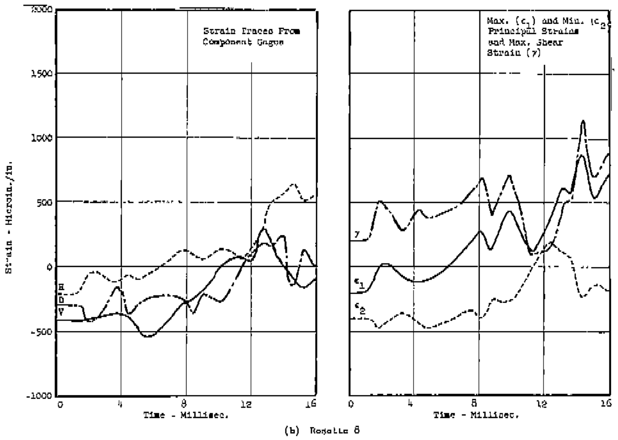


FIG. 6h. STRAIN-TIME RECORDS - TEST 49.

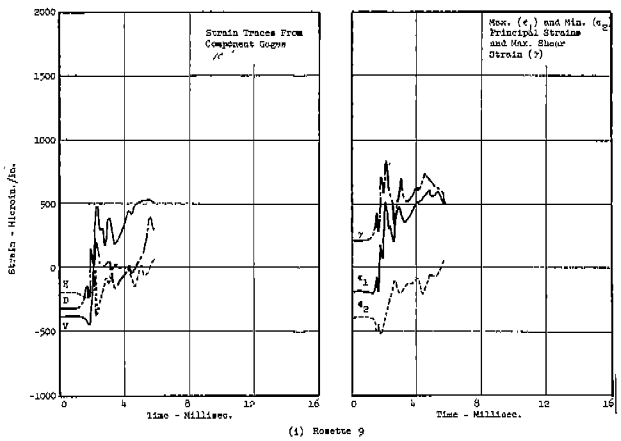


FIG. 6i. STRAIN-TIME RECORDS - TEST 49.

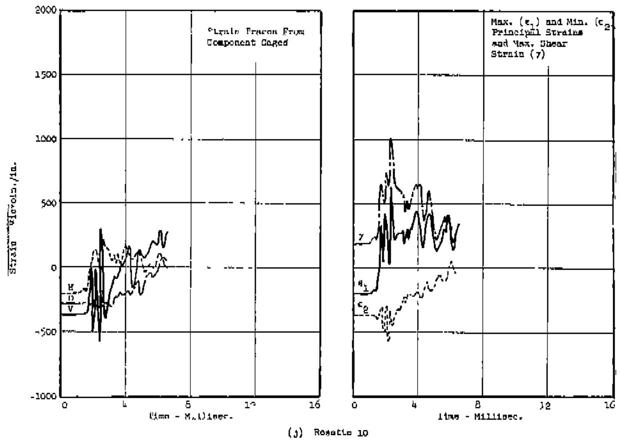


FIG. 6j. STRAIN-TIME RECORDS - TEST 49.

This was the first time satisfactory and complete records were obtained from a specimen in which the fracture arrested. The direction of maximum principal strain also was computed from the strain information and representative directions for various crack lengths are depicted in Fig. 7. The significance of these results is discussed in the next section of this report.

Fracture speed information as determined from the dynamic crack detector records is presented in Fig. 8. Even though the fracture arrested in this test, the pattern of fracture speeds shows no marked change from those obtained in tests where fracture was complete. The maximum average recorded speed was approximately 5650 fps and the lowest average speed was approximately 160 fps. From Fig. 8, it may be noted that, as in

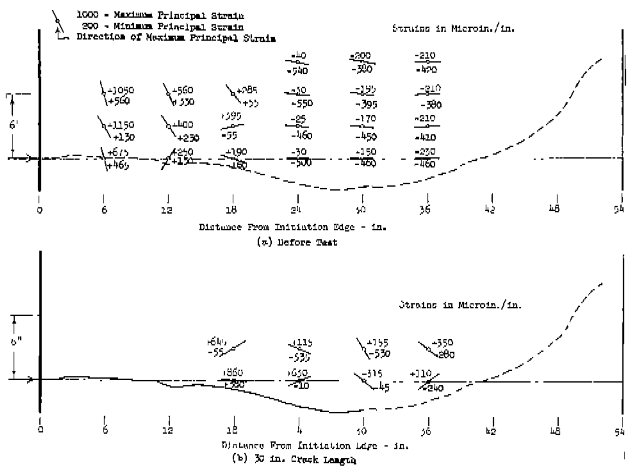
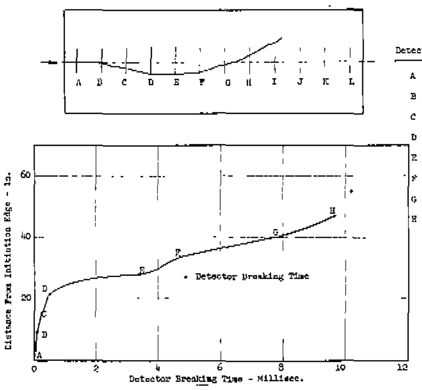


FIG. 7. RESIDUAL PRINCIPAL STRAIN DIRECTION AND MAGNITUDES - TEST 49.



Detector	Distance Between Detectors (inches)	Time Interval (millisec.)	Average Speed (fps)
A			
	6.10	0.09	5650
B			
	6.15	0.13	3940
C			
	6.20	0.25	2070
D			
	6.10	2.90	175
E			
	6.10	1.30	390
F			
	6.45	3.26	165
G			
	6.55	1.70	320
H			

(Fracture Arrested)

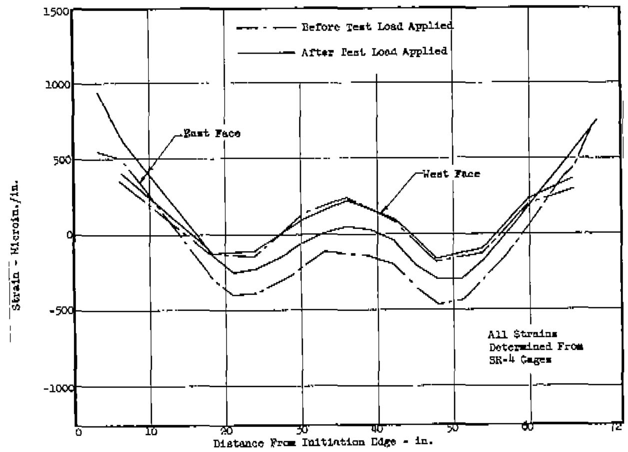
FIG. 8. AVERAGE FRACTURE SPEEDS - TEST 49.

all earlier tests, the highest speeds occurred near the initiation edge and the lower speeds occurred in the central compressive strain region. The general shape of the detector location versus breaking time plot is approximately the same as was observed in earlier tests.

Test 50

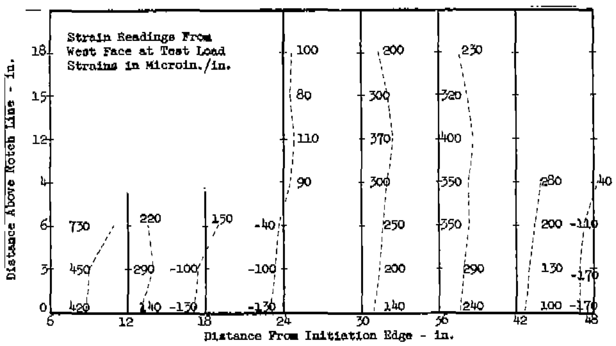
This test was a duplication of Test 49 with two minor exceptions; the location of instrumentation was changed slightly and the tapered slots were welded before the specimen insert had been welded to the pull plates, rather than after. Because the ends were free during welding of the slots, the resulting magnitude of the residual strain field was considerably less than that obtained in Test 49. The average residual compressive strain across the central portion of the plate was only about -100 microin./in. as shown in Fig. 9 (a). Again, these readings represent average values, and in this test, the major portion of instrumentation was located on the side of the specimen on which the lower compressive strain values were recorded. The distribution of longitudinal and transverse strains at selected points on the plate surface are plotted in Fig. 9 (b) and 9 (c). It can be noted from this plot that the distribution of strain in the central portion of the plate is reasonably uniform.

This specimen was tested at an applied stress of 3000 psi and a temperature of -10 F using the same impact initiation procedure. Under these conditions, a brittle fracture propagated completely across the specimen. It is felt that complete fracture in this test



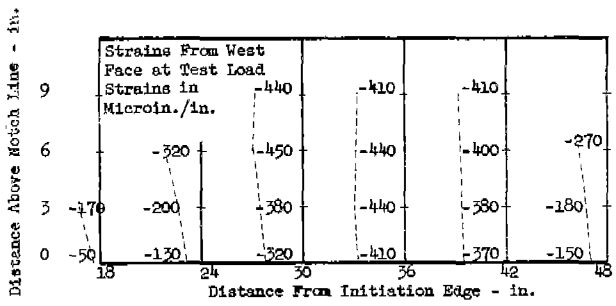
(a) Longitudinal Strain Along Notch Line

FIG. 9a. RESIDUAL STRAIN DISTRIBUTION - TEST 50.



(b) Longitudinal Strain at Selected Points on Plate Surface

FIG. 9b. RESIDUAL STRAIN DISTRIBUTION - TEST 50.



(c) Transverse Strain at Selected Points on Plate Surface

FIG. 9c. RESIDUAL STRAIN DISTRIBUTION - TEST 50.

and only a partial fracture in Test 49 can be attributed to the different residual stress patterns in the plate since all other test conditions for these two tests were identical. A photograph of the fracture path is shown in Fig. 10. The particular shape of the crack

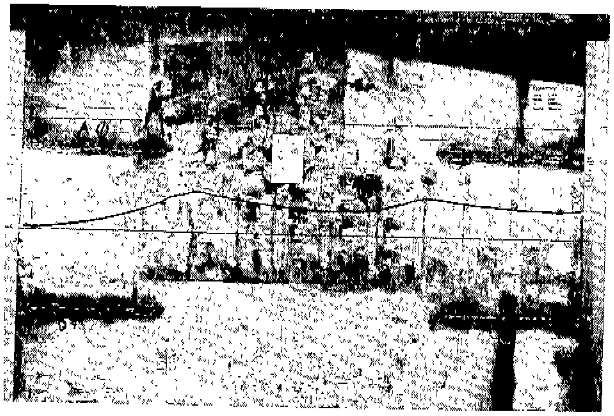


FIG. 10. FRACTURE PATH - TEST 50.

path is similar to the fracture paths observed in Tests 45 and 46 in which complete fractures also occurred. As may be noted from the photograph, the fracture always remained above the notch line during propagation, showing definite changes in direction at the points of maximum strain gradient.

A sketch of the instrumentation layout and crack path for this specimen is presented in Fig. 3. In this test the fracture propagated through the middle of the dynamically instrumented region and excellent strain response records were obtained for this low-velocity fracture. The strain-time records, including the computed principal strain information, are presented in Fig. 11. From the recorded

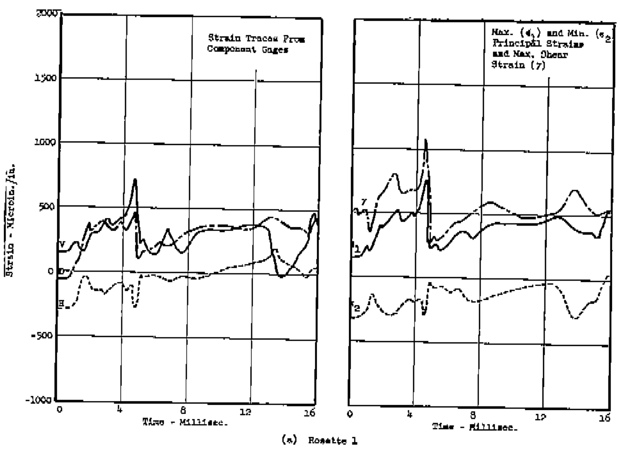


FIG. 11. STRAIN-TIME RECORDS - TEST 50.

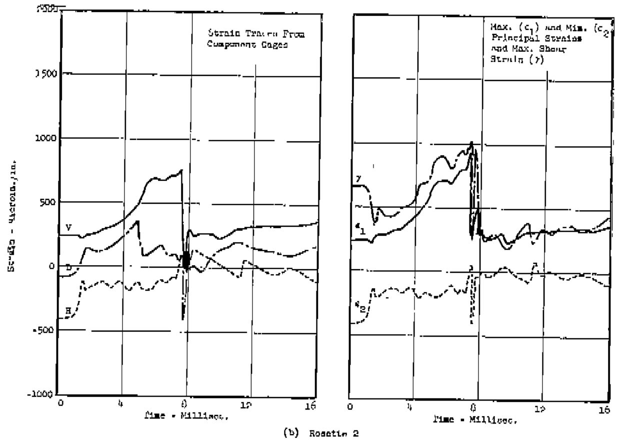


FIG. 11b. STRAIN-TIME RECORDS - TEST 50.

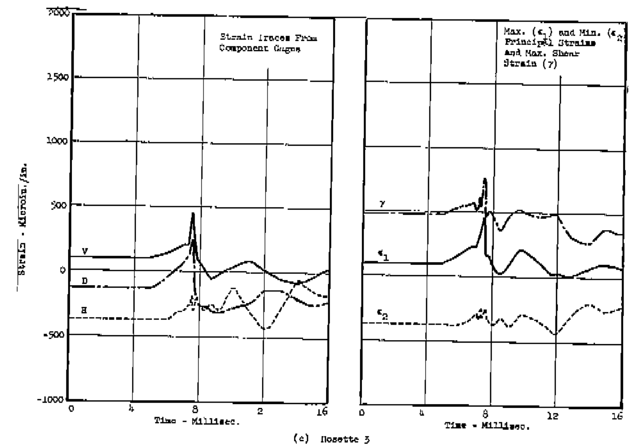


FIG. 11c. STRAIN-TIME RECORDS - TEST 50.

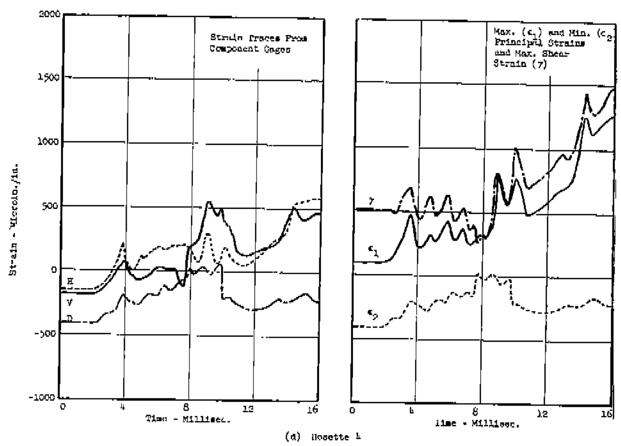
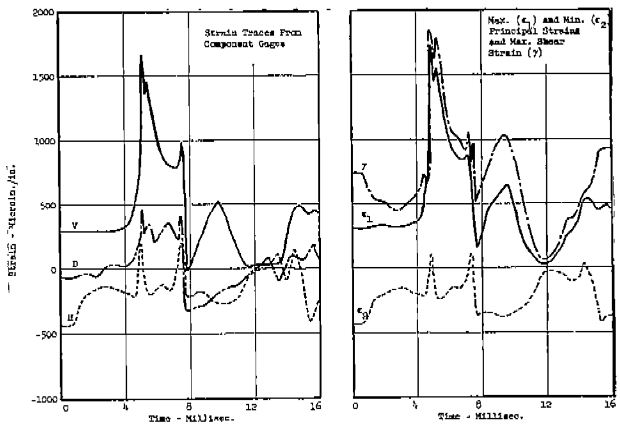
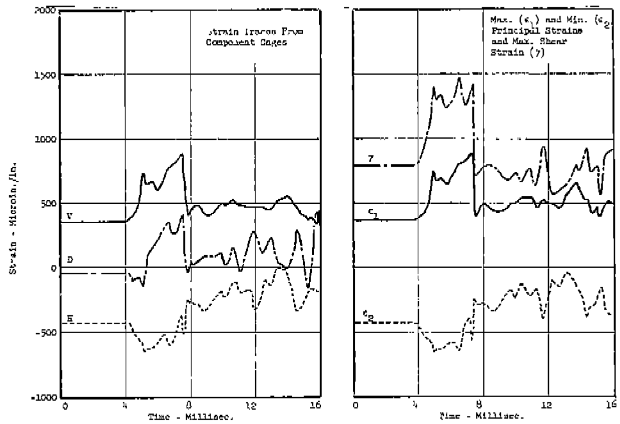


FIG. 11d. STRAIN-TIME RECORDS - TEST 50.



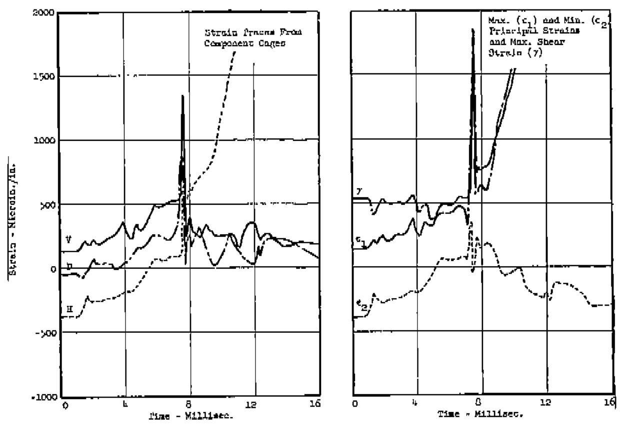
(e) Rosette 5

FIG. 11e. STRAIN-TIME RECORDS - TEST 50.



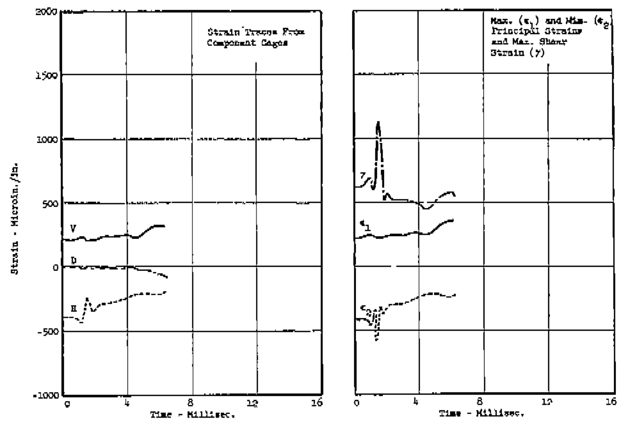
(h) Rosette 8

FIG. 11h. STRAIN-TIME RECORDS - TEST 50.



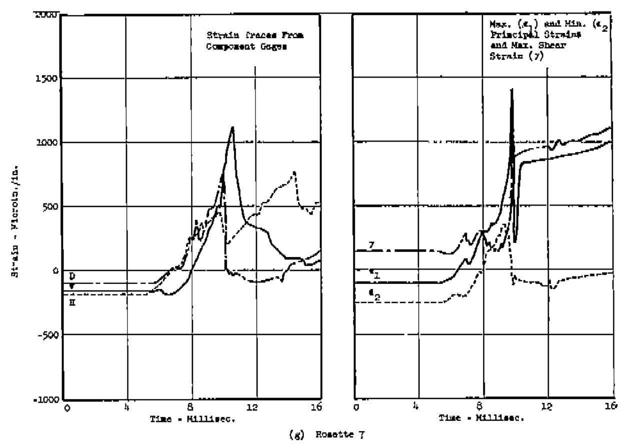
(f) Rosette 6

FIG. 11f. STRAIN-TIME RECORDS - TEST 50.



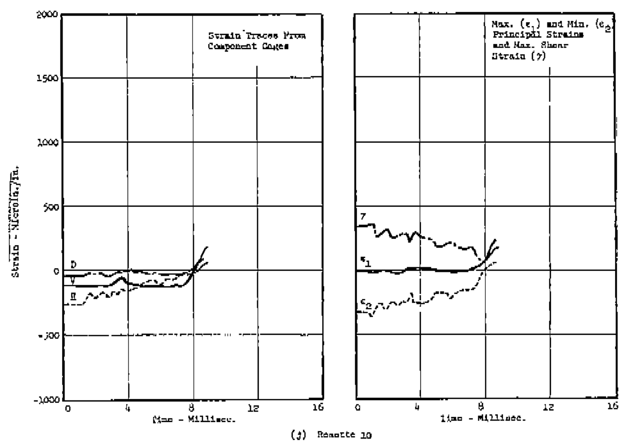
(i) Rosette 9

FIG. 11i. STRAIN-TIME RECORDS - TEST 50.



(g) Rosette 7

FIG. 11g. STRAIN-TIME RECORDS - TEST 50.



(j) Rosette 10

FIG. 11j. STRAIN-TIME RECORDS - TEST 50.

strain information the directions as well as the magnitudes of the maximum principal strains were computed; this information for selected crack lengths is presented in Fig. 12.

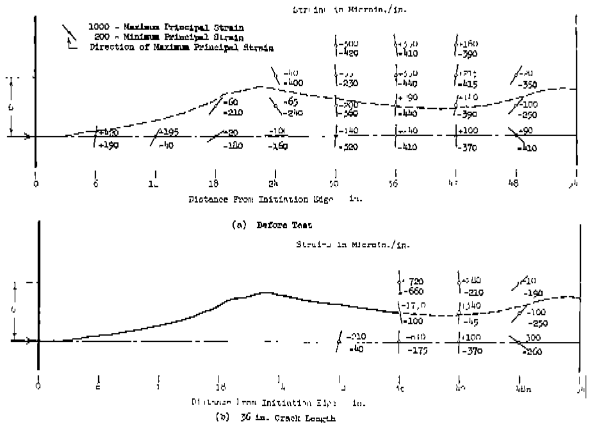


FIG. 12. RESIDUAL PRINCIPAL STRAIN DIRECTIONS AND MAGNITUDES - TEST 50.

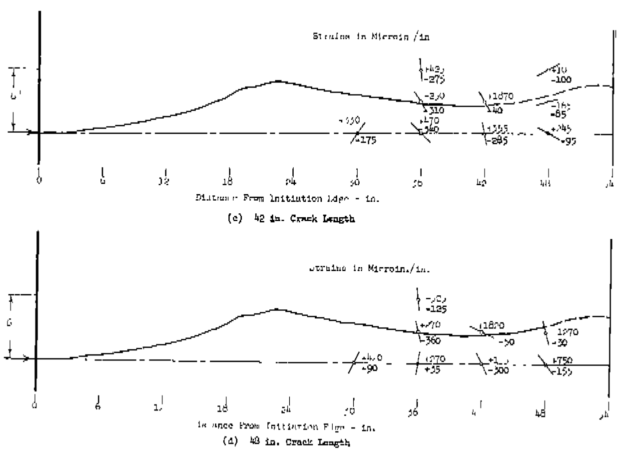


FIG. 12. RESIDUAL PRINCIPAL STRAIN DIRECTIONS AND MAGNITUDES - TEST 50.

Although the fracture propagated completely across the specimen, incomplete fracture speed information was obtained because the fracture passed above some of the crack detectors; only four of the twelve crack detectors were broken by the fracture. The speed information, as obtained from the crack detectors and also peaking of the strain gages, is presented in Fig. 13. Although the speed information is not as complete as that from earlier tests, the data are sufficient to show that the speeds are similar to previously obtained fracture speeds both in magnitude and pattern. The highest average recorded speed was approximately 6400 fps and the lowest speed, averaged over a distance of 24 in. in

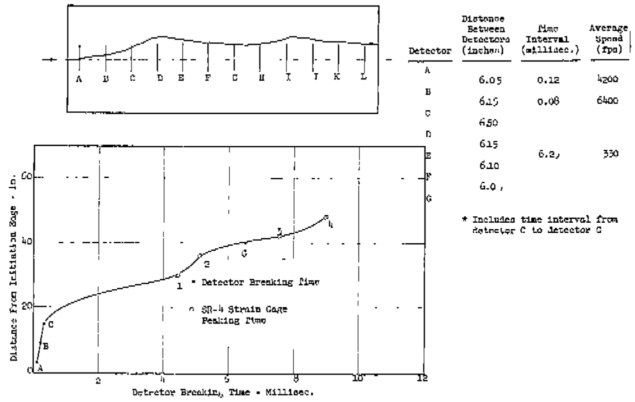


FIG. 13. AVERAGE FRACTURE SPEEDS - TEST 50.

the central region of the plate, was approximately 330 fps. Since this average speed was measured over a considerable distance, it seems reasonable to assume that the actual lowest speed occurring during fracture was quite likely less than 330 fps.

Photographs of the fracture surface for Test 50 are shown in Fig. 14 along with the arrest

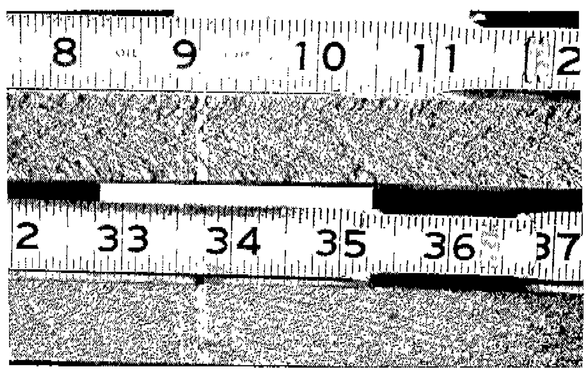


FIG. 14a. FRACTURE SURFACE.
(a) Test 50.

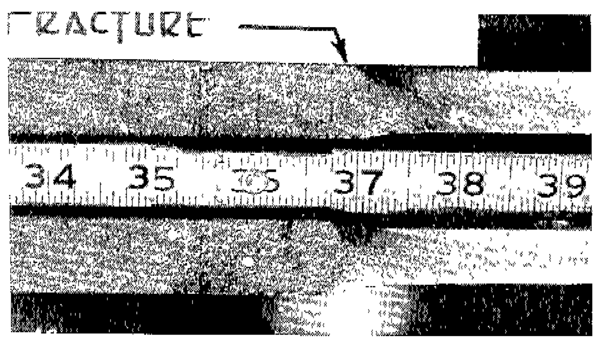


FIG. 14b. FRACTURE SURFACE.
(b) Arrest Region - Test 48.

region of Test 48 which is discussed later. As in all previous tests in this series, the rougher texture was observed to occur adjacent to the initiation edge with a much smoother texture occurring in the central portion of the specimen. The location of each photograph with respect to the initiation edge may be determined from the folding rule included. In the rougher texture near the initiation edge, the chevron markings of the fracture surface are easily visible, while their presence in the smoother region is extremely difficult to discern.

ANALYSIS AND DISCUSSION OF TEST RESULTS

The analysis and discussion which follows is based on the results of Tests 49 and 50 as well as the pertinent observations from the earlier Tests 43-48. All of the tests were conducted on 6-ft-wide plate specimens which had been prestressed by welding tapered slots cut in each plate edge. Even though manual welding was used, and the location and dimensions of the tapered slots varied slightly, the pattern of residual strains resulting from this particular prestressing technique was, in general, similar for all specimens and consisted of high tension near the edges and moderate to low strain fields which throughout the central portion of the specimen could be attributed largely to the restraint present at the time the tapered slots were welded. For the two specimens (Tests 43 and 50) in which no end fixity was provided during welding of the slots, the magnitudes of the residual compressive strains across the central section were much less than for the remaining specimens in which the ends were either welded or clamped to the pull plates (see Table 1 for details) prior to the welding of the slots.

The presence of high residual tensile stresses in the vicinity of the initiation notch made it possible to consistently initiate brittle fractures using the notch-wedge-impact method, even without external applied stress. By way of comparison, in the earlier 6-ft-wide plain plate specimens, where no residual strain field had been induced, an average applied stress in excess of 15,000 psi was necessary to insure initiation under similar test conditions. Apparently, the presence of these residual tensile stresses has the same effect on initiation and to some extent, on propagation, as an externally applied load of the same magnitude. Although the impact effect of the wedge was a necessary factor for successful initiation under the test conditions employed, the fact that brittle fractures occurred in every prestressed specimen indicates that a large field of residual tensile stress is an important factor in the initiation process.

While the residual tension served as an aid to initiation and propagation, the presence of residual compression in the central region of the specimens had just the opposite effect on the fracture characteristics. It not only caused a reduction in the magnitude and extent of the dynamic strain field and resulted in greatly reduced speeds throughout the compressive region, but also was capable of producing arrest.

In the prestressed plates, the fracture speeds in the compressive strain region were considerably lower than those recorded in the 6-ft-wide plain plate tests conducted as a part of Project SR-137. A plot of detector location versus detector breaking time for a typical prestressed plate test is presented in Fig. 15; for purposes of comparison, a similar

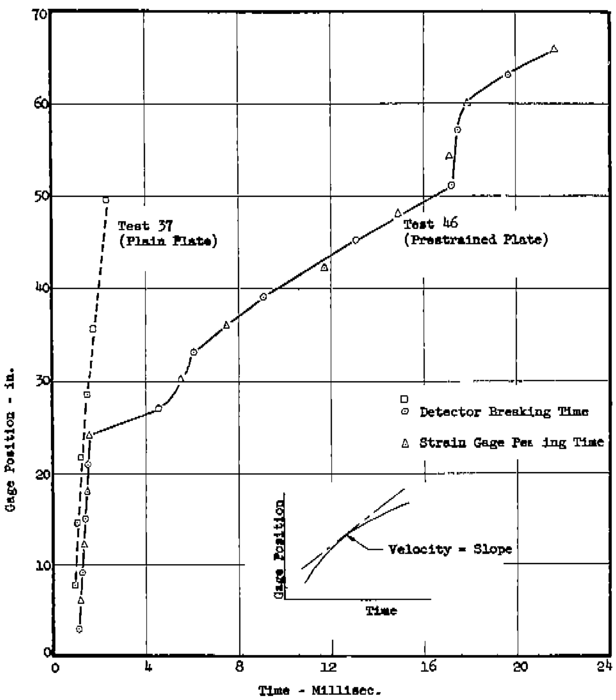


FIG. 15. FRACTURE SPEEDS ACROSS PLATE WIDTHS - TESTS 37 and 46.

plot is presented for a typical plain plate test from Project SR-137. In this plot, the slope of the curve is a measure of the fracture speed at any particular time. As may be seen, the fracture speeds for the two tests are almost identical for approximately the first 20 in. of crack travel. This high speed continued throughout the fracture travel in the plain plate specimen, whereas the fracture speed in the prestressed specimen decreased sharply and continued for the remainder of fracture travel at a greatly reduced value. The same general trend in fracture speeds was observed in all prestressed specimens.

The high initial speeds and the sudden decrease to a much lower value are probably the result of two factors, namely, the residual stress pattern in the specimen and the initiation procedure employed. High fracture speeds would be expected near the initiation edge where residual tension was present and also a decrease in speed would be expected as the fracture propagated into a zone of residual compression. The effect of the initiation procedure on initiation was illustrated by the results of Test 44, in which, after the notch root area had been highly strained by one impact, the initiation technique was sufficient to drive a fracture approximately 19 in. into the specimen.

Because about the same impact energy was used in initiating fractures in all 6-ft-wide specimens, any variation in fracture velocities for the different tests can probably be attributed largely to the particular residual strain pattern present in each specimen. In Fig. 16 are shown plots of both the average residual longitudinal strain across the notch line at test load and the fracture speed across the plate width for Tests 46 and 49; these plots are typical of similar plots for all prestressed specimens. Exact comparisons between the residual strains across the notch line and fracture speeds at corresponding points are not possible because the residual strain shown in Fig. 16 changed somewhat during fracture propagation as a result of redistribution, particularly near the far edge of the plate; however, certain relationships can be observed from the information available. From Fig. 16 it may be noted that the highest fracture speeds occurred where the highest residual tensile strains were present; also, the sudden decrease in speed corresponded to the point where the fracture encountered the maximum

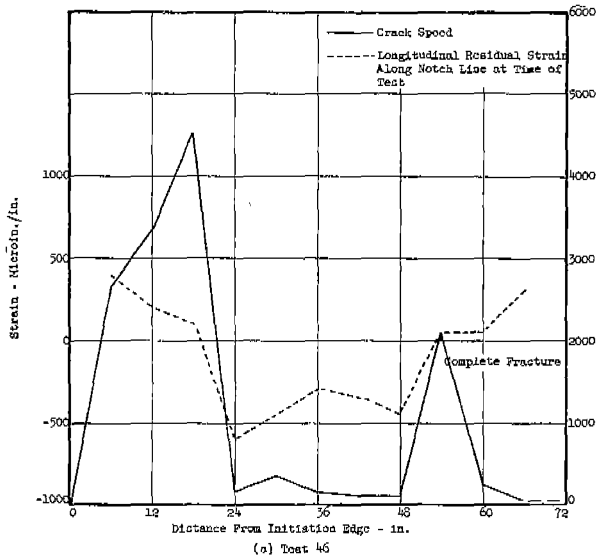


FIG. 16a. VARIATION IN SPEED AND RESIDUAL STRAIN ACROSS PLATE.

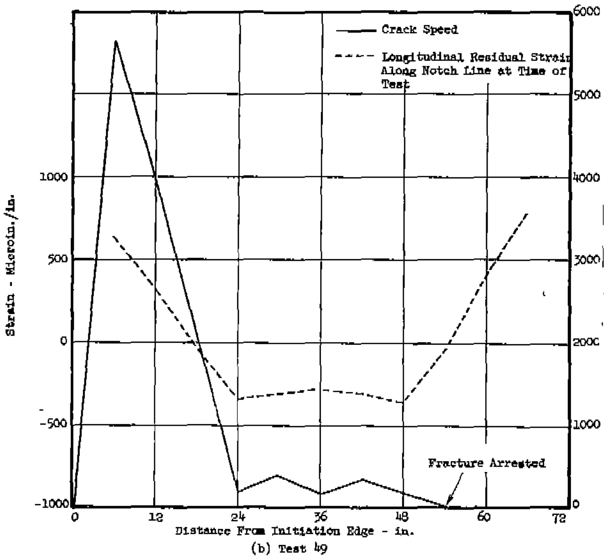


FIG. 16b. VARIATION IN SPEED AND RESIDUAL STRAIN ACROSS PLATE.

residual compressive strain region. Also it was noted that the fracture speed at times increased even though the residual strain was decreasing; this was probably a result of the high energy level present in the plate at that point.

As a result of the apparent correlation between residual strain and fracture speed near the initiation edge, it was felt that perhaps a better indicator of the residual strain versus fracture speed relationship could be obtained by considering only the speed and strain values recorded closest to the point of initiation where effects of load redistribution are eliminated. Although the effect of wedging action was present, it was identical for all tests and thus would not affect a study of other parameters. In Fig. 17 is presented a plot of the average fracture speed occurring 6 in. from the initiation edge versus the average longitudinal residual strain at the same location for six of the prestressed plates. Six in. was chosen because this was the closest point to the initiation edge at which average speeds could be determined. From this plot it appears that

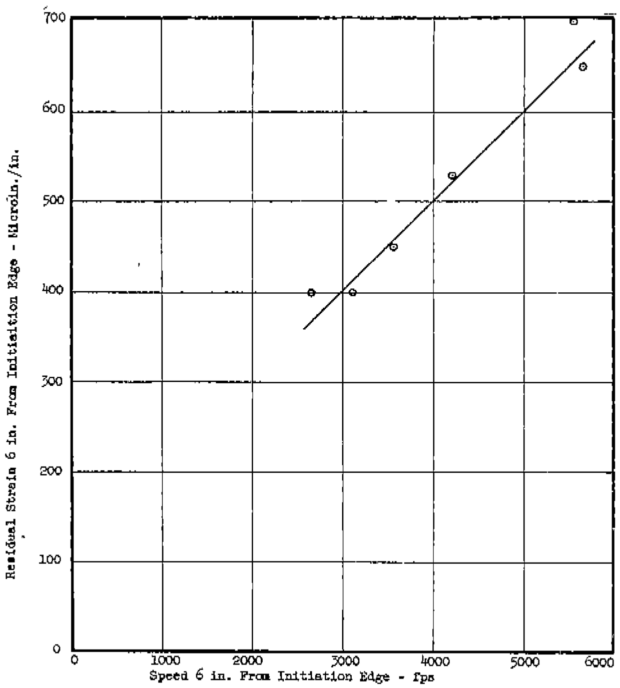


FIG. 17. SPEED VERSUS RESIDUAL STRAIN 6 IN. FROM INITIATION EDGE.

the relationship between these parameters is almost linear, which indicates that the fracture speed is at least partially a function of the residual strains (or better, energy level) present in a specimen. This one set of observations should be interpreted with care, because the relationship is apparently somewhat different at other locations; some differences would be expected by virtue of load redistribution alone.

From the results discussed thus far, it can be seen that fracture speeds were high in tensile strain regions and low in compressive strain regions, generally showing a continued decrease as long as the fracture remained in the compressive zone. It is likely that the magnitude and extent of the initial residual compressive strain fields were sufficient for arrest in every case after the fracture had propagated well into the compressive strain field; however, the elapsed time from the beginning of fracture was apparently long enough to allow redistribution of both residual stresses and any applied stresses to provide sufficient energy for propagation to continue. The results of the various tests in which the specimen fractured completely show that in every case, the fracture speed was extremely low in the compressive strain region and, except for the effects of stress redistribution, all fractures probably would have been arrested.

In the prestressed plate tests the fracture texture in the compressive strain region was considerably smoother than that observed in any previous tests of plain plate specimens. Near the initiation edge where high residual tensile strains were present, and where the highest fracture speeds occurred, the fracture texture was fairly rough showing the familiar herring-bone pattern evident in the plain plate tests. This difference in texture in regions of residual tension and compression may be observed in the photographs of the fracture surface of Test 50 in Fig. 14. Also shown in Fig. 14 is the arrest region of Test 48; it is evident that the fracture texture at the point of arrest also is extremely smooth.

Initially it was felt that the difference in fracture texture noted above was a result of the difference in fracture speed across the plate, since the rougher texture always was present in regions of high fracture speed and the smoother texture in regions of much lower speed. An attempt was made to relate the texture roughness with corresponding fracture speed but no conclusive results could be obtained. Since that time, further study has indicated that the roughness of the surface texture appears to be related not to fracture speed, but to the stress or energy level present in the specimen. This fact was first observed in fracture tests of centrally notched and welded specimens which are described in Part B of this report. The aforementioned test data plus data from the wide plain plate tests suggests strongly that fracture texture is indicative of the stress or energy level, and that it is not related directly to fracture speed.

Examination of the fracture surfaces for all

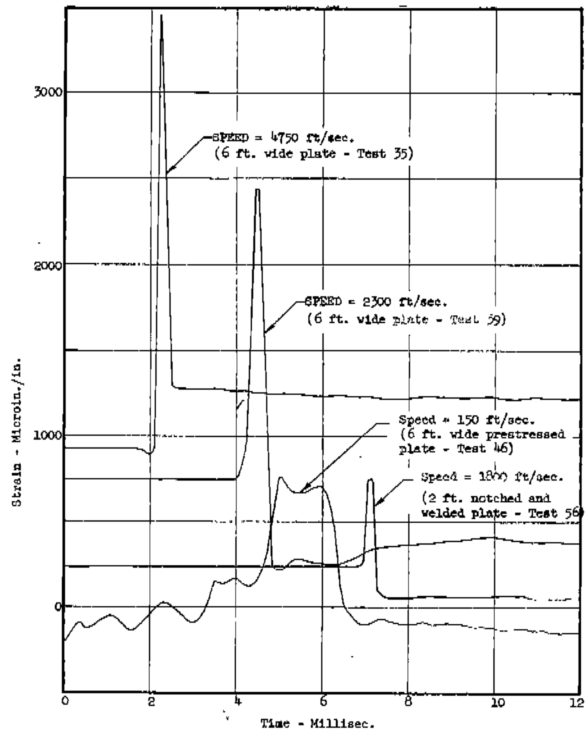


FIG. 18. COMPARISON OF STRAIN-TIME RECORDS FOR LOW-INTERMEDIATE-AND HIGH-SPEED FRACTURES. STRAINS WERE MEASURED APPROXIMATELY 1/2 IN. FROM THE FRACTURE PATH.

prestressed plate tests show a rough texture in the vicinity of the initiation edge. Previous tests, including Test 44 in this series, have indicated this region close to the initiation edge is affected by the initiation technique. Thus, the additional energy supplied to the region of the plate near the point of impact, along with the high residual tensile stress, is felt to be responsible for the rough texture in that region. Elsewhere, where the energy or stress level was relatively low, including the far edge of the plate, the fracture textures are observed to be much smoother.

The dynamic strain records from the various tests give an indication of the marked effect that the residual compression had on the strain field associated with the moving crack. For example, in these tests the peak dynamic strains recorded from component gages 1/2 to 1 in. from the fracture were on the order of 1000 to 1500 microin./in. and gages located more than 6 in. from the fracture showed practically no response. On the other hand, in the earlier plain plate tests in which no residual stresses were present, peak dynamic strains on the order of 2000 to 4000 microin./in. were recorded by gages 1/2 to 1 in. away from the fracture, and gages 6 in. from the fracture still showed a noticeable response. An examination of the dynamic strain records from this series of tests also indicates that in every case the peak strain magnitudes decreased as the fracture entered the compressive strain region. Thus, as the fracture speed decreased, the strain field associated with the fracture also diminished in magnitude and extent; Fig. 18 illustrates this observation extremely well.

Another interesting feature, not recognized in earlier plain plate tests, was the fact that the strain field quite near the tip of the propagating fracture seemed to be approaching a state where tensile strains were recorded for both vertical and horizontal component gages. This phenomenon could be observed only in data taken from gages in the immediate vicinity of the fracture and hence only limited information is available. This phenomenon may be seen by comparing strain-time records of rosette gages 1 and 5 from Test 50 shown in Fig. 11 (a) and 11 (e). It will be noted that the response of the vertical gage of Rosette 1 peaks in tension at the same time the horizontal gage peaks in compression. This is the usual behavior for almost all strain time records observed to date. The records from Rosette 5, however, show both vertical and horizontal gages peaking in tension, although the magnitude of the peak from the horizontal gage is smaller. An examination of previous strain-time records from this and earlier investigations revealed the same phenomenon but apparently strain records show tension peaks on horizontal component gages only if the monitored gages are located less than about 1 in. from the fracture. From the limited information available it also seemed that a higher fracture speed caused this condition to be detected further from the fracture than for a lower fracture speed. This may be noted by examining the record of Rosette 1 of Test 49 (Fig. 6 (a)) where the fracture speed was approximately 2000 fps and the record of Rosette 5 of Test 50 (Fig. 11 (e)) where the fracture speed was less than 1000 fps. Although Rosette 1 of Test 49 was located at a greater distance from the fracture, a much higher strain peak was noted for the horizontal gage than for the horizontal gage of Rosette 5 of Test 50. Comparison of other records indicates the same trend.

In addition to the component strain gage records obtained, corresponding principal strains and their directions were also computed in the tests where rosette gages were used. As may be noted from Fig. 7 and 12, the welding of the slots in Tests 49 and 50 resulted in a completely different pattern of direction of maximum principal strains. In Test 49 the directions of maximum principal strains in the central portion of the plate are all horizontal while in Test 50, the directions are vertical. Also from Fig. 7 and 12, the effect of the approaching fracture on the maximum principal strain and its direction may be noted. Although a zone of residual compression existed throughout the central portion of the test specimens, during propagation maximum principal strains were always tensile in the vicinity of the crack tip. In these figures, the heavy solid lines represent the fracture position corresponding to the depicted strain magnitudes and directions; the extended dashed lines represent the final path of the fracture. On the basis of the data obtained, it seemed that, in general, the path of the fracture in Tests 49 and 50 was normal to the direction of maximum principal strain. This effect of principal strain direction on the path of the fracture also would seem to explain the noticeable changes in the direction of the fracture as it passed through the regions of maximum residual compressive strain.

SUMMARY

The purpose of this investigation was to study the low-velocity propagation of a brittle fracture in 6-ft-wide steel plates in which tensile and compressive residual stresses were present, and to determine from the results of these tests, the effect of residual stress on fracture behavior. As a part of the Project SR-155 investigation two specimens of semi-killed steel were prestressed by welding tapered slots in the edges of the plate. The residual stress field consisted of high tensile stresses at the edges and compressive stresses throughout the central portion of the plate.

The two specimens were subjected to an applied load of 3000 psi and were cooled to about -10 F prior to testing. The fracture was initiated by the notch-wedge-impact method. Instrumentation was provided to determine the crack speed and the strain response.

The results of fracture studies of 6-ft-wide prestressed steel specimens as conducted as a part of this program and the latter phases of Project SR-137 may be summarized as follows:

1) Brittle fractures were initiated in all of the specimens containing a residual stress field; no external load was applied in three of the tests while four specimens were tested at an applied stress of only 3000 psi. By comparison, in the 6-ft-wide plain plate specimens tested under similar conditions (SR-137) an applied stress in excess of 15,000 psi had been found necessary to insure fracture initiation. Thus, the high residual tension in the vicinity of the initiation edge appears to have the same effect on initiation as an externally applied stress.

2) That residual tensile stress is a definite aid to initiation was confirmed by the test of a plain plate specimen (Test 44). This specimen, containing no residual stress, was tested on the laboratory floor and required two impacts to drive a fracture approximately 19 in. No fracture occurred on the first impact but apparently the material at the root of the notch was damaged sufficiently to facilitate fracture upon application of the second impact.

3) The strain field associated with the tip of the propagating fracture and the fracture speed are considerably influenced by the residual strain field present in the specimen. The fracture speed decreased and the magnitude and extent of the strain field around the tip of the crack was considerably reduced as the fracture traversed the region of residual compressive stress.

4) Within about 1 in. of the crack tension peak strains were recorded by both vertical and horizontal gages as the crack passed the gage; generally the effect was more pronounced for the higher crack speeds. This is in contrast to the usual strain behavior noted for gages located further from the crack in plain plate tests where the strain response from the horizontal gage normally showed a compressive peak.

5) A brittle fracture apparently tends to follow a path normal to the direction of the maximum principal strain existing immediately ahead of the crack tip.

6) Fracture speeds varied from as high as 6000 fps near the initiation edge to as low as

50 fps in the compressive strain region. The residual compression in the central portion of the plate caused a large reduction in speed. A nearly linear relationship between residual strain and crack speed appeared to exist 6 in. from the initiation edge in these tests.

7) Comparison of test results makes it appear as though the residual compression in the central portion of the plates tested was sufficient in extent and magnitude to cause arrest had there been no redistribution of stress.

8) The texture of the fracture surface was rough near the initiation edge and quite smooth in the central portion of the plates. It is felt that the texture of the fracture is dependent upon the stress or energy level in the material and not upon the speed. This observation is substantiated by results of other tests described in Part B of this report.

PART B. FRACTURE PROPAGATION IN CENTRALLY NOTCHED AND WELDED STEEL PLATES

INTRODUCTION

Background

The studies of the effect of residual stress on fracture propagation conducted thus far on Projects SR-137 and SR-155 had employed the notch-wedge-impact method of fracture initiation. From time to time research workers have raised questions as to the effects of this artificial crack-starting process on the recorded speeds and strains.

During the past several years work in Great Britain,[8] Japan,[13] and the United States[12] has shown that brittle fractures can be initiated from centrally notched and welded wide plate specimens at low average applied stresses. Although the initiation process is not completely understood as yet, the stress concentration resulting from the notch, the residual tensile stresses resulting from the welding procedure, and perhaps metallurgical changes resulting from the welding process, make it possible for fractures to initiate in these specimens at low applied stresses. Specimens generally fracture either by a short arrested fracture at a low-stress level followed by complete fracture after the specimen has undergone general yielding or, in cases where the stress level is high enough at the time of fracture initiation, it is possible for the specimen to undergo complete single-stage fracture. Quite obviously, the temperature of the test has considerable influence on the fracture mechanism noted. Results of recent studies conducted at the University of Illinois as a part of the Welding Research Council Program utilizing centrally notched and welded plates indicated that this type of specimen might be desirable for use in propagation studies as a part of this brittle fracture mechanics study. By employing this type of specimen it would be possible to obtain low-stress brittle fractures which could be statically initiated thereby eliminating any external initiation device. Since these fractures would be expected to initiate and propagate at a fairly low-stress level it would be expected that the resulting fracture speeds would be in the low to intermediate range which is the primary area of interest in this phase of the investigation.

Object and Scope

The purpose of the tests described in this part of the report was to study the parameters associated with the initiation and propagation of brittle fractures in centrally notched and welded steel plates; more specifically, to evaluate and assess the parameters directly affecting fracture speed. Consideration also necessarily was given to certain aspects of fracture initiation in these specimens and this phase of the fracture process is discussed in some detail in this report.

A total of nineteen specimens was tested as a part of this phase of the program. The tests were all conducted on either 3/4-in. or 5/8-in. steel plate specimens which contained a central precut notch; the majority of the specimens contained either a complete or interrupted longitudinal butt weld to produce the residual tensile stress necessary for low-stress static fracture initiation. Other fabrication procedures were used in a limited number of specimens to facilitate the study of the various parameters under investigation. The specimens are designated as Tests 51 through 69 to conform to the designation of tests conducted as a part of the Brittle Fracture Mechanics Program.

DESCRIPTION OF SPECIMENS, INSTRUMENTATION AND TEST PROCEDURE

Material Properties

The specimens employed in this investigation were fabricated from 3/4-in. and 5/8-in. thick semikilled steel plates. The chemical, mechanical, and Charpy V-notch data for this material are shown in Fig. 19.

Fabrication Procedure

Of the nineteen specimens tested as a part of this phase of the program, seventeen were fabricated of 3/4-in. plate and two of 5/8-in. plate. With the exception of Test 64 which was a 1-ft-wide plate, the specimens were two feet in width, and three feet long. All of the specimens contained a central notch which was cut with either a straight jeweler's saw or a circular cutting wheel, both 0.006 in. thick. A double-Vee notch cross section was employed in all specimens except Test 62 which had a straight notch. The notch geometry for the two types of notches is shown in Fig. 20, and sketches of the various types of specimens are shown in Fig. 21.

The general preparation of all specimens, except for Tests 61 and 63, consisted of cut-

TENSILE TEST DATA

Yield		Maximum		Percent Elongation		Percent Reduction	
L*	T*	L	T	L	T	L	T
33.2	31.6	63.7	62.6	36	30	63	63

*L = Longitudinal
T = Transverse

CHECK ANALYSIS

C	Mn	P	S	Si	Cu	Ni	Al
0.20	0.77	0.017	0.033	0.01	0.06	0.02	0.015

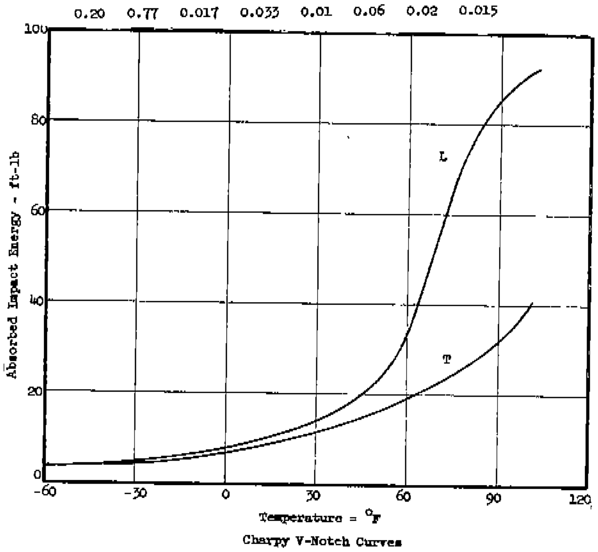


FIG. 19. MATERIAL PROPERTIES.

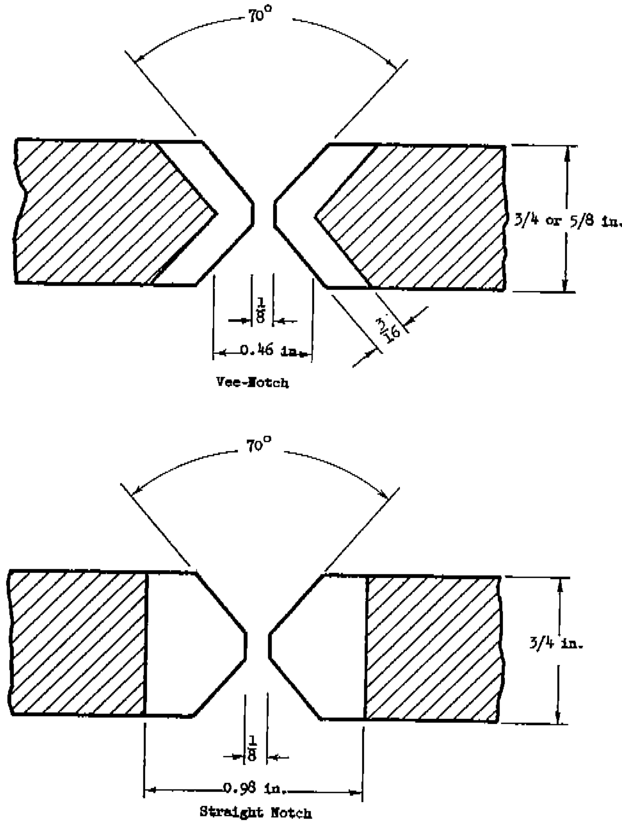


FIG. 20. NOTCH DIMENSIONS.

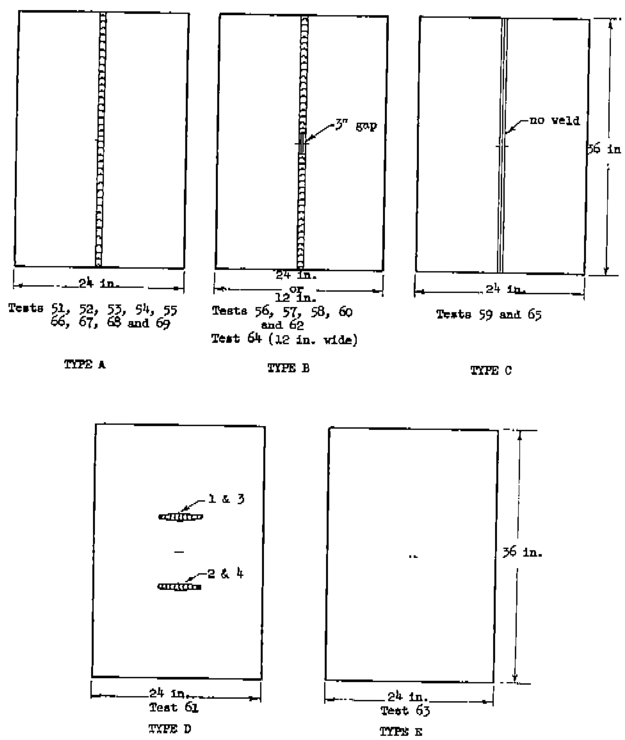


FIG. 21. SPECIMEN LAYOUT.

ting the specimen along its longitudinal center line, beveling and notching the adjacent edges of the resulting two halves, and rejoining the two halves by various methods. In joining the two halves of the notched and beveled specimens, three fabrication procedures (used for Specimen Types A, B and C in Fig. 21) were employed. The Type A specimens were joined with a continuous double-Vee butt weld; the Type B specimens were joined with an interrupted double-Vee butt weld in which a 3 in. section at the notch was left unwelded; in the Type C specimens the two halves of each specimen were merely welded to the pull plates of the testing machine leaving the adjacent notched and beveled edges unwelded. Test 61 (Type D) was prepared by first cutting the central double-Vee notch in a plain plate after which two 6-in.-long transverse slots were cut 5 in. above and below the notch and welded to produce a residual stress field. Test 63 (Type E) was a plain plate specimen in which a central double-Vee notch was cut. All of the specimens were fabricated such that the longitudinal axis was parallel to the direction of rolling of the plate material and parallel to the direction of testing.

A total of six welding passes with 5/32 in. and 3/16 in. diameter E7018 electrodes were required for all of the specimens which contained longitudinal welds, with the 5/32 in. diameter electrodes being used for the first and second passes. In welding, subsequent passes were made on opposite surfaces of the specimen and the maximum interpass temperature was limited to 100 F. The welding procedure followed was slightly different for the Type A and Type B specimens. In the former, each weld pass proceeded from one end of the specimen to the other, whereas the Type B specimens were joined such that each weld pass was placed in two-stages each of which began at the end of the plate and terminated approximately 1 1/2 in. from the notch.

Instrumentation and Measurement Techniques

Instrumentation for this series of tests was provided for the measurement of cyclic strains during welding, longitudinal residual strains, static strains and elongations during loading, and dynamic strains and speeds during fracture propagation. All of the above variables however were not measured for every specimen.

Instrumentation included both electrical and mechanical strain gages. The electrical strain gages employed in this investigation were either Baldwin SR-4 Type A7 (1/4 in. gage length) or Budd Metalfilm Types C6-141B and C6-1X1 32 A (1/4 in. and 1/32 in. gage lengths respectively) strain gages. Budd Metalfilm Type C6-121-R3A strain rosettes were used for the measurement of dynamic strains in two tests. Crack speed detectors were Baldwin SR-4 Type A9 gages (6 in. gage length). Mechanical gages employed in the measurement of residual strains were a 2-in. and a 6-in. Berry gage.

Residual Strain Measurements--The residual strains in the specimens resulting from welding were measured by both electrical and mechanical strain gages. The gages were selected in order to provide a wide range in gage lengths which served as a check on the uniformity of strains. Also, the high temperatures induced during welding made it necessary to use mechanical gages at locations near the weld. In determining the longitudinal residual strain pattern, strains were measured only across the notch line.

Initial strain readings were taken prior to welding with the plate in an unrestrained position. The initial strain readings established the "zero" strain level and all other strains were referenced to this prewelded state. After welding had been completed, another set of strain readings were taken at room temperature from which the residual strain pattern was obtained.

Measurement of Cyclic Strains and Temperatures During Welding--Strain and temperature readings within approximately 1/8 in. of the notch root on the plate surface were recorded during welding on selected specimens. Continuous records of both temperature and strain as a function of time were obtained during welding by connecting the strain gage and thermocouple leads through bridge circuits to two millivolt strip chart recorders, one of which recorded strain and the other temperature. The particular strain gages used were temperature compensated to 250 F.

Measurement of Static Strain and Elongation--Static stress-strain records were obtained for selected specimens during loading Strain records from eight gages could be obtained by connecting the leads from the strain gages to an eight-point motor driven sampling switch which in turn was connected through a bridge circuit to a millivolt strip chart recorder.

In addition to recording static strains during loading, several specimens were instrumented with a 36 in. extensometer. The extensometer provided a continuous record of the specimen elongation during loading.

Dynamic Instrumentation-- Nine channels of cathode ray oscilloscope recording instrumentation for recording the dynamic strains and fracture speeds were utilized in some of the tests described herein. The method of recording dynamic strains and speeds consisted of photographing the strain response and detector breaking times as they appeared on the oscilloscopes during fracture propagation and was identical to the technique used in previous tests on Projects SR-137 and SR-155. The system employed in triggering the oscilloscope sweeps, however, was somewhat different. Because fractures were statically initiated in this series of tests and the strain level at the time of fracture was unknown, it was necessary to trigger the sweeps with a signal proportional to strain rate, independent of the strain magnitude. The triggering was accomplished by connecting the trigger gages through a bridge to a differentiating circuit which produced a signal roughly proportional to the strain rate at the trigger gages. The signal from the differentiating circuit after being amplified by a high-gain amplifier was fed into a sweep generator which triggered the horizontal sweeps of all nine oscilloscope channels.

Two trigger gages were mounted on the notch line of each specimen about 1/4 in. and 3/4 in. from the notch tip where high strain rates would occur with the onset of rapid fracture propagation. The trigger gages were connected in a bridge circuit as shown in Fig. 22. By wiring the trigger gages in this way, a sweep would be initiated by a high strain rate at either of the trigger gages.

Test Procedure

Two testing machines of 600,000-lb and 3,000,000-lb capacity were employed in this study. The specimens were installed in the appropriate testing machine (depending upon the anticipated fracture load), cooled, and loaded statically to failure.

The specimens were cooled by a mixture of solvent and dry ice placed in cooling tanks; a total of four tanks were used, two on either side of the specimen above and below the notch. This cooling technique resulted in a uniform temperature distribution along the notch line.

When the desired test temperature had been attained, loading began and the recording equipment was started. Because the fracture load in these specimens could not be predicted, the film used to record dynamic strains and speeds had to run continuously throughout the test. This recording procedure resulted in satisfactory test records in most cases but occasionally records were lost because of malfunction of the trigger, a short arrested frac-

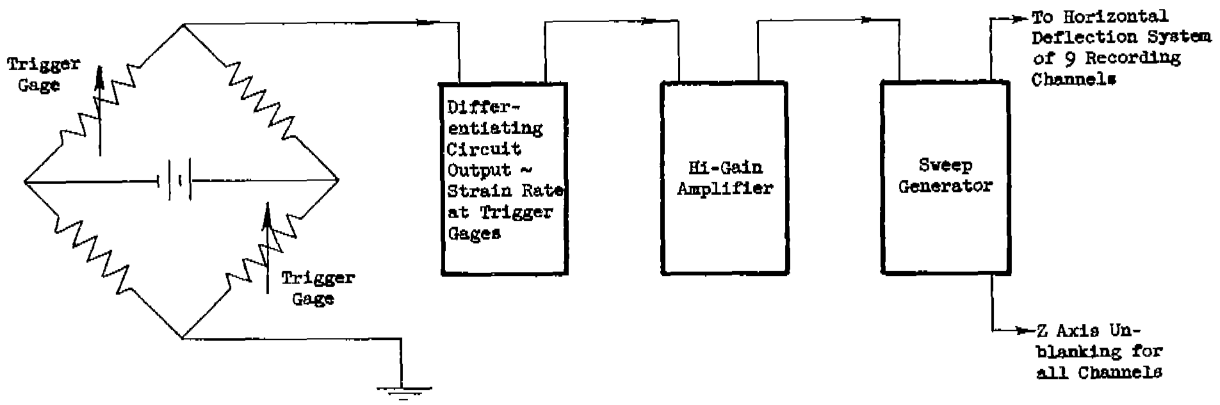


FIG. 22. TRIGGER CIRCUIT.

ture occurred, or because of excessive specimen loading time and the film supply was expended.

PRESENTATION AND DISCUSSION OF TEST RESULTS

General

Brittle-fracture tests were conducted on nineteen centrally notched specimens in which fractures were initiated statically. Nine of these specimens contained a continuous longitudinal weld (Type A), six contained an interrupted longitudinal weld with a 3 in. gap at the notch left unwelded (Type B), one contained two transverse welds above and below the notch (Type D) and three were unwelded (two of Type C and one of Type E). In these tests consideration was given to both initiation and propagation aspects and in the process a number of items, including thermal strain cycling during welding, residual strains resulting from welding, load, strain and deformation at fracture, and dynamic strains and fracture speeds were studied. Table 2 contains a summary of the results of these tests.

Residual Strains

The residual strain field was similar in all of the longitudinally welded specimens (Type A and B) regardless of whether the weld was continuous or interrupted. With reference to a transverse section, the central one-third of these specimens had a residual longitudinal tensile strain, balanced by residual compressive strains in the outer two-thirds of the plate. The residual strain decreased rapidly from a maximum value of 1000 to 2000 microin./in. near the weld to a fairly uniform compressive strain of -300 to -500 microin./in. toward the edges of the plate as shown in the typical residual strain plots presented in Fig. 23. The mechanical and electrical residual strain readings were in general agreement with some differences noted, most likely arising from different gage lengths and inherent difficulties in making the measurements in highly distorted regions.

Unlike the longitudinally welded specimens, the residual strain field in the central portion of Test 61, which contained two transverse welds above and below the notch was fairly uniform except near the notch where a high strain concentration occurred. As shown in Fig. 23 (c) the residual strain was extremely high (approximately 6000 microin./in.) near the notch tip, decreased rapidly a small distance from the notch tip to a residual tensile strain of about 800 microin./in. and then decreased less rapidly until a fairly uniform residual compressive strain of about -500 microin./in. was attained 8-in. from the center line of the specimen. It should be pointed out that the gage used to measure the strain near the tip of the notch was located closer to the notch in this specimen than similar gages in the other specimens, a fact which may account, in part at least, for the extremely high residual strain observed at this point.

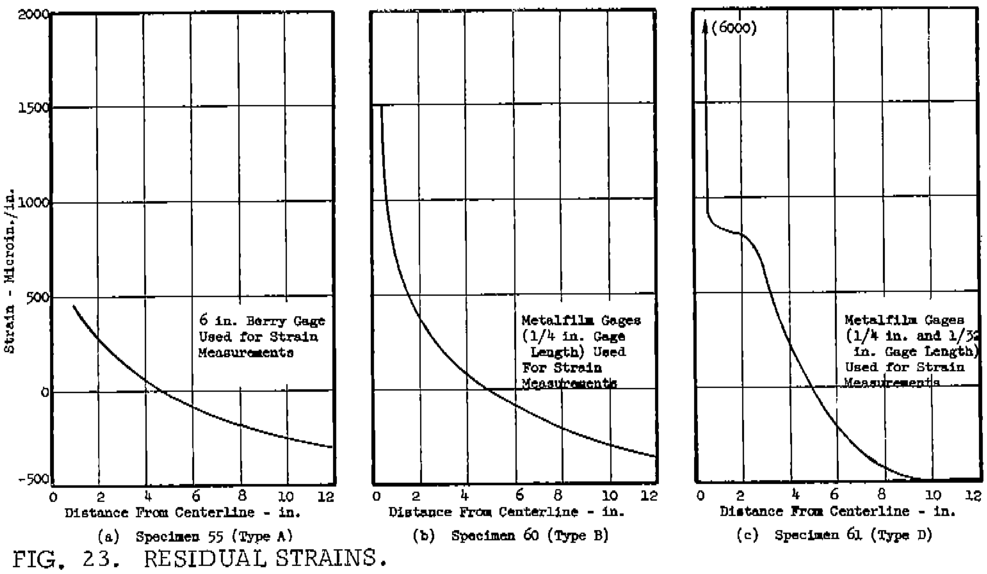


FIG. 23. RESIDUAL STRAINS.

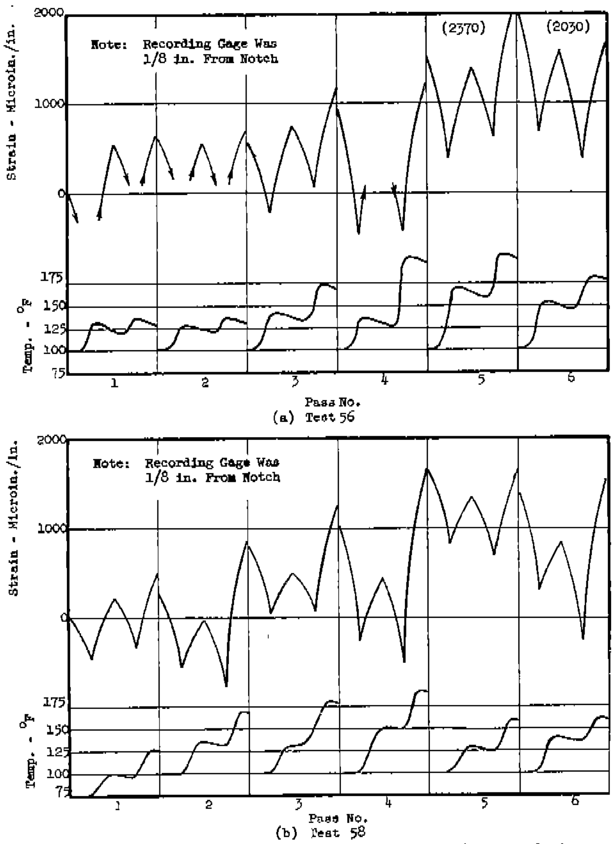
TABLE 2. SUMMARY OF CENTRALLY NOTCHED AND WELDED PLATE TESTS.
All specimens were 3/4 x 24 x 36 in. and contained double-Vee notches with the following exceptions: Tests 51 and 52 were 5/8 x 24 x 36 in.; Test 64 was 3/4 x 12 x 36 in.; Test 62 contained a straight notch. All tests conducted at -40 F.

Test No.	Fracture Stress on Net Area (ksi)	Specimen Type*	Residual Strain (Microin./in.)	Average Speeds High - Low (fps)	Remarks
51	40.0	A	not measured	not measured	5/8 in. thick; misaligned notch; general yielding occurred; rough texture.
52	18.0	A	not measured	not measured	5/8 in. thick; fairly smooth texture
53	10.0	A	not measured	5500 - 3100	Smooth texture.
54	9.2	A	not measured	6000 - 1800	Good dynamic strain records; smooth texture.
55	10.2	A	500 1/4 in. from notch	not measured	Smooth texture.
56	9.0	B	2000 1/8 in. from notch	—— - 1800	Good dynamic strain records; smooth texture.
57	5.0 Initial fracture 33.6 Final fracture	B	1800 1/8 in. from notch	not measured	Initial fracture was 11.5 in. long; smooth texture observed for initial fracture and rough for final fracture.
58	17.4 Initial fracture 31.8 Final fracture	B	1200 1/8 in. from notch	not measured	Misaligned notch; initial fracture was 1 in. long on one side of specimen; rough texture.
59	37.0	C	0	not measured	General yielding occurred; 0.45 in. elongation in 36 in. gage length; rough texture.
60	32.0	B	1500 1/8 in. from notch	not measured	Longer gap in weld than other Type specimens, therefore less cycling; rough texture.
61	35.9	D	6000 0.04 in. from notch	not measured	General yielding occurred; 0.2 in. elongation in 36 in. gage length; rough texture.
62	35.7	B	1700 1/8 in. from notch	not measured	Straight notch instead of Vee-notch specimen fractured at yield stress but without general yielding; rough texture.
63	38.0	E	0	not measured	Misaligned notch; general yielding occurred; rough texture.
64	13.9	B	2800 1/16 in. from notch	not measured	12 in. wide specimen; smooth texture
65	37.2	C	0	not measured	General yielding occurred; 0.27 in. elongation in 36 in. gage length; rough texture.
66	9.7	A	not measured	not measured	Smooth texture.
67	8.5	A	not measured	5000 - 1800	Good dynamic strain records; smooth texture.
68	11.6	A	not measured	not measured	Smooth texture.
69	9.0	A	not measured	not measured	Good dynamic strain records; smooth texture.

* See Fig. 21.

Thermal Strain Cycling

Among the most interesting observations made during this series of tests were measurements of the thermally induced strains during fabrication of four Type B specimens, and the specimen containing the transverse welds (Test 61). In all of these specimens it was possible to obtain strain records during welding from electrical strain gages mounted near the notch on the surface of the plate since the temperature of the material in this region rarely exceeded 200 F. The strain and temperature records obtained during welding of the Type B and D specimens are plotted in Fig. 24. In presenting these records, portions of the strain data recorded between weld passes where the strain was approximately constant have been omitted; by way of illustration of one complete cycle, the record for one welding pass is shown in Fig. 25.



Note: As noted in text, welding was accomplished in two-stages; each stage proceeded from one end of the specimen to a point 1 1/2 in. from the notch followed by an identical stage beginning at the other end of the specimen on the same side of the plate

FIG. 24. STRAIN AND TEMPERATURE DURING WELDING.

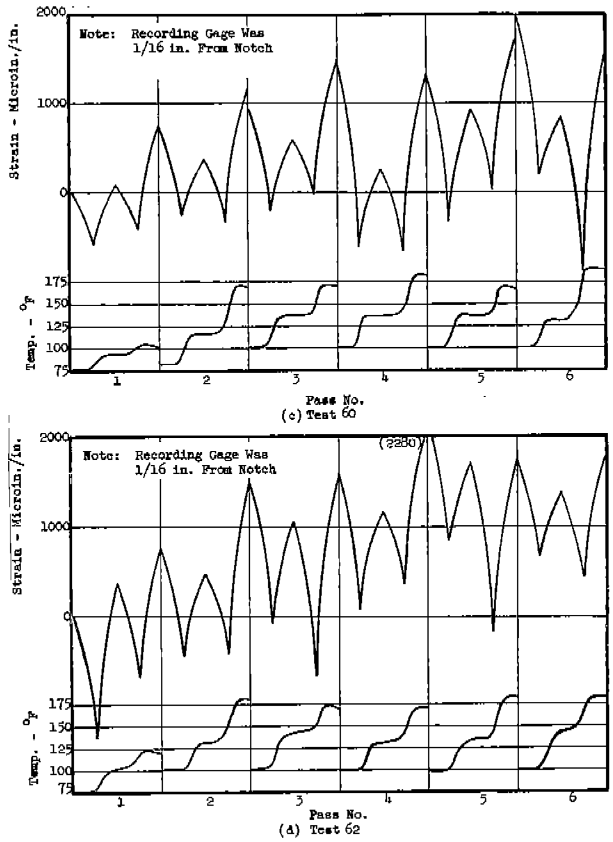


FIG. 24. STRAIN AND TEMPERATURE DURING WELDING.

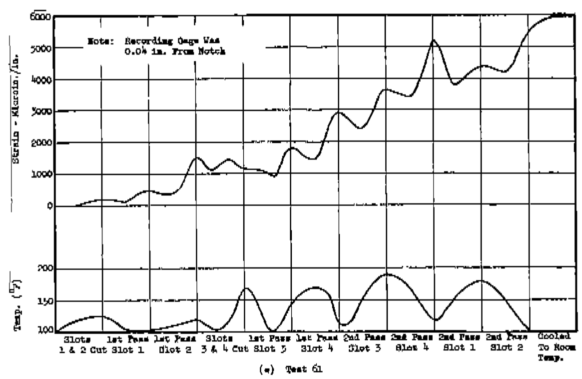


FIG. 24. STRAIN AND TEMPERATURE DURING WELDING.

Note that in Fig. 24 (a) through 24 (d) there are two complete strain cycles for each welding pass; this arises from the particular welding procedure employed in which one weld pass was placed in two stages, namely, from one end of the specimen to within 1 1/2 in. of the notch followed by an identical second half pass from the other end on the same side of the plate. Consequently, the recording strain

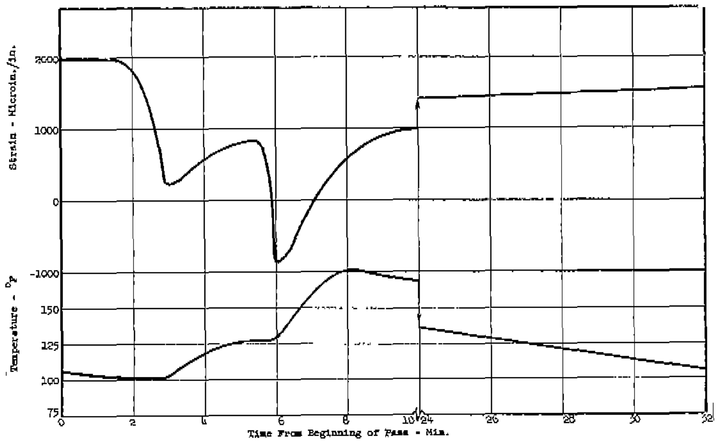


FIG. 25. TYPICAL STRAIN RECORD FOR ONE WELDING PASS.

gage was approached twice by the welding electrode for each welding pass, thus producing two strain pulses for each pass as may be seen in Fig. 24 or 25.

Another interesting observation is that during welding a total strain range of over 2000 microin./in. was recorded for a single pass and as much as 3600 microin./in. for the complete welding sequence. This range is no doubt quite dependent upon gage location with respect to the notch root and therefore it is difficult to predict the amount of cyclic strain experience by the volume of material at the notch root.

Welding of the transverse slots in Test 61 produced little cycling as shown in Fig. 24 (e). There was a slight variation in strain during welding of this specimen but compared to the records obtained from the Type B specimens it was negligible, especially when considered in light of the fact that the gage for Test 61 was closer to the notch than those on the Type B specimens.

Static Stress-Strain Records

Typical plots of average applied stress versus strain obtained from static gages during loading of several specimens are shown in Fig. 26. The locations of the gages are indicated on each plot. Where possible, the strain values for zero stress correspond to the residual strain existing in the plate before loading. For the specimens in which fractures initiated at about 10 ksi average applied stress, the static stress-strain plots were nearly linear up to fracture. For specimens in which fractures occurred at or above yield, the strain records indicated a definite yielding of the material with the load at which a particular gage yielded depending upon the location of the gage. Note particularly Fig. 26 (a) which is the static record obtained during loading of Test 51. As shown in this plot, four of the gages which were located three or more inches away from the weld yielded at approximately 38 ksi (approximately yield stress at the -40 F temperature), whereas one gage located on the weld indicated yielding at an applied stress of about 16 ksi.

In Test 57 the static strain gages with the exception of gage 9 were located above the notch line as shown in Fig. 26 (c). Fracture in this specimen occurred in two stages; the first fracture propagated about 6 in. from the center line of the specimen before arresting. In the same figure it can be seen that gages 1 and 2 experienced greater compressive strains after the initial fracture than before loading began. These measurements would seem to indicate that a considerable residual strain field continued to exist throughout the plate, even in the semirelaxed material directly above the fracture. As is usually the case with two-stage fracturing, complete fracture occurred after general yielding of the remaining portions of the specimen.

In Fig. 26 (d), the static strain records for Test 61 are presented. This specimen (Type D) was prepared by welding 6 in. long transverse slots 5 in. above and below the notch. The transverse section through the welded slots was slightly thinner than the thickness of the plate, being about 5/8 in. thick at the weld as opposed to an overall plate thickness of 3/4 in.

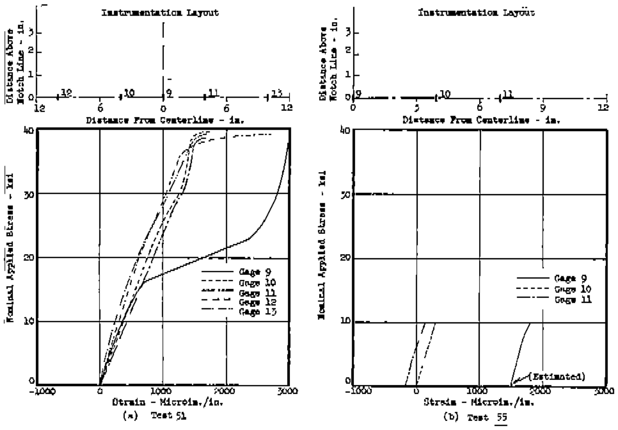


FIG. 26. STRESS-STRAIN PLOTS OBTAINED DURING LOADING.

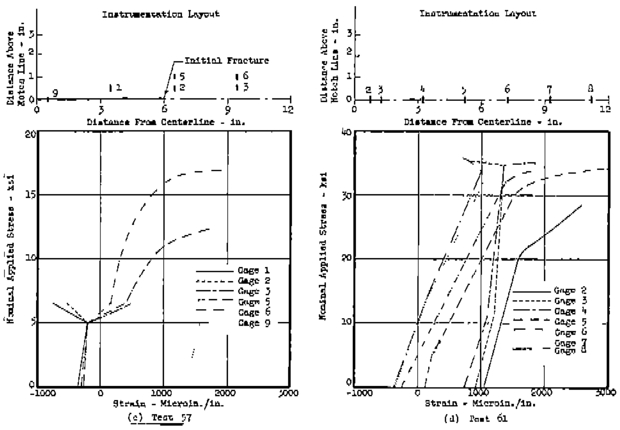


FIG. 26. STRESS-STRAIN PLOTS OBTAINED DURING LOADING.

With this fact in mind, it can be observed that the rate of straining of gages 2, 3 and 4 between the slots was slightly less than that of the other gages in the pre-yield range, probably because this section was not resisting as much of the applied load as the edge areas of the plate. Although not described here, it is interesting to note in Fig. 26 (d) the effect of the specimen geometry and relaxation on the strain behavior across the cross section at the notch with the onset of general yielding.

In Fig. 27 are presented load-deformation curves for the three specimens (Types C and E) which did not have induced residual stress fields. It will be noted that general yielding and considerable inelastic deformation occurred prior to fracture at -40 F.

Fracture Stresses

The fracture stress data for all specimens

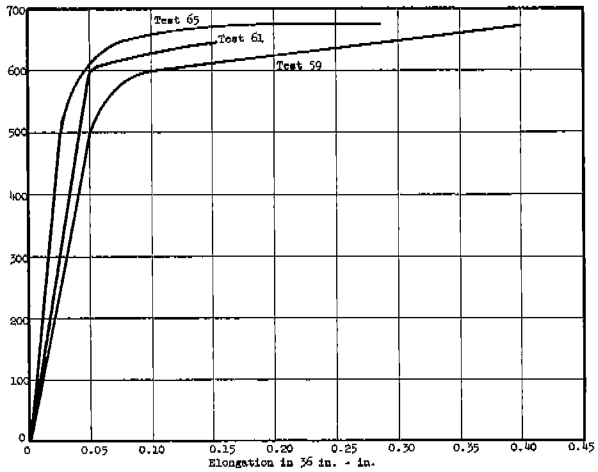


FIG. 27. LOAD DEFORMATION CURVES.

is summarized in Table 2. The Type A specimens with continuous welds contained high residual tensile stresses at the notch and the material near the notch had been subjected to thermal strain cycling and high temperatures during welding. All seven 3/4-in. specimens fractured consistently at an applied tensile stress of about 10 ksi. Tests 51 and 52 were 5/8 in. thick and fractured at stresses of 18 and 40 ksi; the latter high stress quite likely can be attributed to a misaligned notch which was observed after fracture.

In properly Vee-notched specimens containing interrupted welds (Type B), complete or partial brittle fractures occurred at consistently low applied stresses (5 - 13 ksi) as was the case for the previous specimens containing complete welds. In the three remaining Type B specimens, one contained a misaligned notch and a first stage fracture occurred at approximately 17 ksi; in the remaining two specimens, complete fractures occurred at 32 and 35.7 ksi. This abnormally high stress level required for fracture may be attributed to the straight notch used in one specimen and to a larger gap, resulting in reduced strain cycling, in the second specimen. Offhand, the strain cycling record in Fig. 24 (c) does not substantiate this conclusion; however, the gage from which this record was obtained was closer to the notch than similar gages in other specimens, and thus in a region of higher strain concentration.

While the properly notched and longitudinal butt-welded specimens (with the exception of Test 51) failed at low stresses well below yield, the unwelded specimens and the notched specimens containing transverse welds all fractured after general yielding. Test 61, as previously noted, contained extremely high residual tensile stresses near the notch tip but had not been subjected to thermal cycling or high temperatures. This specimen fractured at a stress above yield after 0.20 in. of elongation in a 36 in. gage length, indicating that residual stress in itself was not sufficient to cause fracture at a low applied stress.

Dynamic Strains and Speeds

Dynamic strain records from longitudinally oriented component gages were obtained from Tests 54 and 56, and from strain rosettes in Tests 67 and 69. These records are plotted in Fig. 28. Because of the various difficulties involved with certain aspects of the dynamic

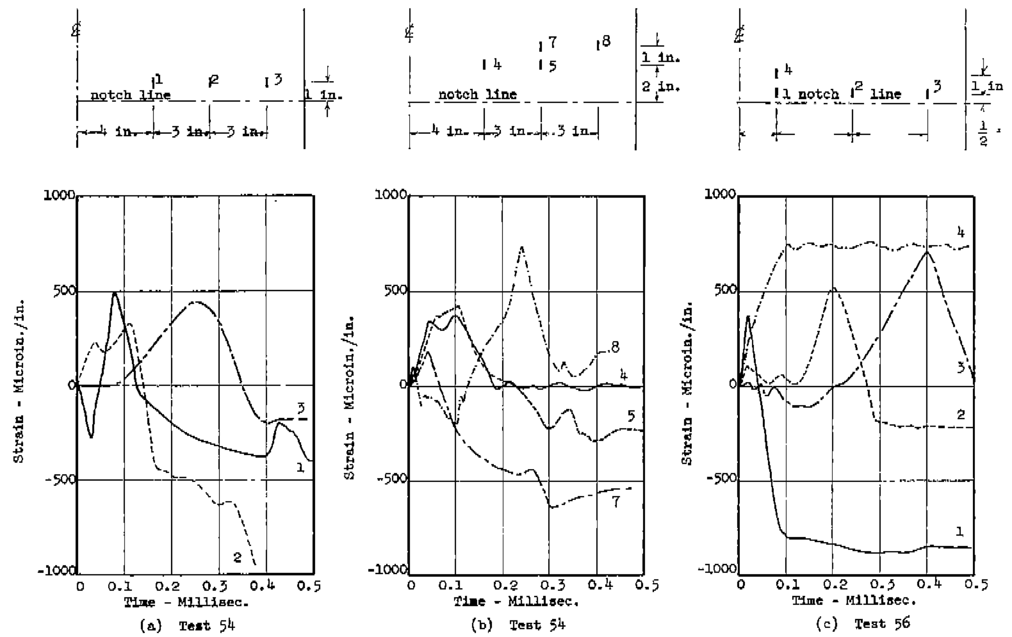


FIG. 28. STRAIN-TIME RECORDS.

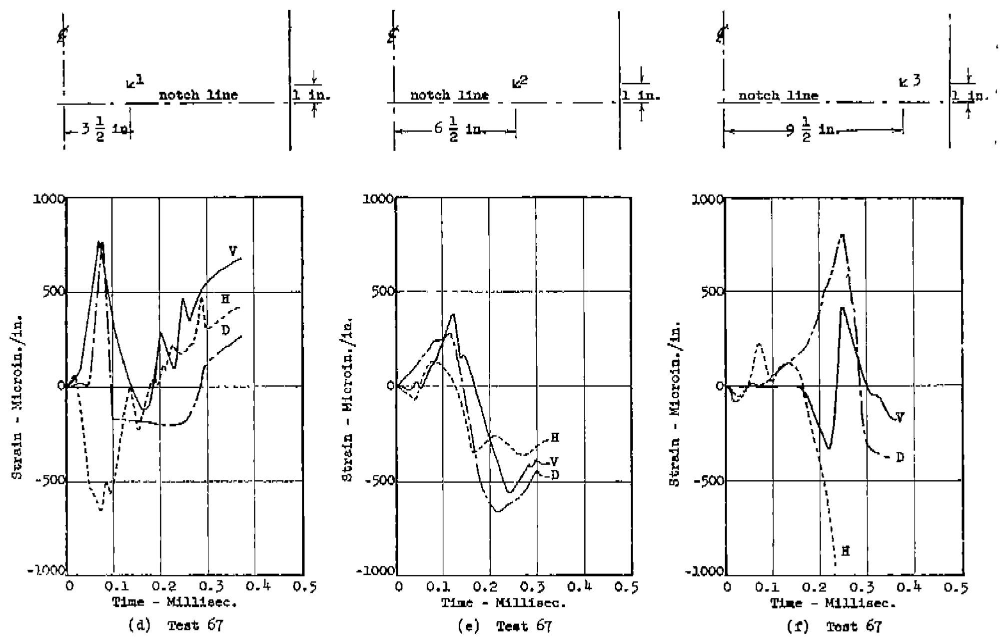


FIG. 28. STRAIN-TIME RECORDS.

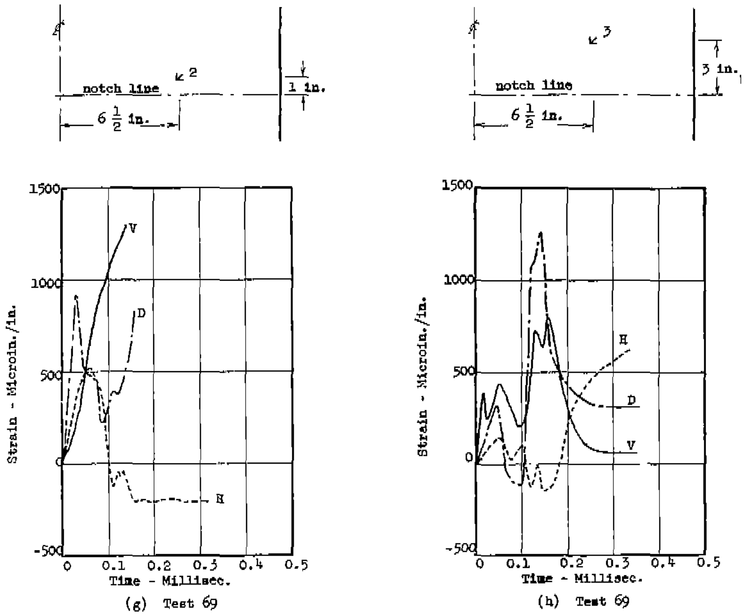


FIG. 28. STRAIN-TIME RECORDS.

recording, it was not possible to obtain the complete strain history for each of the dynamic gages from the beginning of loading until fracture initiation. In other words, it was possible to monitor the strain history from the time of welding up to the time of testing; however, because of the recording techniques employed it was not possible to obtain the strain corresponding to the exact test load level. For this reason all strain records are plotted with the zero strain level corresponding to the strain level of the measuring gage at the time of fracture initiation. This limitation does not affect the validity of the strain records nor does it restrict in any way the interpretation of these strain pulses when compared to similar pulses obtained on other tests. However, in the case of rosette gages it does prohibit calculation of principal strains in the sense that principal strains calculated from the observed component strains have little meaning. Because this situation was recognized quite early for those specimens instrumentated with strain rosettes, for convenience, the gages were placed on the specimens after the specimens had been fabricated.

As far as the dynamic strain records themselves are concerned, a study of Fig. 28 will show that the component gage traces arising from tests in which only longitudinally oriented gages were employed, or tests in which rosette gages were employed, all show about the same trend. At first glance examination of the traces in Fig. 28 suggest a difference between these dynamic records and those of earlier tests, especially for the strain traces for horizontal and diagonal component gages. However, if one estimates the actual strain level corresponding to the time of initiation, all the traces appear to fall more in proper perspective; any interpretation of the strain traces, as for example studying trends across the plate width, must include consideration of the probable base strain level. In general, the strain gage traces are similar in nature to those which have been found in earlier tests involving the notch-wedge-impact method of initiation.

Several observations can be made about these strain records. For the vertical component gages it was found that the peak vertical strains ranged from 300 to 1000 microin./in., but apparently the peak strains were not as dependent upon the distance from the fracture as had been found in earlier wide plate tests as indicated in Fig. 29. However, it will be noted in Fig. 28 (c) that for gages located 1/2 in. from the crack the peak strain was about 700 microin./in. This is in line with observations made for the 6-ft-wide prestressed plates. There are some anomalies in the records; for example, in Fig. 28 (c) Gage 4 shows a trace which is not consistent with what would be expected from the large number of other records and probably this is caused by a mechanical malfunction, such as stretching of wires or some other phenomenon during the

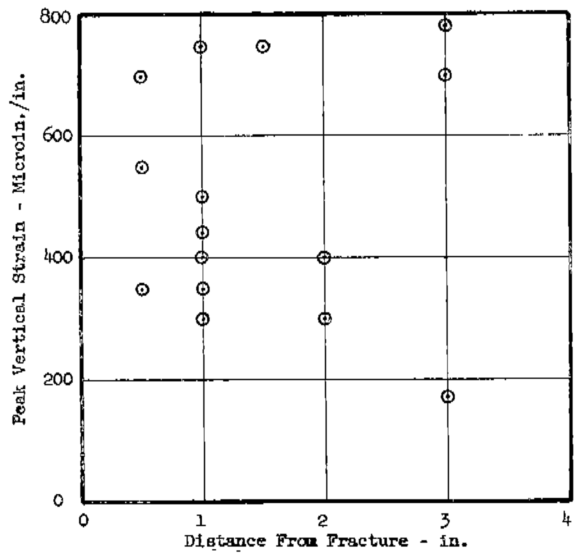


FIG. 29. RELATIONSHIP BETWEEN PEAK LONGITUDINAL STRAINS AND DISTANCE OF THE MEASURING GAGE FROM THE FRACTURE PATH.

testing operation. Also, Gage 1 which is quite close to the initiation source does not show an extremely high peak which one might expect in the region of high speeds as observed in a large number of previous tests. However, for another specimen for which the records are shown in Fig. 28 (d) a vertical gage 3 1/2 in. from the source of initiation shows a strain peak which is more in line with what one would expect in this region.

With regard to the response of the component gages of the rosettes, the traces were quite similar to those observed in other tests made as a part of this program. The horizontal gage of Rosette 2 in Tests 67 and 69 (Fig. 28 (e) and 28 (g)) peaked in tension as had been observed in earlier tests for rosettes located close to the fracture. The behavior of the other component strains was quite typical of those recorded in earlier tests on Projects SR-137 and SR-155.

Average fracture speeds were determined from the peaking times of the longitudinally oriented gages and in Test 53 from the detector breaking times. The strain gage peaking times and detector breaking times are plotted as a function of the distance of the particular strain gage or detector from the trigger gage location in Fig. 30. The slopes of these curves are an indication of the average fracture speeds.

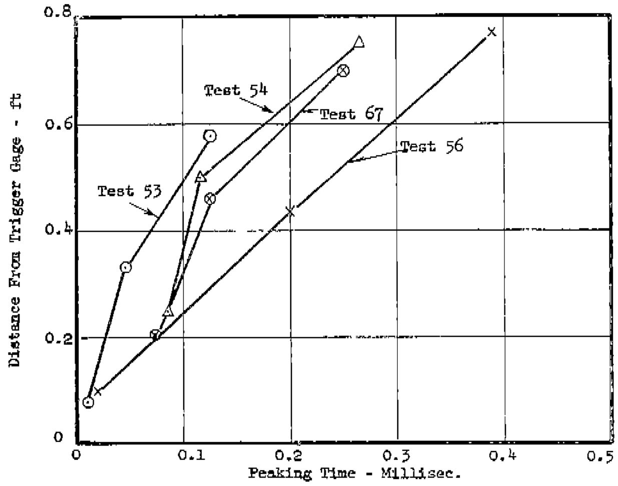


FIG. 30. FRACTURE SPEEDS.

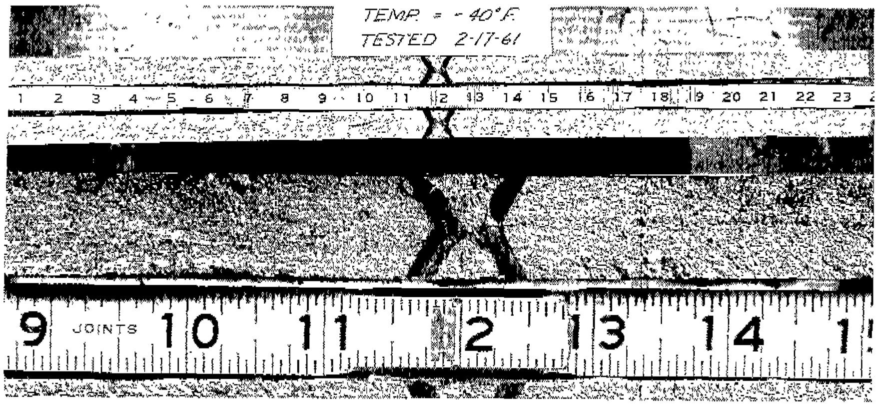
The fracture speeds as indicated by Fig. 30 appear to have decreased when the fracture propagated into the region of low residual strain. In general, speeds ranged from 5000 to 6000 fps near the initiation source to about 1800 fps after the fracture had propagated a few inches. This variation in fracture speed also is reflected in the dynamic strain records in which it can be observed that the length of time required for peaking was longer for strain gages located near the edges of the specimens than for those located near the center.

Although the recorded data is average in nature, one extremely important observation arises from these estimations of fracture speeds. It will be noted in Fig. 30 that the fracture speed attains a high value, in the range of 5000 fps within a distance of approximately 1 to 2 in. of the fracture source. It may be recalled that in tests involving the notch-wedge-impact method of initiation, it had not been possible to measure speeds at distances closer than about six inches to the initiation source. Thus, we now have evidence that even in the case of a statically initiated fracture the speed can become very high within a short distance from the source of initiation.

Another indication of the relevant magnitude of the speeds involved in these tests is given by the width of the strain pulses. It has been observed previously in plain plate tests that in the high-speed region the tensile pulses for vertically oriented gages can be as short as 100 microsec. or less. On the other hand, in the prestressed 6-ft-wide plate tests, where the speeds were as low as 50 fps, some of the strain pulses were observed to be as long as 2 to 5 millisec. In the present series of tests the comparable traces in the compressive strain region were observed to have base pulse widths on the order of 100 microsec. or more which would tend to indicate that these pulses were associated with an intermediate speed range.

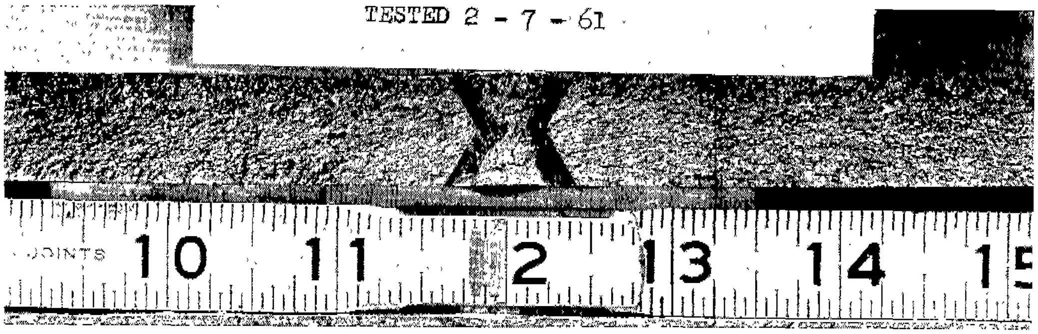
Fracture Appearance

In general the fracture texture became rougher and the fracture path tended to wander slightly as the fracture stress increased. Figure 31 (a) which is a photograph of the fracture surface of Test 53 which failed at 10 ksi, shows the smooth texture typical of all of the



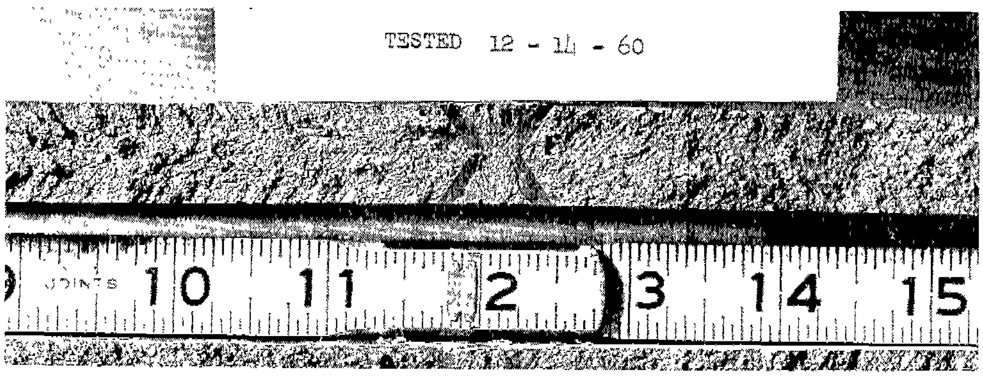
(a) Test 53

FIG. 31a. FRACTURE APPEARANCE.



(b) Test 52

FIG. 31b. FRACTURE APPEARANCE.



(c) Test 51

FIG. 31c. FRACTURE APPEARANCE.

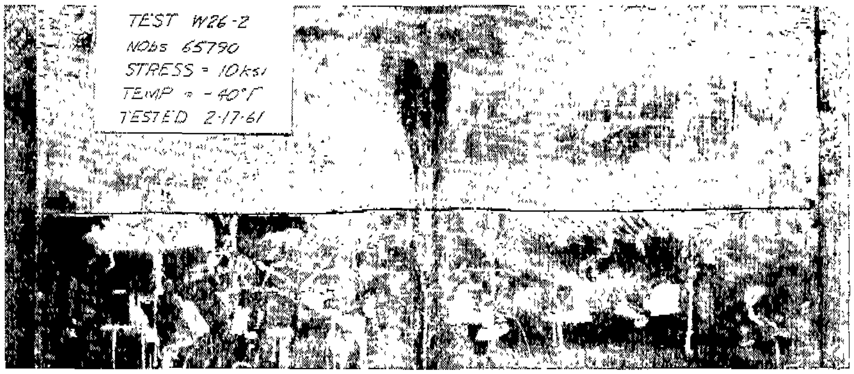
specimens which fractured at quite low average applied stresses. The chevron markings of this fracture are barely visible and only a slight shear lip can be observed near the surfaces of this plate. Low-stress fractures, in addition to having a smooth texture, displayed a uniform texture across the entire plate width. The fracture texture of Test 52 (Fig. 31 (b)) which failed at 18 ksi, when compared with that of the low-stress fractures just noted, is slightly rougher with a wider shear lip and more discernable chevron markings. The typical high-stress fractures (yield point and above) are characterized by a very rough texture and clearly visible shear lips and chevron markings as can be seen in Fig. 31 (c).

The fracture paths in the various specimens also apparently were influenced by the fracture stress as shown in Fig. 32. The low-stress fractures generally followed a fairly straight path whereas those fractures occurring near the yield point of the material were likely to wander slightly as may be seen in the figure.

Figure 33 shows the fracture surface of Test 57 in which a partial length fracture occurred at 5.0 ksi. Note the extremely smooth texture of the initial fracture as compared to that of the final stage which occurred at a net stress of 33.6 ksi. The zone of arrest noted by the arrow and the thumbnail also is interesting to observe because the tip of the arrested crack was not symmetrical with respect to the thickness. Reinitiation of this fracture appears to have originated at mid depth of the plate even though the geometry of the crack tip was not symmetrical.

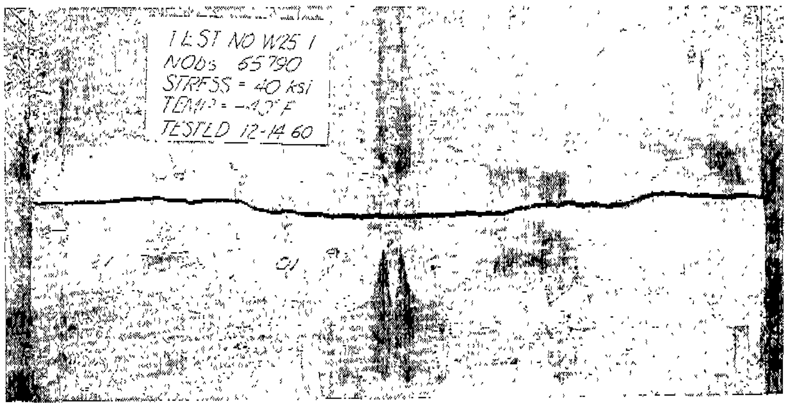
SUMMARY

In this particular study considerable information relating to the propagation and



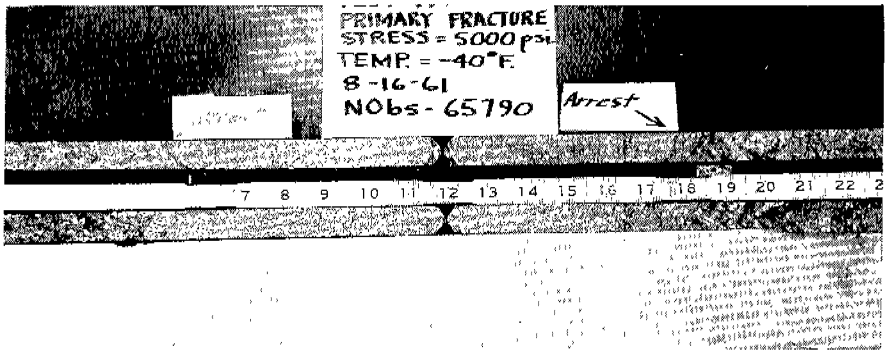
(a) Low Stress Fracture - Test 53

FIG. 32a. FRACTURE PATH.



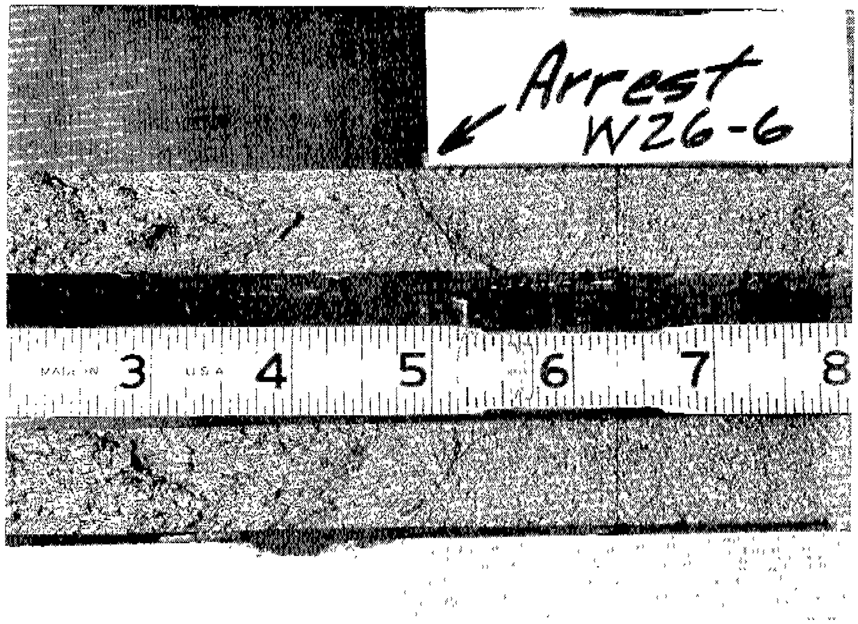
(b) High Stress Fracture - Test 51

FIG. 32b. FRACTURE PATH.



(a) Fracture Appearance

FIG. 33a FRACTURE APPEARANCE FOR TWO STAGE FRACTURE -TEST 57.



(b) Arrest Region

FIG. 33b FRACTURE APPEARANCE FOR TWO STAGE FRACTURE - TEST 57.

initiation aspects of brittle fractures was obtained. For convenience of presentation, this summary is subdivided into two sections, namely, propagation and initiation.

Propagation Studies

In the following discussion, it should be kept in mind that all dynamic measurements were obtained from specimens which fractured at a low average applied stress (8 to 12 ksi).

The recorded fracture speeds in these tests ranged from about 5000 fps in the central portions of the specimens, where residual tensile stresses were high, to approximately 1800 fps throughout the remaining portion of the plate. This decrease in speed as the fracture propagated into the region of residual compressive strains was similar to the behavior of the fractures discussed in Part A of this report and serves to verify the point of view that changes in speed are dependent to some extent on the stress level existing in the plate. Another interesting observation about the fracture speeds is that in these tests high fracture speeds on the order of 5000 fps were recorded at distances as close as 2 in. from the initiation source. This is the first time that an indication of the fracture speeds this near a source of initiation, particularly in the case of a statically initiated fracture, has been obtained in the work of Projects SR-137 and SR-155.

From the strain traces recorded from the individual vertically oriented strain gages and from the component gages of strain rosettes, it was observed that the traces from the component gages were similar to those recorded in the earlier plain and prestressed plate tests involving the notch-wedge-impact method of initiation. In the case of vertical component gages, the peak strain magnitude recorded was on the order of 700 to 800 microin./in. In comparing these peak values with the results from other tests for gages at about the same location with respect to the fracture path, it is concluded that the peak strain values are of about the same order of magnitude for the applied strain field conditions encountered. For the horizontal and diagonal component gages, the resulting strain-time records were somewhat different than would have been expected on the basis of previous tests. It should be kept in mind, however, that any interpretation or comparison of this dynamic strain data must include a consideration of the base strain level at the time of fracture.

The effect of residual compression on the strain field surrounding the tip of the propagating fracture, could not be fully identified in the tests because the dynamic strains were recorded after the fracture had propagated into the zone of residual compression and consequently no strain records, recorded in a region of high residual tension, were available for comparison.

The fracture texture observed from the specimens appeared to be dependent upon the stress or energy level present in the plate prior to fracture. The texture became rougher with more easily identifiable chevron markings as the stress at the time of fracture increased. The fracture path also appeared to depend upon the stress level; the path was quite straight for the low stress fractures and had a tendency to wander slightly for the high-stress fractures.

Initiation Studies

The fabrication procedures employed in this investigation resulted in various conditions of residual strain in the several specimens, as well as different strain and temperature histories for the material in the vicinity of the notches.

The following statements apply in general to the 3/4-in.-thick specimens which comprised the majority of the tests. The results from the two 5/8-in. specimens fall in line, as discussed in the text, when the peculiarities of the particular specimens are considered.

In Type A specimens the fabrication procedure employed (continuous longitudinal weld) resulted in high residual tensile strains in the vicinity of the welds as well as high temperatures and high strain cycling at the notch. The fractures always initiated at an average applied stress of between 8 and 12 ksi when tested at -40 F. This consistency of fracture stress at initiation is indeed remarkable considering all the variables involved.

In the Type B specimens, which were fabricated with an interrupted longitudinal weld leaving a gap of about 3 in. in the vicinity of the notch, low stress, high stress, and some two-stage fractures occurred. In all of these specimens the gap in the weld resulted in temperatures not exceeding about 200 F in the vicinity of the notch; it was observed that the residual tensile strain field in the vicinity of the notch was almost identical to that induced in the Type A specimens. Low stress and two-stage fractures were observed in the properly notched specimens which had been subjected to high strain cycling in the vicinity of the notch. Of the two Type B specimens exhibiting high-stress fractures, the strain cycling during welding quite likely was less in one because the weld gap was longer, and the other contained a straight notch of different geometry.

Type D specimens, which consisted of a Vee-notch in the center of the plate, had a residual strain field induced by the welding of transverse slots 5 in. above and below the notch. This welding of the slots induced extremely high residual tensile stresses at the tips of the notch. The temperature rise at the notch associated with the welding of these slots was negligible. Also, it was observed that the strain cycling at the tips of the notch was much less than any of the strain cycling observed in the other types of welded specimens. The one specimen made by this method failed at a high stress.

The Type C specimens consisted of two plate halves containing the central Vee-notch but without any welding; the ends of the plates were welded to the pull plates prior to testing.

The Type E specimen was a plain plate with a Vee-notch in the center. In these plates, obviously, there was no effect arising from welding to create residual stresses, temperature effects, or strain cycling effects. In all cases these plates failed at high stresses after undergoing considerable plastic deformation.

A study of the results of these limited initiation studies leads one to conclude that the residual tensile strain field alone is not sufficient to initiate low average stress brittle fractures. From the studies made as a part of this investigation and other related studies it appears that the notch geometry, and strain cycling in the vicinity of the notch play a significant role in the initiation process.

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