SSC-112

STUDIES OF BRITTLE FRACTURE PROPAGATION IN SIX-FOOT WIDE STRUCTURAL STEEL PLATES

by

R. Lazar

and

W. J. Hall

SHIP STRUCTURE COMMITTEE

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September 17, 1959

Dear Sir:

As part of its research program directed toward improvement of hull structures of ships, the Ship Structure Committee is sponsoring at the University of Illinois a study of the mechanics of propagation of brittle cracks in ship plate. Herewith is the Second Progress Report, SSC-112, of this project, entitled "Studies of Brittle Fracture Propagation in Six-Foot Wide Structural Steel Plates," by R. Lazar and W. J. Hall.

This project is being conducted with the specific advisory guidance of the Brittle Fracture Mechanics Advisory Committee under the general program of the Committee on Ship Structural Design of the National Academy of Sciences-National Research Council.

This report is being distributed to individuals and groups associated with or interested in the work of the Ship Structure Committee. Please submit any comments that you may have to the Secretary, Ship Structure Committee.

Sincerely yours,

E H Thiele

E. H. Thiele
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

Serial No. SSC-112

2nd Progress Report
of
Project SR-137

to the

SHIP STRUCTURE COMMITTEE

on

STUDIES OF BRITTLE FRACTURE PROPAGATION IN SIX-FOOT WIDE STRUCTURAL STEEL PLATES

by

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University of Illinois
Urbana, Illinois

under

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ABSTRACT

Presented in this Second Progress Report are the results of tests on 6-ft wide plates, conducted between November 29, 1955 and November 15, 1956, that were instrumented to measure crack speed and strain response as the brittle fracture propagated across the plate.

The test procedure consisted of initiating a brittle fracture at the edge of a plate by the notch-wedge-impact method and recording strain and speed detector signals with cathode-ray oscilloscope equipment as the brittle fracture propagates across the plate.

For most of the tests, the average net stress was about 18.0 ksi, and the temperature of the rimmed-steel plate was about 0°F. Recorded surface crack speeds ranged from 1800 to 7550 ft per sec; however, 75% of the speeds fell within the range of 2100 to 3900 ft per sec.

The majority of the strain measurements recorded during crack propagation were made in the immediate vicinity of the fracture path. Strain magnitudes exceeding 0.002500 in./in. have been measured on the plate surface near the fracture, with negligible permanent set remaining after fracture. Thus far, vertically oriented strain gages in front of the crack indicate that there is negligible strain redistribution on the section of the plate ahead of the crack. Studies indicated that the strain response associated with the initiation impact-wedging action was relatively small as compared to that recorded during the fracture process.

The complete brittle fracture of a pull plate subjected to static loading with no artificial stress concentration is also reported.

TABLE OF CONTENTS

INTRODUCTION

1. General

The widespread acceptance of steel as a building material can be attributed in large measure to its mechanical properties. One of the most important of these is its ductility, which permits local inelastic deformation while retaining the useful load-carrying capacity of the member. The failure of steel members at ultimate load normally is characterized by a ductile fracture involving a relatively large amount of deformation and energy absorption. However, under certain conditions of stress, temperature and geometry, the normal ductility of steel may not be developed and the structure may suddenly, and without previous warning, fracture in a brittle manner.

Brittle fractures have a long history of incidence and are not restricted to any one type of structure. Storage tanks, pipe lines, bridges, and ships (at sea and at dockside) are typical examples of riveted and welded structures which have failed in a brittle manner. During the past fifteen years, extensive research has revealed many of the factors that may contribute to the initiation, propagation and, occasionally, arrest of brittle fractures. However, a more thorough understanding of the brittle fracture mechanism is required before satisfactory design procedures and construction methods for minimizing the possibility of brittle fracture can be developed.

2. Object and Scope

The object of this investigation is to study the propagation of brittle fractures in wide structural-steel plates. To date the primary effort on the test program has been to obtain measurements of crack speed and strain response in the vicinity of the crack during the propagation of the fracture. Strain records, computed speeds, and other results of the 6-ft wide-plate tests that were completed from November 29, 1955 through November 15, 1956 as a part of this program, are presented and discussed in this report.

In the case of the tests described in this report, rimmed steel was used for the seventeen instrumented tests, and semikilled steel was used for the four specimens of the pilot tests that were not instrumented. All specimens were 3/4 in. thick and tested in the as-rolled condition except for one specimen that was tested after being prestrained to approximately 2% permanent elongation. Each specimen contained two symmetrical notches, one on each edge; one notch was used to initiate the fracture and the other notch was used to avoid eccentric loading of the specimen. All of the specimens were tested at average stresses of 17.0 to 20.5 ksi on the net section.

In fifteen tests, twelve with instrumentation, a brittle fracture was propagated completely across the plate at temperatures ranging from +5 to -11 F. Five tests (with instrumentation) were performed to evaluate the effect of the fracture initiation method on the measured plate response. This latter group of tests was performed at room temperature, other conditions being similar to those existing for a complete fracture test. The one additional test was an unsuccessful attempt to initiate a brittle fracture in a plate of semikilled steel.

The brittle fracture of a pull plate (A-285 Grade C Flange Steel) with no intentional stress concentration is also reported. This fracture occurred at an average net stress of 32.0 ksi and at room temperature. The crack initiated from the toe of a fillet weld on the plate edge and propagated across the entire plate.

3. Brief Review of Previous Work

The first wide-plate tests at the University of Illinois were conducted under the direction of Professor W. M. Wilson in 1944-46 and involved static tests of internally notched steel plates of various widths.[1] A number of these tests resulted in brittle fractures at stresses slightly above the yield strength.

In 1953, after the failure of two large oil storage tanks in England, the Standard Oil Development Company undertook an extensive brittle fracture test program[2, 3] of various compositions of steel plate in widths ranging from 10 in. to 72 in. In these tests the fractures, initiated by means of an external impact in much the same manner as the tests described in this report, propagated across the plates at stresses as low as 10,000 psi and at temperatures in the range of -40 to 0°F.

With regard to the current program, another report[4] describes the development work and the tests of 2-ft wide-plate specimens that preceded the work described in this report. A recent paper[5] presents a summary of the foregoing work and includes a brief description of some of the 6-ft wide-plate tests reported herein.

Other experimental and analytical work in the field of brittle fracture mechanics is reported in publications by G. R. Irwin,[6] E. Orowan,[7] A. A. Wells,[8] and T. S. Robertson.[9] Most of the important work in this field may be traced through the extensive bibliographies contained in each of the cited references.

4. Acknowledgment

The tests described in this report were conducted as a part of a program entitled "Brittle Fracture Mechanics" sponsored by the Ship Structure Committee through the Bureau of Ships, Department of the Navy, Contract NObs 65790, Index-No. NS-731-034 (SR-137). The members of the Brittle Fracture Mechanics Advisory Committee under the Committee on Ship Structural Design of National Academy of Sciences-National Research Council have acted in an advisory capacity in the planning of this program.

The tests were performed in the Structural Research Laboratory, Department of Civil Engineering, University of Illinois. The project is under the general direction of N. M. Newmark, Professor and Head of the Civil Engineering Department. The authors wish to thank Dr. Newmark, W. H. Munse, Research Professor of Civil Engineering, R. J. Mosborg, Associate Professor of Civil Engineering, and V. J. McDonald, Associate Professor of Civil Engineering (in charge of instrumentation) for their helpful advice during the course of the investigation. The authors gratefully acknowledge the help of T. J. Hall, T. M. Lynam, W. H. Walker, J. N. Chopy, and particularly S. T. Rolfe, Research Assistants in Civil Engineering, who assisted in the laboratory work and with the preparation of the figures.

This report has been drawn from a M. S. dissertation of the same title by R. Lazar which was submitted to the Graduate College of the University of Illinois in 1957.[10]

5. Nomenclature

The following terms are commonly used throughout the text.

Dynamic Strain Gage -- SR-4 strain gage whose signal is monitored on an oscilloscope during the fracture test.

Static Strain Gage -- SR-4 strain gage read at selected static loads by means of a portable strain indicator.

Crack Detector -- A single wire (6-in. gage length) SR-4 Type A-9 strain gage which is mounted perpendicular to the expected crack path and which is broken by the fracture. A rough measure of the crack speed may be obtained from a knowledge of the distance between detectors and the time interval corresponding to breaking of adjacent detectors.

Notch Line -- An imaginary straight line connecting the notches on opposite edges of the specimen.

Submerged Crack -- A relatively short, arrested crack that does not cleave through the plate surface.

Complete Fracture Test -- A test in which the fracture propagates across the entire plate.

Striking Test -- A test in which the specimen is subjected to the notch-wedge-impact method of initiation at the usual test stress, but at a temperature generally high enough to prevent complete fracture.

DESCRIPTION OF SPECIMENS AND APPARATUS

6. Specimens and Material Properties

All instrumented specimens were cut from 3/4-in. thick Lukens rimmed-steel plates, heat No. 16445, in the as-rolled condition and with a nominal width of 72 in. The depth of the specimen insert was either 32 in. or 54 in. as explained in the next paragraph. The insert was welded with double-V butt welds, made with E7016 electrodes, to pull plates in a 3,000,000-lb hydraulic testing machine. The welding was performed in such a manner as to keep warping and residual stresses to a minimum. The pull plates were approximately 6 3/4 ft long, 6 ft wide and 1 in. thick.

TABLE 1.

OUTLINE OF TESTS

TEST (FIG.)	PLATE DESIGNATION	INITIAL LOAD (lb)	AVERAGE STRESS ON NET SECTION (KSI)	AVERAGE TEMP. (F)	REMARKS
The tests were conducted on 6-ft wide specimens of rimmed steel in a 3,000,000-lb hydraulic testing machine. The test piece was an insert 3/4 x 54 x 72 in. welded to one-inch pull plates to give a specimen 6 ft wide by 18 ft long in plan dimension, exclusive of the pull-heads. Following the first fracture test on a given specimen, the fracture was generally cut out and the remaining portion of the insert (32 in. x 72 in.) was used for a second test. The former size of insert is designated by an (A), the latter by a (B) in the remarks column. Notch length 1 in. Dimensions as noted in Section 7 of text.					
12	Z1F1-1	1,065,000	20.0	-10	(A) Complete fracture. Record lost.
13 (5)	Z1F1-2	1,065,000	20.0	0	(B) Complete fracture. Good record.
14 (6)	Z2D1-1	960,000	18.0	-8	(A) Complete fracture. Record extremely poor; considerable noise.
15 (7)	Z2D1-2	960,000	18.0	-5	(B) Complete fracture. Fair record.
16	Z2D2-Impact 2	990,000	18.5	74	(A) Room temp. Final load -- 990,000 lb. No record obtained. Submerged crack 1/2-in. long.
17 (8)	Z2D2-Impact 1	990,000	18.5	74	(A) Room temp. Final load -- 990,000 lb. Good record. Crack 3/8-in. long on east side and 1/8-in. long on west side.
18 (9)	Z2D2-1	990,000	18.5	8	(A) Final load -- 990,000 lb. Good record. Submerged crack 2-in. long. Essentially a striking test at low temperature.
Notch length changed from 1 in. to 1 1/8 in. Dimensions as noted in Section 7 of the text.					
19 (10)	Z2D2-2	1,070,000	20.5	-7	(A) Complete fracture. Good record.
20	Z2D2-3	960,000	18.0	0	(B) Complete fracture. Record lost. Evidence of branching at center of plate.
21 (11)	Z1C1-Impact	960,000	18.0	85	(A) Room temp. Final load -- 960,000 lb. Good record. No submerged cracks.
22 (12)	Z1C1-1	960,000	18.0	-10	(A) Complete fracture. Good record.
23 (13)	Z1C1-2	960,000	18.0	-11	(B) Complete fracture. Good record, except part was lost.
24 (14)	Z1C2-1	960,000	18.0	5	(A) Complete fracture. Record quality excellent, validity questionable.
25 (15)	Z1C2-2	960,000	18.0	2	(B) Complete fracture. Good record except part was lost. Duplicate test of Z1C1-2.
The following series of four tests were conducted on 6-ft wide semikilled steel specimens with the same notch dimensions as above. No instrumentation. Modification of gas operated piston device made here (See Section 7 of text).					
26 (2)	X2E1-1	890,000	17.0	-1	(A) Final load -- 890,000 lb. No submerged cracks.
27 (2)	X2E1-2	1,050,000	20.0	5	(A) Complete fracture.
28 (2)	X2E1-3	945,000	18.0	-4	(B) Complete fracture.
29 (2)	X2E1-4	890,000	17.0	-2	Plate X2E1-3 (previous test) was cut in half to obtain 16-in. insert. Complete fracture.
Instrumented tests resumed on 6-ft wide rimmed steel specimens.					
30 (16)	X2C2-Impact	960,000	18.0	78	(A) Room temp. Final load -- 960,000 lb. Good record. No submerged cracks.
31 (17)	Z2C2-1	960,000	18.0	-3	(A) Complete fracture. Good record.
32 (18)	Z2C2-2	960,000	18.0	-1	(B) Prestrained specimen. Complete fracture. Good record.

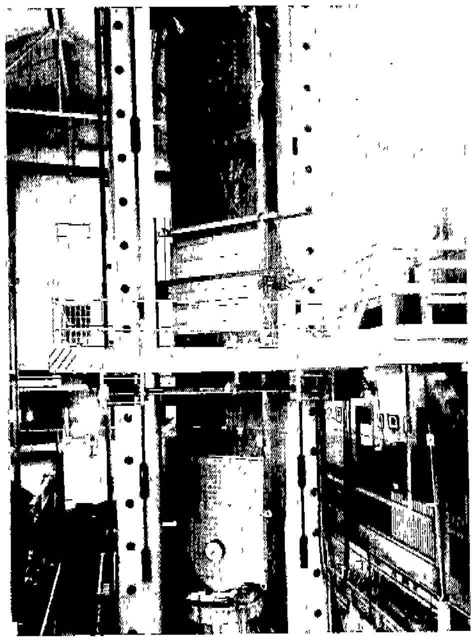
This made the dimensions of the test member 16 x 6 ft or 18 x 6 ft in plan dimension, depending on the size of the insert, with the thickness changing from 3/4 in. to 1 in. at the pull plate insert junction. The net width at the notch line was 2 in. or 2 1/4 in. less than the gross width noted in Table 1 because of the notches on each edge.

Each insert originally was 54 in. deep with the notches placed 16 in. below the top of the insert for a complete fracture test and 27 in. below the top for some of the striking tests. If a striking test was to be performed on the insert, it would always be performed before a complete fracture test. Since the notch lines for these tests were generally 11 in. apart (vertically), the insert was not materially affected by the striking test with regard to subsequent complete fracture tests. In two cases a striking test was performed on the same notch line as the subsequent complete fracture test, but from the opposite notch. After the first complete fracture test, the cracked portion would be cut out 6 in. below the test notch line and the remaining insert would then be 32 in. deep. The notch line for the second complete fracture test would be at the center of the remaining portion of the insert, or 16 in. from either the top or bottom weld. One insert (Test 32) was prestrained to approximately 2% permanent deformation before testing. The check analysis and mechanical properties of the rimmed steel are presented in Fig. 1, together with a line diagram of a specimen and a photograph of a typical test setup.

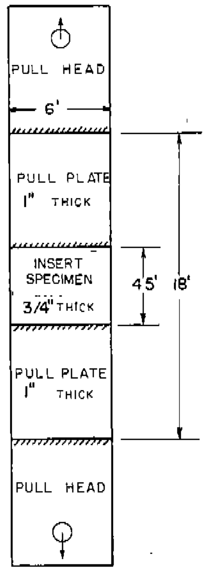
Four pilot tests were performed on a 3/4-in. thick U. S. Steel semi-killed steel plate, heat No. 64M487, with a nominal width of 6 ft. The check analysis and mechanical properties of this steel are shown in Fig. 2, together with photographs of the crack paths resulting from the tests.

7. Fracture Initiation

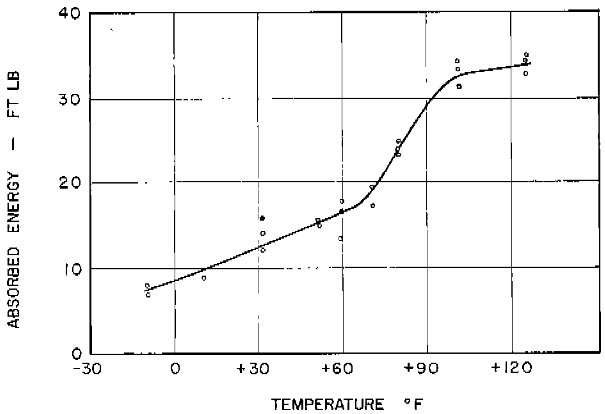
One of the first problems encountered in any brittle fracture propagation test program is that of finding a consistent method of fracture initiation. Ideally, the conditions for the tests should be similar to actual service conditions; this suggests limiting the stress to normal working stresses



SIX-FOOT WIDE SPECIMEN
IN 3,000,000 - LB. MACHINE



LINE DIAGRAM OF PLATE SPECIMEN



CHARPY V-NOTCH IMPACT RESULTS FOR RIMMED STEEL

TENSILE TEST DATA FOR LUKENS RIMMED STEEL
HEAT NO. 16445

DIRECTION OF ROLLING	YIELD STRENGTH KSI	ULTIMATE STRENGTH KSI	ELONGATION IN 2 IN. %	REDUCTION OF AREA %
PARALLEL	34.7	68.1	36	58
NORMAL	35.2	68.7	31	52

CHECK ANALYSIS OF LUKENS RIMMED STEEL
HEAT NO. 16445

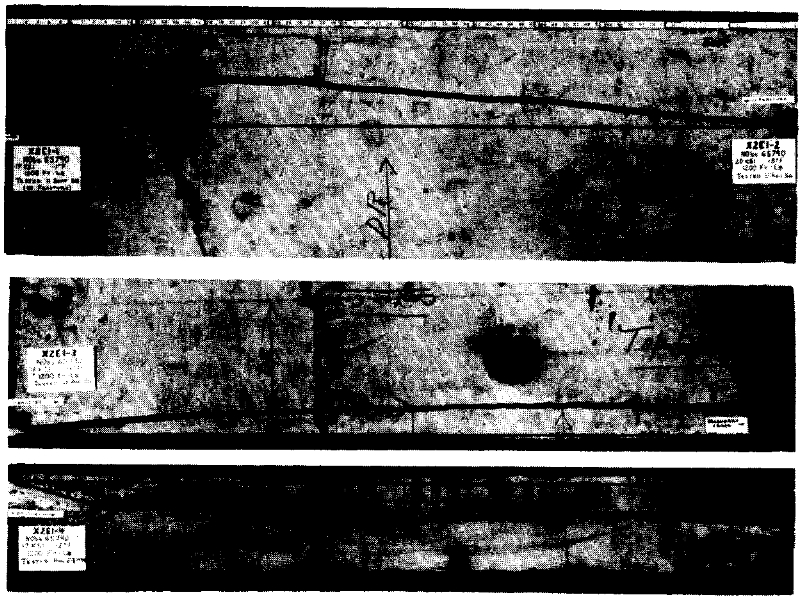
C	Mn	P	S	Si	Cu	Cr	Ni	Al
0.18	0.42	0.013	0.031	0.02	0.23	0.07	0.14	0.003

FIG. 1 TYPICAL TEST SETUP AND PROPERTIES OF RIMMED STEEL

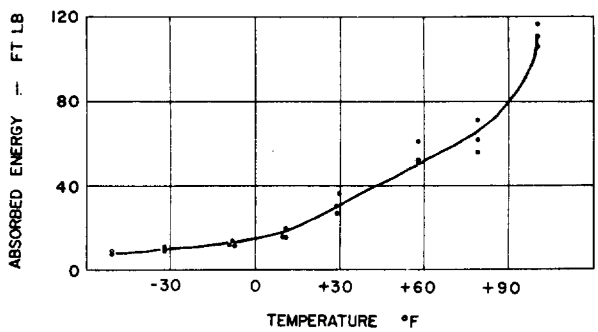
TEST 26 → ← TEST 27

TEST 28 →

TEST 29 →



FRACTURE PATHS — SEMI-KILLED STEEL



CHARPY V-NOTCH IMPACT RESULTS FOR SEMI-KILLED STEEL

TENSILE TEST DATA FOR U S S SEMI-KILLED STEEL
HEAT NO. 64 M 487

DIRECTION OF ROLLING	YIELD STRENGTH KSI	ULTIMATE STRENGTH KSI	ELONGATION IN 2 IN. %	REDUCTION OF AREA %
PARALLEL	34.9	66.7	39	65
NORMAL	34.3	60.1	39	59

CHECK ANALYSIS OF U S S SEMI-KILLED STEEL
HEAT NO. 64 M 487

C	Mn	P	S	Si	Cu	Cr	Ni	Al
0.20	0.76	0.019	0.040	0.03	0.04	0.02	0.16	0.002

FIG. 2 FRACTURE PATHS AND PROPERTIES OF SEMI-KILLED STEEL

and the temperature to ordinary service temperatures. However, at present the static initiation of brittle fractures under such conditions cannot be controlled consistently in the laboratory. As a matter of interest, of the forty-odd tests performed in the laboratory as a part of this program only one failure involving static initiation occurred (this is discussed in Section 14).

After some preliminary work[4, 5] the so-called "notch-wedge-impact" method of initiation was perfected and used for all the tests. The notch-wedge-impact method of fracture initiation involves the driving of a wedge into a prepared notch in the edge of the plate. The driving of the wedge causes a very high rate of strain at the tip of the notch and for certain steels under selected conditions of stress and temperature, provides a consistent method of initiating brittle fractures. Only once did this method fail to initiate a brittle fracture with the stresses and temperatures employed in the tests. As explained in Section 12, this method of initiation apparently does not affect significantly the propagation behavior of the fracture.

The notch used in Tests 12 through 25 had a total length of 1 in. The first 7/8 in. of the notch was four hacksaw blades in width (approximately 0.141 in.), the next 1/16 in. was one hacksaw blade in width (approximately 0.034 in.) and the last 1/16 in. was a jeweler's saw-cut in width (approximately 0.012 in.). For Test 26 and all subsequent specimens, a notch having a total length of 1 1/8 in. was used. The first cut was made 1 in. long, with all other dimensions remaining as noted above. The wedge used was a standard 1 in. octagonal cold-chisel (included angle of tip was approximately 16 degrees) cut to a length of 4 3/4 in. and weighing 1.0 lb.

The impact was provided by a gas-operated piston device. The activating pressure and the stroke of the 4.0-in. diameter piston could be varied to produce any desired impact up to 3000 ft-lb. The pressure was supplied by bottled nitrogen gas. A stroke of 5 in., and a pressure of 280 psi were used in all the tests. This resulted in a theoretical energy output of approximately 1200 ft-lb. To absorb the reaction of the device during acceleration of the piston, the device was tied to a weight of approximately 120 lb that bore against the far side of the specimen at the notch line.

Several methods were used to calibrate the piston device in order to determine the amount of energy delivered to the wedge. Measurement of the velocity of the piston was not particularly successful. Comparison of the measurement of the deformation of brass cylinders that were 1 1/2 in. long and 1 1/2 in in diameter with that obtained in a drop-weight machine provided more satisfactory results. These calibration tests showed that the piston device was occasi ally delivering a much lower energy output than anticipated, sometimes as low 40% efficiency. This fact may possibly account for the failure to initiate and propagate a brittle fracture in Test 18. A general overhaul and slight modificati of the piston device was made between Tests 25 and 26 as noted in Table 1. Th recalibration results indicated that more consistent operation was then obtained The efficiency of the modified piston device as determined by the deformation method was approximately 90%, or an actual energy output of about 1080 ft-lb f a theoretical energy input of 1200 ft-lb.

8. Cooling Apparatus

The cooling of the specimen to the desired temperature was accomplishe by placing crushed dry ice in 3-in. thick containers that were hung against the sides of the specimen. Each container was approximately 2 ft by 6 ft in plan dimension, and three containers were connected to cover an area of 6 ft by 6 ft. The tanks are shown in place in Fig. 1. The center tanks were recessed so that neither the ice nor the tanks contacted the specimen near the gage locations. The specimen temperature obtained by this method of cooling was quite uniform near the notch line and varied only a few degrees across the entire plate. The thermocouple locations and typical temperature traces at time of test are presented in Fig. 3.

9. Instrumentation

(a) Sensing Devices

The strain measurements were made with Baldwin SR-4 Type A-7 strain gages (1/4 in. gage length). These gages were used to obtain both the static and dynamic gage readings. They were attached to the specimen using a thin layer of Duco cement, dried as specified, and then covered with a moistureproofing material. To minimize temperature induced strains, care was taken to ensure that an equal length of lead wire was used for each gage, and also that the length of wire cooled with the specimen was constant for all the strain gages.

The crack speed was measured through a system of surface crack detectors. These detectors (SR-4 Type A-9 single-wire strain gages, 6-in. gage length) were cemented to the specimen using a thin layer of Duco cement. As the crack passed and broke the detector, an electrical circuit was interrupted. From a knowledge of the time corresponding to breaking of the detectors, and the distance between the detectors, the average surface speed of the crack could be computed. Investigation revealed that it was immaterial whether the distance between detectors was measured along the horizontal or along the crack path.

The speed of the crack also was computed on the premise that the strain signals peaked at the instant the crack passed the strain gages. However, observations indicate that the time of peaking is affected by the distance of the crack path from the gage location. Therefore a slight error was introduced when gages spaced at varying distances from the crack path were used to calculate the speed.

It must be emphasized that these methods of speed measurements constitute an average surface measurement only, and thus may not give the true speed of the crack front; also, the exact positions of neither the surface crack nor the interior portion of the crack are known at the instant the detector breaks or the strain gage peaks. Thus, in computing the crack speeds it was assumed that all the detectors and strain gages (in this case, strain gages close to, and a constant distance from, the crack) responded similarly. These methods of speed determination were considered to be the best available approximation. However the equipment limitations, the difficulty in defining the actual crack, and the possible detector and strain gage inconsistencies are recognized. All speeds noted herein are rounded off to the nearest 50 fps.

Two types of triggers were used in these tests. A plate-surface trigger (SR-4 Type A-9 strain gage denoted by T in the diagrams) was mounted about 1 in. beyond the tip of the initiating notch; the breaking of this gage by the fracture started the recording equipment. The plate-surface trigger allowed the use of a short time base for the test records (approximately three milliseconds), since the crack was already started when the trigger gage was broken. The external trigger, an electrical circuit activated by movement of the wedge and denoted by ET in the diagrams, required a longer time base (approximately six milliseconds) to allow for the time lapse between the triggering and the actual initiation of the fracture. The external trigger permitted the recording of signals from gages close to the fracture initiation point; this was not possible with the plate-surface trigger. In the latter case a short record was obtained while in the former case a longer, more complete record was obtained. Fig. 4 shows the trigger circuit. In this diagram the triggering devices shown are a SR-4 Type A-9 strain gage (plate-surface trigger), a micro-switch (μSW) and a strip of aluminum foil (the external triggers). Any one device could trigger the circuit but all three types of triggers were used as a safeguard.

Ten copper-constantan thermocouples were located at various points across the specimen to provide a temperature profile during cooling of the specimen. These thermocouples were installed in No. 54 drill holes about 1/4 in. deep.

(b) Recording Devices

A maximum of nine channels of high-speed cathode-ray oscilloscope equipment with photographic accessories were available for the recording of the strain and crack speed signals. Four dual-beam cathode-ray oscilloscopes provided eight of these channels. The photograph in Fig. 4 shows nine channels of oscilloscope equipment, the temperature recorder and calibrating oscillator.

All signals were recorded photographically as a function of a common time base supplied from the single-channel oscilloscope. This same oscilloscope provided all nine beams with the desired unblanking and intensifying signals used to minimize fogging of the record before and after the test period.

The four traces from two dual-beam oscilloscopes were optically superimposed on a single frame in the interest of maximum photographic definition. Thirty-five-millimeter strip-film cameras (used as single-frame cameras) were employed with the dual-beam equipment and a single-frame 35-mm camera was used with the single-channel oscilloscope. This equipment is shown in the block diagram in Fig. 4.

Six of the oscilloscope channels were sufficiently sensitive to allow at least 1 1/2 in. of trace deflection for 1000 microinches per inch of strain. The other three channels had about one third this sensitivity. Whenever possible the latter channels were used to record the highest electrical magnitudes. The frequency response of the single-channel oscilloscope was flat from 0 to 1000 kc. The response of the dual-beam units was flat from 0 to 100 kc and decreased not more than 50% at 300 kc. Since the majority of the records are two or more milliseconds long and the recorded signals do not approximate step functions, the latter response is considered adequate. For example, consider a time base of two milliseconds, a frequency of 100 kc per second and a scope face 4 in. long. Each complete cycle or period should then be 0.02 in. long. Since the recording spot on the scope face has to be of a definite size and intensity (approximately 0.01 in. in diameter) to register properly on the film, the resulting record at this high frequency would be a solid band, the height of which would be the amplitude of the signal. Thus the band width or time definition of the recording equipment surpasses the photographic or optical definition of the record. The band width, or frequency response, of the measuring gage and its associated wiring has been assumed to be in excess of any of these values.

The temperature was recorded during the cooling process in order that the cooling rate and the temperature gradient could be observed before the test. For this purpose an automatic recorder that provided a sensitivity of about 1 F per 0.1 in. on the record was used. The various thermocouples were sequentially sampled by a motor driven switch and the temperatures were directly recorded in degrees Fahrenheit.

(c) Input Circuits

The signals fed to the cathode-ray recording equipment consisted of a sweep triggering pulse followed by strain and crack location signals. The detectors, which broke as the crack crossed the plate, opened an electrical circuit. Each detector fed to the recording channel a different step voltage whose amplitudes were in the ratio of 1:2:4:8:16. Each step had a different magnitude and could be identified with the particular detector to which it was connected, thereby providing a positive identification of sequence.

The time base was initiated by the trigger. Opening the trigger circuit removed the bias signal from a triggering thyratron and allowed it to start conducting. The step voltage, which resulted at the start of conduction, was fed into the standard circuits of the single-channel oscilloscope unit. Reinitiation could not occur until the thyratron was reset manually. This prevented subsequent multiple sweeps which could be triggered by chatter of the initiating wedge, accidental grounding of the broken trigger wire, etc. and thus would have obscured the traces of interest on the single recorded frame.

The strain gages were connected in the customary wheatstone bridge circuit. Dummy gages which completed the bridge circuit were mounted externally to the specimen. These bridges were excited by direct current and their outputs fed to the recording channels. Typical input circuits are shown in Fig. 4.

(d) Measurement Procedure and Calibration

The strain measuring channels were calibrated by shunting gages with a resistance whose equivalent strain value was known or measurable. Both the active arm and the adjacent dummy gage were shunted successively to obtain compression and tension calibrations. Only one calibrating value was used because other tests indicated that the linearity of the recording system was adequate within the limit of resolution of the record. Crack detector calibration was obtained by successively opening switches in series with the various detectors and recording the trace steps. The time axis was calibrated by putting a time signal of known frequency on all channels simultaneously and photographing one sweep immediately after the test was completed.

Although the deflection plates were connected in parallel and were driven from a common amplifier, individual construction of the various guns and deflection systems resulted in slight horizontal displacements between the traces and in slight differences of deflection with a simultaneous signal. The stability of gain magnitude and trace deflection in this system was found to be satisfactory by a series of investigations and by the consistency of trace lengths and locations in the various tests.

(e) Data Reduction

Features of the data reduction that may not be standard procedure were the method of tying the various traces together with respect to time and the significance of the time axis values. In general, some arbitrary point was taken along the time base and called zero time. This may or may not have corresponded to the earliest point on the recorded traces. The point was selected near the early portion of the sweep at the first peak of the time calibration sine-wave. This provided a convenient and definite reference point common to all traces. The record was then reduced in the customary manner of reading signal amplitude against time, each trace being read with an individual calibration on both the time and signal axes. The earliest time noted for any record was some finite but unknown period of time after the breaking of the sweep trigger wire, approximately 20 microseconds. Thus the earliest recorded time was a variable, and occurred some finite small time after the initiating wedge entered the plate.

10. Test Procedure

The notches were cut in the edge of the specimen insert after it was welded to the pull plate in the testing machine. In the case of the one prestrained plate, the prestraining was done before the notches were cut into the plate edges. The strain gages were then attached and the thermocouples installed. The strain gages were checked at room temperature by cycling (i.e. loading and unloading) the specimen to the test load. This was done in order to check the gages and the strain distribution in the specimen. Since many of the inserts were slightly warped, sizable strain residuals were sometimes observed following one load cycle. To reduce these residuals the specimen was usually cycled four times but never stressed higher than the test load.

All the wiring adjacent to the cooled specimen was sprayed with a plastic compound to improve the insulation. The gages and wiring also were covered with a plastic curtain to minimize the amount of condensation coming in contact with the instrumentation and to prevent stray pieces of dry ice from coming into direct contact with the steel plate.

After the cooling tanks, gas-operated piston device, and reaction weight were suspended from the upper pull plate, the instruments were connected and checked and the dry-ice tanks were filled. As the desired test temperature was approached, the test load was applied to the specimen and the recording devices were calibrated. When the specimen reached the temperature selected for the test, the gas-operated piston device was pressurized and fired.

The static strain gage readings were recorded as soon after the test as possible. In the case of complete fractures an estimate of the residual strains in the plate could be made from these readings. Also at this time a check of the dynamic strain gages was made to aid in later interpretation of the test records.

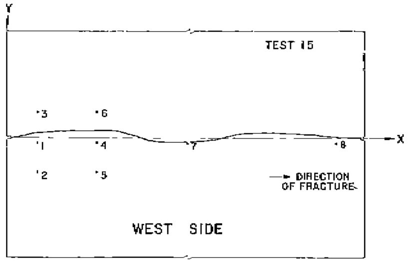
RESULTS AND INTERPRETATION OF TESTS

11. Test Records

The results of the instrumented tests are shown in Figs. 5 through 22. The tables in each figure indicate the position of the strain gages, crack detectors, trigger, the vertical position (Y_c) of the crack with respect to the notch line, the strain level for each strain gage at test load, crack speeds as determined from the detectors, and the test conditions. A record of the strain-time relationships as obtained from the dynamic strain gages is shown. In all cases the strain traces are plotted to start at a strain level corresponding to the initial test load strain; thus, the strain values shown may be considered as absolute strain values. The detector-breaking time is indicated on the record to denote the approximate location of the crack front.

The quality of the records from the tests varies considerably. Typical enlarged photographic records of strain traces are presented in Figs. 23 and 24. These were considered to be of good quality. Poor records may result from many causes such as faulty or late triggering, incorrect focus of the camera or the oscilloscope, or poor lead wire connections. A record also is considered poor when the strain traces overlap on the recording film to such an extent that it is not possible to determine exactly to which strain gage the ensuing trace belongs. This generally occurred in the latter part of the record

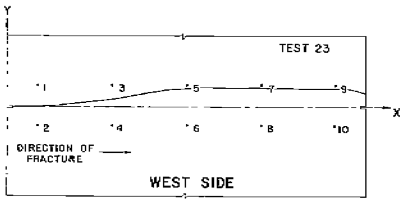
(Text continued on pg. 27)



NO	X in	Y in	TEMP. AT TIME OF TEST
1	6.0	-1.0	-4
2	6.0	-7.0	-2
3	6.0	5.0	-7
4	18.0	-1.0	-2
5	18.0	-7.0	-3
6	18.0	5.0	-9
7	36.0	-1.0	-4
8	66.0	-1.0	-6

NOTE THIS THERMOCOUPLE LAYOUT USED FOR TESTS 12-18

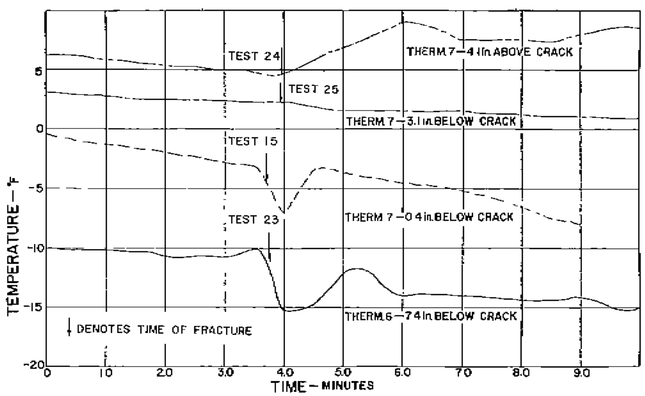
THERMOCOUPLE LOCATIONS AND TEMPERATURE – TEST 15



NO.	X in	Y in	TEMP AT TIME OF TEST
1	6.0	4.0	-14
2	6.0	-4.0	-12
3	21.0	4.0	-11
4	21.0	-4.0	-10
5	36.0	4.0	-11
6	36.0	-4.0	-11
7	51.0	4.0	-11
8	51.0	-4.0	-10
9	66.0	4.0	-13
10	66.0	-4.0	-10

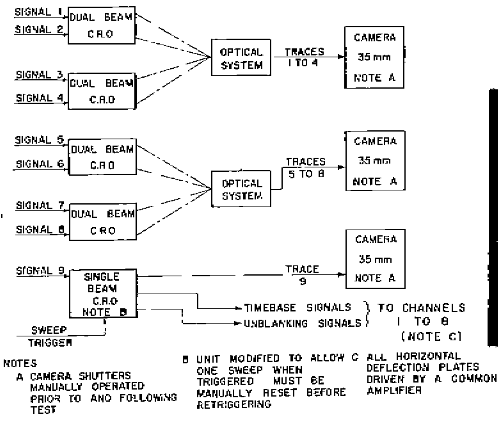
NOTE THIS THERMOCOUPLE LAYOUT USED FOR TESTS 19 – 32

THERMOCOUPLE LOCATIONS AND TEMPERATURE – TEST 23

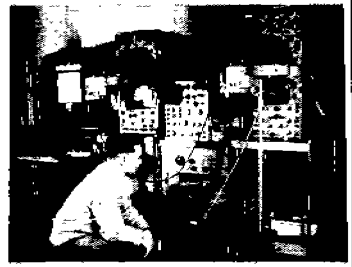


TYPICAL TEMPERATURE TRACES AT TIME OF TEST

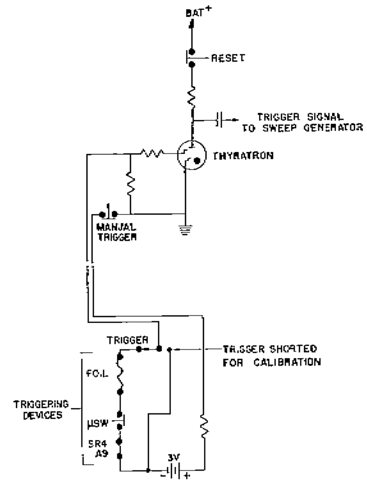
FIG. 3 THERMOCOUPLE LOCATIONS AND TYPICAL TEMPERATURE TRACES AT TIME OF TEST



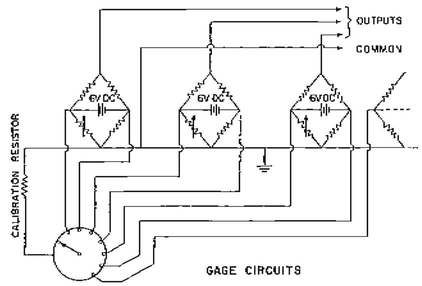
BLOCK DIAGRAM OF RECORDING EQUIPMENT



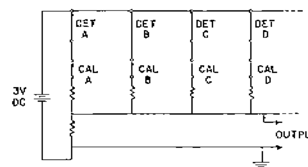
GENERAL VIEW OF RECORDING INSTRUMENTATION



TRIGGER CIRCUIT

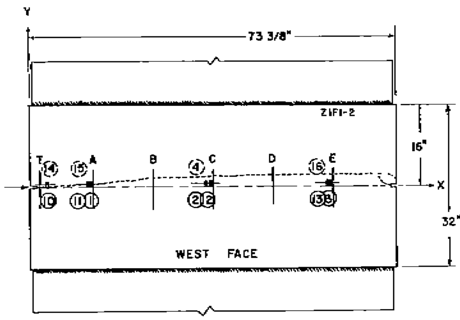


GAGE CIRCUITS



CRACK DETECTOR CIRCUITS

FIG. 4 INPUT CIRCUITS AND RECORDING INSTRUMENTATION



TEST CONDITIONS
AVERAGE STRESS = 20 KSI
TEMPERATURE = 0°F
THEORETICAL IMPACT - 1200 FT LB
○ GAGES ON EAST FACE
◌ GAGES ON WEST FACE

STATIC STRAIN GAGES

NO.	ORIEN-TATION	X In.	Y In.	INITIAL STRAIN
10	V	+3.5	+1.0	+860
11	V	+11.5	+1.0	+680
12	V	+36.0	+1.0	+720
13	V	+59.5	+1.0	+690
14	V	+3.5	+1.0	+700
15	V	+11.5	+1.0	+570
16	V	+59.5	+1.0	+650

DYNAMIC STRAIN GAGES

NO	ORIEN-TATION	X In.	Y In.	Yc In.	INITIAL STRAIN
1	V	12.0	+1.0	+0.7	+630
2	V	35.5	+1.0	+2.7	+715
3	V	60.0	+1.0	+3.0	+660
4	V	35.5	+1.0	+2.7	+720

DETECTORS

NO.	X In.	SPEED
A	+12.5	
B	+24.5	3750
C	+36.5	3400
D	+48.5	3450
E	+60.5	

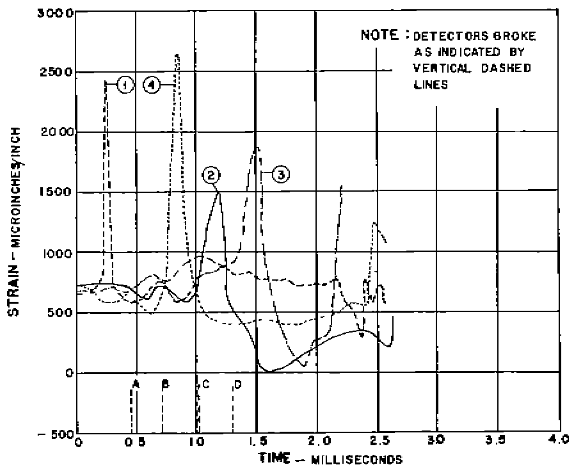
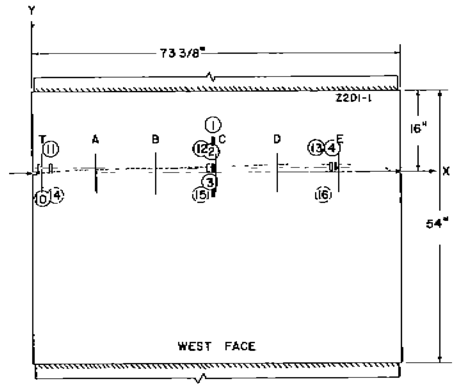


FIG. 5 INSTRUMENTATION AND RECORD —— TEST 13



TEST CONDITIONS
AVERAGE STRESS = 18.0 KSI
TEMPERATURE = – 8° F
THEORETICAL IMPACT = 1200 FT LB
○ GAGES ON EAST FACE
◌ GAGES ON WEST FACE

STATIC STRAIN GAGES

NO.	ORIEN-TATION	X In.	Y in.	INITAL STRAIN
10	V	1.0	+1.0	+1340
11	V	3.5	+1.0	+570
12	V	35.5	+1.0	+320
13	V	59.5	+1.0	+460
14	V	3.5	+1.0	+1120
15	V	35.5	+1.0	+770
16	V	59.5	+1.0	+790

DYNAMIC STRAIN GAGES

NO.	ORIEN-TATION	X In.	Y In.	Yc in.	INITIAL STRAIN
1	V	38.0	+8.0	+1.5	+180
2	V	38.0	+1.0	+1.5	+300
3	V	36.0	-4.0	+1.5	+450
4	V	60.0	+1.0	+1.4	+480

DETECTORS

NO	X in	SPEED
A	12.5	
B	24.5	3700
C	36.5	2850
D	48.5	3450
E	60.5	3250

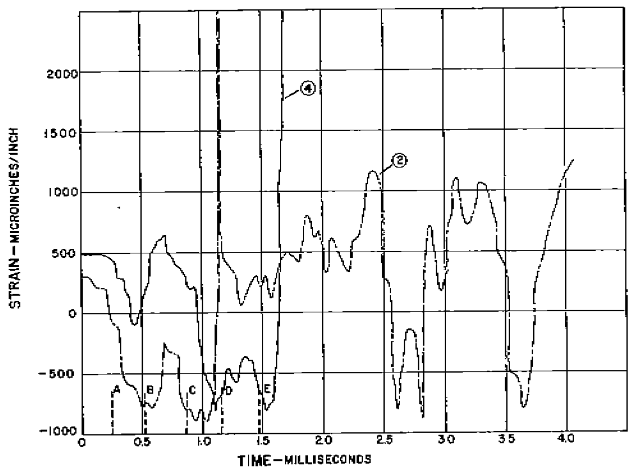
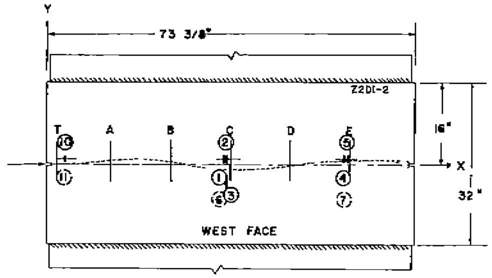


FIG. 6 INSTRUMENTATION AND RECORD —— TEST 14



TEST CONDITIONS
AVERAGE STRESS = 18 KSI
TEMPERATURE = −5° F
THEORETICAL IMPACT = 1200 FT LB
○ GAGES ON EAST FACE
◌ GAGES ON WEST FACE

STATIC STRAIN GAGES				
NO.	ORIEN-TATION	X In.	Y In.	INITIAL STRAIN
10	V	3.5	+1	+800
11	V	3.5	+1	+1170

DYNAMIC STRAIN GAGES					
NO.	ORIEN-TATION	X In.	Y In.	Yc In.	INITIAL STRAIN
1	V	35.5	+1	−0.6	+640
2	V	36.0	+1	−0.6	+490
3	V	36.0	−4	−0.6	+780
4	V	59.5	+1	+0.9	+660
5	V	60.0	+1	+0.9	+670
6	V	35.8	+1	−0.6	+540
7	V	59.5	+1	+0.9	+510

DETECTORS		
NO.	X In	SPEED
A	+12.5	
B	+24.5	3050
C	+36.5	2900
D	+48.5	2800
E	+60.5	2400

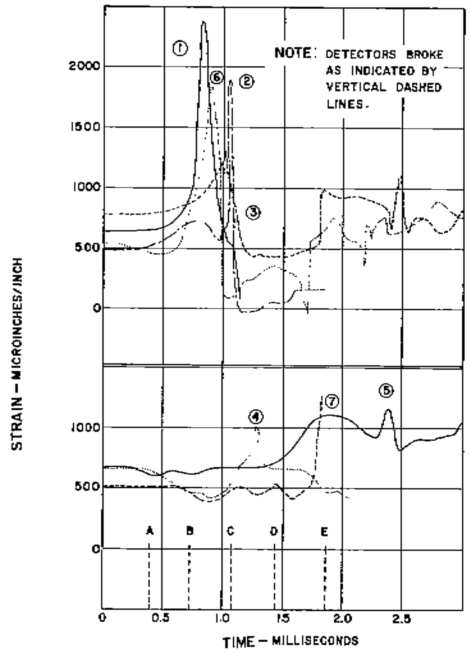
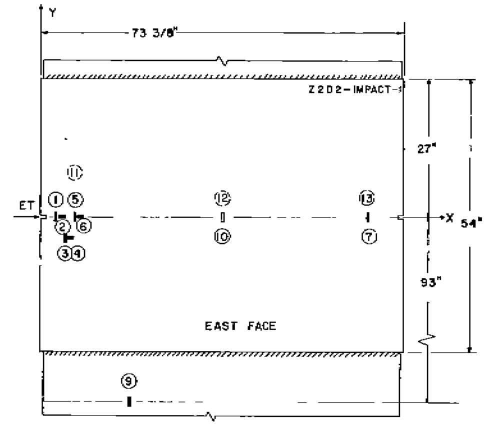


FIG. 7 INSTRUMENTATION AND RECORD —— TEST 15



TEST CONDITIONS
AVERAGE STRESS = 18.5 KSI
TEMPERATURE = 74° F
THEORETICAL IMPACT = 1200 FT LB
○ GAGES ON EAST FACE
◌ GAGES ON WEST FACE

STATIC STRAIN GAGES				
NO	ORIEN-TATION	X In.	Y In	INITIAL STRAIN
10	V	36.4	0	+600
11	V	7.0	0	+680
12	V	36.4	0	+630
13	V	66.4	0	+580

DYNAMIC STRAIN GAGES				
NO	ORIEN-TATION	X in	Y In	INITIAL STRAIN
1	V	3	0	+820
2	H	3.5	0	−150
3	V	5	−4	+610
4	H	5.5	−4	−170
5	V	7	0	+640
6	H	7.5	0	−150
7	V	66.4	0	+480
9	V	187	−93	+500

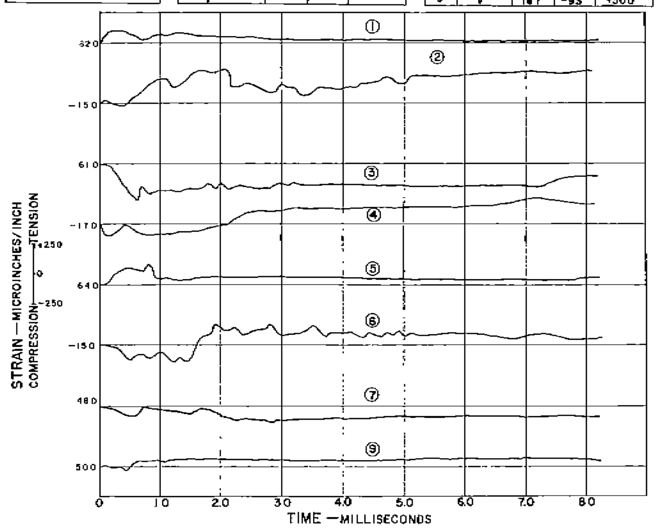
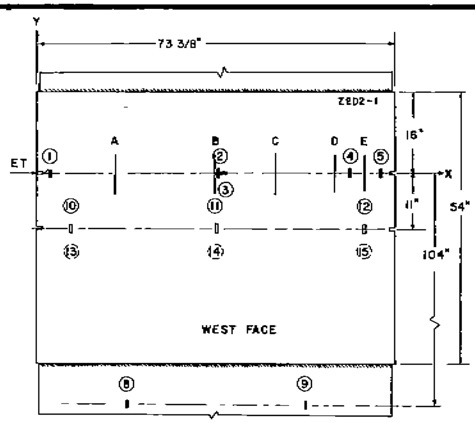


FIG. 8 INSTRUMENTATION AND RECORD —— TEST 17



TEST CONDITIONS
AVERAGE STESS = 18.5 KSI
TEMPERATURE =+ 8°F
THEORETICAL IMPACT = 1200 FT LB
○ GAGES ON EAST FACE
◌ GAGES ON WEST FACE

STATIC STRAIN GAGES

NO.	ORIEN-TATION	X In.	Y In.	INITIAL STRAIN
10	V	6.0	-11	+470
11	V	36.0	-11	+590
12	V	66.0	-11	+590
13	V	6.0	-11	+620
14	V	36.0	-11	+630
15	V	66.0	-11	+680

DYNAMIC STRAIN GAGES

NO	ORIEN-TATION	X in.	Y In	INITIAL STRAIN
1	V	3.0	0	+510
2	V	36.5	0	+570
3	H	37.0	0	-200
4	V	64.2	0	+530
5	V	70.2	0	+540
6	V	18.7	-104	+400
9	V	54.7	-104	+430

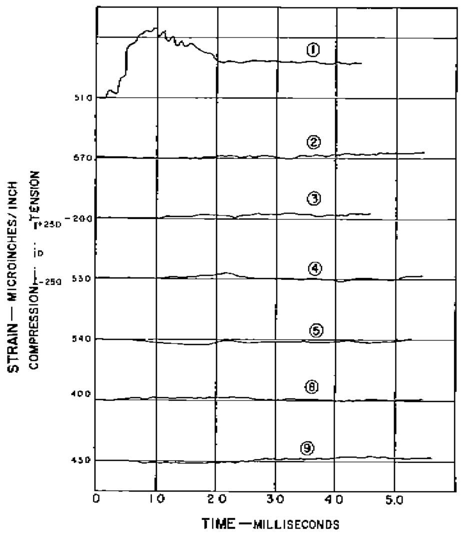
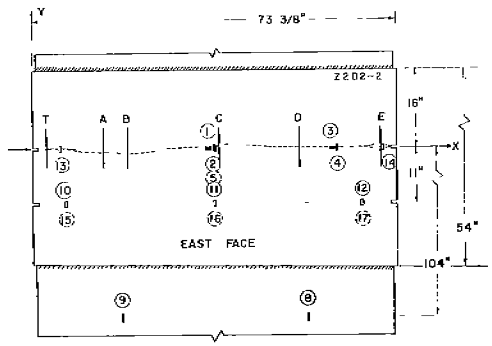


FIG. 9 INSTRUMENTATION AND RECORD —— TEST 18



TEST CONDITIONS
AVERAGE STRESS = 20.5 KSI
TEMPERATURE = -7°F
THEORETICAL IMPACT = 1200 FT LB
○ GAGES ON EAST FACE
◌ GAGES ON WEST FACE

STATIC STRAIN GAGES

NO.	ORIEN-TATION	X In	Y in	INITIAL STRAIN
10	V	+7.0	-11.0	+700
11	V	+36.5	-11.0	+620
12	V	+66.4	-11.0	+590
13	V	+6.0	0	+580
14	V	+70.4	0	+870
15	V	+7.0	-11.0	+710
16	V	+36.5	-11.0	+670
17	V	+66.4	-11.0	+710

DYNAMIC STRAIN GAGES

NO.	ORIEN-TATION	X in.	Y in.	Yc in.	INITIAL STRAIN
1	H	36.0	0	+0.6	-340
2	V	36.5	0	+0.6	+470
3	H	60.5	0	0.0	-30
4	V	61.0	0	0.0	+550
5	V	36.5	0	+0.6	+940
8	V	54.7	-104	0.0	+490
9	V	18.7	-104	-0.6	+490

DETECTORS

NO	X in.	SPEED
A	+10.5	
B	+19.5	3750
C	+37.5	3800
D	+54.0	3450
E	+69.5	

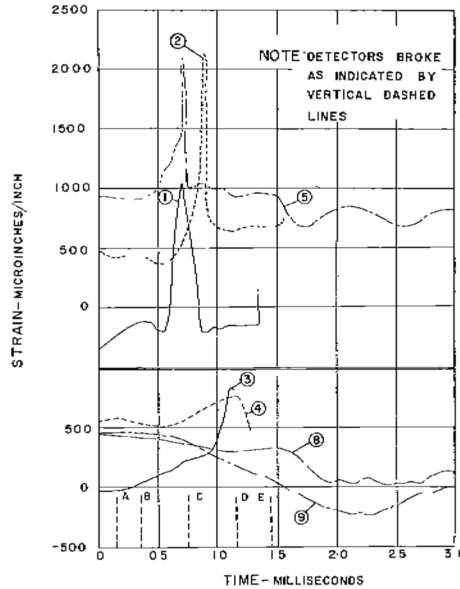
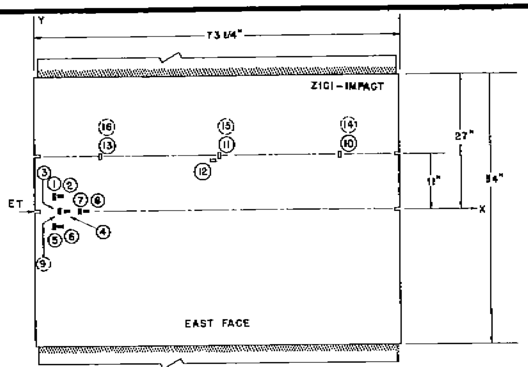


FIG. 10 INSTRUMENTATION AND RECORD —— TEST 19



TEST CONDITIONS
AVERAGE STRESS = 18.0 KSI
TEMPERATURE = 85° F
THEORETICAL IMPACT = 1200 FT LB
○ GAGES ON EAST FACE
◌ GAGES ON WEST FACE

STATIC STRAIN GAGES

NO.	ORIEN-TATION	X In.	Y In.	INITAL STRAIN
10	V	61.25	+11	+630
11	V	36.0	+11	+560
12	H	35.75	+10	-160
13	V	13.25	+11	+620
14	V	61.25	+11	+420
15	V	36.0	+11	+540
16	V	13.25	+11	+570

DYNAMIC STRAIN GAGES

NO.	ORIEN-TATION	X in	Y in	INITIAL STRAIN
1	V	4.0	+3	+640
2	H	4.5	+3	+160
3	V	5.0	0	-170
4	H	5.5	0	+620
5	V	4.0	-3	-150
6	H	4.5	-3	+440
7	V	9.0	0	+420
8	H	9.5	0	+410
9	V	5.0	0	+360

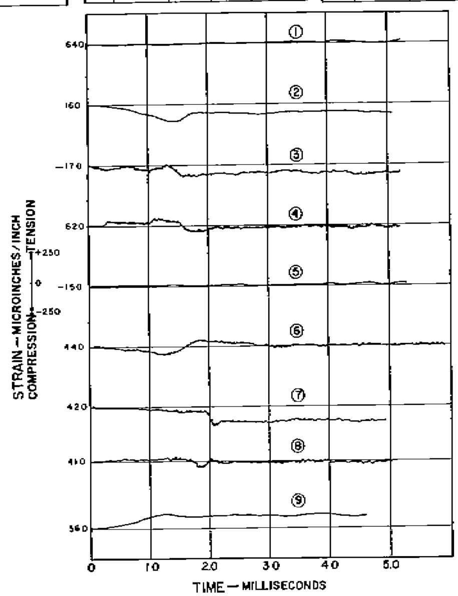
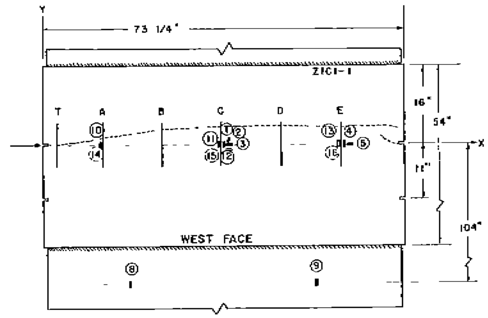


FIG. 11 INSTRUMENTATION AND RECORD — TEST 21



TEST CONDITIONS
AVERAGE STRESS = 18 KSI
TEMPERATURE - 10° F
THEORETICAL IMPACT = 1200 FT LB
○ GAGES ON EAST FACE
◌ GAGES ON WEST FACE

STATIC STRAIN GAGES

NO	ORIEN-TATION	X in	Y in	INITIAL STRAIN
10	V	12.0	0	+630
11	V	36.0	0	+560
12	H	37.5	-1.0	-160
13	V	60.0	0	+620
14	V	12.0	0	+420
15	V	36.0	0	+540
16	V	60.0	0	+570

DYNAMIC STRAIN GAGES

NO.	ORIEN-TATION	X in.	Y in.	Yc in.	INITIAL STRAIN
1	V	37.0	0	+35	+640
2	D	37.5	40.5	+35	+160
3	H	37.5	0	+35	-170
4	V	61.0	0	+35	+620
5	H	61.5	0	+35	-150
8	V	18.8	-104	+24	+428
9	V	54.6	-104	+35	+390

DETECTORS

NO	X In	SPEED
A	12.5	3300
B	24.5	
C	36.5	
D	48.5	
E	60.5	

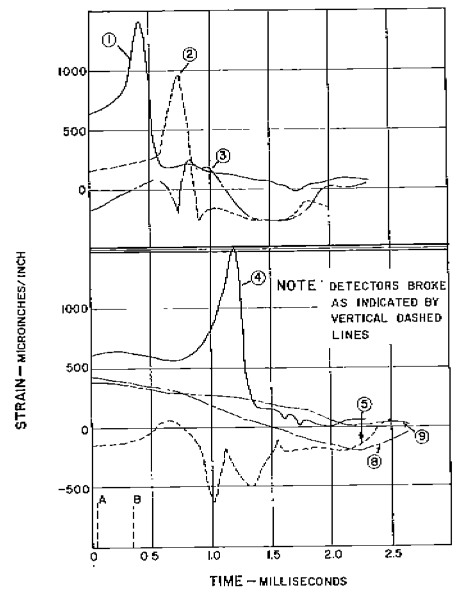
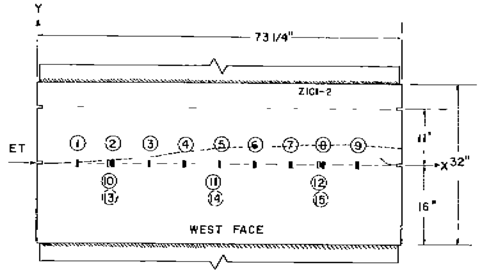


FIG. 12 INSTRUMENTATION AND RECORD — TEST 22



TEST CONDITIONS
AVERAGE STRESS = 18 KSI
TEMPERATURE = -11° F
THEORETICAL IMPACT = 1200 FT LB
○ GAGES ON EAST FACE
◌ GAGES ON WEST FACE

STATIC STRAIN GAGES

NO	ORIEN-TATION	X in	Y in	INITIAL STRAIN
10	V	14.5	0	+620
11	V	35.5	0	+660
12	V	56.5	0	+630
13	V	14.5	0	+530
14	V	35.5	0	+530
15	V	56.5	0	+570

DYNAMIC STRAIN GAGES

NO.	ORIEN-TATION	X in	Y in.	Yc in	INITIAL STRAIN
1	V	8.0	0	0.3	+610
2	V	15.0	0	0.7	+620
3	V	22.0	0	1.3	+620
4	V	29.0	0	2.2	+630
5	V	36.0	0	3.0	+670
6	V	43.0	0	3.4	+670
7	V	50.0	0	3.5	+640
8	V	57.0	0	3.5	+630
9	V	64.0	0	3.5	+620

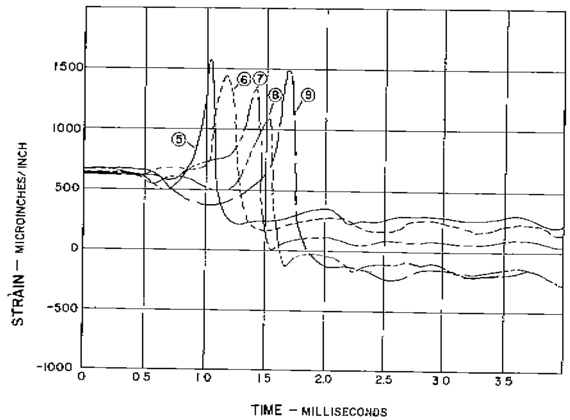
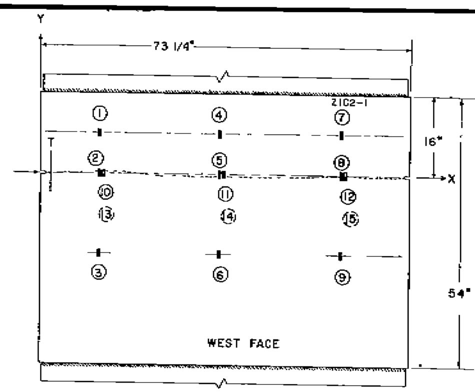


FIG. 13 INSTRUMENTATION AND RECORD — TEST 23



TEST CONDITIONS
AVERAGE STRESS 18 KSI
TEMPERATURE = + 5° F
THEORETICAL IMPACT = 1200 FT LB
○ GAGES ON EAST FACE
◌ GAGES ON WEST FACE

STATIC STRAIN GAGES

NO	ORIEN-TATION	X in	Y in	INITIAL STRAIN
10	V	12.5	0	+480
11	V	36.5	0	+470
12	V	60.5	0	+490
13	V	12.5	0	+640
14	V	36.5	0	+630
15	V	60.5	0	+610

DYNAMIC STRAIN GAGES

NO.	ORIEN-TATION	X In.	Y In.	Yc In.	INITIAL STRAIN
1	V	12.0	+ 8.0	+0.5	+570
2	V	12.0	0	+0.5	+470
3	V	12.0	-16.0	+0.5	+570
4	V	36.0	+8.0	-0.3	+550
5	V	36.0	0	-0.3	+480
6	V	36.0	-16.0	-0.3	+540
7	V	60.0	+ 8.0	-0.1	+556
8	V	60.0	0	-0.1	+500
9	V	60.0	-16.0	-0.1	+540

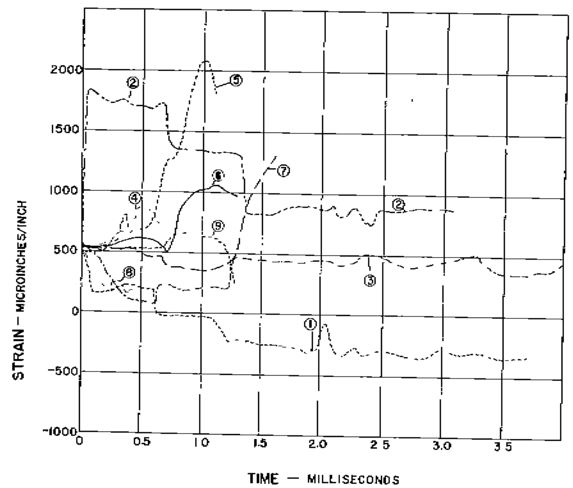
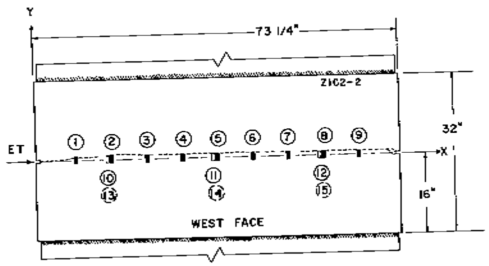


FIG. 14 INSTRUMENTATION AND RECORD — TEST 24



TEST CONDITIONS
AVERAGE STRESS = 18 KSI
TEMPERATURE = + 2° F
THEORETICAL IMPACT = 1200 FT LB
○ GAGES ON EAST FACE
◌ GAGES ON WEST FACE

STATIC STRAIN GAGES

NO.	ORIEN-TATION	X in.	Y in	INITAL STRAIN
10	V	14 5	0	+610
11	V	35 5	0	+590
12	V	56 5	0	+560
13	V	14 5	0	+570
14	V	35.5	0	+610
15	V	56 5	0	+610

DYNAMIC STRAIN GAGES

NO.	ORIEN-TATION	X in	Y in	Yc in.	INITIAL STRAIN
1	V	8.0	0	+0.5	+ 590
2	V	15.0	0	+0.8	+ 610
3	V	22.0	0	+0.7	+ 610
4	V	29.0	0	+0 7	+ 560
5	V	56.0	0	+0.9	+ 600
6	V	43.0	0	+1.0	+ 610
7	V	50.0	0	+0.9	+ 620
8	V	57.0	0	+0.9	+ 610
9	V	64.0	0	+0.8	+ 610

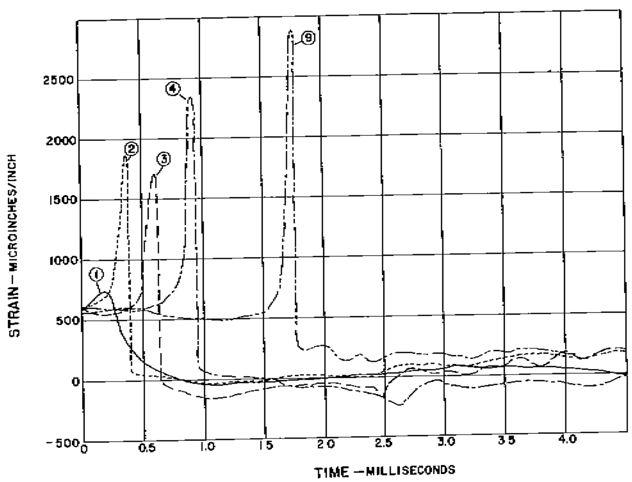
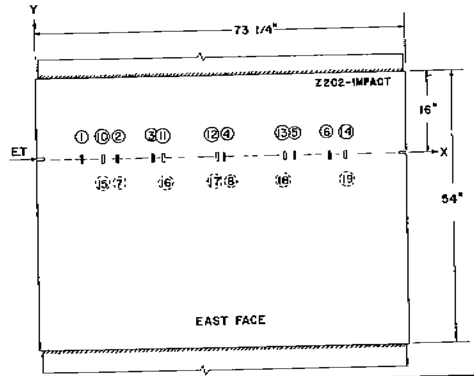


FIG. 15 INSTRUMENTATION AND RECORD — TEST 25



TEST CONDITIONS
AVERAGE STRESS = 18.0 KSI
TEMPERATURE = 78° F
THEORETICAL IMPACT = 1200 FT LB
○ GAGES ON EAST FACE
◌ GAGES ON WEST FACE

STATIC STRAIN GAGES

NO	ORIEN-TATION	X in.	Y in.	INITAL STRAIN
10	V'	13 3	0	+530
11	V	253	0	+510
12	V	363	0	+480
13	V	49.3	0	+460
14	V	61.3	0	+510
15	V	13.3	0	+640
16	V	25.3	0	+690
17	V	36.3	0	+730
18	V	49.3	0	+710
19	V	613	0	+660

DYNAMIC STRAIN GAGES

NO.	ORIEN-TATION	X in.	Y in	INITIAL STRAIN
1	V	9.3	0	+560
2	V	16.3	0	+560
3	V	23.3	0	+520
4	V	373	0	+470
5	V	513	0	+460
6	V	583	0	+490
7	V	163	0	+650
8	V	373	0	+710

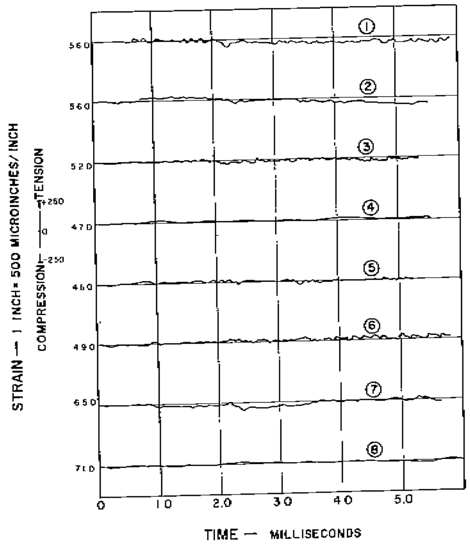
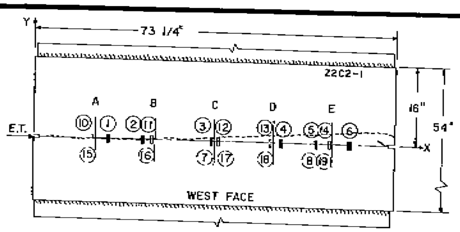


FIG. 16 INSTRUMENTATION AND RECORD — TEST 30



TEST CONDITIONS
AVERAGE STRESS = 18.0 KSI
TEMPERATURE = -3° F
THEORETICAL IMPACT = 1200 FT LB
○ GAGES ON EAST FACE
◌ GAGES ON WEST FACE

STATIC STRAIN GAGES

NO.	ORIEN-TATION	X in.	Y in	INITAL STRAIN
10	V	12.0	0	+510
11	V	24.0	0	+460
12	V	37.0	0	+480
13	V	48.0	0	+510
14	V	60.0	0	+530
15	V	12.0	0	+660
16	V	24.0	0	+710
17	V	37.0	0	+730
18	V	48.0	0	+690
19	V	60.0	0	+640

DYNAMIC STRAIN GAGES

NO.	ORIEN-TATION	X in.	Y in.	Yc in.	INITIAL STRAIN
1	V	15.0	0	+0.1	+490
2	V	22.0	0	+0.1	+460
3	V	36.0	0	+0.9	+470
4	V	50.0	0	+1.6	+520
5	V	57.0	0	+1.8	+560
6	V	64.0	0	+2.3	+560
7	V	36.0	0	+0.9	+710
8	V	57.0	0	+1.8	+650

DETECTORS

NO	X in.	SPEED
A	12.5	
B	24.5	3450
C	36.5	2150
D	48.5	2400
E	60.5	3250

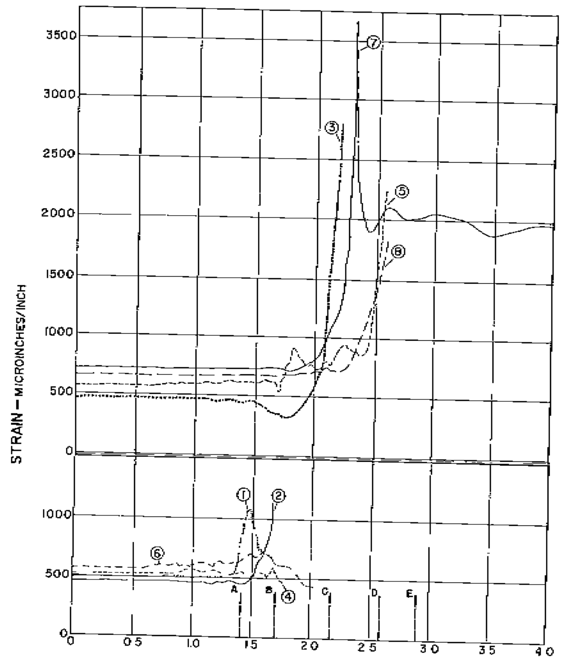
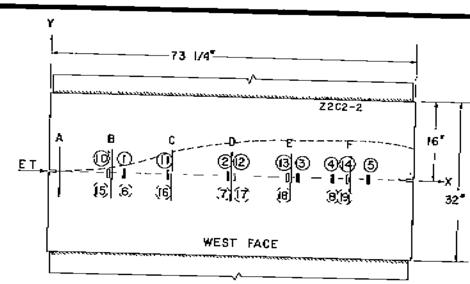


FIG. 17 INSTRUMENTATION AND RECORD —— TEST 31



TEST CONDITIONS
AVERAGE STRESS = 18 KSI
TEMPERATURE = -1° F
THEORETICAL IMPACT = 1200 FT LB
○ GAGES ON EAST FACE
◌ GAGES ON WEST FACE

STATIC STRAIN GAGES

NO	ORIEN-TATION	X in	Y in	INITAL STRAIN
10	V	12.0	0	+490
11	V	24.0	0	+510
12	V	37.0	0	+550
13	V	48.0	0	+520
14	V	60.0	0	+540
15	V	12.0	0	+550
16	V	24.0	0	+510
17	V	37.0	0	+620
18	V	48.0	0	+510
19	V	60.0	0	+640

DYNAMIC STRAIN GAGES

NO	ORIEN-TATION	X in.	Y in.	Yc in.	INITIAL STRAIN
1	V	15.0	0	+2.0	+570
2	V	36.0	0	+6.6	+550
3	V	50.0	0	+7.2	+550
4	V	57.0	0	+7.1	+540
5	V	64.0	0	+6.8	+510
6	V	15.0	0	+2.0	+610
7	V	36.0	0	+6.6	+630
8	V	57.0	0	+7.1	+570

DETECTORS

NO	X in	SPEED
A	2.0	
B	12.5	3150
C	24.5	
D	36.5	
E	48.5	
F	60.5	

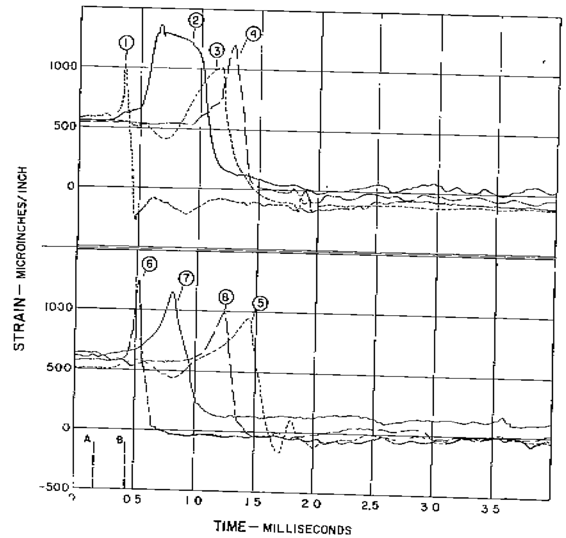


FIG. 18 INSTRUMENTATION AND RECORD —— TEST 32

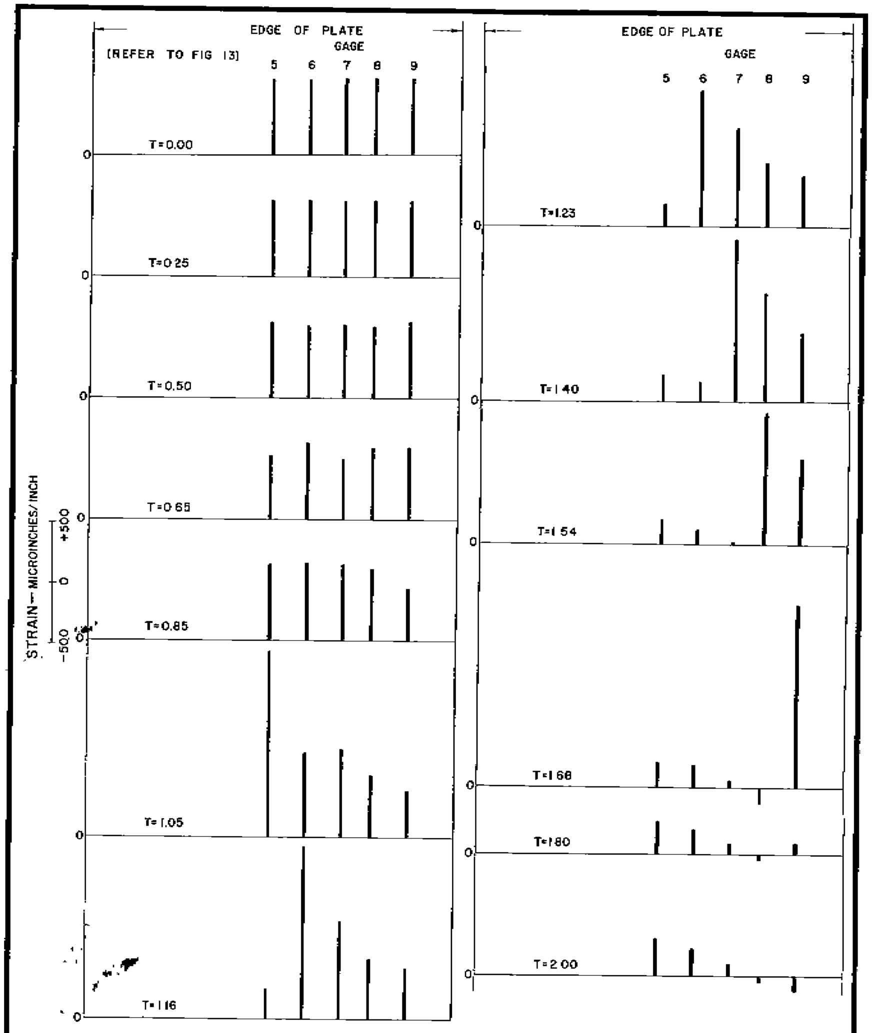


FIG. 19 STRAIN DISTRIBUTION AT VARIOUS TIMES — TEST 23

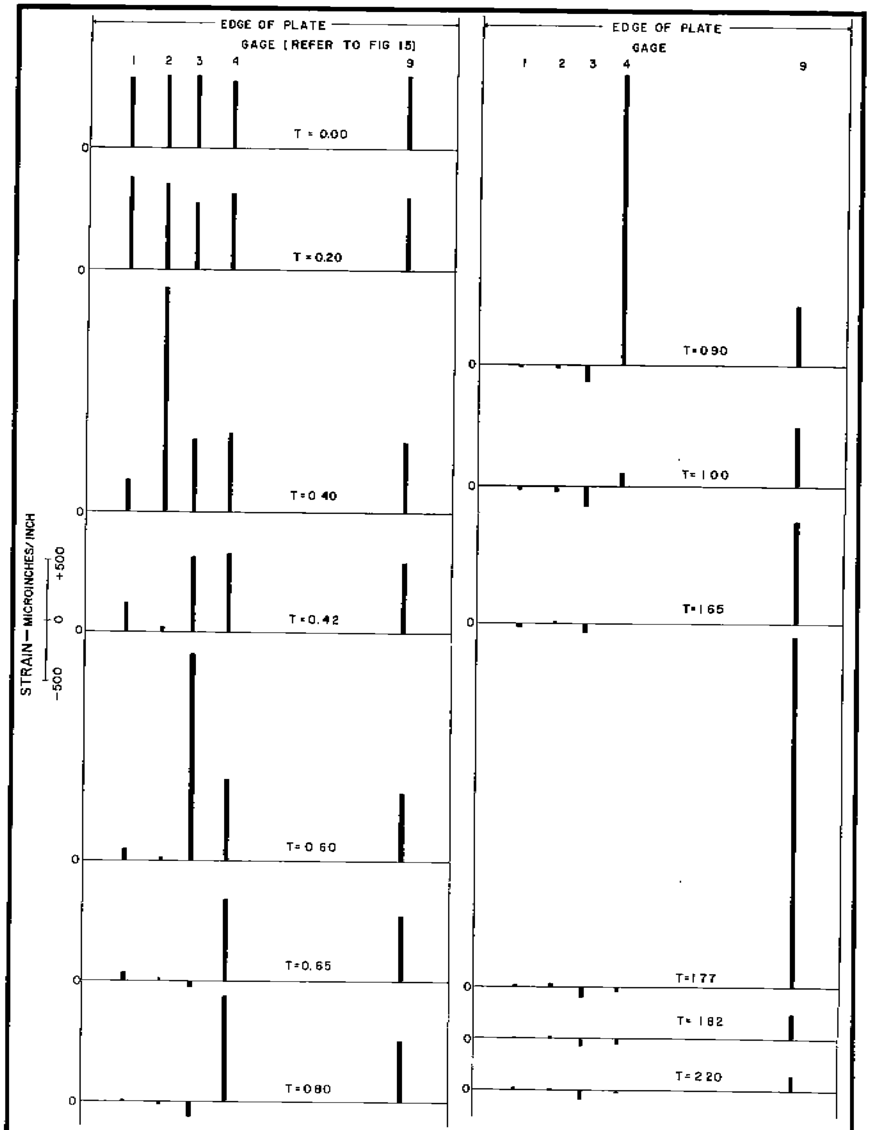


FIG. 20 STRAIN DISTRIBUTION AT VARIOUS TIMES — TEST 25

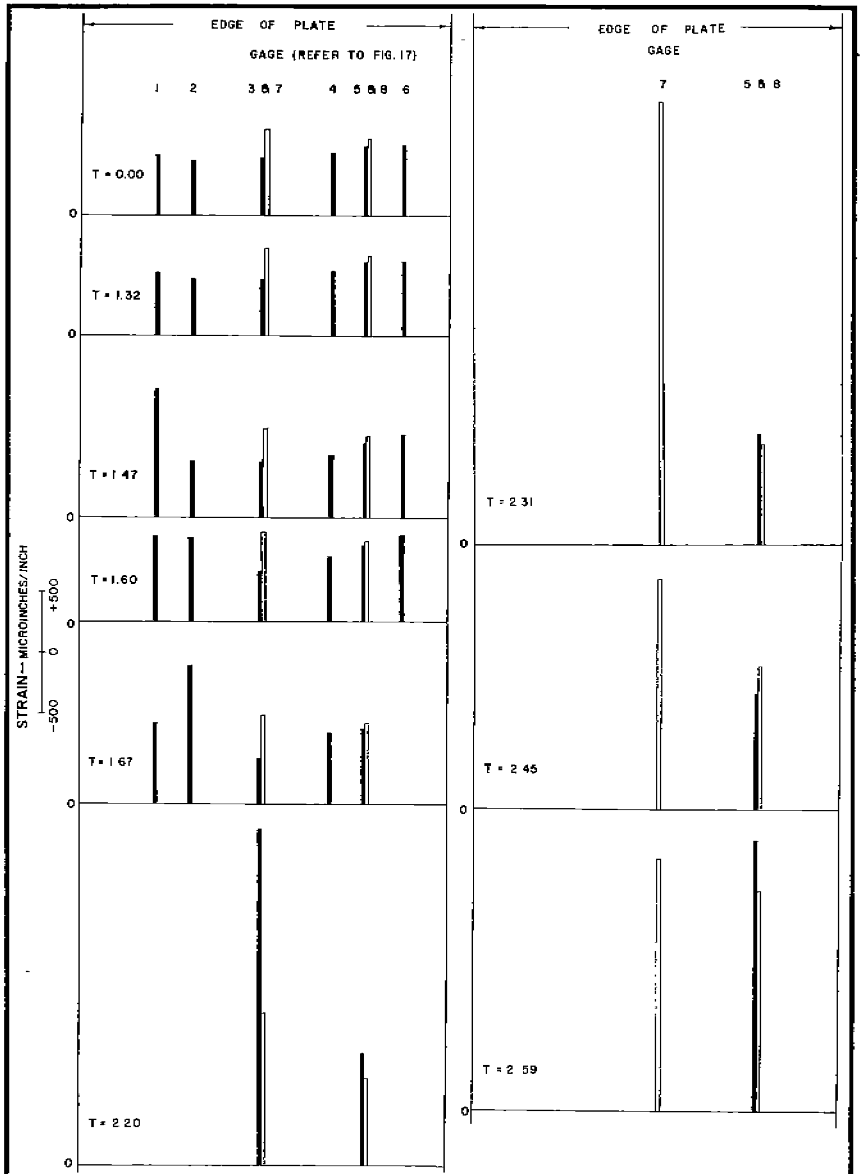


FIG. 21 STRAIN DISTRIBUTION AT VARIOUS TIMES — TEST 31

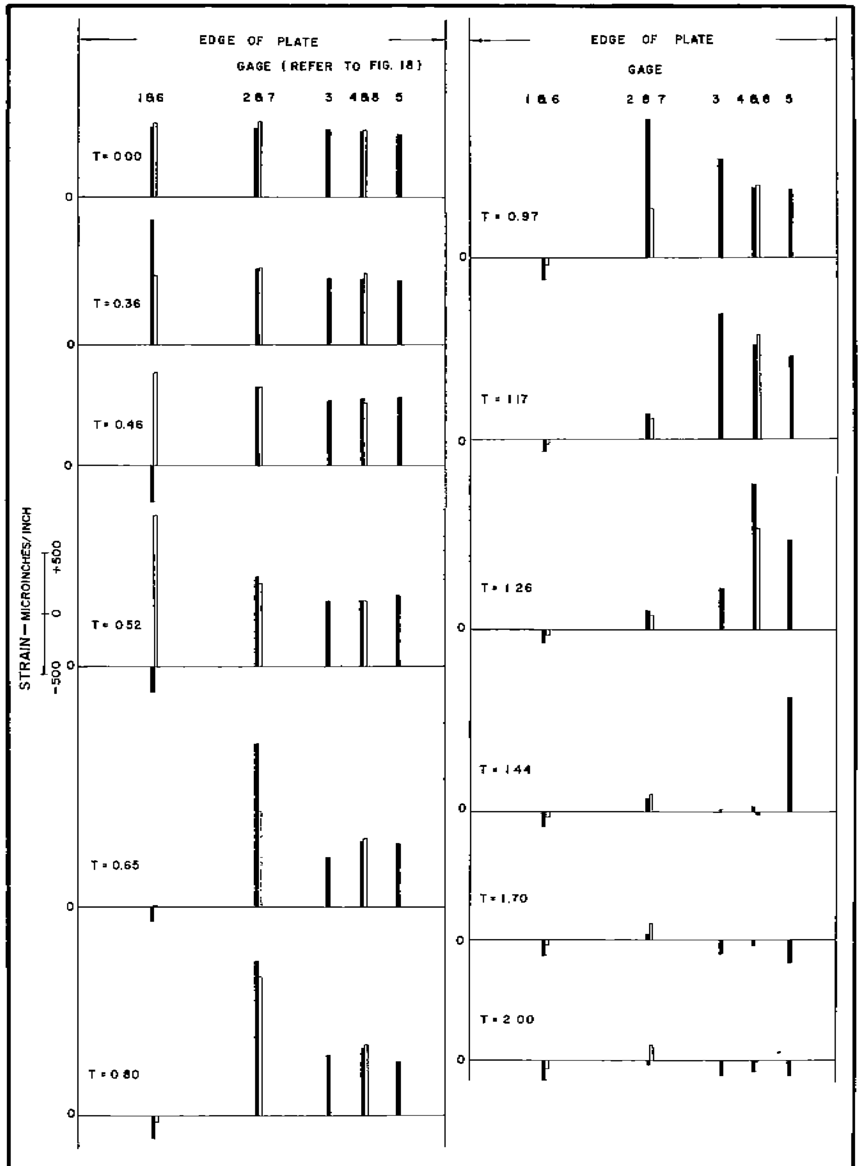


FIG. 22 STRAIN DISTRIBUTION AT VARIOUS TIMES — TEST 32

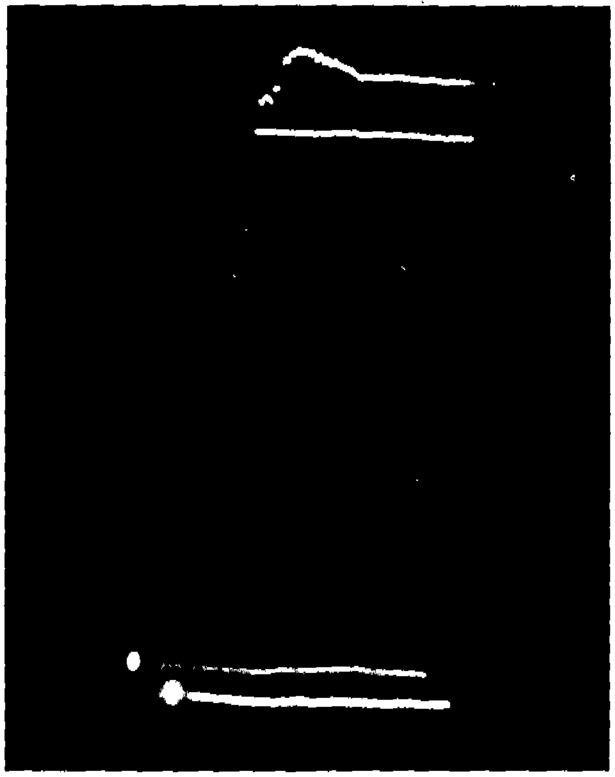
if it occurred at all. A partial record is one on which some of the strain traces are recorded, while the remainder are not. This may be due to a number of factors such as a failure of the gage or gages by condensation on exposed lead wires, or equipment failure during the tests.

The strain signal in most records is an erratic, oscillating trace after the first 1.5 to 2 milliseconds, i.e. after the plate breaks completely (for an example see Fig. 13). This oscillation may be the result of the motion of gage lead wires, ringing of the plate due to the impact force, vibration of the two parts of the plate, etc. Many of the strain signals have high frequency noise superimposed on the actual signal (for an example see the signal for gages 2 and 8 in Fig. 18). Normally the noise level was very low and has been ignored in plotting the record in order to clarify the resulting trace. In the few cases that a high noise level was recorded the disturbance occurred at the same time and to about the same degree on all the traces. This was attributed to an electrical disturbance since all gages were fed from a common source and grounded in common.

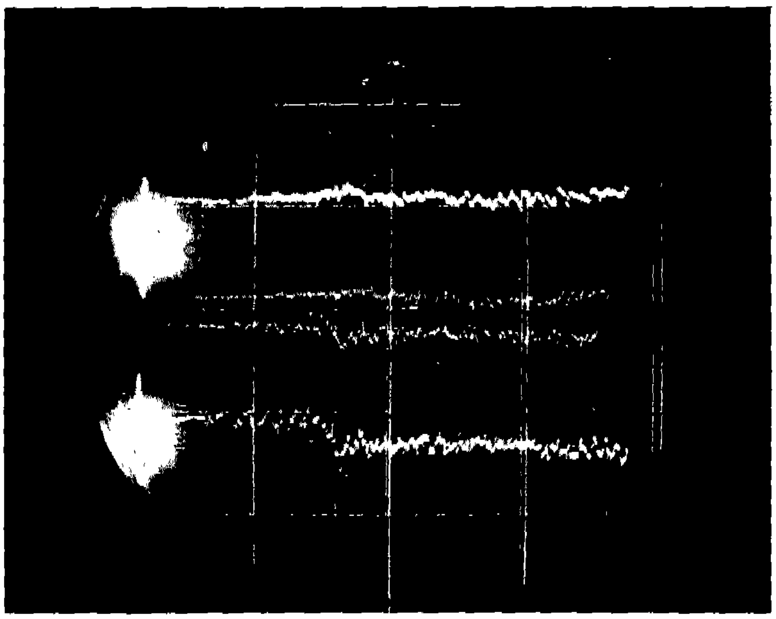
To study the strain behavior in the vicinity of the fracture, the strain gages must be located close to the anticipated fracture path. The effect of a fracture passing either through or very near (within 1/4 to 1/2 in.) a strain gage may affect the recorded traces in several ways. The trace for such a gage often exhibits an extremely rapid rise and leaves the scope face (for the sensitivities used in these tests), and may or may not return within the duration of the record. Also, since all the gages have a common ground wire, the destruction of one gage may cause a voltage jump (or occasionally noise) in the other gages; this explains the erratic behavior observed in Fig. 14.

12. Striking Tests

The object of this series of five tests was to evaluate the effect of the notch-wedge-impact method of crack initiation on the strain response of the specimen. In the striking tests the specimen was subjected to the notch-wedge-impact method of crack initiation, but at a temperature generally higher than the temperature for the complete fracture tests in order to prevent crack



TEST 18



TEST 30

FIG. 23 TYPICAL PHOTOGRAPHIC RECORDS FOR IMPACT TESTS

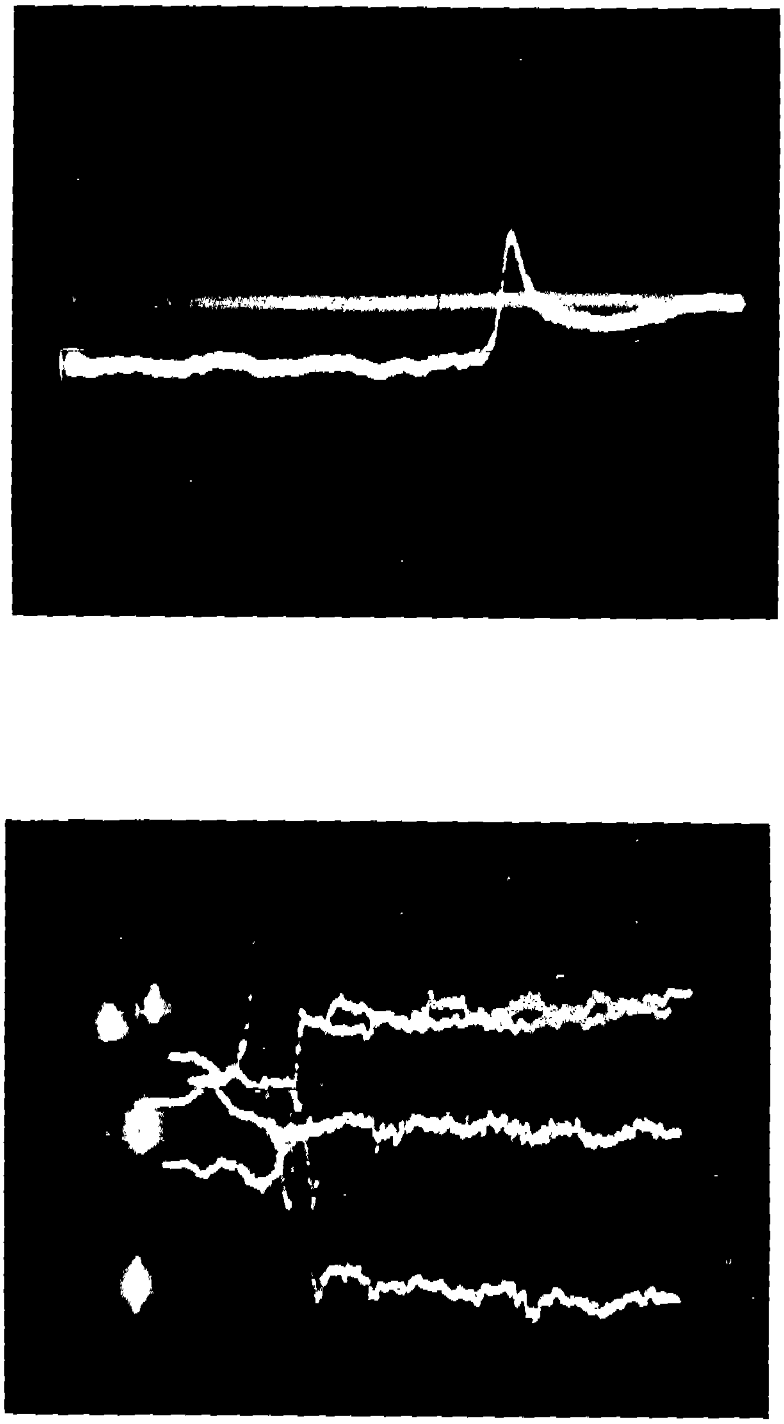


FIG. 24 PHOTOGRAPHIC RECORDS FOR TEST 23

initiation. The standard notch, wedge, and theoretical impact force was used in these tests. The stress varied from 18.0 to 18.5 ksi; the temperature was approximately 75 F for Tests 16, 17, 21 and 30 and approximately 0°F for Test 18.

In three of these tests the strain response in the general vicinity of the notch was studied. Test 17 (Fig. 8) resulted in the initiation of a 1/2-in. submerged crack and all gages showed an immediate response, several as high as 250 microinches per inch. Test 21 (Fig. 11) showed no sign of any submerged cracks but all gages showed an immediate response, some as much as 220 microinches per inch of strain. It is of interest to note that gages 3 and 9, back-to-back on the specimen, showed strain changes of opposite signs. No record was obtained in Test 16 because of a faulty trigger circuit.

The other two tests of this series were concerned with the strain response of gages located on the fracture-test notch line; the same gages were subsequently used in a complete fracture test. Test 18 (Fig. 9) was the only 6-ft wide-plate specimen which thus far has failed to fracture completely under normal fracture conditions. As explained previously in Section 10, this may have been due to the gas-operated piston device delivering a slightly reduced starting energy. The test resulted in a partly submerged crack, approximately 2.3 in. long. This crack was considerably longer than the cracks formed by similar tests at room temperature. With the exception of gage 1, the gages showed strain responses of not more than 50 microinches per inch. Gage 1 peaked to approximately 1000 microinches per inch, and retained about 300 microinches per inch of permanent set, probably because of its proximity to the crack. Test 30 (Fig. 16), at room temperature, did not show any signs of a submerged crack. The strain response was not over 50 microinches per inch for any gage. The notches used for Tests 18 and 30 were the source of secondary cracks when the inserts were later fractured completely in tests in which the fracture was initiated from the opposite companion notch.

It was concluded from the above tests that the present notch-wedge-impact method of fracture initiation produces a relatively small strain response as compared to the strain response which is recorded during the fracture tests.

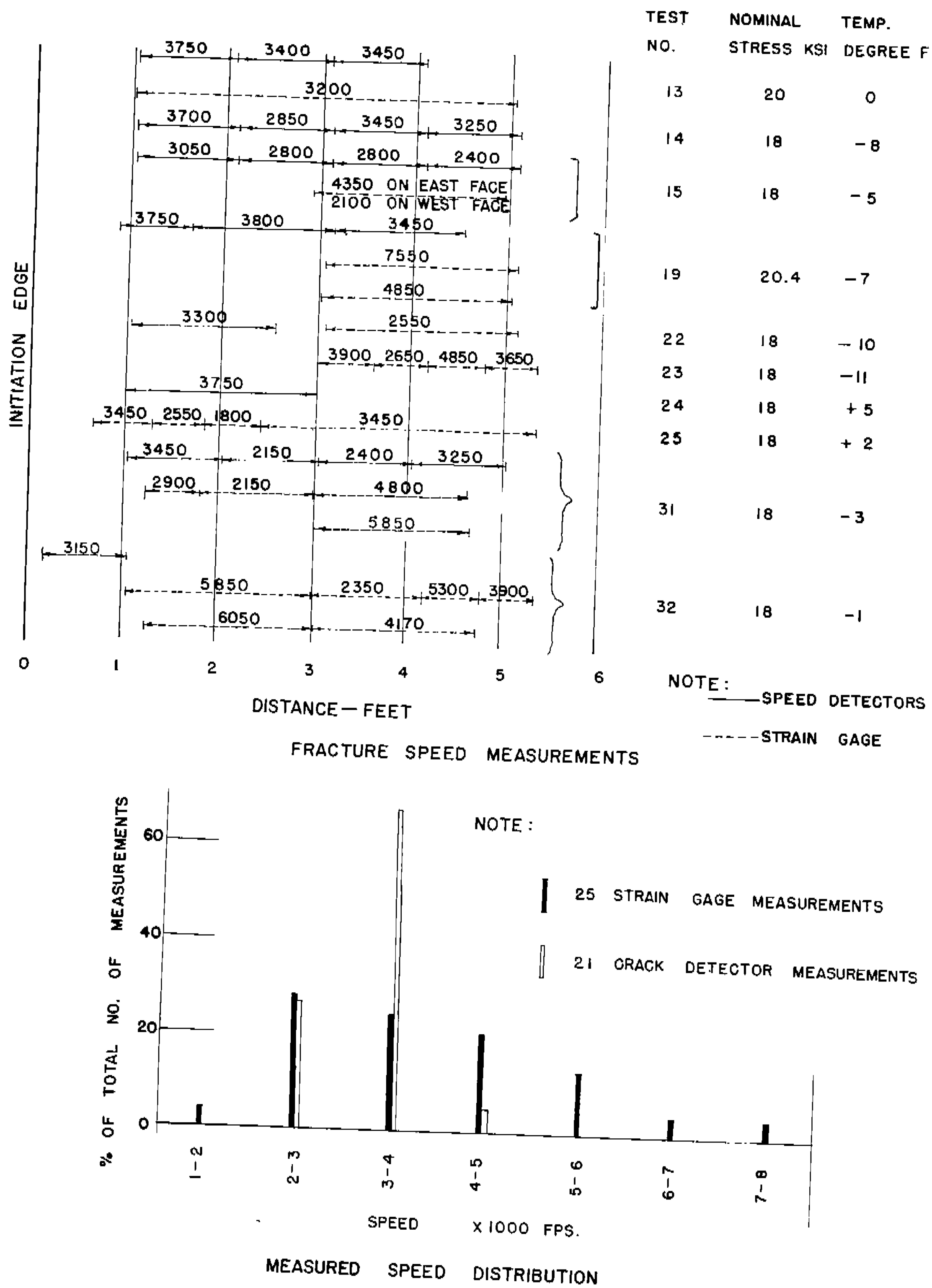


FIG. 25 FRACTURE SPEED IN SIX FOOT WIDE STEEL PLATES

The records indicate that the impact is felt throughout the plate; however, the strain magnitude, particularly at the center and far side of the plate, is small.

A question which remains unanswered by these tests is how far must a crack be driven by the impact force to enable the fracture to propagate across the entire plate. Obviously, other factors such as stress (or strain, strain rate, and related strain energy), temperature and imparted impact energy influence the propagation. The formation (or non-formation) of submerged cracks, and the variation of their length under similar physical test conditions, admittedly are not completely understood. On the basis of Test 18, it would seem that in the range of stress and temperature in which these tests were being conducted, the relationship between external impact energy and driven crack length must have been fairly critical.

13. Complete Fracture Tests

(a) Fracture Speed

The speeds of propagation of the brittle fracture on the plate surface for the 6-ft wide-plate tests are shown in Fig. 25. The speeds as measured by the crack detectors varied from 2150 to 3800 fps and from 1800 to 7550 fps as measured by the strain gages. This wide variation in speed occurs despite the fact that all the tests were performed under similar test conditions. However, 75% of all recorded speed data is in the 2100 to 3900 fps range.

The crack detectors spaced at intervals of approximately 12 in. appear to give more consistent values of speed than the strain gages. Ninety-five per cent of the computed speeds from crack detectors are in the 2100 to 3900 fps range, while only 55% of the computed speeds from strain gages are in this range. Other evidence of inconsistencies in the two methods of measurement may be seen in Test 15 where the speed of the crack across the latter part of the plate was 4350 fps on the basis of the record from the vertical dynamic strain gages on the east face of the plate. For this same distance on the same section of plate, the crack detectors, also on the east side, gave an average speed of 2600 fps. The vertical strain gages on the west side show a speed of 2100 fps in this region. In Test 19, the vertical strain gages indicate a speed of 7550 fps, the horizontal strain gages 4850 fps, and the crack detectors approximately 3500 fps. In this particular test, the speed for the section between detectors D and E is omitted; detector E was broken in two places, once by the main fracture and once by a secondary fracture, and it is not known which break occurred first. All these gages (detectors and strain gages) for Tests 15 and 19 were located in the same section on the east face of the plate. Again in Test 31, the speeds on the first half of the plate agree closely with each other and with other speeds recorded on this section of the plate, while on the second half a considerable difference in values was noted. However, the speeds as determined by the detectors for Tests 13, 14, 15, 19, 22 and 31 all agree fairly well with each other.

The speed of fracture propagation appears to reach a constant value within the first 4 to 6 in. of the fracture. Test 32 indicates a speed of 3150 fps in the first foot of the plate. Tests of this and other investigations,[4] also indicate this same tendency. In most cases the magnitude of the speed (approximately 3500 fps), as measured with the crack detectors, remained about the same as the crack propagated across the plate specimen.

A study of all the speed data from tests of 6-ft wide plates (including speed measurements made as part of the Crack Arrestor Study, Project SR-134) indicates no definite speed versus average static stress, or speed versus average temperature relationship, although the average net stress ranged from 18 to 33 ksi, and the temperature ranged from 5 to -33 F. A slight increase of speed for lower temperature and higher stress seems to be apparent from the Crack Arrestor tests, but this is not consistently observed. The speed of fracture propagation on one test of a semikilled steel plate (Project SR-134 data) was not noticeably different from the speed of fracture noted in the rimmed-steel plate tests.

In conclusion, if each specimen is considered individually, and then the group of specimens considered as a whole (all tested under similar conditions), it appears that measurements of brittle fracture speeds by widely spaced crack detectors on the plate surface result in more uniform than those measurements from similarly spaced strain gages. The variation in measured speed is often more apparent over short lengths of the plate. However, there is no reason to believe that the fracture progresses uniformly across the width of the plate. It is conceivable that, as the inner portion of the fracture proceeds across the width of the plate, the surface may open intermittently; the surface fracture may start, skip a section, and then continue on with the skipped section breaking slightly later. This concept might help explain why adjacent or back-to-back strain gages do not peak at the same time, and also may explain many of the apparent inconsistencies in speed measurements. However, for the tests made under approximately similar conditions of stress, temperature, and impact, it seems reasonable to expect that the average speed of propagation from plate to plate should be approximately the same. In any evaluation of the speed data, it must be recognized that the methods used provided only approximate measurements, but were felt to be the best methods available (Refer to Section 9 for a discussion of speed measurements).

(b) Dynamic Strain Measurements

Strain-time relationships are shown for ten tests, Figs. 5 through 18. The majority of the strain measurements were made with vertically oriented strain gages in the vicinity of the crack path. Also, several strain traces from horizontally oriented gages and one strain trace from a gage oriented 45° to the vertical were obtained in the vicinity of the crack.

During the course of the fracture, the vertically oriented strain gages in the vicinity of the crack path displayed a similar behavior in that the signal peaked when the crack approached or passed the gage location. However, the precise position of the fracture at the time the peak was reached is uncertain. The peaks for back-to-back gages, and gages mounted on the same side and only 0.5 in. apart, were found to be as far apart as 0.3 milliseconds (Figs. 5 and 7). In Test 13 (Fig. 5) it is interesting to compare the signals from strain gages 2 and 4 which were mounted back-to-back at the center of the plate. The difference in time between the peaking of the two gages is about 0.4 milliseconds, which for an average speed of crack propagation of 3400 fps would indicate one side of the fracture preceeded the other by 16 inches. In addition there is a sizable (1200 microinches per inch) difference in the amplitude of the strain peaks. Also, in this test gage 2 was approached by the crack path before detector C, but the strain gage peaked 0.16 milliseconds after the crack detector broke.

The foregoing is one basis for the suggestion that the fracture of the plate surfaces may not be continuous and symmetrical. In addition, it was found that upon recovery some of these gages showed an increase of strain over the initial strain, several strain gages showed a decrease, and several showed no change at all. To some extent, but not entirely, this difference in behavior may be correlated with the distance of the strain gage from the fracture, but just as likely may be related to stretched lead wires, etc., as discussed later in this section.

The magnitude of the peaks follows no set pattern, although in comparable records (Tests 23, 24, 31 and 32) there seems to be a slight increase in the magnitude of the strain peak for gages located closer to the fracture path. However this behavior is not consistent, as back-to-back gages which were the same distance from the crack sometimes had peaks of greatly differing magnitudes. This inconsistency in strain magnitudes has been noted particularly in records from tests in which the crack passed through at least one strain gage. This effect was discussed in Section 11.

The magnitude of peak strains from gages further away from the crack path is less than the peak strain for gages located very near the fracture path. For example, the magnitude of the peak strain was approximately 1400 microinches per inch for gages 3 to 4 in. away from the crack path in Test 23, and approximately 1100 microinches per inch for gages 6 to 7 in. away from the crack path in Test 32. This would indicate a rapid decrease in magnitude of the strain peak for points further away (vertically) from the horizontal fracture; this corresponds to observations reported in Reference 4. It is important to note that the peak strain magnitude does not show any definite correlation with the gage positions across the plate. It was anticipated that, as the crack progressed across the plate, it would produce strain peaks of increasing magnitude; however, neither this nor any other particular tendency was observed.

After reaching a peak value, the strain signals moved toward the zero strain level. However many of the traces did not return precisely to this value as noted

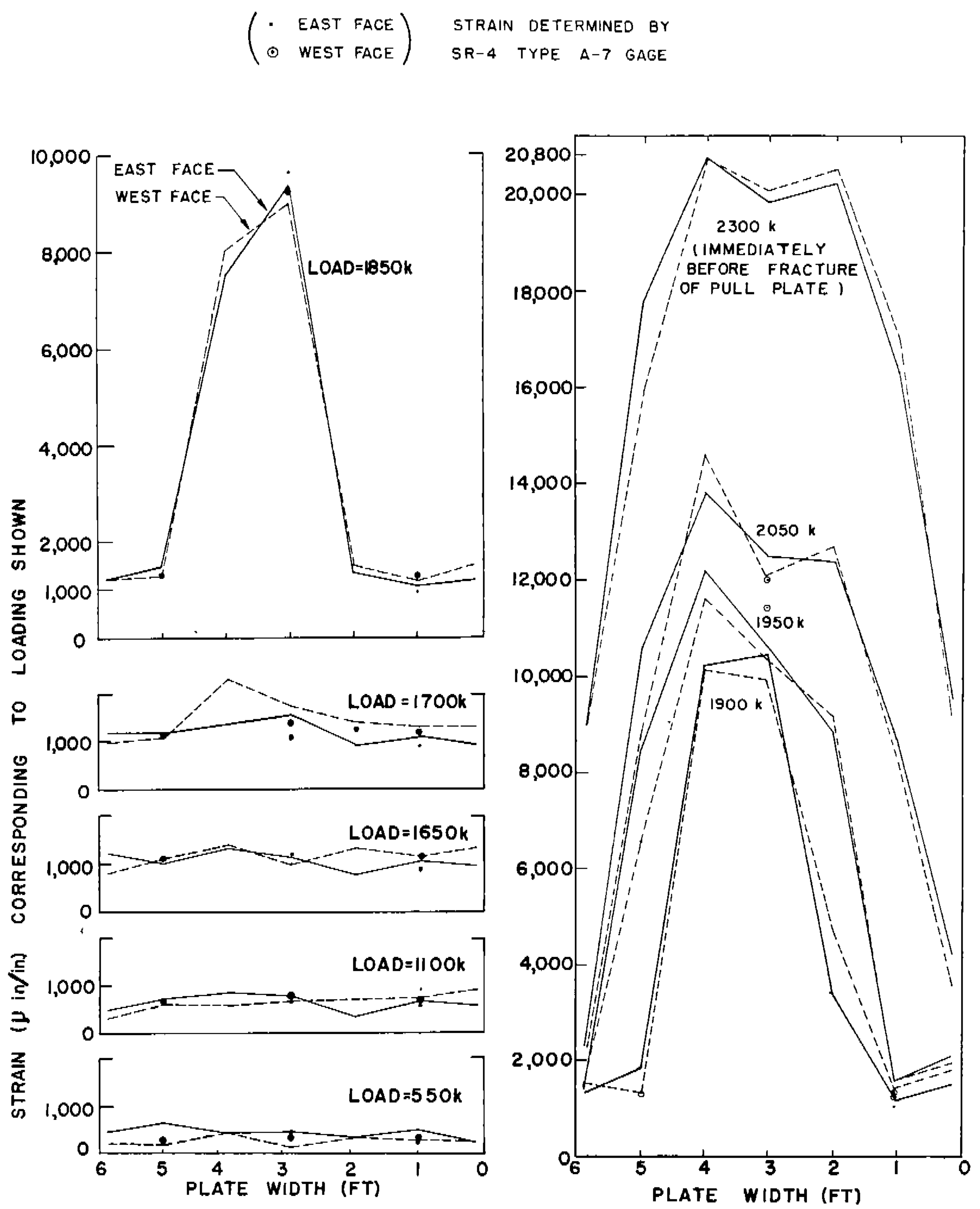


FIG. 26 DISTRIBUTION OF STRAIN ACROSS PLATE FOR VARIOUS LOADS DURING PRESTRAINING —— TEST 32

in Figs. 5, 6 and 12. This variation in leveling-off or final strain may have been caused in part by such effects as the relaxation of residual strains, inelastic strain resulting from fracture, and stretching of the lead wires after fracture. Also, a comparison of strain readings made immediately before and after the test, with gages used for static monitoring purposes, reveals an erratic array of residual strain values. However, in the majority of cases in which the gages were at some finite distance from the crack (greater than 1 to 2 in.) and did not have pulled lead wires, etc., the residuals (final strains) were small.

It has been observed that the static strain level at test load sometimes varied considerably both across the width of the test plate and through the thickness. Across the width of a plate on one side only, excluding that region immediately adjacent to the notches, base strains had been found to vary by as much as 200 microinches per inch. In the thickness direction a difference in strain values of as much as 200 microinches per inch had been noted for an average strain level of approximately 600 microinches per inch. The strain response during crack propagation has been studied to try to ascertain the effects of these large differences in base strain; it is believed that both the differences in dynamic peak values and the time lag in peaking of back-to-back gages may be affected to some degree by the variation in base strain.

Test 32 (Figs. 18 and 26) was performed on a steel plate prestrained to approximately 2% strain. It was believed that the prestraining would reduce the strain differential in both the width and thickness directions and thus gages mounted back-to-back would have records which would be in better agreement, both as regards time of peaking and magnitude of strain. The test results indicate that the magnitudes of the strain peak were quite uniform for back-to-back strain gages, but the time of peaking was still inconsistent. In this test, gage 6 peaked after gage 1 and gage 7 peaked after gage 2, but gage 8 peaked before gage 4. This one test would seem to indicate the differences in dynamic peak strain magnitudes and the time lag in peaking of back-to-back gages are probably not affected markedly by the variation in base strain.

The distribution across the plate of vertical strain at various times during the fracture is shown in Figs. 19 through 22 by bar graphs. Figs. 19 and 21 seem to indicate that a vertically oriented strain gage located close to the crack path (up to 2.3 in.) is unaware of the approaching fracture until quite suddenly the strain trace exhibits a rapid rise followed by a rapid drop, i.e., there is little change in the strain level on the uncracked portion of the plate until some time just prior to peaking. This would indicate that even though there is a reduction in the net section as the crack progresses across the plate, the strain (and corresponding load) on the remaining section does not have time to change; thus, there is no evidence of a gross redistribution of load on the net section during the fracture process. A study of strain response patterns in Figs. 19 through 22 suggests a strain concentration (associated with the crack front) which travels across the plate and leaves a brittle fracture in its wake.

Some of the tests contain records from gages 8 and 9 which were located about 104 in. below the notch line, as shown in Figs. 10 and 12. The gages were oriented vertically, and in order to eliminate the effect of bending in the plate, the response from back-to-back gages was averaged electrically. The response of these gages was very similar in both tests. Both gages began to show a decrease in strain at the moment the record commenced, with the gage nearest the striking edge dropping off more rapidly than the other gage; the rate of change in strain increased, after about half the plate had fractured. A record of these gages from another test (Project SR-134 data) with a longer sweep time indicates that these two gage signals oscillated for some time after fracture, and eventually approached the zero load strain value.

Tests 19 and 22 (Figs. 10 and 12) show the records for strain gages oriented horizontally. The strain records for these horizontal gages are somewhat different than those observed in the 2-ft wide plate tests.[4] In the latter case, the records usually indicated a reduction in the initial compressive strain as the fracture approached the gage, followed by a sharp compressive strain peak at the time the companion vertically oriented gage peaked in tension. This general type of behavior is seen in Fig. 12, but not in Fig. 10; in the latter case, there is a large tension peak at the time there would normally be a compression peak. Although the precise reason for this difference in behavior is not known in this case, it may be due in part to the fact that the fracture passed very close to the particular gage in Test 19 (Fig. 10).

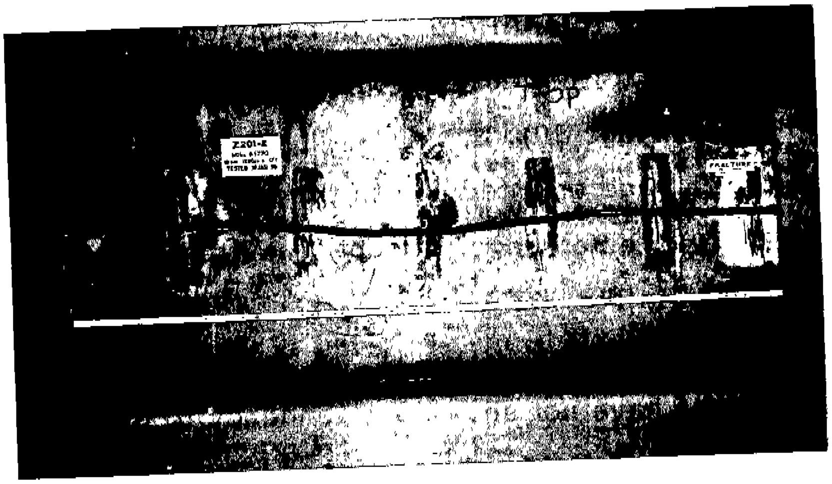
The behavior of a gage oriented 45° to the vertical is quite similar to that of an adjacent vertically oriented gage, except that it peaks somewhat later. A typical example is shown in Fig. 12.

(c) Crack Path and Texture

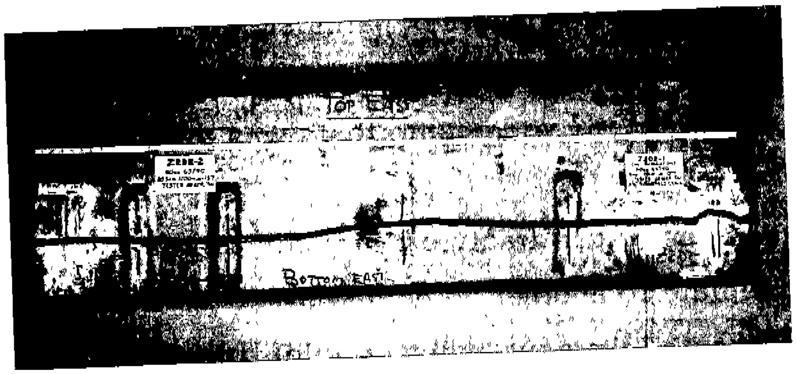
The fracture paths have not shown any tendency to follow a particular direction. The great majority of the fractures sloped upward from the point of initiation, then leveled off or wandered. Several crack paths for 6-ft wide plates are shown in Figs. 27 and 28. The crack paths shown in Fig. 28 are from the tests in which no strain records were obtained. The maximum deviation of a crack path from the notch line for the wide-plate tests was approximately 7.3 in. (Test 32).

The texture of the brittle fractures vary considerably from test to test and from one part of the plate to another. The texture of the fracture surface may range from very flat and smooth (chevrons indiscernible) to very coarse (chevrons may protrude up to approximately 1/8 in.). Typical examples of crack texture may be observed in Figs. 29 through 32. In some specimens the fracture texture was so coarse that small pieces of metal were torn completely away from the parent plate. The textures for tests of rimmed steel, prestrained rimmed steel and the semikilled steel were similar in that they could not be correlated with other test conditions or results.

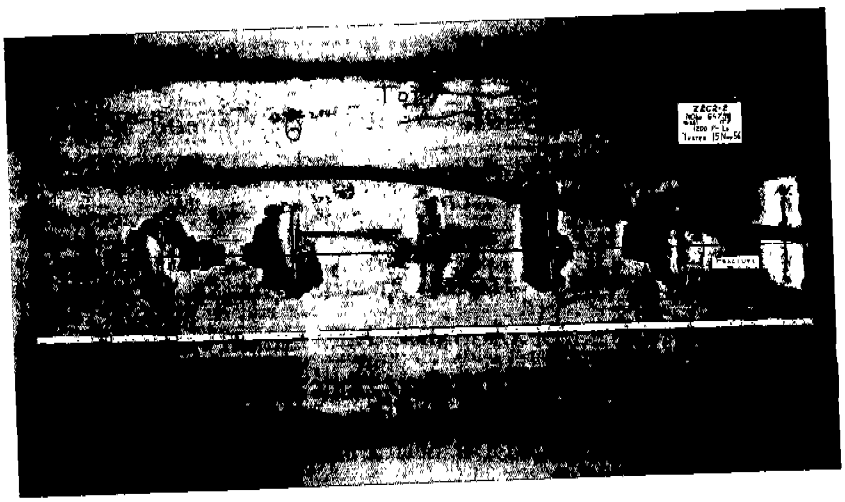
It was thought that some correlation might exist between the texture of the fractured surface and the speed of propagation, namely, the smoother the texture, the faster the speed, and vice-versa. However no definite correlation is evident at this time. Measurements indicate a reduction in thickness in the region of coarse texture of .010 in. to .020 in. (1 to 2% of plate thickness) while there is only .001 in. to .004 in. reduction in thickness (0.1 to 0.3% of plate thickness) in regions of fine texture. This was noticed in the tests of semikilled steel specimens also.



TEST 15

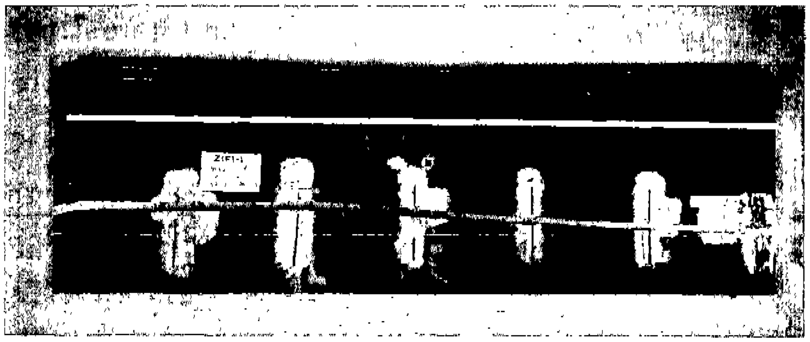


TEST 19

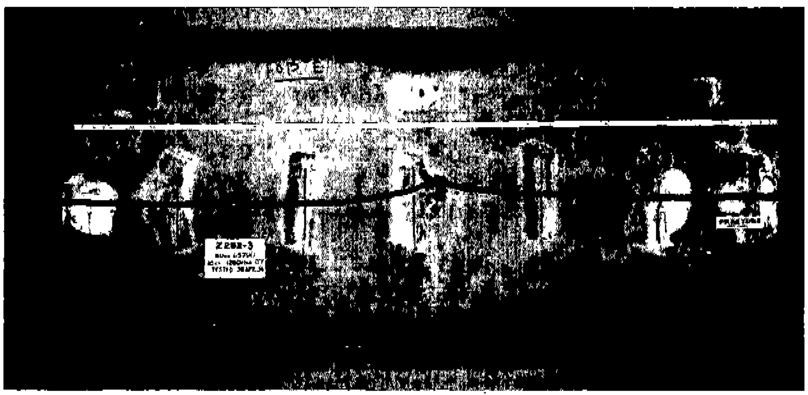


TEST 32

FIG. 27 TYPICAL CRACK PATHS



TEST 12



TEST 20

FIG. 28 CRACK PATHS FROM TESTS WITH NO RECORDS

(d) Semikilled Steel Tests

Four tests (Tests 26 to 29) without instrumentation were conducted on a semikilled steel with a Charpy V-notch 15 ft-lb value of 0°F, to determine the stress level necessary for fracture propagation. An interesting feature of these tests was that Test 26 at 17,000 psi and -1 F did not fracture, while Test 29 at 17,000 psi and -2 F did fracture. In these tests the original insert was 3/4 x 60 x 72 in. and after each test the fractured portion of the plate was cut out and the remainder rewelded to the pull plates so that the insert for Test 29 was only 3/4 x 16 x 72 in.

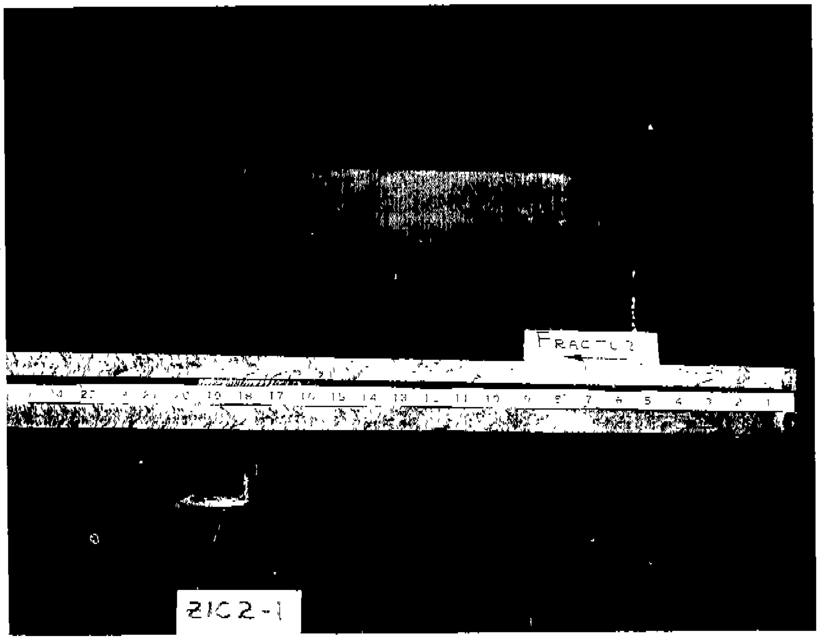
Complete fractures were obtained in the last three tests (see Table 1, Tests 27--29) leading to the conclusion that the test conditions required for propagation of a brittle fracture in this semikilled steel approach those of the rimmed steel presently used.

(e) Secondary Cracks

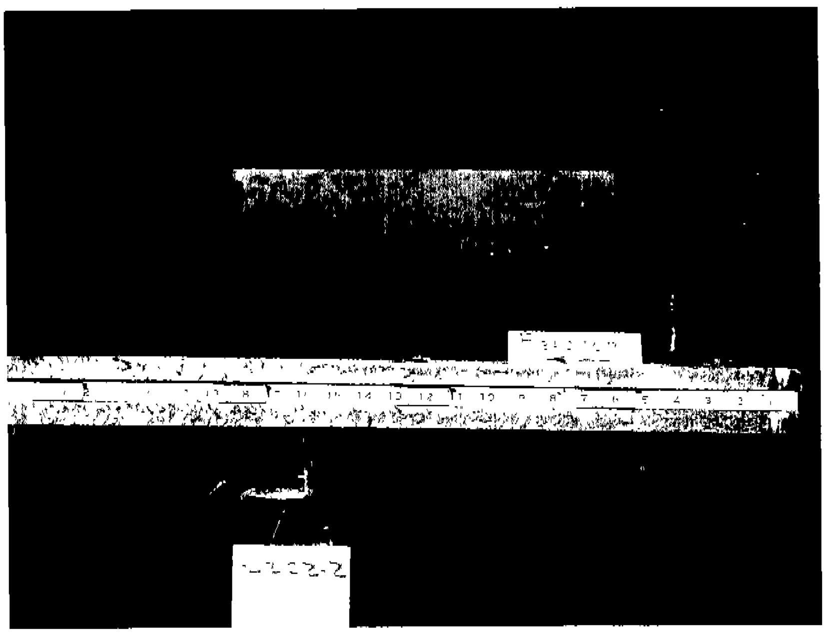
A secondary crack is a brittle fracture generally initiated during the test from the notch opposite the test notch. The chevron markings indicated that these secondary cracks propagated toward the advancing brittle fracture from the notch opposite the point of initiation. They either arrested within the plate or terminated by joining the main fracture. Typical secondary fractures are shown in Fig. 32. Figure 30 shows the far edge of the specimen for Test 18 after fracture. The submerged crack from the previous test on this insert, which propagated only 2.3 in. as shown by the arrow, reinitiated and joined the main fracture which approached from the left. Figure 31 shows a close-up of the specimen from Test 20 (Refer to Fig. 29 for the crack path) where the fracture started to branch. There is no strain record for this test.

(f) Change in Temperature During Test

On several specimens an attempt has been made to collect data involving the change in temperature resulting from the fracture phenomena. Several cooling records beginning a few minutes before the test and extending for several minutes afterward are shown in Fig. 3. Changes of as much as several degrees F have been noted in a number of the tests immediately following fracture, but the results are inconsistent and at this time no conclusions may be drawn.



TEST 24



TEST 32

FIG. 29 TYPICAL CRACK TEXTURE AT INITIATION EDGE

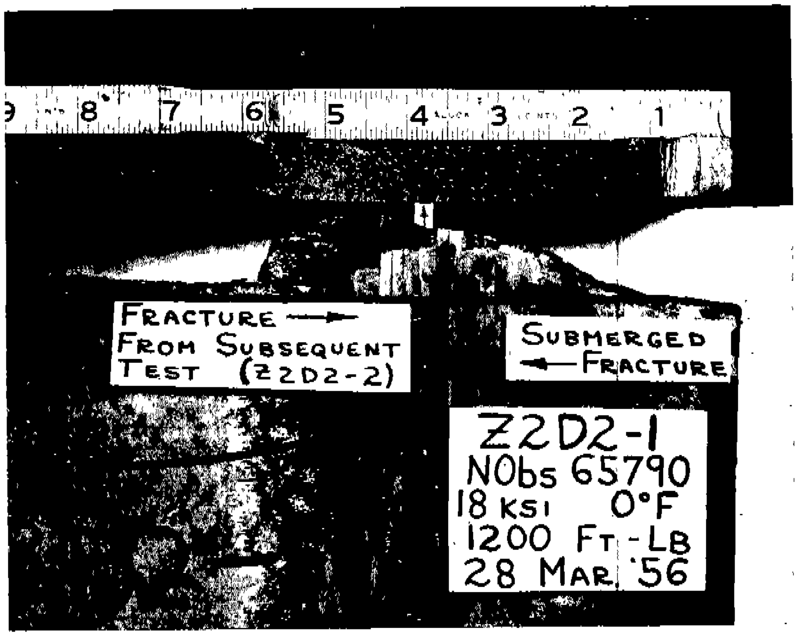


FIG. 30 REINITIATION OF FRACTURE FROM PARTLY SUBMERGED CRACK - TEST 18

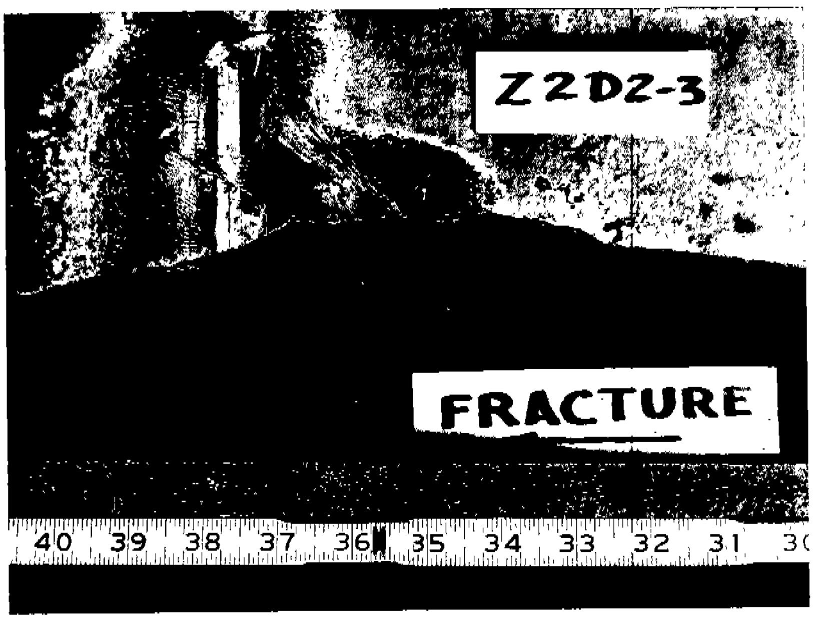


FIG. 31 BRANCHING OF CRACK NEAR CENTER OF SPECIMEN - TEST 20

14. Fracture of the Pull Plate

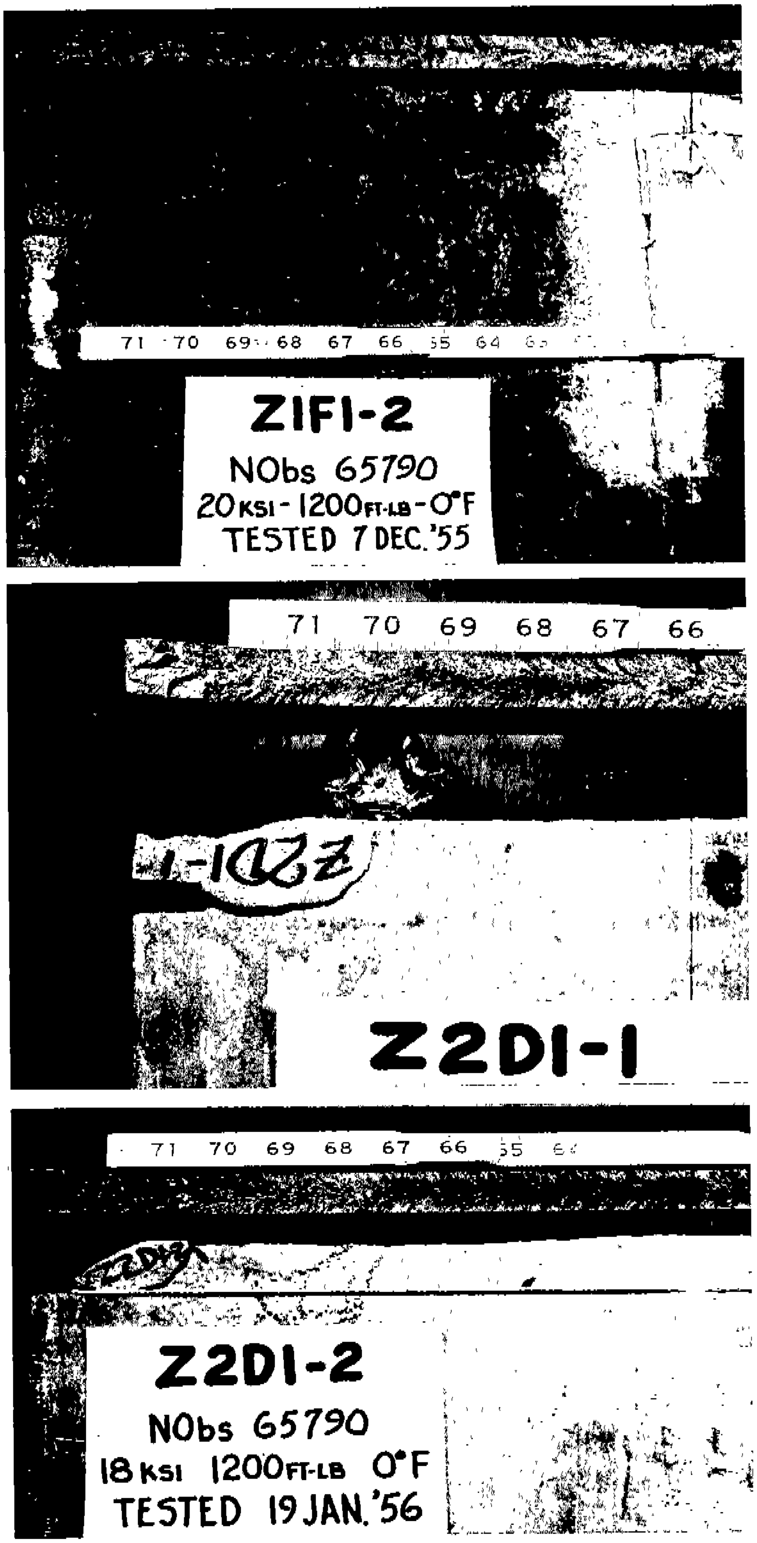
This fracture resulted during the prestraining of the specimen insert for Test 32. The fracture occurred at room temperature (approximately 79 F) and at an average stress of 32 ksi. The fracture initiated from the toe of a weld on the edge of the pull plate. The weld held a bracket that was used to support the initiation and cooling equipment for the regular tests. There was no external load on the bracket at the time of failure. A secondary crack about 3 to 4 in. long was initiated from the toe of a weld on the opposite edge of the pull plate.

The brittle fracture had a distinct shear edge or thumbnail at the beginning (see Fig. 33). The texture of most of the fracture varied from coarse to very coarse.

This pull plate had a long strain history, but the addition of the welds on the edges had been relatively recent. The check analysis and tensile data supplied by the fabricator for the heat from which this plate was rolled are shown in Fig. 33. The mechanical properties and check analysis for the fractured pull plate material are presented in Table 2, and show a lower yield strength and a higher maximum strength than reported for the original heat. Of particular interest is the exhaustion of ductility which is indicated by the strain corresponding to the beginning of strain hardening (ϵ_{sh}). This value is tabulated in Table 2 and indicates that the previous strain history of the plate had exhausted roughly one-half of the foregoing strain (ϵ_{sh}) normally available. The Charpy V-notch data appear to be in line with other data for the same type of steel as reported by the Standard Oil Development group.[3]

SUMMARY

This program is concerned with the study of the propagation of brittle fractures in wide steel plates. Presented in the Second Progress Report are the results of one series of tests of 6-ft wide plates. The plates were tested under similar conditions of stress and temperature, and the fractures were initiated at an edge notch by a wedge subjected to an impact. The specimens were



TEST 13

TEST 14

TEST 15

FIG. 32 VARIOUS SECONDARY CRACKS

TABLE 2.

MECHANICAL PROPERTIES AND CHECK ANALYSIS

A285 Grade C Flange Steel
Tensile and Charpy Specimens were cut from mid-width of plate adjacent to fracture.

(a) Tensile Data
(0.505 in. dia. round test coupon)

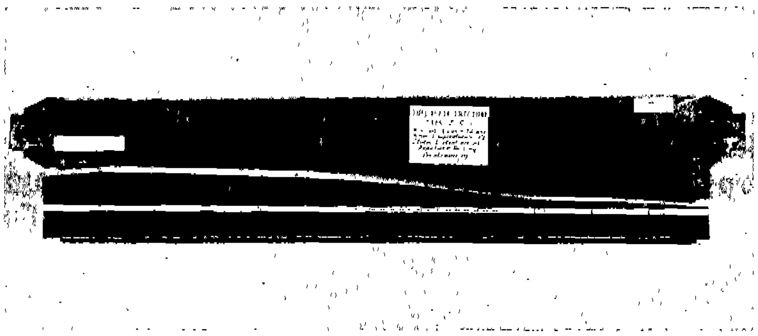
	Avg. of 2 Specimens Parallel to Direction of Rolling (Vertical)	One Specimen Transverse to Direction of Rolling
Yield Strength, Lower (ksi)	32.2	30.2
Maximum Strength (ksi)	65.2	64.6
Elongation in 2 in. (per cent)	38.0	36.0
Reduction in Area (per cent)	56.0	51.0
Strain at beginning of strain hardening (ϵ_{sh}) in./in.	0.008	0.005

(b) Charpy V-Notch Data
Specimen Axis parallel to direction of rolling and transverse to fracture. V-Notch axis perpendicular to plate surface.

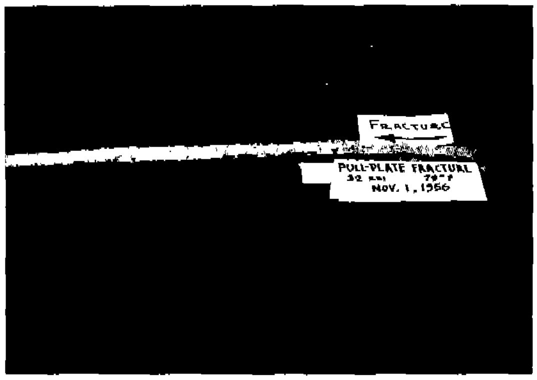
Temperature, F	Absorbed Energy, Ft-lb
196	48
190	46
180	44, 47
160	31, 35, 40
120	24, 25, 26
100	18, 18, 20
82	15, 15, 16
58	11, 12, 12
40	7, 8, 8
20	5, 5, 6
0	4, 5, 6, 7
-40	4, 4, 4

(c) Chemical Analysis

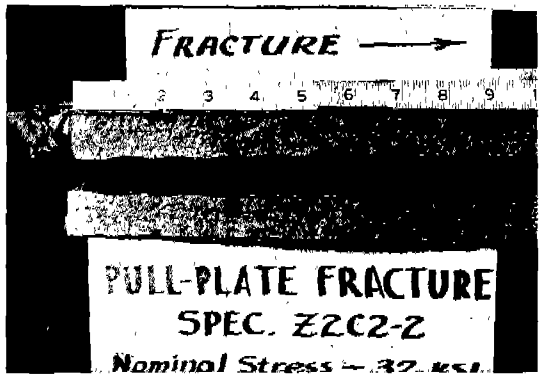
C	Mn	P	S	Si	Cu	Cr	Ni	Al
0.17	0.42	0.021	0.046	0.02	0.30	0.18	0.22	0.08



FRACTURE PATH



LOWER PORTION OF FRACTURED PULL PLATE SHOWING STRAIN LINES



FRACTURE SURFACE IN REGION OF INITIATION

TENSILE TEST DATA FOR A 285 GRADE C FLANGE STEEL		
YIELD STRENGTH KSI	ULTIMATE STRENGTH KSI	ELONGATION IN 2 IN. %
37 2	58.3	31

CHECK ANALYSIS OF A 285 GRADE C FLANGE STEEL			
C	Mn	P	S
0 25	0 49	0 016	0.040

FIG. 33 PULL PLATE FRACTURE

instrumented to provide a record of strain response and crack speed as the fracture propagated across the plate.

Striking tests, in which the specimen was not fractured, indicated that the strain response resulting from the impact-wedging action was relatively small when compared to the strain response recorded during the fracture process. Although the records indicated the impact was felt throughout the entire plate, it appeared that the strain at the center and far side of the 6-ft wide plate was not materially affected by the wedging action.

The majority of the strain and speed measurements recorded in the fracture tests have been made in the immediate vicinity of the fracture path. Strain magnitudes exceeding 2500 microinches per inch have been measured on the plate surface near the fracture with negligible permanent set remaining after fracture. In general, the nearer a vertically oriented gage is to the fracture path, the sharper and greater the magnitude of the strain pulse; as the distance increases, the strain pulse extends over a longer period of time, but the precise shape of the pulse depends on the distance from the fracture path. Thus far, vertically oriented strain gages in front of the crack indicate that there is negligible strain redistribution on the remaining section ahead of the crack.

Strain signals from gages adjacent to the fracture and mounted back-to-back on the plate, or immediately adjacent to each other, attest to the discontinuous nature of the surface fracture; in terms of fracture length the time lag between strain trace peaks in the case of gages mounted back-to-back has amounted to a differential crack length on the two surfaces of as much as 16 in. Such measurements may help to explain many of the inconsistencies of speeds and strain patterns that have been observed. Fracture speeds ranging from 1800 to 7550 have been measured, with 75% of the speeds within the range of 2100 to 3900 fps. Although a number of inconsistencies in the speed measurements have been noted, the speed measured from crack detectors has been fairly constant across the plate. However, no definite speed versus strain, or speed versus temperature relationship is apparent as yet.

In the wide-plate tests, the fracture appearance in many specimens has varied from extremely smooth to coarse, but no correlation has been observed between the fracture appearance and the measured speed or strain response. Studies show that the smooth texture is accompanied by negligible reduction in plate thickness while the very coarse texture is generally associated with reductions in plate thickness of 1 to 2%.

The brittle fracture of a pull plate with no artificial stress concentration is reported. This plate failed at room temperature, in a brittle manner, and at an average stress of 32 ksi, 86% of the original yield strength.

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