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BRITTLE-FRACTURE TESTS OF STEEL PLATES CONTAINING RESIDUAL COMPRESSIVE STRAIN

by

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Dear Sir:

As part of its research program related to the improvement of hull structures of ships, the Ship Structure Committee is sponsoring an investigation of Brittle Fracture Mechanics at the University of Illinois. Herewith is a copy of the Third Progress Report, SSC-117, "Brittle-Fracture Tests of Steel Plates Containing Residual Compressive Strain," by S. T. Rolfe, W. J. Hall, and N. M. Newmark.

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

Sincerely yours,

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

Serial No. SSC-117

Third Progress Report
of
Project SR-137

to the

SHIP STRUCTURE COMMITTEE

on

BRITTLE-FRACTURE TESTS OF STEEL PLATES CONTAINING RESIDUAL COMPRESSIVE STRAIN

by

S. T. Rolfe, W. J. Hall and N. M. Newmark

University of Illinois
Urbana, Illinois

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Washington, D. C.
National Academy of Sciences-National Research Council
July 2, 1959

Brittle-Fracture Tests of Steel Plates Containing Residual Compressive Strain

Investigation undertaken to produce a residual compressive-strain field in the central portion of a two-foot wide steel plate, and to study the propagation of brittle fractures in such plates

BY S. T. ROLFE, W. J. HALL AND N. M. NEWMARK

ABSTRACT. This investigation was undertaken in an attempt to determine some of the effects a residual compressive-strain field may have on a propagating brittle fracture. Brittle-fracture tests were conducted on $^3/_4$-in. thick by 2-ft wide by 5-ft long steel plates in which there was a longitudinal residual compressive strain in the central portion of each plate, and a region of high longitudinal tensile strain at each edge. This strain field was developed by welding tapered slots cut perpendicular to the edges of the plates.

The tests show clearly that the residual strain field affects the initiation and propagation of a brittle fracture. In all these tests the residual tensile strain at the edge of the plate was effective in reducing the applied stress at the notch required for fracture initiation. In one test in which the fracture propagated completely across the plate, the residual compressive strain field decreased the crack speed and the associated strain response. In two other tests, in which the residual compressive strains were much greater, the brittle fractures arrested in the compressive strain fields.

The results suggest the possibility of prestressing elements of ships or structures, or perhaps entire structures, as a means of arresting brittle fractures or providing a barrier for fracture initiation.

Introduction

In the past there has been considerable discussion as to what effect a compressive strain field may have on the propagation of a brittle fracture in a steel plate. The problem is complicated by the fact that the extent and magnitude of the compressive strain field, as well as the nature of the adjacent strain field, affect the propagation of the fracture. In spite of these complications, it still is of interest and importance to ascertain whether a compressive strain field, in which the major compression is perpendicular to the expected crack path, can arrest a brittle fracture. To investigate this problem, several fracture tests were made of 2-ft wide plates in which there existed a longitudinal residual compressive strain in the central portion of the plate.

The initial phases of this study consisted of investigating two methods of producing a compressive strain field in the central portion of $^3/_4$-in. thick by 2-ft wide by 5-ft long steel plates. The first method consisted of flame heating and water quenching wedge-shaped areas along both edges of a plate; the second method consisted of welding tapered slots cut perpendicular to the edges of a plate. It was believed that if the nature of the strain field were satisfactory, it would be possible to initiate and propagate a brittle fracture from one edge of the plate; this in turn would permit a study of the behavior of the specimen as the fracture entered the compressive region.

Brittle-fracture tests were conducted on three specimens prepared by the method of welding tapered slots. The specimens, tested at relatively low average applied stresses of 12,000 and 2000 psi, were cooled prior to testing. The fractures were initiated at an edge notch by the notch-wedge-impact method of fracture initiation, from a nominal impact energy of 1200 ft-lb. The plates were instrumented with SR-4 strain gages to provide a record of strain response and crack speed while the fracture was propagating.

Preparation of Specimens

Residual Strain Measurements

The residual strains resulting from the flame heating or welding were measured by means of Type A-7 SR-4 strain gages and a 6-in. Berry mechanical gage. Berry gage holes (6-in. gage length and oriented vertically) were placed every 1 in. across the central portion of the flame-heated specimens and every 1 in. across the entire width of the welded specimens. SR-4 strain gages used to measure residual strains were located only in the central region of the plates. In general, for any particular specimen there was good agreement between the strains recorded by the SR-4 gages and the Berry gage.

After a specimen was placed in position for either heating or welding, the initial Berry gage and SR-4 gage readings were taken. At this time, the plates were unstrained with respect to the as-rolled condition; all succeeding strain measurements were referred to this zero strain level. The specimen was subjected to the flame heating or welding process and allowed to cool to room temperature before the final strain measurements used to determine the residual strains were made.

Flame-Heated Specimens

Three procedures were followed in preparing the flame-heated specimens and are illustrated in Fig. 1.

(*a*) *Specimen 1.* The first method investigated to produce a residual compressive strain in the central portion of a plate consisted of flame heating an arc along both

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Paper to be presented at the AWS 40th Annual Meeting to be held in Chicago, Ill., Apr. 6–10, 1959.

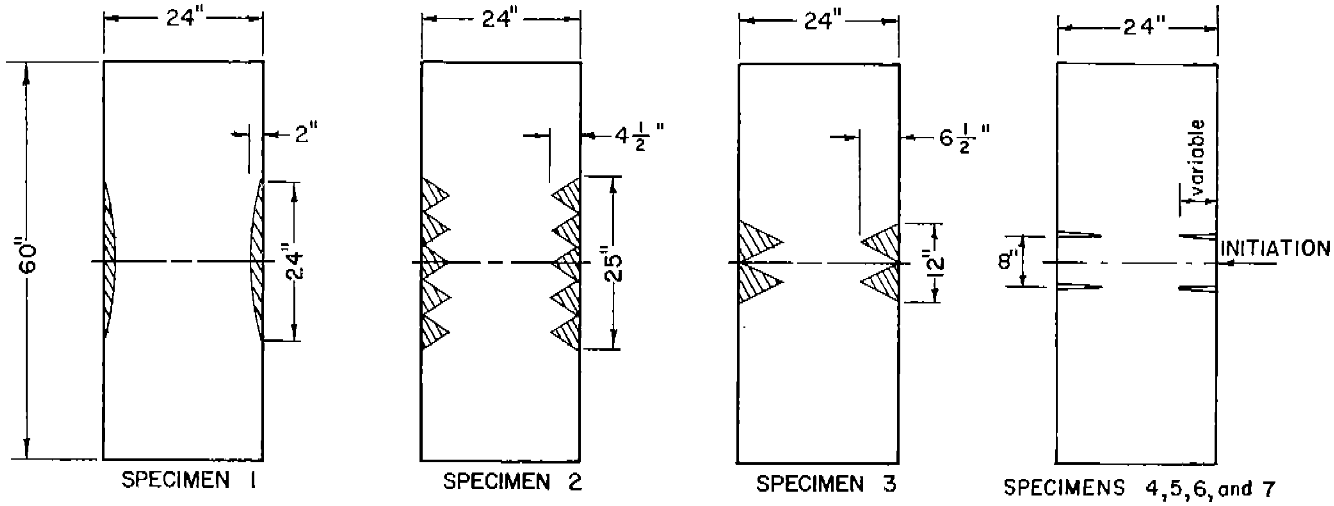

Fig. 1—General layout of specimens

edges of a killed and normalized steel plate while cooling the central portion of the specimen with dry ice. Strain measurements recorded with the Berry gage showed an erratic residual-strain distribution.

(*b*) *Specimen 2.* Wedge-shaped areas were flame heated to about 1650° F along both edges of this killed and normalized steel plate while the central portion was cooled with dry ice. The wedge-shaped areas were heated successively, with each individual "wedge" being water quenched immediately after heating. The resulting residual compressive strain is shown in Fig. 2.

(*c*) *Specimen 3.* Four deep "wedges" were heated to 1650° F on the same plate used as Specimen 2; the wedges were water quenched immediately after heating. Residual strains at the center of the specimen, as determined by Berry gage readings, reached a maximum of about −0.0025 in./in. in a longitudinal direction. However, the strain gradient was quite steep as may be noted in Fig. 2. The plotted strains are the average of readings from back-to-back gages; very little bending was evident.

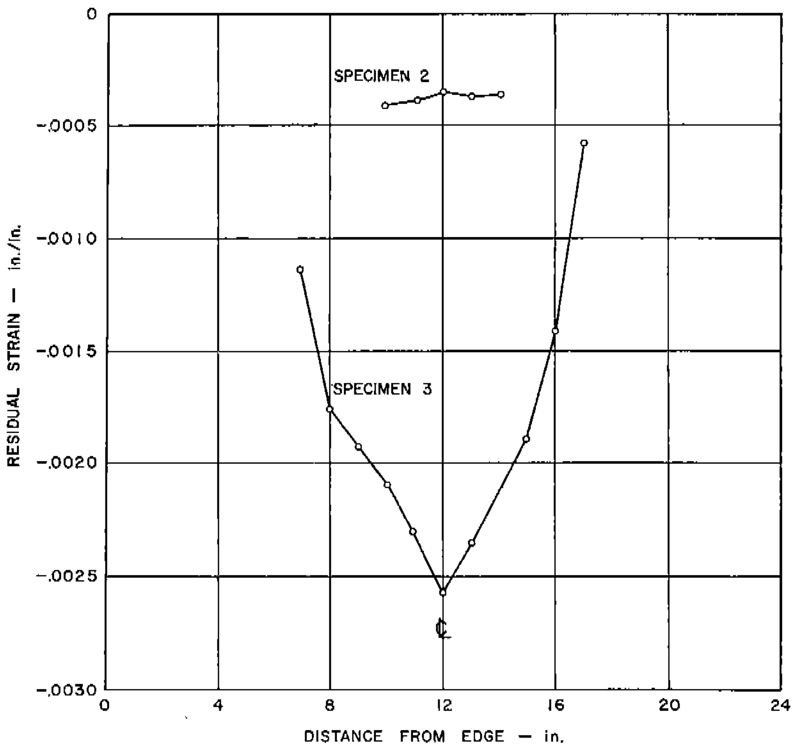

Fig. 2—Average longitudinal strain distribution across plate at notch line after flame heating and water quenching—Specimens 2 and 3

From Specimens 1 through 3 it was concluded that high compressive strains could be produced in the central portion of the plate by heating wedge-shaped areas and water quenching them immediately. However, the resulting longitudinal strain distribution exhibited a steep gradient along the horizontal as well as the vertical axis which was not considered to be desirable in this series of tests. The steep strain gradients and also the possible effect of heating and quenching on the brittle-fracture initiation and propagation characteristics of the material made an investigation of welded-plate specimens desirable.

Welded Plates

Four specimens were prepared by the method of welding tapered slots, cut perpendicular to the edges of a plate. Figure 1 shows the general layout of the specimens. Specimens 4 and 5 were prepared from a killed and normalized steel plate and Specimens 6 and 7 were prepared from a rimmed steel plate. The vertical distance between slots was 8 in. for all specimens, but the slot lengths varied for each specimen; Specimens 4, 5, 6 and 7 had slot lengths of 4, 5, 6 and 7 in., respectively. The four slots in each plate were tapered from $^3/_{16}$ in. at the edge of the plate to $^1/_8$ in. at the tip of the slots. A photograph of the slots for Specimen 6 is presented in Fig. 3.

The welding sequence was similar for Specimens 4 through 7 and will be described briefly with reference to Fig. 3. For each slot, welding began at a point two-thirds of the way toward the tip of the slot and proceeded to the tip. For example,

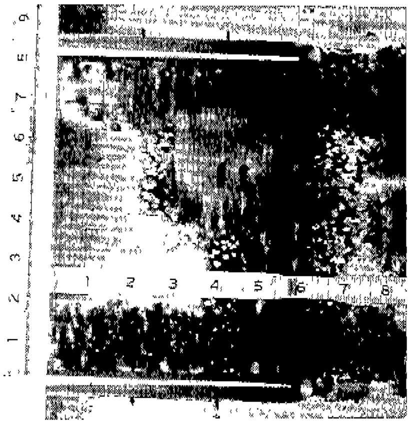

Fig. 3—Tapered slots before welding —Specimen 6

in Fig. 3, welding began at a point 4 in. from the edge of the plate and proceeded to the tip of the slot. The same number of passes was made on each side of the plate and they were placed alternately until the end one-third of all four slots was filled. All four slots were then welded in the same manner again, this time beginning at a point one-third of the way toward the tip of the slots and working to the previously completed welds; the last one-third of each slot was welded in the same manner. It was felt this welding sequence would keep the bending to a minimum, and produce a high uniform residual compressive strain in the central portion of the plate.

Welding of the four different slot lengths produced different amounts of residual compressive strain across the central portion of each plate as may be seen in Fig. 4. In general, the deeper slots produced a greater residual compressive strain. The strains on both faces were measured every 1 in. across the plate width with the Berry gage and, as are all the other strains reported herein, are plotted with respect to the as-rolled prewelded condition. It will be noted in Fig. 4 that, for any test, the tension and compression areas approximately balance, thus serving as a partial check on the recorded strains.

After the residual strains were recorded, the regular $1^1/_8$-in. deep notch, used in the notch-wedge-impact method of fracture initiation, was sawed in both edges midway between the tapered slots; relaxation in strain in the central portion of the plate resulting from the notching was only 0.00001 to 0.00002 in./in.

Brittle-Fracture Tests

General

Brittle-fracture tests were made with three of the plate specimens in which the residual compressive strain was produced by welding tapered slots (Specimens 5, 6 and 7). The welded specimens were ideally suited for fracture tests because of the high longitudinal residual tensile strains that existed at both edges of the plate. The yielded tensile region extended in from the edges of the plate for a dis-

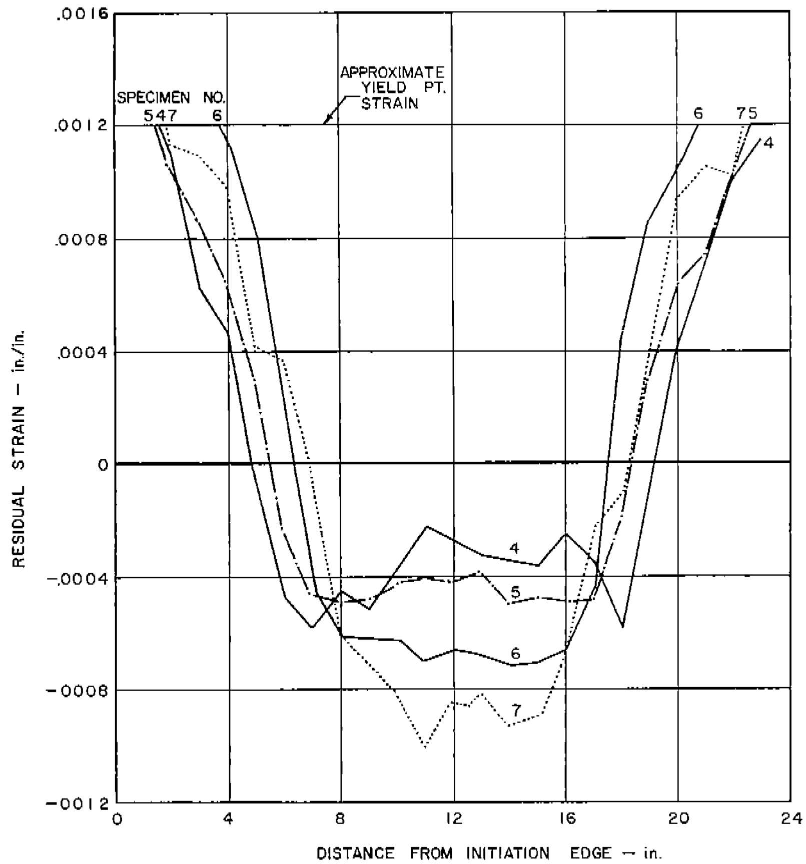

Fig. 4—Average longitudinal strain distribution across plate at notch line after welding—Specimens 4, 5, 6, and 7

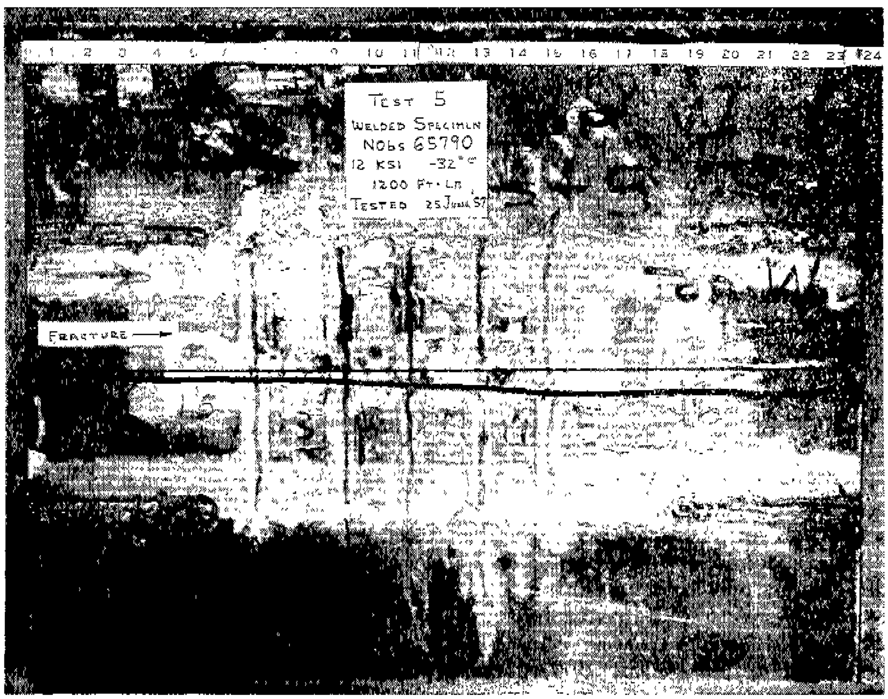

Fig. 5—Fracture path—Specimen 5

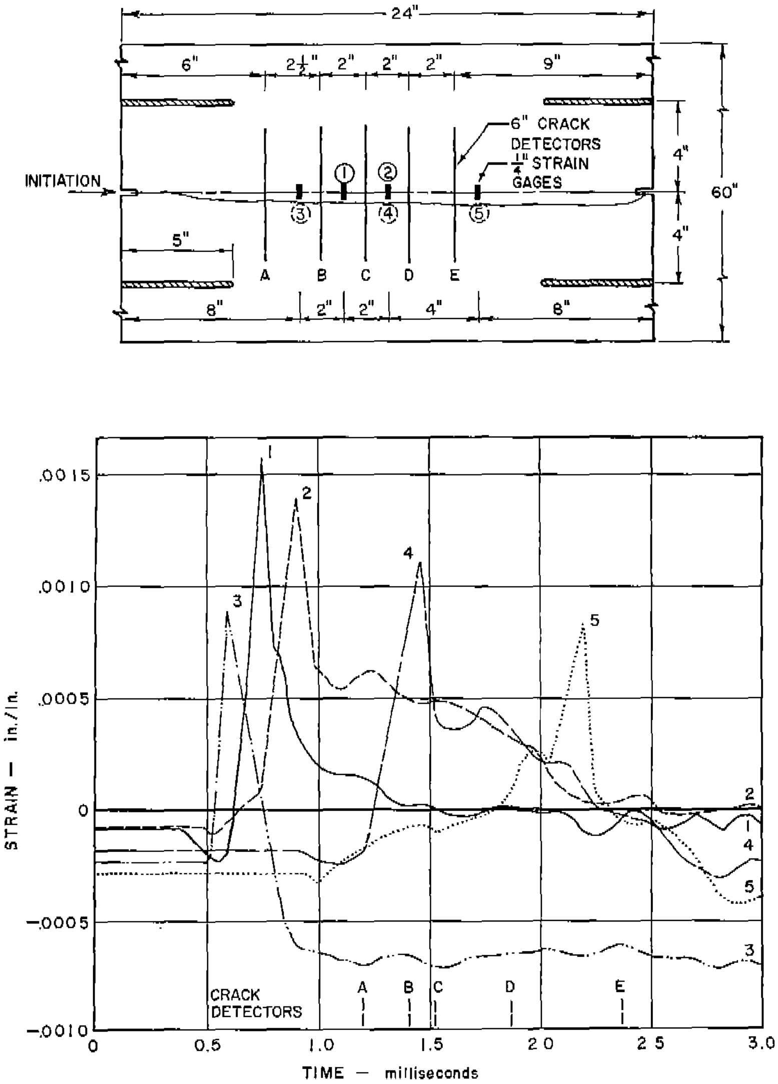

Fig. 6—Instrumentation layout and strain-time record—Specimen 5

tance of several inches as may be noted in Fig. 4. Since high-tensile strains existed at the edges even before any test load was applied, it was possible to initiate the fracture at a low applied stress; in fact, as described later, in two of the tests the applied net stress was only 2000 psi.

Eight channels of high-speed cathode-ray oscilloscope and associated photographic equipment were used to record the strain and crack signals from SR-4 strain gages as the crack propagated across the plate. Details of the instrumentation equipment, calibration, measuring procedure and data reduction were essentially the same as those described in an earlier paper.[1]

The specimens to be tested had dimensions of $^3/_4$ x 24 x 60 in., and were welded to pull plates having dimensions of 9 ft between the pull heads mounted in the 600,000-lb screw-type testing machine.

The yield strength and maximum tensile strength values for material from Specimen 5 were 34.8 and 59.8 ksi, and for material from Specimens 6 and 7 were 34.9 and 68.4 ksi, respectively. The Charpy V-notch 10 ft-lb value for the killed and normalized steel used in the test of Specimen 5 was about −30° F. The Charpy V-notch 10 ft-lb value for the rimmed steel used in the tests of Specimens 6 and 7 was about 12° F.

The test procedure consisted of cooling the plate, loading it to the desired stress level and initiating the fracture by means of an impact that drives a wedge into a notch in the edge of the plate. A more complete description of the testing procedure may be found in other reports and papers.[1−3]

Test of Specimen 5

This welded plate was the first of three specimens on which brittle-fracture tests were conducted. The test was made at an average applied net stress of 12,000 psi, a temperature of −32° F and an impact of 1200 ft-lb for fracture initiation. After applying the test load, the compressive strain over the central 10-in. portion of the plate averaged about −0.00015 in./in. During the test, a brittle fracture propagated across the entire specimen as is shown in Fig. 5; the black string denotes the notch line, i.e., an imaginary line connecting the edge notches.

The dynamic - instrumentation layout, strain-time traces of the strain gages recorded during the fracture process and the breaking times of the crack detectors are presented in Fig. 6. The zero strain level on the strain-time curve corresponds to the as-rolled prewelded strain condition. In other words, the initial strain values in Fig. 6 correspond to the residual strain plus the strain associated with the applied test load.

With several exceptions, the resulting records were similar to those of nonprestrained plates.[2] The strain trace of Gage 3, which was mounted at the edge of the compressive-strain field, was similar to that found in tests of nonprestrained plates in that it peaked sharply in tension and relaxed immediately. The traces of Gages 1, 2 and 4 which were in the center of the compressive-strain region, peaked sharply, relaxed rapidly to a strain value approximately one-half of the peak value, and then took about one millisecond to return to their respective final strain levels.

The trace of Gage 5 at the far edge of the compressive-strain region behaved in a different manner; the trace took 1 millisecond to reach one-half of the maximum peak strain, peaked sharply to the maximum strain value and then relaxed to its final strain fairly rapidly. Possibly, as the speed of the fracture decreased, redistribution of load began; then, as the fracture propagated past Gage 5, the strain trace showed the customary tension peak.

The fracture speed as determined by crack detectors and strain gage peaks was quite low. Between detectors A and B, and B and C, the fracture speed was 950 and 1600 fps, respectively; the fracture speed decreased to 450 and 350 fps between detectors C and D, and D and E, respectively, which were located in the center of the compressive strain region. Fracture speeds based on the time interval between the strain peaks of the dynamic strain gages were 400, 1100 and 450 fps between Strain Gages 3 and 4, 1 and 2, and 4 and 5, respectively. All of these fracture speeds (with the exception of the 1600 fps value) were well below any of those previously recorded as a part of this program. It is of interest to note that both the fracture speed and the magnitude of each successive strain peak decreased as the fracture traversed through the compressive-strain field.

The fracture surface appearance was not noticeably different than that observed in other plain-plate tests. In general, the fracture texture was fairly smooth for the first 3 in., rough for the next 7 in. and then became smooth again for the remainder of the fracture. Thus, the slower fracture speeds were recorded in a region of slightly finer crack texture.

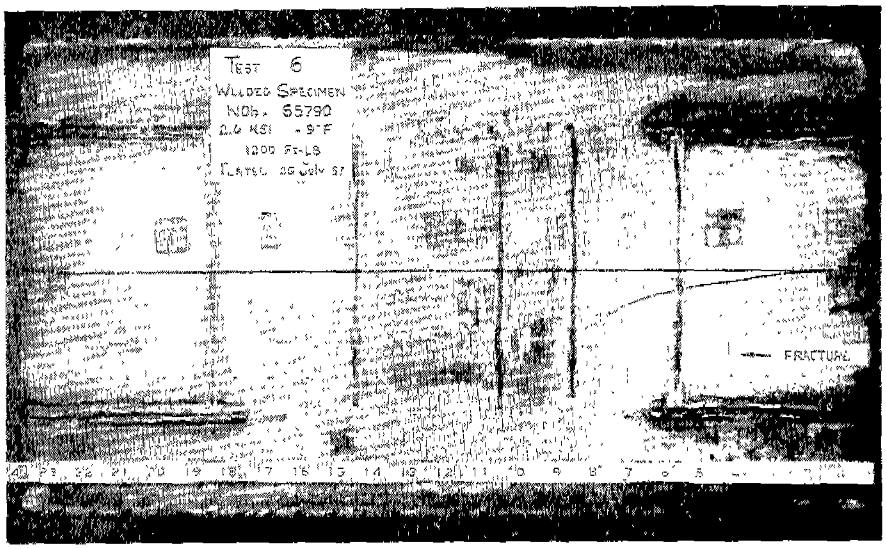

Fig. 7—Fracture path—Specimen 6

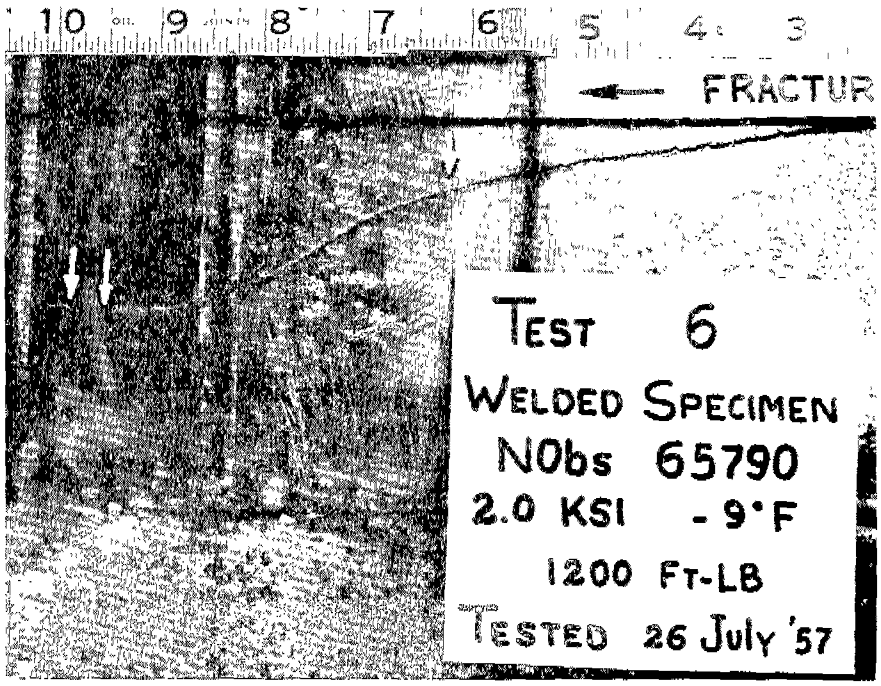

Fig. 8—Fracture region—Specimen 6

Test of Specimen 6

The welding of the slots for this plate resulted in an average residual compressive strain of −0.00065 in./in. across the central 10-in. portion of the specimen (Fig. 4). The specimen was tested at an average applied net stress of 2000 psi, at a temperature of −9° F, and with an impact of 1200 ft-lb for fracture initiation. In this test, only enough load was applied (32,000 lb) to keep the specimen taut in the testing machine. This was done for two reasons, namely: (*a*) to retain the high longitudinal compressive strain in the central region of the plate, and (*b*) to verify that a brittle fracture could be initiated with a low applied net stress and a region of high residual tensile strain. Earlier 2-ft wide plain-plate tests[2] indicated that an applied net stress of 15,000 psi was necessary for fracture initiation.

The brittle fracture propagated about 10 in. and stopped in the central compressive region; the last 4 in. of the fracture had the appearance of a submerged crack. Photographs of the fracture are presented as Figs. 7 and 8. The change in direction of the fracture as it neared the compressive strain field may be seen in the figures. On one face of the specimen a surface fracture $^3/_4$ in. long is clearly visible in the submerged-crack region; the location of this surface fracture is noted in Fig. 8 by the two small arrows about $9^1/_2$ in. from the edge of the plate. The arrow at $6^1/_4$ in. marks the point at which the visible surface fracture ended.

The instrumentation layout and the strain-time traces are presented in Fig. 9. The traces of Gages 1 and 6, which were mounted in the region of high-tensile strain near the edge of the plate, exhibited the usual response of vertically oriented gages with the exception that the peak-strain magnitude was low (approximately 0.0005 in./in.). The traces of dynamic strain gages mounted on the specimen exhibited behavior similar to that noted in crack-arrester tests.[4] As the fracture speed decreased and the fracture was arrested (at approximately 0.5 milliseconds), there was a redistribution of strain as evidenced by the shift of the strain traces toward the zero-strain level.

The initial strain distribution across the plate resulting from welding of the tapered slots, and the final strain distribution across the plate after the brittle fracture had arrested and the final test load was removed, are shown in Fig. 10. The initial and final strain distributions were determined from the average of back-to-back static SR-4 and Berry gage readings taken at room temperature. It will be noted that the areas under the strain plot along the notch line measured after fracture do not balance; this results in part from the fact that the crack did not follow the notch line. The final strain levels of the dynamic gages (minus the strains corresponding to the final test load of 19,700 lb) are also plotted in Fig. 10 and agree

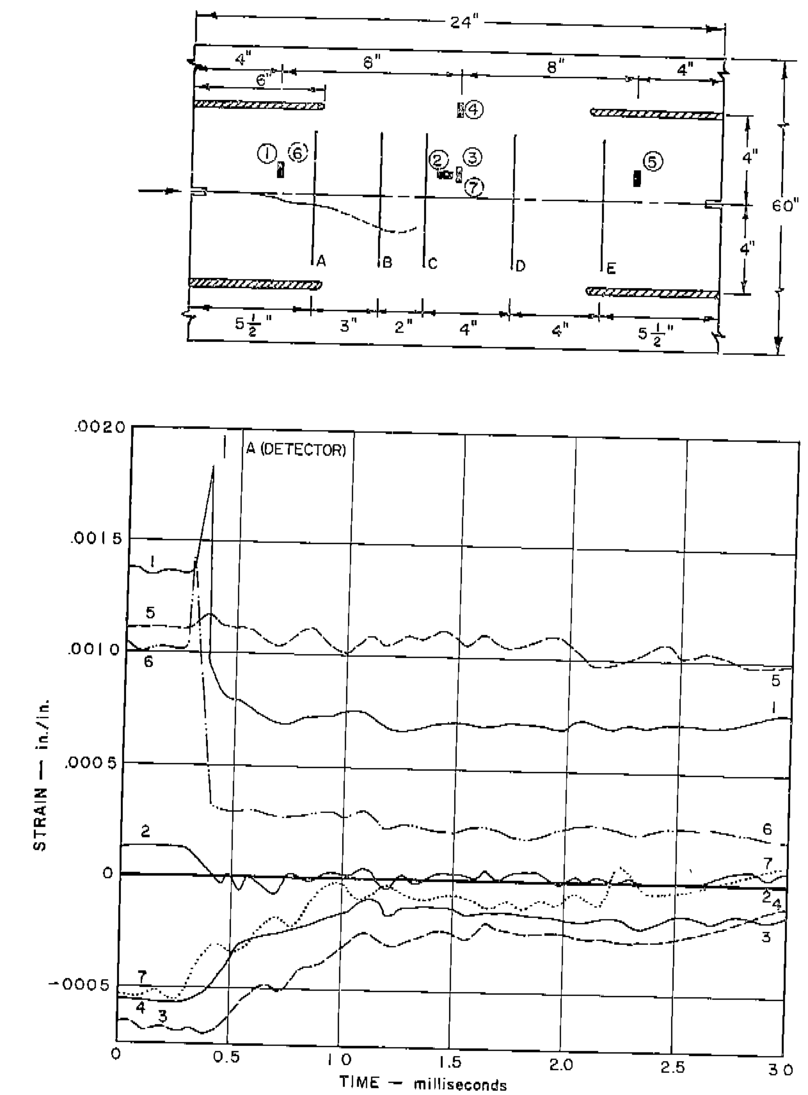

Fig. 9—Instrumentation layout and strain-time record—Specimen 6

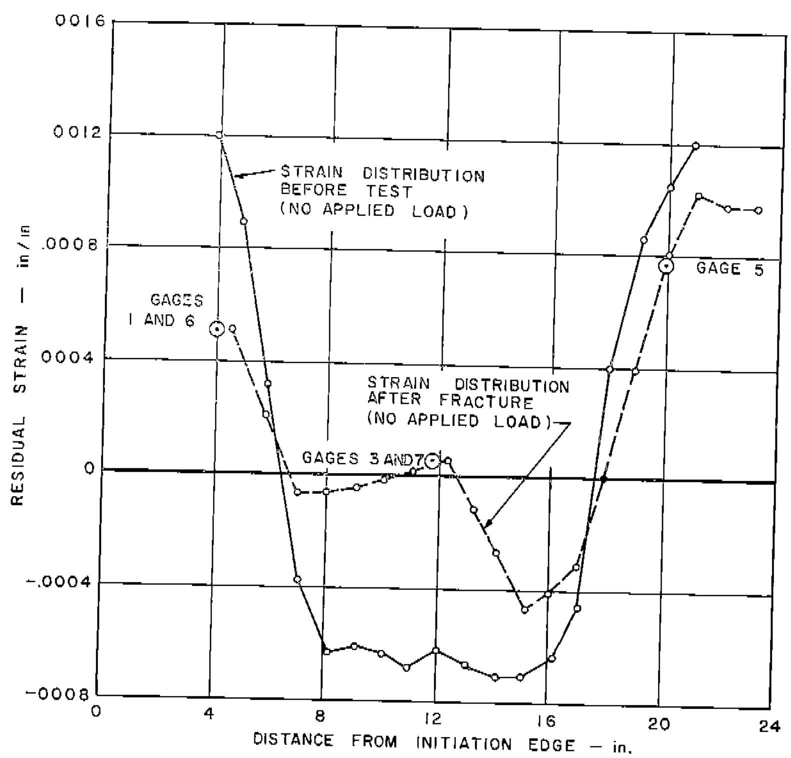

Fig. 10—Average longitudinal strain distribution across plate at notch line —Specimen 6

quite well with the strain distribution as determined by the static gages.

Because only one crack detector broke and only one set of back-to-back strain gages peaked in the usual sense, no fracture speeds could be computed for this test. A portion of the fracture (resembling a submerged crack) passed beneath the second crack detector but did not break it.

The reduction in plate thickness along the surface fracture was on the order of 1 to 2%; in the region of the submerged crack the reduction in plate thickness was about 2 to 4%. The surface texture in the fractured region was similar to that found in complete fracture tests.

Test of Specimen 7

The test of Specimen 7 was essentially a duplicate of the test of Specimen 6 with the exception that the length of the slots was increased from 6 to 7 in. The strain records were quite similar to those of Specimen 6, and are not presented.

The specimen was tested at an average applied net stress of 2000 psi, at a temperature of −5° F, and with an impact of 1200 ft-lb for fracture initiation. After applying the test load, the compressive strain over the central 8-in. portion of the plate averaged −0.00075 in./in.

A brittle fracture propagated about 10 in. and arrested in the compressive strain region. The length and appearance of the fracture were similar to that of the fracture occurring in the test of Specimen 6. A photograph of the fracture region is shown in Fig. 11. The small arrows on the photographs, 9 and 10 in. from the initiation edge, show where the fracture changed direction after it entered the compressive-strain field. The visible surface fracture ended at a point between the second and third crack detectors.

The average fracture speed between the first and third detectors (located $1^1/_2$ and $7^1/_2$ in. from the initiation edge) was 550 fps. The fracture passed beneath the second detector but did not break it.

Summary

The objects of the tests reported in this paper were to investigate methods for producing a residual compressive-strain field in the central portion of a 2-ft wide steel plate, and to study the propagation of brittle fractures in such plates.

Two methods of obtaining the desired residual compressive-strain field in the central portion of the plate were investigated. The first method consisted of flame heating and water quenching wedge-shaped areas along both edges of a plate, and the second method consisted of welding tapered slots cut perpendicular to the edges of a plate. The welding of these slots produced a fairly uniform longitudinal compressive strain in the central region of the specimens, as well as a region of high longitudinal tensile strain at each edge of the plates.

Brittle-fracture tests were conducted on three specimens prepared by the method of welding tapered slots, and the results of these tests may be summarized as follows.

In all three tests, and particularly in the last two tests, a low applied net stress was used. Thus, it appears that a high-tensile residual strain of yield magnitude at the edge of a 2-ft wide plate, and little or no applied stress, is sufficient for fracture initiation and propagation with the notch-wedge-impact method of fracture initiation. It should be noted that the other test conditions, namely temperature and impact, were similar to those used for previous tests of 2-ft wide plain plates, in which an applied net stress of about 15,000 psi was necessary for fracture initiation.

The residual-strain distribution obtained in the welded-slot type of specimen decreased the speed of a brittle fracture to the range of 400 to 1600 fps as the fracture propagated through a longitudinal compressive-strain field of low magnitude (−0.00015 in./in.); in the other two tests, the brittle fracture was arrested as it entered the compressive-strain field of higher magnitude (average longitudinal compressive strain of −0.00060 and −0.00075 in./in., respectively).

The strain traces of gages located in the tensile-strain region of all three plates exhibited a sharp tensile strain peak as the fracture propagated by the gage; this behavior is similar to that observed in tensile-strain regions of plain plates. The strain traces of gages located in the compressive-strain region on plates in which the fracture arrested exhibited a behavior similar to that observed in crack-arrester tests, in that as the fracture arrested, the redistribution of strain on the remaining section was evident.

This investigation has demonstrated that, under certain conditions, a residual compressive strain field may constitute an effective crack arrester; similarly, such a strain field also could constitute an effective barrier for crack initiation. In the opposite sense, these tests also demonstrated that a residual tensile strain at the edge of a plate was effective in reducing the applied stress at the notch required for fracture initiation.

Although this study was of an exploratory nature and of very limited extent, these tests suggest that, under certain circumstances, it may be desirable to consider prestressing elements of ships or structures, or perhaps entire structures, as a means of arresting brittle fractures or providing a barrier for fracture initiation.

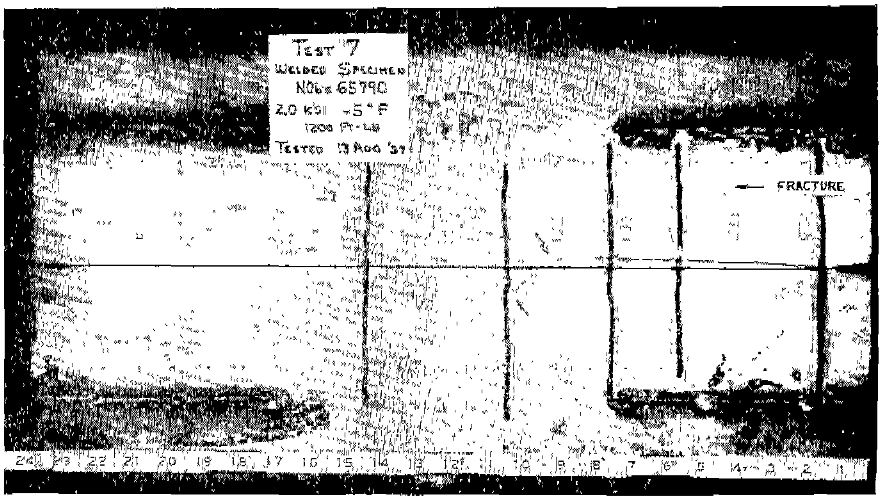

Fig. 11—Fracture path—Specimen 7

Acknowledgment

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