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BRITTLE FRACTURE TESTS OF TWO FOOT WIDE STEEL PLATES WITH A RESIDUAL COMPRESSIVE STRAIN IN THE CENTRAL PORTION

By
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A Technical Report
for the
Ship Structure Committee
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Bureau of Ships, U. S. Navy
Contract NObs 65790
Index No. NS-731-034
Subproject SR-137

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ABSTRACT

This investigation was undertaken in order to attempt to answer some of the questions that have been raised in the past as to what effect a compressive residual strain field may have on a propagating brittle fracture. Residual compressive strains were induced in the central portion of a two foot wide steel plate by two methods; one method involved heating and quenching the edges of the plate, and the other method involved welding tapered slots cut perpendicular to the edges of the plate.

Brittle fracture tests were conducted with three plates in which the residual compressive strain field was produced by the latter method. The tests show clearly that the residual compressive 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 residual compressive strain in the central portion of the plate was relatively small, the fracture propagated completely across the plate at speeds which were much lower than any previously recorded as a part of the brittle fracture propagation study at the University of Illinois. In the other two tests in which the residual compressive strains were much greater, the brittle fracture was arrested in the center of the plate.

Although the investigation was of an exploratory nature, and of very limited extent, the results of the tests suggest there is a possibility 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.

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I. INTRODUCTION

1. Object and Scope

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 of two foot wide plates were made in which there existed a longitudinal residual compressive strain in the central portion of the plate.

The three methods considered initially for producing a relatively high longitudinal residual compressive strain in the central portion of a plate were as follows: (a) welding prestressed plate strips together, (b) flame heating the edges of a plate, and (c) welding tapered slots cut perpendicular to the edges of the plate. Plate specimens were actually prepared using only the latter two methods, and a strain field of the desired nature was produced by the method involving welded tapered slots. The results of the investigations of methods for producing a residual compressive strain are presented in Section II of the report.

Brittle fracture tests were made with three specimens in which the residual compression was induced by means of welded slots. In one test, in which the residual compressive strain in the central portion was of a low magnitude, the fracture propagated completely across the plate, but at a speed much lower than any previously recorded as a part of this program. In the other two tests, in which the central compressive strain was higher, the fracture was arrested. These tests were conducted under conditions of temperature and impact similar to those used in the preliminary test series of two-foot wide specimens described in an earlier report (1)*. The plates were instrumented to measure the strain distribution and crack speed as the fracture propagated across the plate. The test results are presented and discussed in Section III.

The tests have practical significance from the crack arrest or initiation standpoint in that they suggest it may be advisable under certain circumstances 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. Some of the practical implications of the tests are discussed briefly in Section IV.

2. Acknowledgments

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The program is under the general direction of N. M. Newmark, Professor and Head of the Department of Civil Engineering. The authors wish to thank Dr. Newmark and W. H. Munse, Professor of Civil Engineering for their

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* Raised numbers in parentheses refer to listings in the bibliography.

valuable suggestions in connection with this particular phase of the program. The instrumentation was under the supervision of V. J. McDonald, Associate Professor of Civil Engineering.

Captain J. A. Brown, U. S. Navy, Bureau of Ships, suggested the general configuration of slots which, upon being welded, produced the desired residual strain field.

3. Nomenclature

The following terms are commonly used throughout the text:

Dynamic strain gage -- SR-4 Type A-7 (1/4-in. gage length) strain gage whose signal is monitored with respect to time on an oscilloscope during the fracture test.

Static strain gage -- SR-4 Type A-7 (1/4-in. gage length) strain gage used to monitor the static strain level.

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

Initiation edge -- The edge of the specimen at which the brittle fracture is initiated.

Notch line -- An imaginary horizontal line connecting the fracture initiation notches on opposite edges of the plate specimen.

Submerged crack -- A relatively short, arrested crack which does not cleave through the plate surface. It is characterized by a clearly defined depression on the plate surface.

II. PREPARATION OF PLATE SPECIMENS WITH A RESIDUAL STRAIN FIELD

4. General

The initial phases of this particular study consisted of investigating various methods of producing a longitudinal residual compressive strain field in the central portion of a two-foot wide steel plate, while keeping the edges of the plate in tension. 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 compression region.

Specimens were prepared by (a) flame heating the edges of a plate and (b) welding tapered slots cut perpendicular to the edges. The material properties, the instrumentation procedure used to determine the residual strain distribution, the method of plate preparation and the resulting residual strain distributions are described in this section of the report. All specimens were 60 in. long, 24 in. wide, and 3/4 in. thick. The direction of rolling was parallel to the vertical axis of the plate.

5. Material Properties

The first five specimens were cut from a 3/4-in. thick killed and normalized steel plate used in an earlier program (2). A Charpy V-notch curve, chemical analysis, and tensile properties for the material are presented in Fig. 1.

Specimens 6 and 7 were cut from a rimmed steel plate used in the previous two-foot wide plate tests made as a part of this program. The Charpy V-notch curve, check analysis, and tensile properties as determined in the earlier tests are presented in Fig. 2.

6. Methods Used in Measuring Residual Strains

The residual strains resulting from the flame heating of the edges of the plate were measured by means of either Baldwin Type A-7 SR-4 strain gages or a 6-in. Berry mechanical gage. In the case of the welded specimens, both of the aforementioned methods of measuring strains were used on each specimen.

Since both the flame heating and welding techniques produced high temperatures along the edge of the plate, the SR-4 gages could be used only in the central portion of the plates during heating or welding of the specimens. However, in general this was satisfactory because the magnitude of compressive strain in the central region produced by the heating or welding processes was the item of primary interest.

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. Berry gage readings were taken at the edges in the flame heated regions but the results could not be interpreted because the material had been upset.

After the specimen was clamped in position for either heating or welding, the initial Berry gage and/or SR-4 gage readings were recorded. The specimen was subjected to the flame heating or welding process and allowed to cool to room temperature before the final strain readings were taken. In the welded specimens, strains as measured by the Berry gage and the SR-4 gages were averaged to obtain the strain distribution with respect to the as-rolled condition, which has been taken as the base strain in all cases; in general for any particular specimen there was good agreement between the strains recorded by the SR-4 gages and the Berry gage.

7. Plate Preparation and Residual Strain Results

A. Flame Heated Plates

The procedures followed in making the flame heated specimens are summarized briefly in Table 1 and Fig. 3.

(a) Specimen 1 -- The first method investigated to produce a residual compressive strain in the central portion of the plate consisted of flame heating an arc along both edges of the plate (Fig. 3) while cooling the central portion of the specimen with dry ice.

At the end of the heating cycle the dry ice was removed and the specimen was allowed to cool slowly to room temperature. Strain measurements recorded with the Berry gage showed an erratic residual strain distribution across the central portion; the maximum recorded compressive residual strain amplitude in the central portion of the plate was less than -0.0002 in./in.

On the basis of this test it was decided that a higher compressive residual strain in the central portion of the plate might result if a greater proportion of the material were heated in a shorter time, and if the heated area were water quenched immediately.

(b) Specimen 2 -- The procedure for Specimen 2 consisted of flame heating wedge shaped areas along both edges of the plate to about 1650 deg. F. while cooling the central portion of the specimen (Fig. 3). The wedge shaped areas were heated successively, with each individual 'wedge' being water quenched immediately after heating. The resulting residual compressive strain averaged about -0.0004 in./in. across the central 8-in. portion of the plate as determined by SR-4 gage readings (Fig. 4).

On the basis of these results it was decided to increase the depth of the 'wedges' and repeat the process in an attempt to increase the compressive strain in the central portion of the plate.

(c) Specimen 3 -- The same plate used for Specimen 2 was used again as Specimen 3. Four deep 'wedges' (Fig. 3) were heated to 1650 deg. F. and water quenched immediately. The residual strain 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. 4. Mechanical and SR-4 gage readings 8 in. above and below the notch line of the specimen showed strains of only about -0.0002 in./in. in a longitudinal direction. Berry gage readings were taken in the flame heated regions but could not be interpreted because the material had been upset. However, by balancing the compression and tension residual strain areas along the notch line it was concluded that the residual strain at the edge of the plate was near or in excess of the yield point value.

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 case. This and also the possible effect of heating and quenching on brittle fracture initiation and propagation characteristics made an investigation of welded plate specimens appear desirable.

B. Welded Plates

(d) Specimen 4 -- This was the first specimen in which a compressive residual strain in the central portion of a two-foot wide plate was obtained by welding tapered slots cut perpendicular to the edges of the plate. Four slots 4 in. deep, two per edge, were cut in the edge of the plate as indicated in Fig. 5; the vertical distance between slots on each edge of the plate was 8 in. for all specimens. The layout of the instrumentation used to measure the residual strains resulting from the welding of the slots is shown in the same figure. A typical pair of tapered slots (for Specimen 6) is shown in Fig. 6.

The welding sequence was similar for Tests 4 through 7 and will be described briefly with reference to Fig. 6. For each slot, welding began at a point two-thirds of the way towards the tip of the slot and proceeded to the tip of the slot. For example, in Fig. 6 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, i.e., the first pass on the east face of the first slot, the second pass on the west face of the same slot, the third pass on the east face of the second slot, and so on 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 slot and working to the previously completed weld; the last one-third of the slot was welded in the same manner. It was felt this welding sequence would (a) keep the bending to a minimum, (b) give the greatest contraction at the edges of the plate and (c) produce a resulting high uniform residual compressive strain in the central portion of the plate.

Specimen 4 was the first plate of this test series in which the longitudinal strain distribution across the entire width of the plate could be obtained. As may be seen in Fig. 7, welding of the slots resulted in an average residual compressive strain of -0.00035 in./in. across the central 12-in. region of the plate. All strains were plotted assuming that the zero strain level corresponded to the as-rolled condition. It will be noted in Fig. 7, that for any test the tension and compression areas balance approximately, thus serving as a partial check on the recorded strains. The other curves of Fig. 7 show the strain distribution with respect to the as-rolled condition for Specimens 5, 6 and 7, the preparation of which are described later.

After the residual strains resulting from welding of the tapered slots 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.

The strain distribution across the central portion of Specimen 4 was not very uniform as may be seen in Fig. 7. Thus it was decided that in the next specimen the length of the slots would be increased in an effort to obtain a higher and more uniform compressive prestrain than that obtained using the 4 in. deep slots.

(e) Specimen 5 -- The residual strains in this plate were induced in the same manner as in the case of Specimen 4 except that the tapered slots were 5 in. deep and 1/4 in. wide at the edge of the plate. Welding of the slots resulted in an average residual compressive strain of -0.00045 in./in. across the central 10-in. portion of the plate (Fig. 7).

It was felt that the magnitude of the residual compressive prestrain was such that a brittle fracture test of this plate should be made. The results of this test are described in Section III; because a brittle crack propagated across the entire plate in the test, it was decided to again lengthen the slots in the next specimen in an attempt to increase the magnitude of the residual compressive strain field.

(f) Specimen 6 -- For this specimen the slots were lengthened to 6 in. The welding of the slots resulted in an average residual compressive strain of -0.00065 in./in. across the central 10-in. portion of the plate (Fig. 7).

The longitudinal and transverse strain distribution measured along the vertical center line of the specimen is shown in Fig. 19; it may be noted that the transverse residual strain is 20 to 32 per cent of the longitudinal strain and of opposite sense.

(g) Specimen 7 -- In the interests of exploring the effect of still longer slots, one additional plate was prepared in which the slots were 7 in. long. Welding of these slots resulted in an average residual compressive strain of -0.0008 in./in. across the central 8-in. portion of the plate (Fig. 7).

The longitudinal and transverse strain distribution measured along the vertical center line of this plate is shown in Fig. 25. The greater length of the tapered slots produced a noticeable change in the transverse strain at the center of the plate in line with the welds.

III. BRITTLE FRACTURE TESTS OF PLATES WITH A RESIDUAL COMPRESSIVE STRAIN IN THE CENTRAL PORTION

8. 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 as a result of welding the slots. No brittle fracture tests were made on specimens prepared by the flame heating method.

The maximum tensile strain on the edges of the welded plates exceeded the yield strength of the material and the yielded tensile region extended in from the edges of the plate for a distance of several inches as may be observed in Fig. 7. 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 net applied stress was only 2000 psi.

The test conditions, data obtained from the fracture tests, and a discussion of the results of these tests are presented in this section. The test conditions for the three brittle fracture tests (Tests 40, 41 and 42) are summarized briefly in Table 2. Test Numbers 40, 41 and 42, which correspond to tests of Specimens 5, 6 and 7, were used in order to coordinate these brittle fracture tests with all of the other tests made as a part of Project SR-137.

9. Instrumentation and Test Procedure

In the brittle fracture tests, eight channels of high-speed cathode ray oscilloscope and associated photographic equipment were used to record the strain and crack signals. The traces from each set of two dual-beam oscilloscopes were superimposed optically in such a manner that four traces were recorded on one 35 mm film strip. Six of the oscilloscope channels were sufficiently sensitive to allow 1-1/2 in. of trace deflection for a strain of 0.0010 in./in. The sensitivity of the remaining two channels was less, being about 1/2 in. of trace deflection for a strain of 0.0010 in./in. The time base was supplied mechanically by continuous motion of the film in Dumont strip film cameras. A modulated timing signal, and synchronizing pulses, were fed directly to each trace to establish a common time base.

SR-4 Type A-7 strain gages were used as dynamic gages and SR-4 Type A-9 strain gages were used as crack detectors. The crack detectors, which failed as the fracture propagated across the plate, opened an electrical circuit and fed step voltages to the recording channel. Each step was identified with the corresponding detector and the fracture speed could be computed from a knowledge of the distance between detectors and the time interval corresponding to breaking of adjacent detectors.

In these tests the specimens, having dimensions of 3/4 in. x 24 in. x 60 in., were welded to pull plates having dimensions of 3/4 in. x 24 in. x 24 in. This provided a clear distance of 9 ft between pull heads. The specimens were tested in a 600,000-lb screw type machine.

Prior to the fracture tests, all specimens were preloaded statically at room temperature to the test load. This corresponded to a load of 195,500 lb for Test 40, 32,000 lb for Test 41, and 32,000 lb for Test 42. The selection of a load of 32,000 lb for Tests 41 and 42 was arbitrary, the only objective being that there be enough load to keep the specimens taut in the machine.

All three specimens were tested at a temperature below the Charpy V-notch 10 ft lb value for the plate material used. This was done to increase the chances of fracture initiation. As may be seen in Fig. 1, the Charpy V-notch 10 ft lb value for the killed and normalized steel used in Test 40 was about -30 deg. F. The Charpy V-notch 10 ft lb value for the rimmed steel used in Tests 41 and 42 was about 12 deg. F. (Fig. 2).

The test procedure consists of cooling the plate, loading to the desired average stress level, and initiating the fracture by means of an impact that drives a wedge into a notch in the edge of the plate. With the exceptions noted above, the details of the instrumentation and test procedure are essentially the same as those used in previous tests and are described in earlier technical reports (1, 3) and a published paper (4).

10. Results of Brittle Fracture Tests

A. Test 40

This welded plate was the first of three similar specimens of which brittle fracture tests were made. This particular specimen was tested at an average net applied stress of 12,000 psi, a temperature of -32 deg. F., and with an impact of 1200 ft lb for fracture initiation. As discussed in Section II, the residual strains resulting from welding of the tapered slots amounted to -0.00045 in./in. across the central 10-in. portion of the plate. After applying the test load the compressive strain over the central portion of the plate averaged about -0.00015 in./in. A brittle fracture propagated across the entire specimen.

Prior to testing, the specimen was preloaded to determine the strain distribution across the plate at the test load; the strain distribution during preloading is shown in Fig. 8. Very little bending resulted from the welding of the specimen to the pull plates and the plotted values in Fig. 8 are representative of the strain distribution measured on each face of the plate.

The initial strain distribution shown in Fig. 8 was recorded after the notches for fracture initiation had been sawed in the edges of the plate; this strain distribution differs only slightly from that measured immediately after welding the slots but before the notches were cut, as shown in Fig. 7.

In Fig. 9 it may be seen that the load-strain behavior of each gage during preloading, was nearly linear, and that the permanent strain following unloading was negligible.

The instrumentation layout and crack path are shown in Fig. 10. The strain-time traces of the dynamic gages recorded during the fracture process and the breaking times of the crack detectors are presented in Fig. 11. All strain-time traces were plotted with the strain at zero time equal to the absolute test load strain as determined from the preloading. With several exceptions, the resulting records were similar to those of nonprestrained plates (1). The strain response 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. However, the trace of gage 3 did not return to the zero strain level based on the as-rolled condition; this suggests that the initial test load strain of the gage was somewhat in error. This could easily have occurred because the gage was located at a point on the surface where the strain gradient was extremely steep. The traces of gages 1, 2 and 4, which were in the center of the compressive strain region, peaked sharply but relaxed 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.

Gage 5, at the far edge of the compressive strain region, behaved in a different manner, i.e., taking one millisecond to reach one-half of the maximum peak strain, peaking sharply to the maximum strain value, and then relaxing to its final strain level 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.

Apparently, the compressive strain field decreased the magnitude of the strain peaks (in comparison to results found in previous tests) in addition to decreasing the speed of the fracture as is noted later. The peak magnitude may be a function of the fracture speed, i.e., a lower fracture speed may cause a lower peak strain magnitude. In earlier tests on this program there was no consistent correlation noted between fracture speed and peak strain magnitude; however, the fracture speed range in the earlier tests was much higher.

The fracture speed as determined by crack detectors and strain gage peaks was lower than any previously recorded. Between detectors A and B, and B and C, the fracture speed was 950 fps and 1600 fps, respectively. The fracture speed decreased to 450 fps 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 gages were 400 fps, 450 fps and 1100 fps between strain gages 3 and 4, 4 and 5, and 1 and 2, respectively. All of these fracture speeds (with the exception of the 1600 fps value) are well below any of those previously recorded as a part of this program.

The fracture surface may be seen in Fig. 12. The appearance was not noticeably different than that observed in other plain plate tests. In general, the fracture texture was fairly smooth although the texture was slightly more coarse at the edges than in the central compressive region. Thus the slower fracture speeds were recorded in a region of finer crack texture.

The reduction in plate thickness was on the order of 1 to 2 per cent and corresponds to the reduction in thickness found in the nonprestrained plates tested earlier in this investigation. The fracture passed close to, but slightly below, all strain gages as may be seen in Fig. 13.

B. Test 41

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. 7). The specimen was tested with an average net applied stress of 2000 psi, at a temperature of -9 deg. 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 compressive strain in the central region of the plate, and (b) to verify that a brittle fracture could be initiated in a region of high residual tensile strain.

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. 14 and 15. The change in direction of the fracture as it neared the compressive 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. 15 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 is shown in Fig. 16 and the strain-time traces are presented in Fig. 17. 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 other dynamic strain gages mounted on the specimen exhibited behavior similar to that noted in crack arrestor tests (Project SR-134), i.e., as the fracture speed decreased and the fracture was arrested (at approximately 1/2 millisecond) there was a redistribution of strain. This redistribution may be seen clearly in Fig. 17.

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 removed, are shown in Fig. 18. The initial and final strain distributions were determined from the 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 is reasonable since 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. 18 and agree quite well with the strain distribution as determined by the static gages.

The longitudinal and transverse strain distribution measured along the vertical center line of the specimen is shown in Fig. 19. Initially, the transverse strain was 20 to 32 per cent of the longitudinal strain and of opposite sense. After the plate had partially fractured, the static strain distribution had changed markedly. Actually, a symmetrical uniaxial strain distribution was not present before or after testing and thus there is no reason to expect a fixed ratio between strains as they were recorded.

As a result of the partial fracture the load dropped from 32,000 lb to 19,700 lb. The measured strain distribution correlates poorly with the theoretical strain distribution for the cracked plate; however, this poor agreement should be expected because of the marked alteration of the residual strain field.

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 Test 41. 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 per cent; in the region of the submerged crack the reduction in plate thickness was about 2 to 4 per cent.

C. Test 42

Test 42, the last of this series of tests, was essentially a duplicate of Test 41, with the exception that the length of the slots was increased from 6 in. to 7 in. The results were quite similar to those of Test 41.

The specimen was tested with an average net applied stress of 2000 psi, at a temperature of -5 deg. 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 stopped in the compressive region. The length and appearance of the fracture were similar to that of the fracture occurring in Test 41. Figures 20 and 21 show the specimen and a closeup of the fracture region. The small arrows on the photographs (9 in. 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 beneath detector B.

Figure 22 shows the instrumentation layout and the location of the fracture. Seven channels of strain and one channel of detectors were recorded. The strain-time records are presented in Fig. 23. It will be noted that the strain-time records for Tests 41 and 42 are essentially identical. Gages located in the fractured region (Gages 1 and 6) exhibited the usual response of vertically oriented gages. The other dynamic gages show the effect of strain redistribution which started during or after fracture arrest. The load dropped from 32,000 to 20,200 lb during the test. The final strain levels recorded by the dynamic gages about one-half second after fracture initiation are shown at the far edge of Fig. 23.

Immediately after the test the dynamic gages were connected as static gages and the final strain levels were recorded. These values are shown on Figs. 24 and 25. The initial and final strain distributions shown in Figs. 24 and 25 were determined by averaging the static SR-4 gage and 6-in. Berry gage readings. With the exception of gage 5, there is good agreement between the final strain levels as shown in Fig. 23 and the strain levels determined statically as presented in Figs. 24 and 25. Similarly in this case, as in Test 41, it will be noted that the areas under the strain plot along the notch line measured after fracture do not balance; however, since the fracture path followed the notch line more closely than in Test 41, the tension and compression areas are in better agreement in Fig. 24.

The average fracture speed between detectors A and C (located 1-1/2 in. and 7-1/2 in. from the initiation edge) was 550 fps. The fracture passed beneath detector B but did not break it. This offers further evidence of the fact that the fracture process may be of a very discontinuous nature.

In both Tests 41 and 42 the fractures became submerged at the point on the specimens where the residual tension and compression strains were zero (about 6 in. from the initiation edge). The residual strain at the point where the fracture in Test 42 changed direction sharply was about -0.00085 in./in.

The reduction in plate thickness along the surface fracture was on the order of 1 to 2 per cent; in the region of the submerged crack the reduction in thickness was about 2 to 4 per cent. The surface texture of the fracture could not be seen but the low reduction in thickness and general appearance of the specimen surface indicate the fracture was similar to that found in complete fracture tests.

IV. PRACTICAL IMPLICATIONS

This investigation was of an exploratory nature and it is realized that three fracture tests by themselves provide extremely limited data from which to draw any conclusions. However, the investigation has demonstrated that under certain conditions a residual compressive strain field may constitute an effective crack arrestor; similarly, it 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 the plate was effective in reducing the applied stress at the notch required for fracture initiation.

Although the stress in the plates tested herein was of a uniaxial nature in so far as the applied load was concerned, it must be remembered that the welded slots introduced a biaxial strain field in the central portion of the plate. In the general case under such conditions there could be a high tensile strain at right angles to the compressive strain which could change the direction of propagation and conceivably provide the necessary conditions for continued propagation. In one particular test reported herein there was a tendency for the fracture to turn at right angles to the direction of major compression.

Nevertheless these tests suggest there is a possibility 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. The compressive strain regions could be produced by welding, as was done in these tests, or perhaps by more conventional devices, for example prestressing rods or cables. The method used would depend largely on the type or nature of the structure, and the magnitude, extent and direction of the compressive prestrain desired, as well as a consideration of any induced tensile strains.

V. SUMMARY

The object of the tests reported in this paper was twofold, namely, (a) to investigate methods for producing a residual compressive strain field in the central portion of a two-foot wide steel plate, and (b) to study the propagation of brittle fractures in such plates.

Three methods of obtaining the desired residual compressive strain field in the central portion of the plate were considered, although only two methods were actually investigated. The first method consisted of flame heating and water quenching wedge-shaped areas along both edges of the plate. A high compressive strain was obtained in the central portion of the specimen by heating the edges, but the compressive strain field was not considered to be satisfactory as regards shape and extent. The second method consisted of welding tapered slots cut perpendicular to the edges of the plate. The welding of these slots produced a fairly uniform compressive strain in the central region of the specimen. Since the specimens prepared by the method of welding tapered slots proved satisfactory for this investigation, no specimens were prepared using the third method under consideration, namely the welding of prestressed plate elements.

Brittle fracture tests were conducted on three specimens prepared by the method of welding tapered slots. The specimens, tested at a relatively low applied stress, were cooled prior to testing and the fractures initiated at an edge notch by the notch-wedge-impact method of fracture initiation. The specimens were instrumented to provide a record of strain response and crack speed while the fracture was propagating. The results of the three brittle fracture tests may be summarized as follows:

1) In all three tests, and particularly in the last two tests, a low applied stress was used. Thus, it appears that a high tensile residual strain of yield point magnitude at the edge of a two-foot 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 two-foot wide plain plates, in which an applied stress of about 15,000 psi was necessary for fracture initiation.

2) The residual compressive 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 compressive strain field of low magnitude (-.00015 in./in.); in the other two tests, the brittle fracture was arrested as it entered the compressive strain field of higher magnitude (average compressive strain of -0.00060 and -0.00075 in./in., respectively).

3) Vertically oriented strain gages in the tensile strain region exhibited a strain response similar to that observed in plain plate tests, i.e., as the fracture propagated past the gage the strain trace peaked sharply and then relaxed immediately.

4) The response of a vertically oriented strain gage located in the compressive strain region exhibited very little change in strain until after the fracture reached about the center of the high tensile strain region. At that time, the strain trace generally exhibited a relaxation of compression as the fracture continued to propagate through the tensile strain region. If the fracture propagated by the gage located in the compressive strain region, the gage trace exhibited the usual peak; if the fracture arrested in the compressive

strain field and did not pass by the gage, the gage trace continued to show a relaxation of compression (associated with a redistribution of the load strain and the residual strains) and then leveled out at the final strain value. The final strain levels of the dynamic gages depended upon the relaxation of the residual strain field caused by the fracture propagating through a portion of the plate and to a lesser extent the small eccentric load on the remaining net section.

5) The reductions in plate thickness in the completely fractured and arrest regions were on the order of 1 to 2 per cent, and 3 to 4 per cent, respectively.

6) In Test 41, a surface fracture occurred in the region where the fracture arrested, i.e., the surface appeared to have fractured intermittently as the crack front propagated across the specimen. In Test 42 the fracture broke the first and third detectors without breaking the second detector, further attesting to the fact that the surface fracture may propagate across a plate in a discontinuous manner.

Although the investigation was of an exploratory nature, and of very limited extent, the results of the investigation suggest there possibly may be some practical implications with respect to the design of structures as discussed in Section IV.

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2. Wilson, W. M., Hechtman, R. A., and Bruckner, W. H., "Cleavage Fractures of Ship Plates," University of Illinois, Engineering Experiment Station Bulletin No. 388, 95 pp. (1951).

3. Lazar, R., and Hall, W. J., "Studies of Brittle Fracture Propagation in Six-Foot Wide Structural Steel Plates," Technical Report for the Ship Structure Committee under the Bureau of Ships, U. S. Navy, Contract NObs 65790, Civil Engineering Studies, Structural Research Series No. 136, University of Illinois, June 1957.

4. Hall, W. J., Mosborg, R. J., and McDonald, V. J., "Brittle Fracture Propagation in Wide Steel Plates," The Welding Journal, 36 (1), Research Supplement, pp. 1-s to 8-s (1957).

TABLE 1

RESULTS OF PREPARATION OF FLAME HEATED SPECIMENS

Specimen No. and Date of Preparation	Area Heated (See Fig. 3)	Residual Strain in Comp. Region (in./in.)	Approx. Width of Comp. Region (in.)	Remarks
1 28 March 1957	Arc along each edge 2 in. deep, 24 in. long	————	6	Non-uniform strain distribution as measured with Berry gage.
2 16 April 1957	10 'wedges' 4.5 in. deep, 5 per edge	-.0004 (Average)	8	Uniform strain distribution as measured with SR-4 strain gages. (See Fig. 4)
3 18 April 1957	4 'wedges' 6.6 in. deep, 2 per edge	-.0025 (Peak)	11	Same specimen as Test 2. Very steep strain gradient as measured with Berry gage. (See Fig. 4)

Note: Specimens 1, 2 and 3 were cut from plate 12A, a normalized and killed steel. (Fig. 1.)

TABLE 2

SUMMARY OF PREPARATION AND TEST CONDITIONS OF WELDED SPECIMENS

(All specimens 60 in. long, 24 in. wide, and 3/4 in. thick)
(E7016 electrodes were used in welding the tapered slots.)

Specimen No., (Test No.) and Date of Test	Type* of Steel	Length of Slots (in.)	Ave. Strain** across Comp. Region (in./in.)	Approx. Width Comp. Region (in.)	TEST CONDITIONS			Remarks
					Average Applied Stress (psi)	Net Strain across Center After Load Applied (in./in.)	Temp. (deg. F)	
4 (not tested) 16 May 57	Normalized and Killed	4.0	-.00035	12	Specimen not tested			Strain dist. in central region non-uniform.
5 (40) 25 June 57	Normalized and Killed	5.0	-.00045	10	12,000	-.00015	-32	Complete brittle fracture. Low fracture speed recorded.
6 (41) 26 July 57	Rimmed	6.0	-.00065	10	2,000	-.00060	-9	Initial load -- 32,000 lb. Final load -- 19,700 lb. 10-in. brittle fracture with last 4 in. of a submerged crack nature.
7 (42) 13 Aug. 57	Rimmed	7.0	-.00080	8	2,000	-.00075	-5	Initial load -- 32,000 lb. Final load -- 20,200 lb. Same type of fracture as Test 41.

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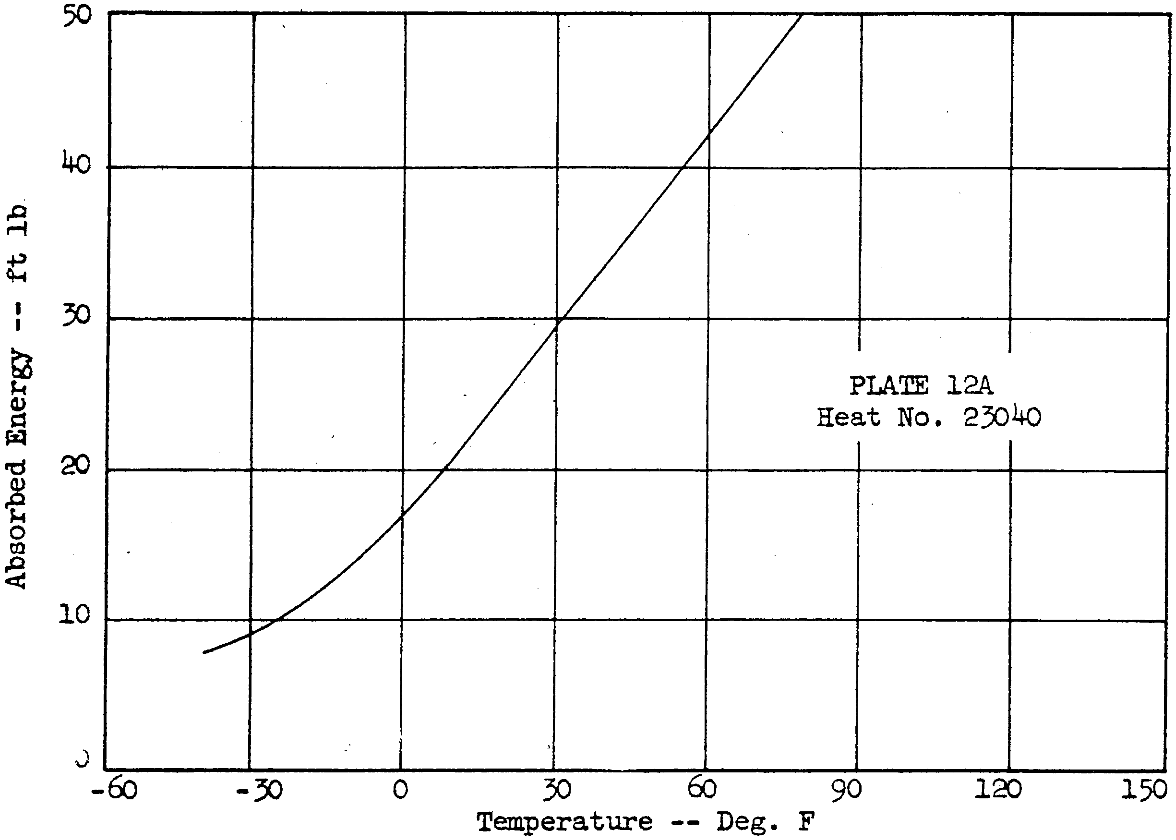
* See Figs. 1 and 2

** See Fig. 7



(a) Charpy V-Notch Curve

C	Mn	P	S	Si	Al	Ni	Cu	Cr
.19	.54	.011	.024	.19	.019	.15	.22	.12

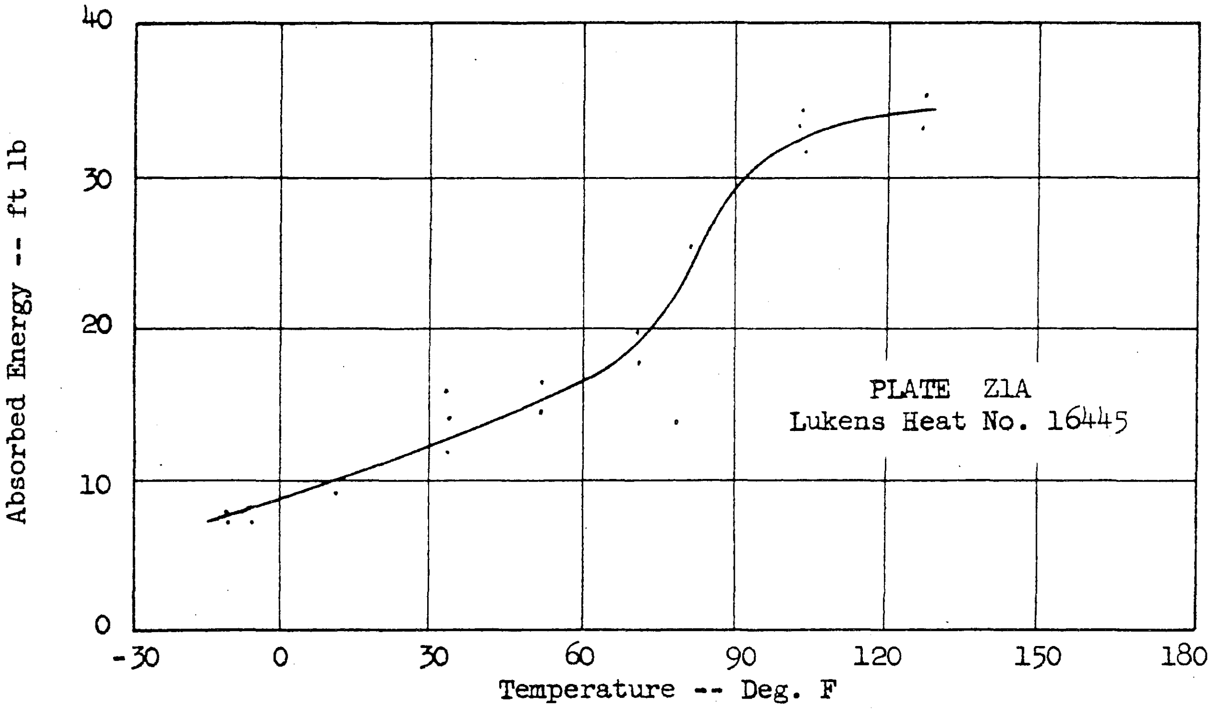
(b) Chemical Analysis -- per cent

Yield Strength (ksi)	Ultimate Strength (ksi)	Elongation in 2 in. (per cent)	Reduction in Area (per cent)
34.8	59.8	31.4	57.4

(c) Tensile Test Data -- 0.505 in. dia. specimen

Data taken from University of Illinois Experimental Station Bulletin No. 388 (2)

FIG. 1 PROPERTIES OF NORMALIZED AND KILLED STEEL



(a) Charpy V-Notch Curve

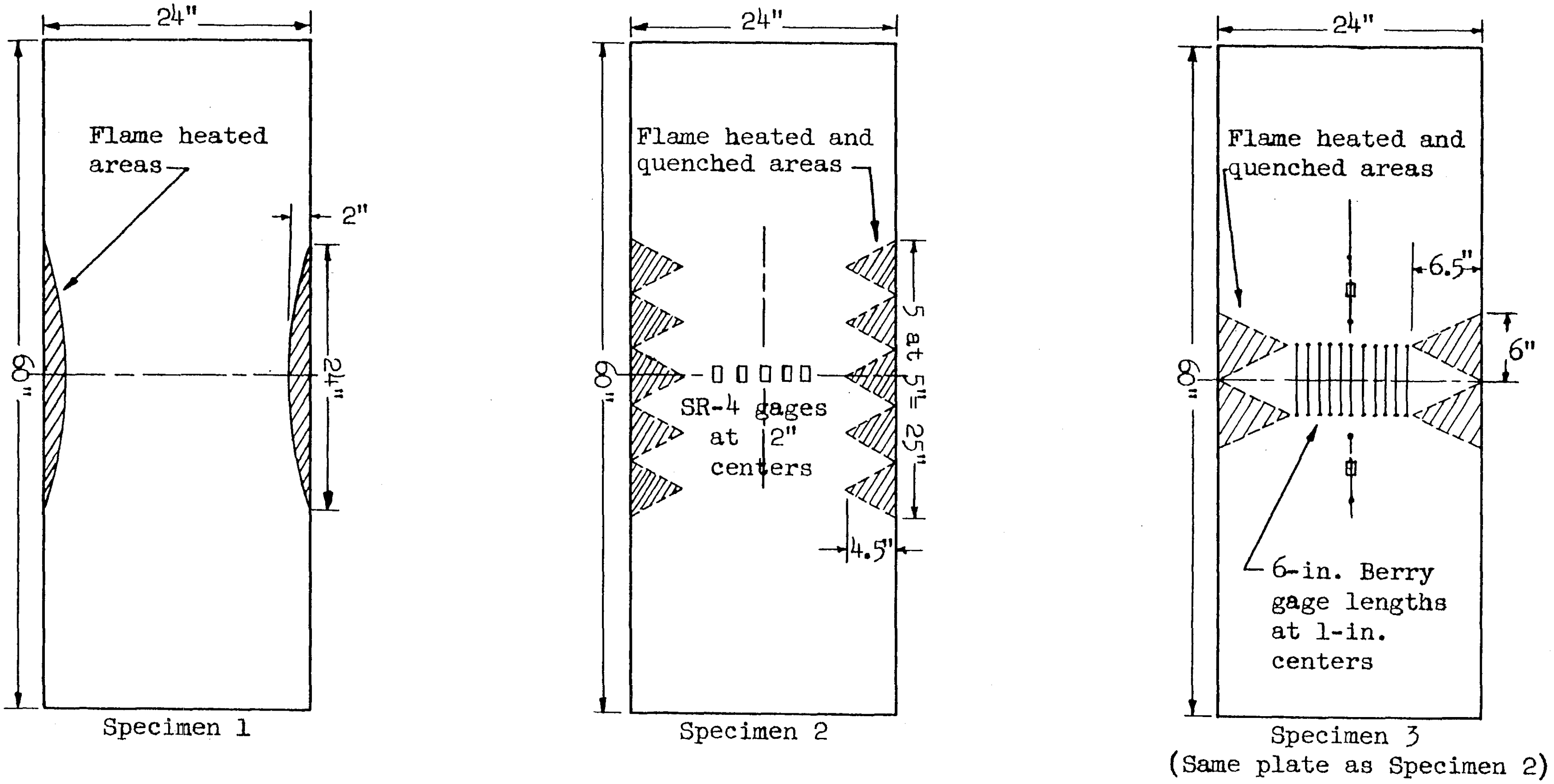
C	Mn	P	S	Si	Cu	Cr	Ni	Al
0.18	0.42	0.013	0.031	0.02	0.23	0.07	0.14	0.003

(b) Check Analysis -- per cent

Yield Strength (ksi)	Ultimate Strength (ksi)	Elongation in 2 in. (per cent)	Reduction in Area (per cent)
34.9	68.4	33.9	54.6

(c) Tensile Test Data -- 0.505 in. dia. specimen

FIG. 2 PROPERTIES OF RIMMED STEEL



Specimen 1

Specimen 2

Specimen 3
(Same plate as Specimen 2)

Notes: Both faces of each specimen identical as regards instrumentation and heating.
Central portion of each plate cooled with dry ice prior to and during heating period.

FIG. 3 FLAME HEATED AREAS AND INSTRUMENTATION LAYOUT -- SPECIMENS 1, 2, AND 3

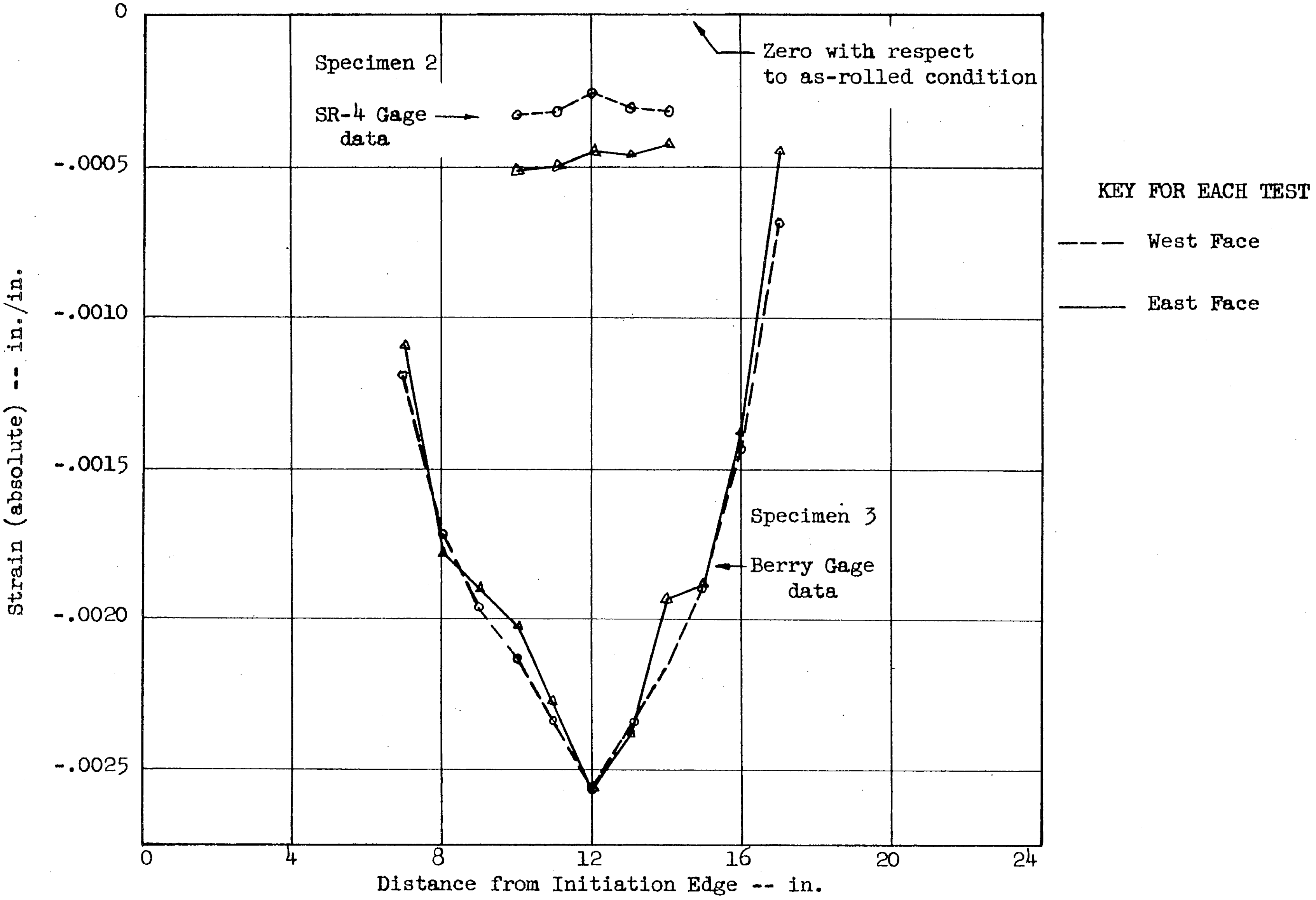
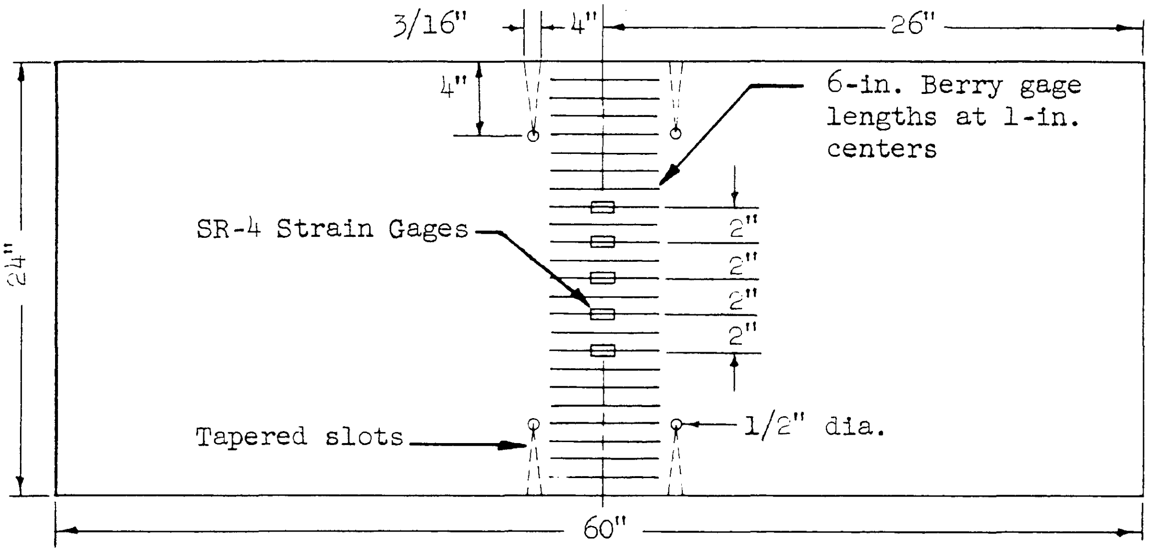


FIG. 4 STRAIN DISTRIBUTION AFTER FLAME HEATING AND WATER QUENCHING -- SPECIMENS 2 AND 3



NOTE: Instrumentation identical on both faces of specimen

FIG. 5 INSTRUMENTATION LAYOUT AND TAPERED SLOTS -- SPECIMEN 4

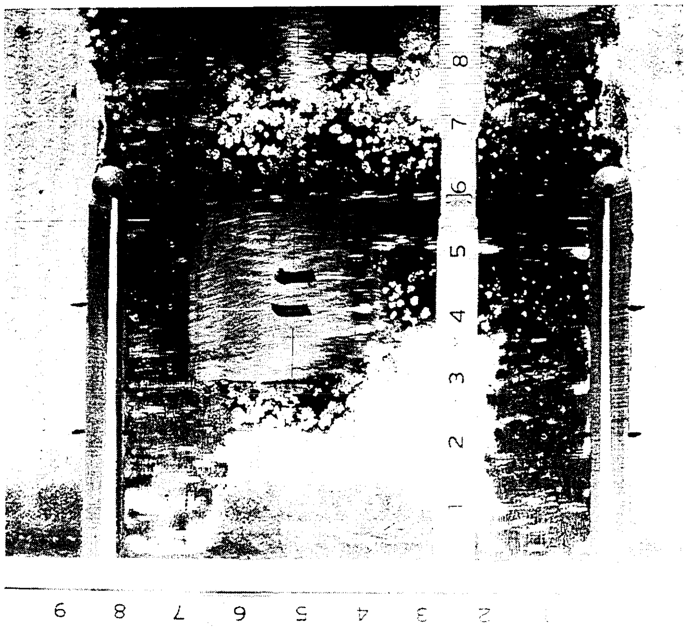


FIG. 6 CLOSEUP OF TAPERED SLOTS BEFORE WELDING -- SPECIMEN 6

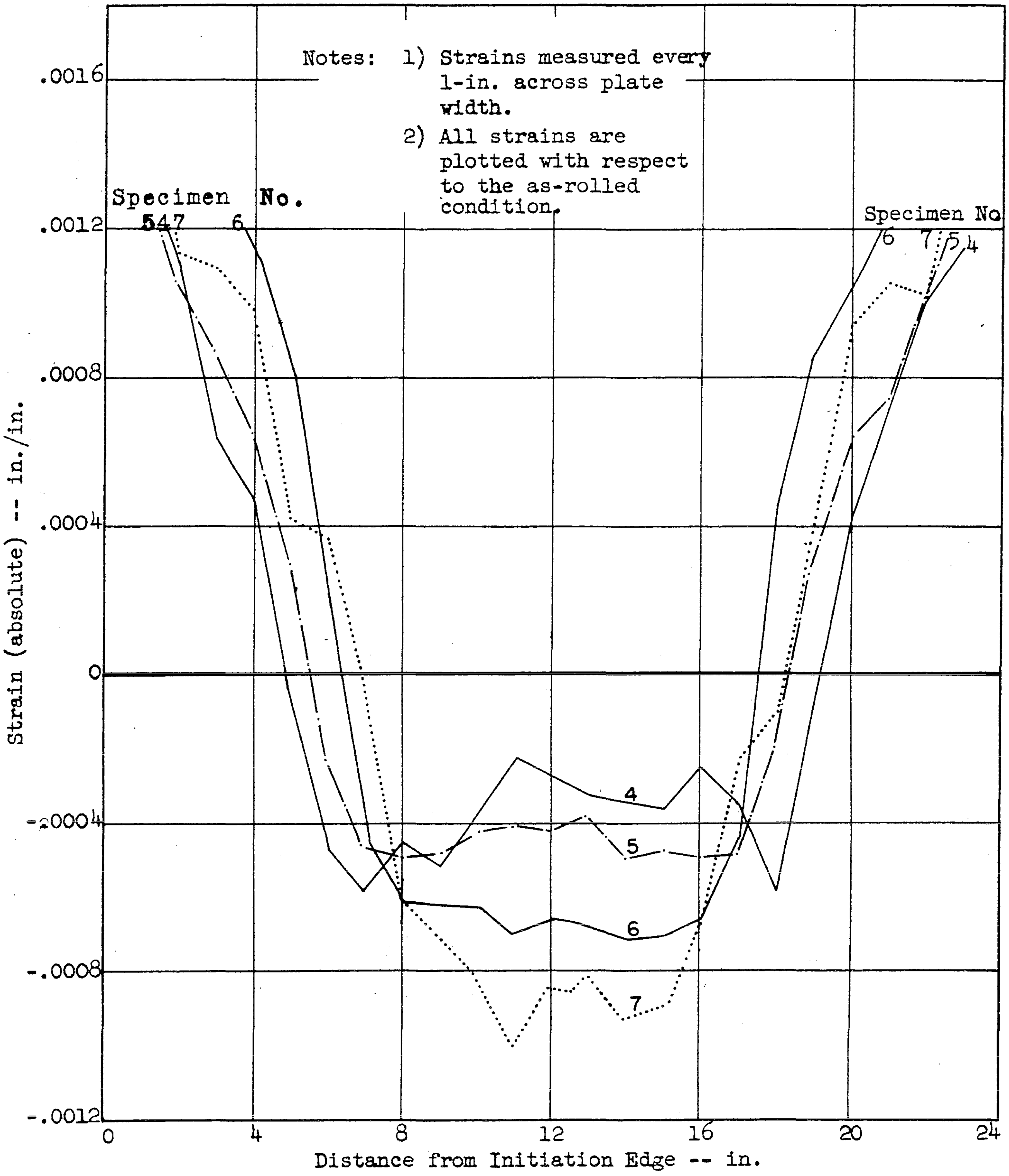


FIG. 7 AVERAGE LONGITUDINAL STRAIN DISTRIBUTION ACROSS PLATE AT NOTCH LINE AFTER THE TAPERED SLOTS WERE WELDED -- SPECIMENS 4, 5, 6, AND 7

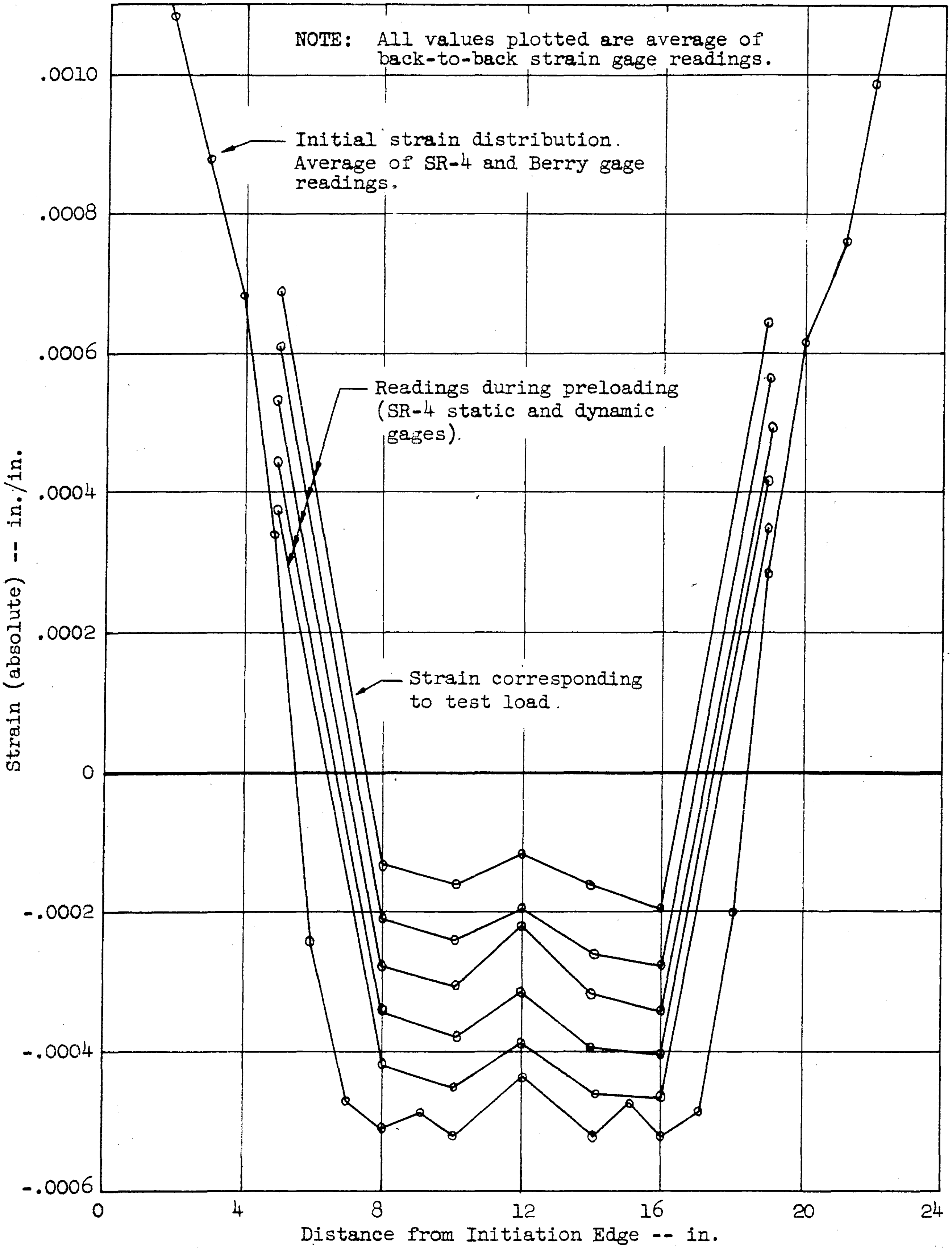


FIG. 8 AVERAGE LONGITUDINAL STRAIN DISTRIBUTION ACROSS PLATE AT NOTCH LINE DURING PRELOADING -- TEST 40

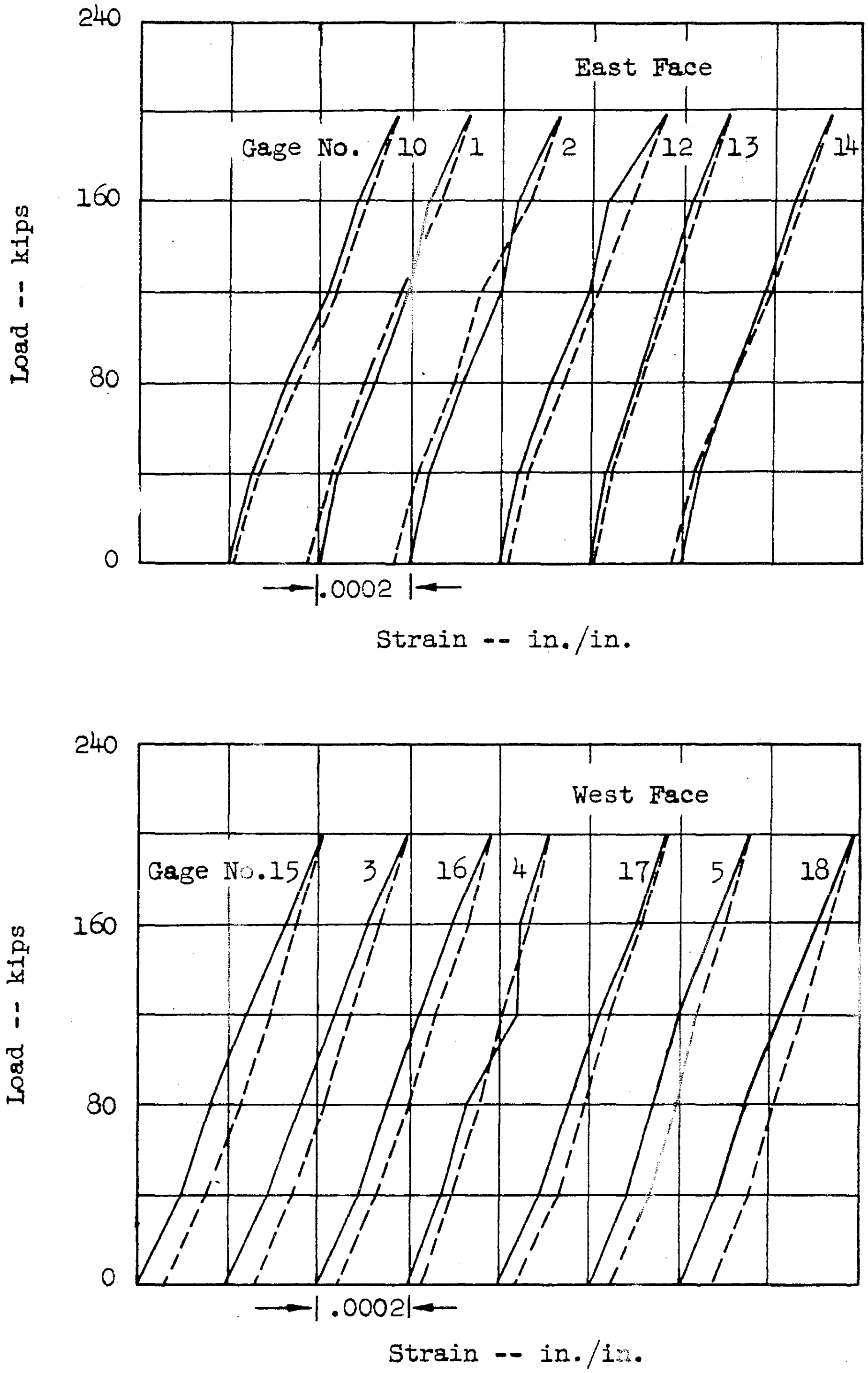
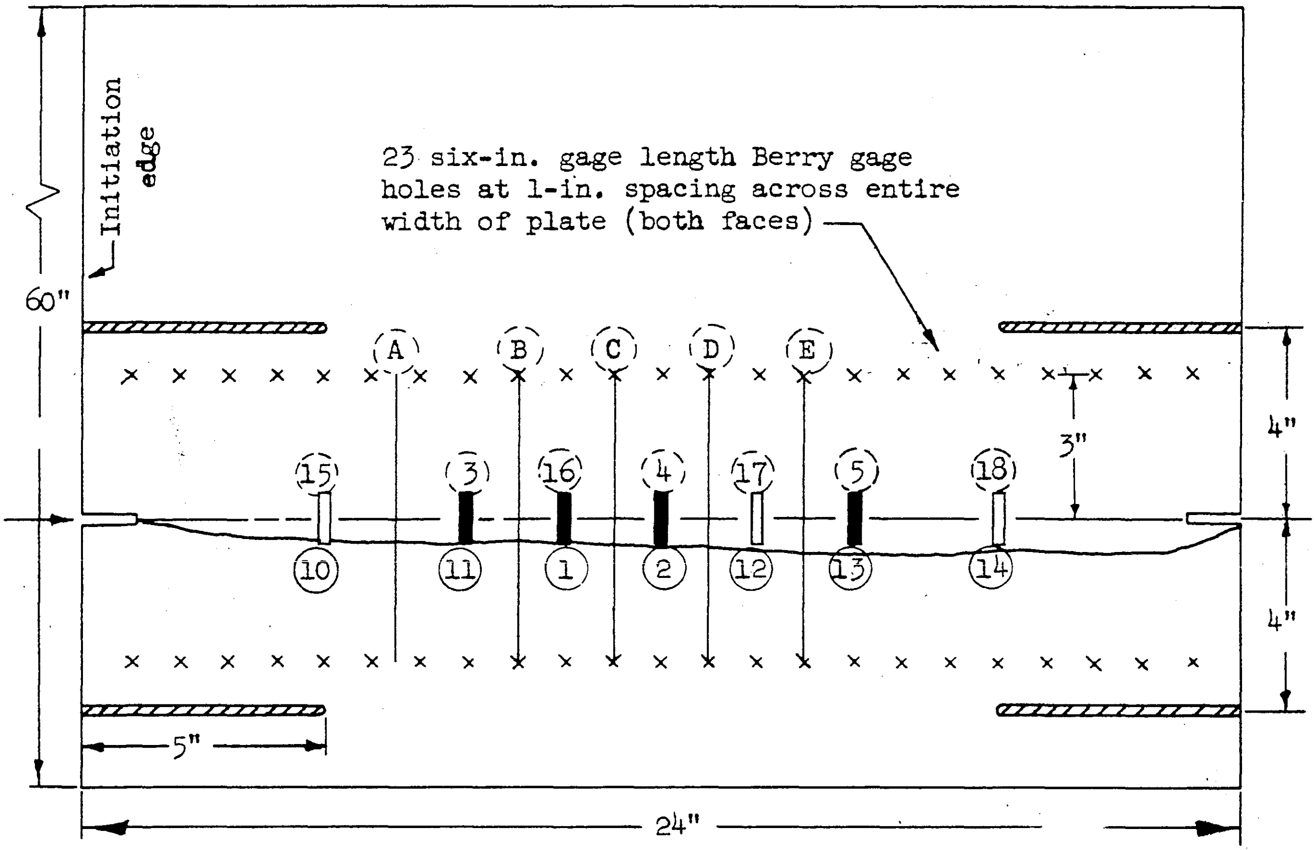


FIG. 9 LOAD VERSUS STRAIN DURING PRELOADING -- TEST 40



23 six-in. gage length Berry gage holes at 1-in. spacing across entire width of plate (both faces)

Detectors* |
(A-9)
A at 6.5"
B at 9.0"
C at 11.0"
D at 13.0"
E at 15.0"
(West Face)

Static Strain Gages* ▯
10 and 15 at 5.0"
11 at 8.0"
16 at 10.0"
12 and 17 at 14.0"
13 at 16.0"
14 and 18 at 19.0"
(E) (W)

Dynamic Strain Gages* ▮
East 1 at 10.0"
East 2 at 12.0"
West 3 at 8.0"
West 4 at 12.0"
West 5 at 16.0"

* All distances measured from initiation edge.

○ East Face

◌ West Face

FIG. 10 INSTRUMENTATION LAYOUT AND FRACTURE PATH -- TEST 40

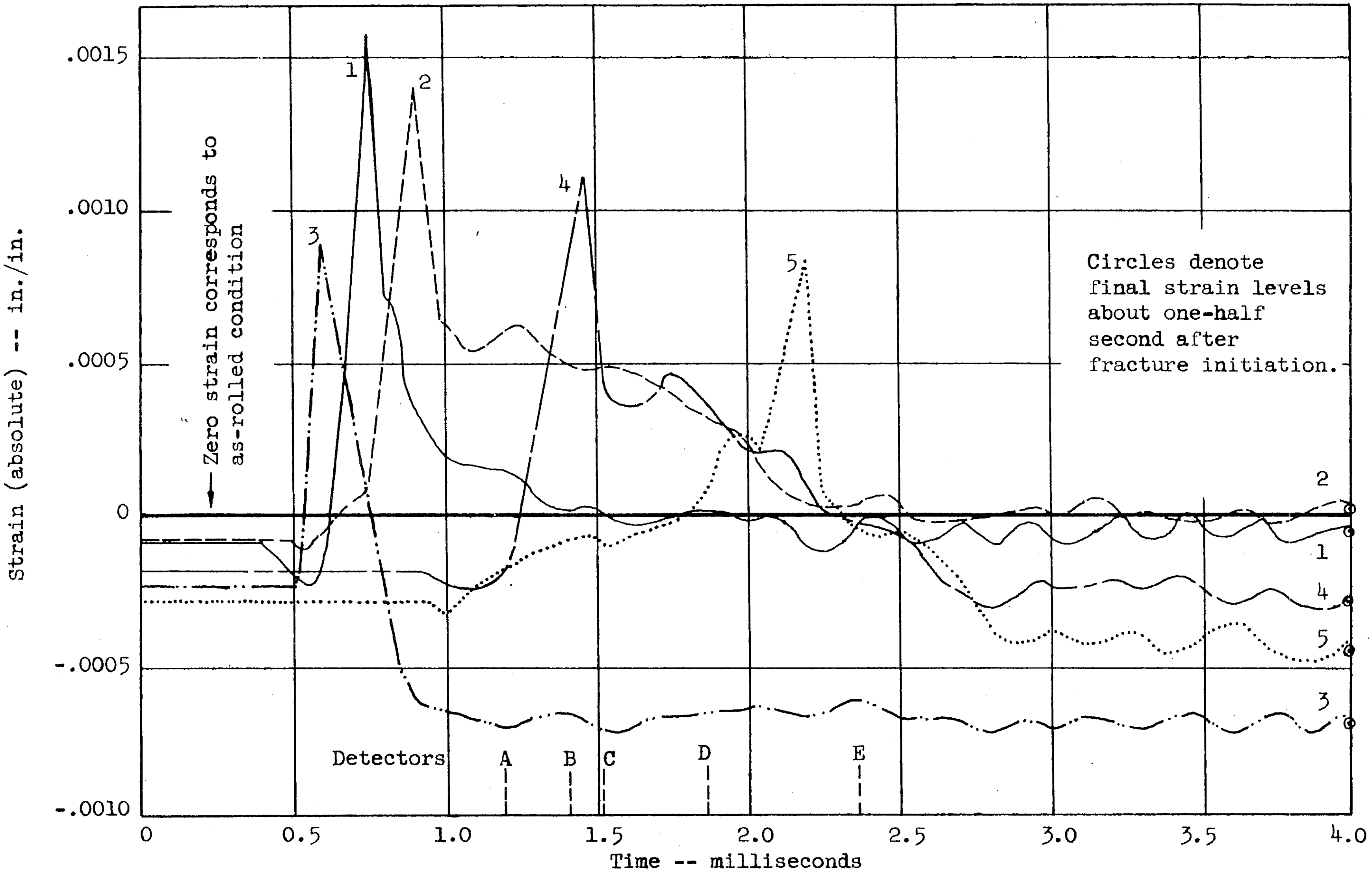


FIG. 11 STRAIN-TIME RECORD -- TEST 40

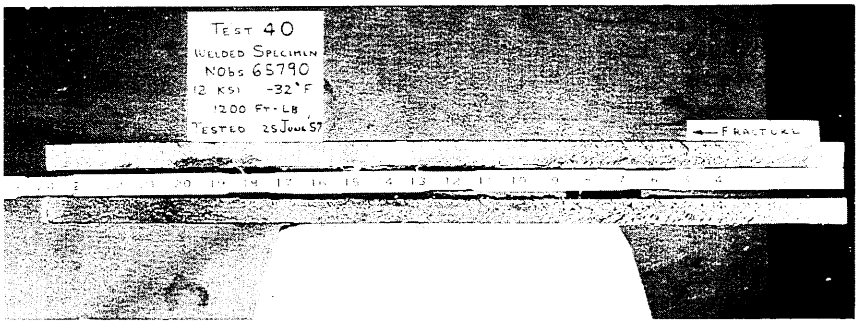


FIG. 12 FRACTURE SURFACE -- TEST 40

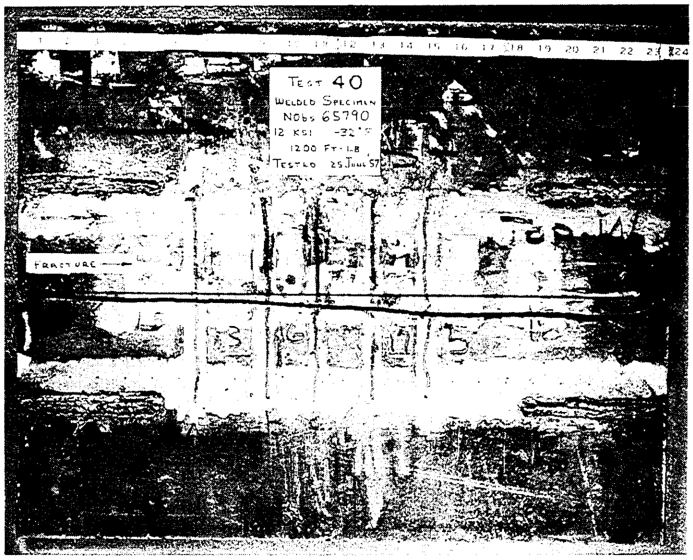


FIG. 13 FRACTURE PATH -- TEST 40

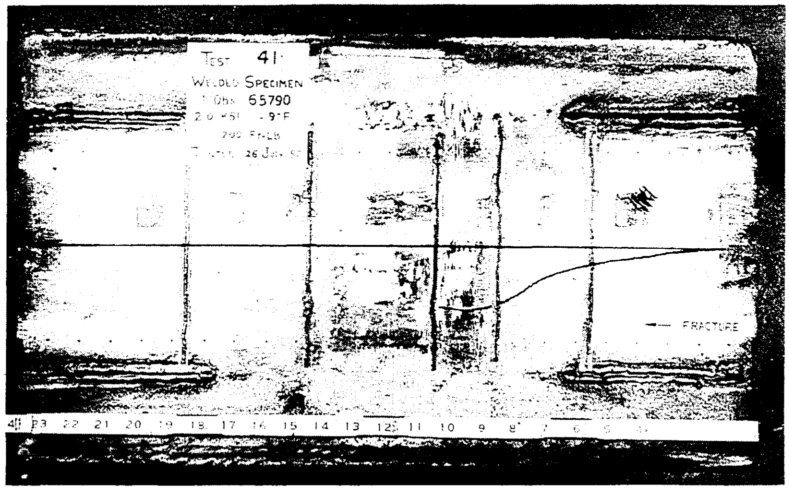


FIG. 14 FRACTURE PATH -- TEST 41

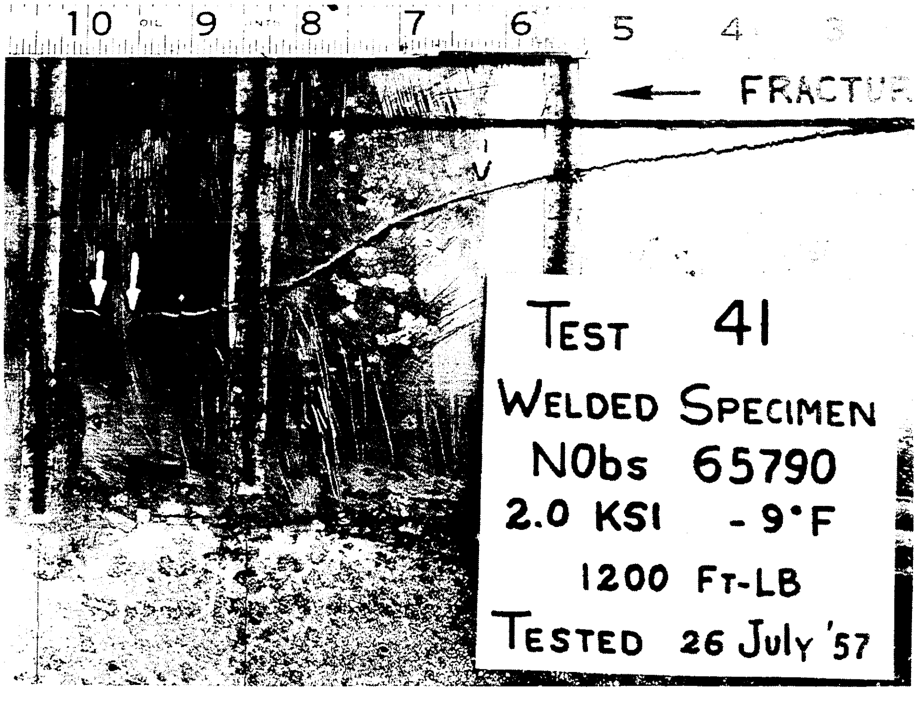
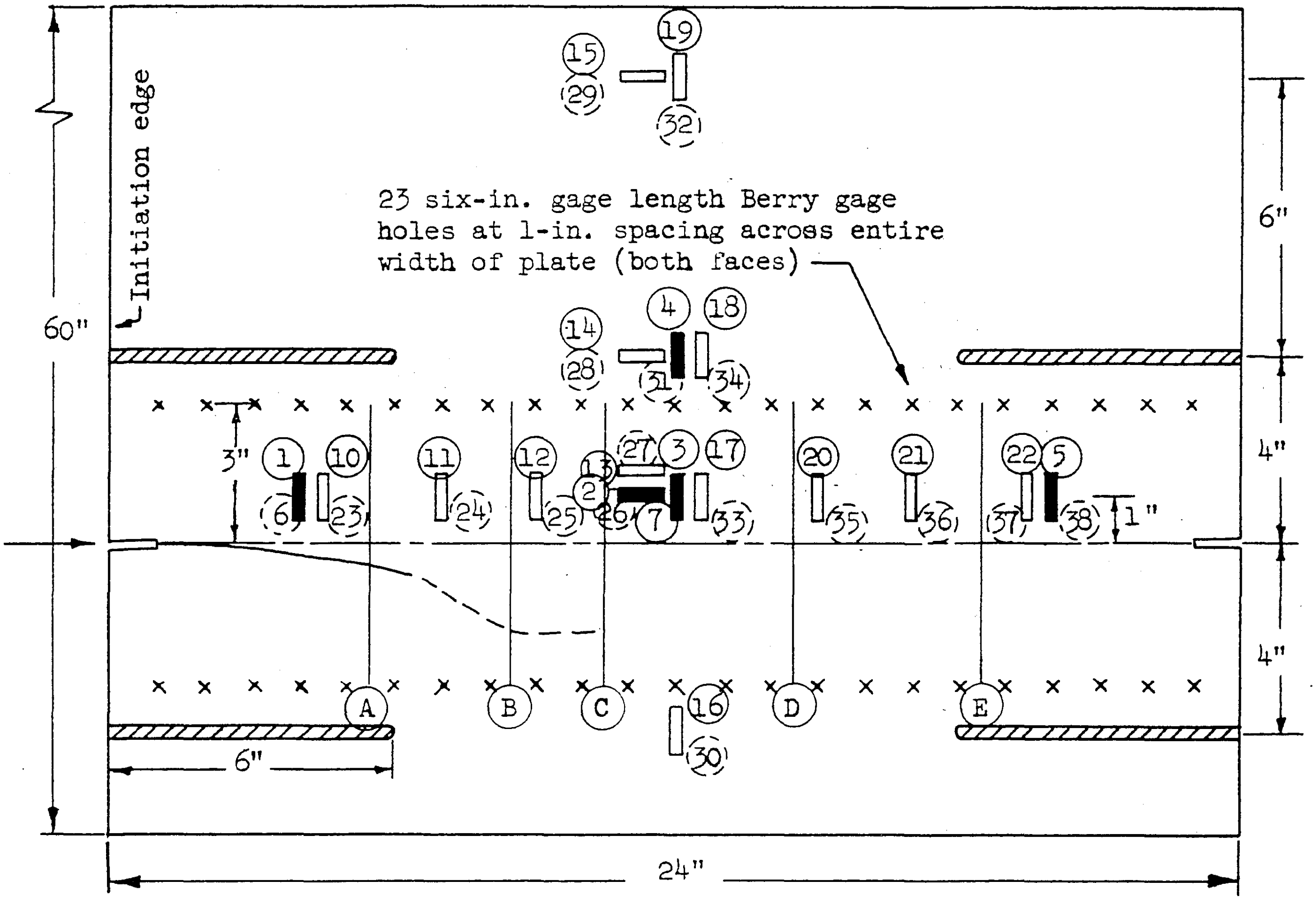


FIG. 15 CLOSEUP OF SUBMERGED FRACTURE REGION -- TEST 41



23 six-in. gage length Berry gage holes at 1-in. spacing across entire width of plate (both faces)

Detectors* | (A-9)

A	st	5.5"
B	at	8.5"
C	at	10.5"
D	at	14.5"
E	at	18.5"

(East Face)

Static Strain Gages* ▯

10	and	23	at	4.5"
11	and	24	at	7.0"
12	and	25	at	9.0"
		26	at	11.25"
13	and	27	at	11.25"
14	and	28	at	11.25"
15	and	29	at	11.25"
16	and	30	at	12.0"
		31	at	12.0"
19	and	32	at	12.0"
17	and	33	at	12.5"
18	and	34	at	12.5"
20	and	35	at	15.0"
21	and	36	at	17.0"
22	and	37	at	19.5"
		38	at	20.0"
(E)		(W)		

Dynamic Strain Gages* ▮

1 and 6	at	4.0"
2	at	11.25"
3 and 7	at	12.0"
4	at	12.0"
5	at	20.0"

○ East Face

◌ West Face

* All distances measured from initiation edge

FIG. 16 INSTRUMENTATION LAYOUT AND FRACTURE PATH -- TEST 41

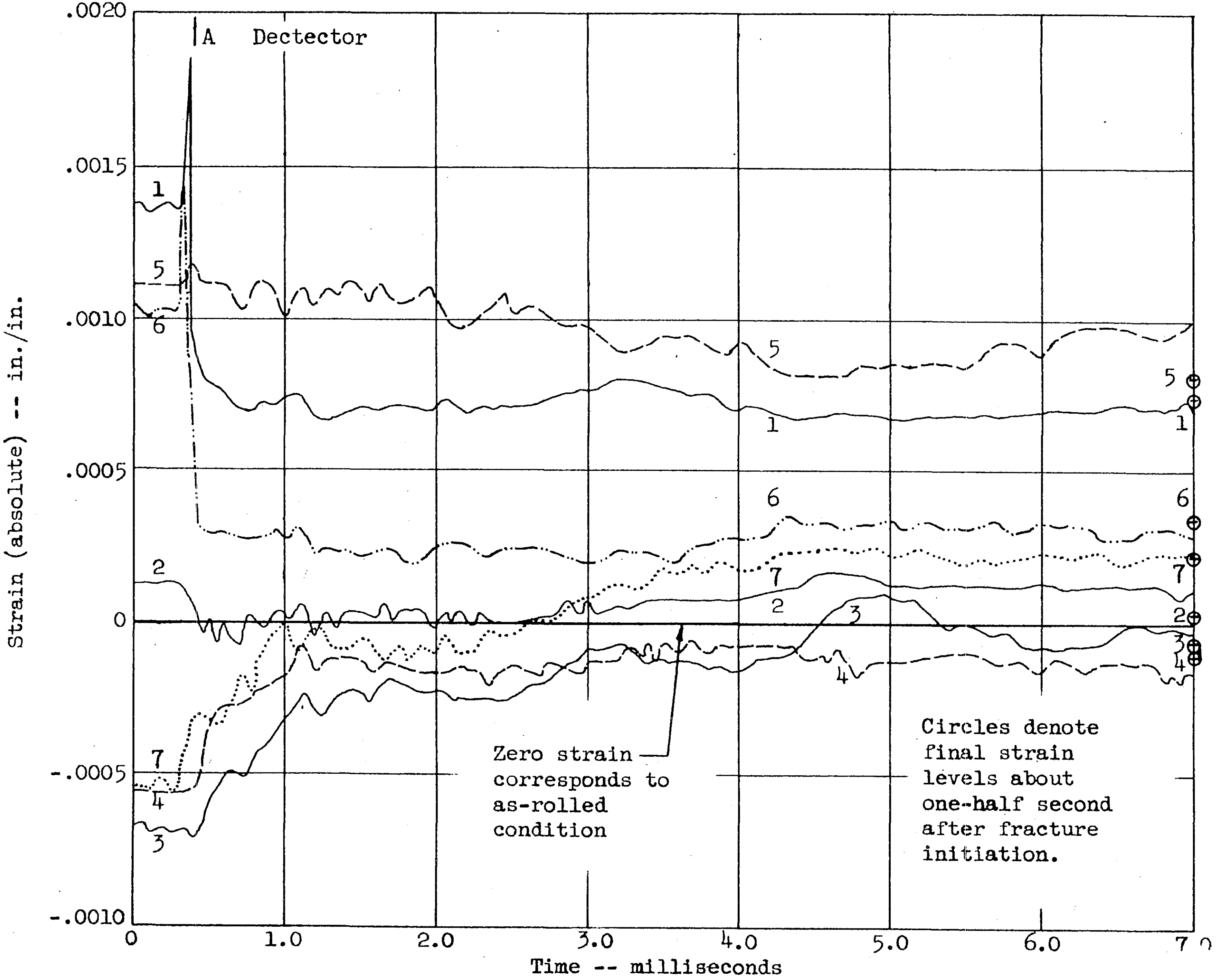


FIG. 17 STRAIN-TIME RECORD -- TEST 41

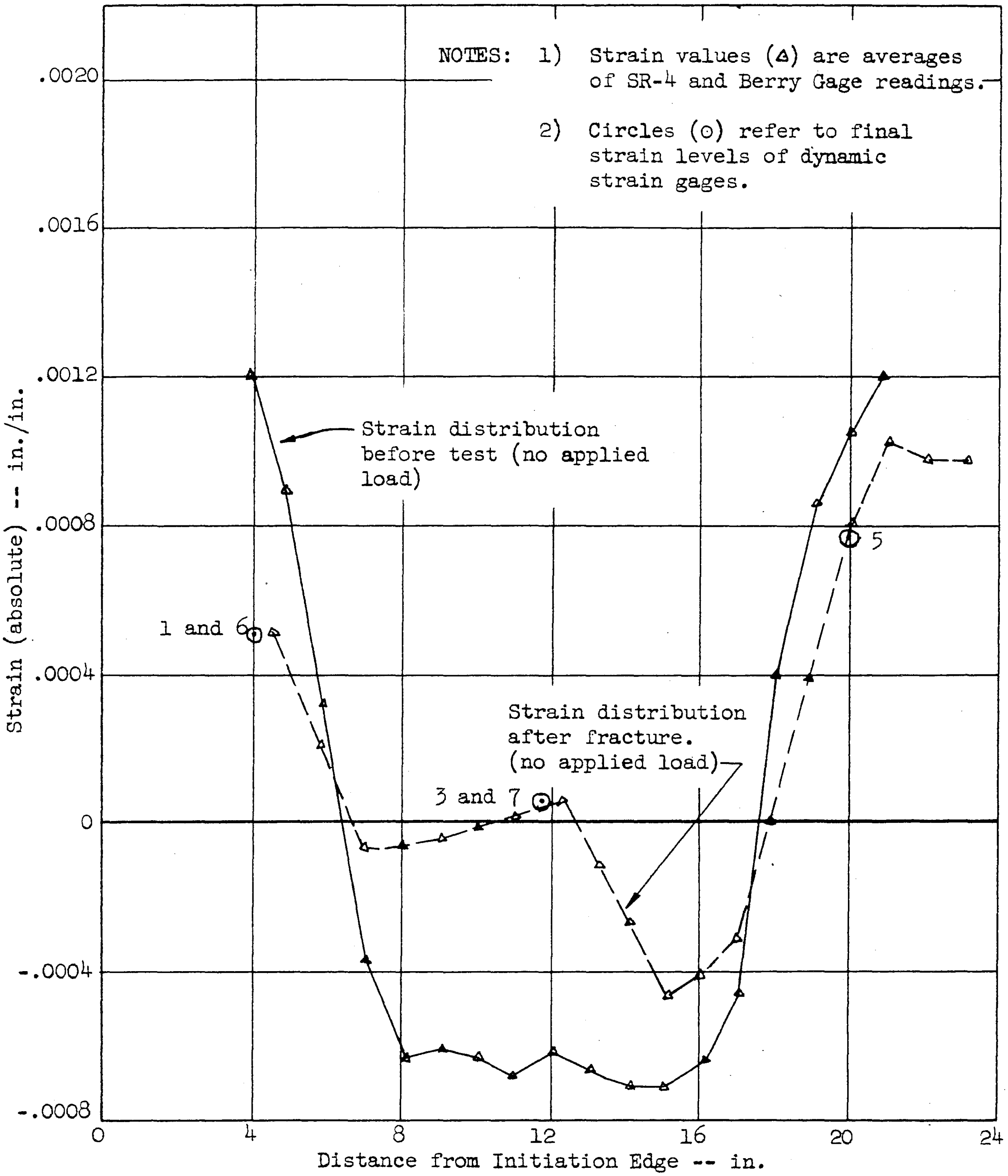
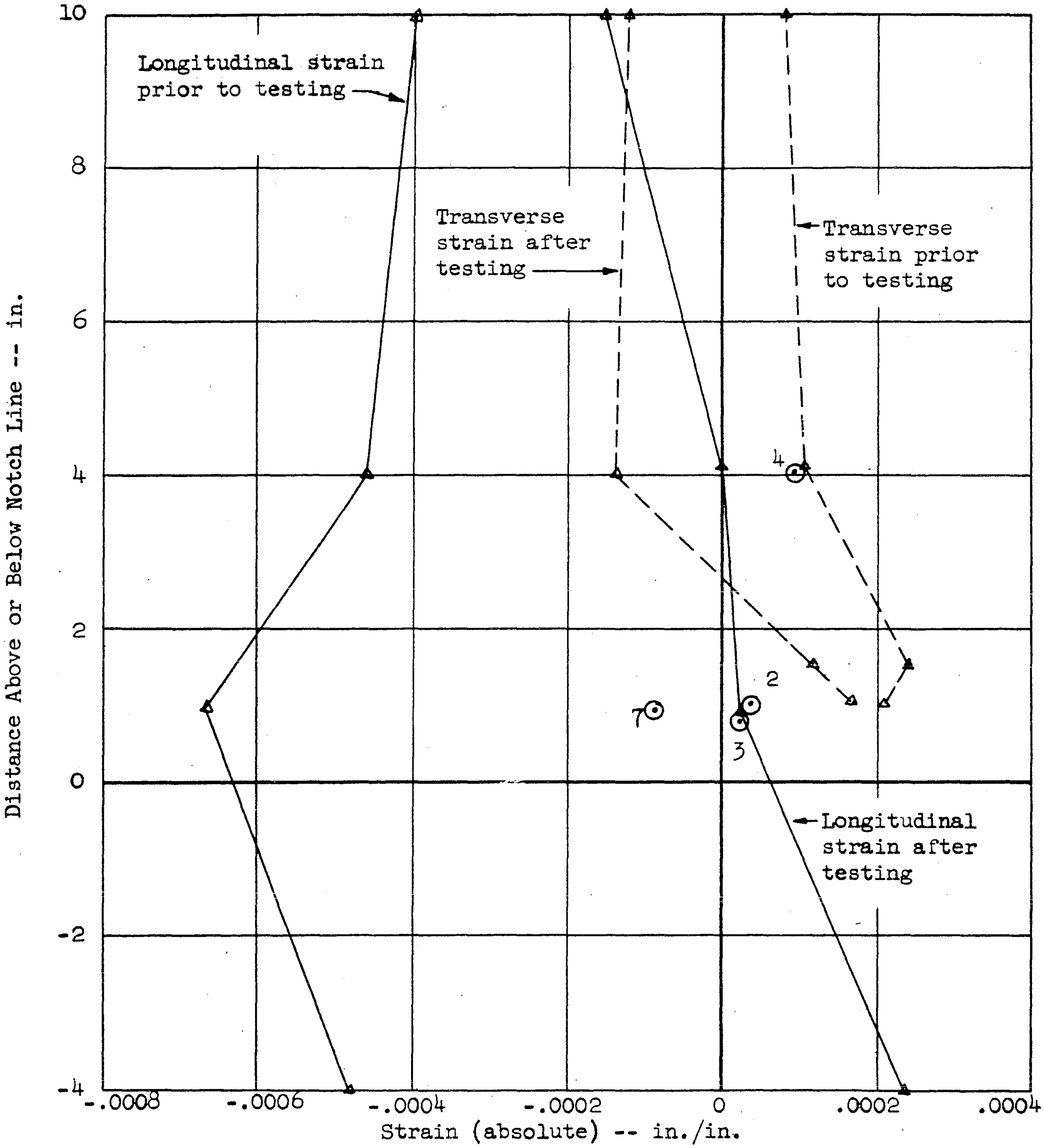


FIG. 18 AVERAGE LONGITUDINAL STRAIN DISTRIBUTION ACROSS PLATE AT NOTCH LINE -- TEST 41



Note: (1) Strain values (△) were taken with no applied load on the specimen and are average of back-to-back gages.

(2) Circles (⊙) refer to final strain levels of dynamic gages.

FIG. 19 AVERAGE STATIC STRAIN DISTRIBUTION ALONG VERTICAL CENTER-LINE OF SPECIMEN 6 (TEST 41)

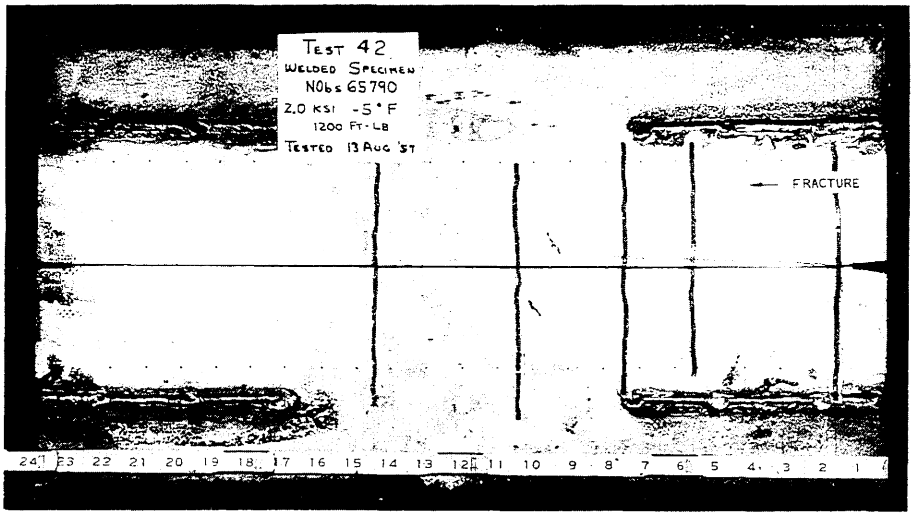


FIG. 20 FRACTURE PATH -- TEST 42

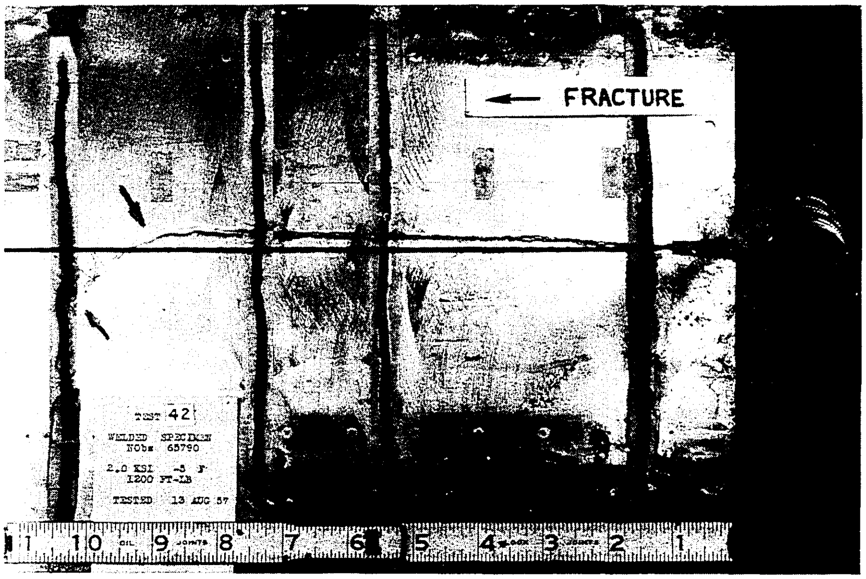
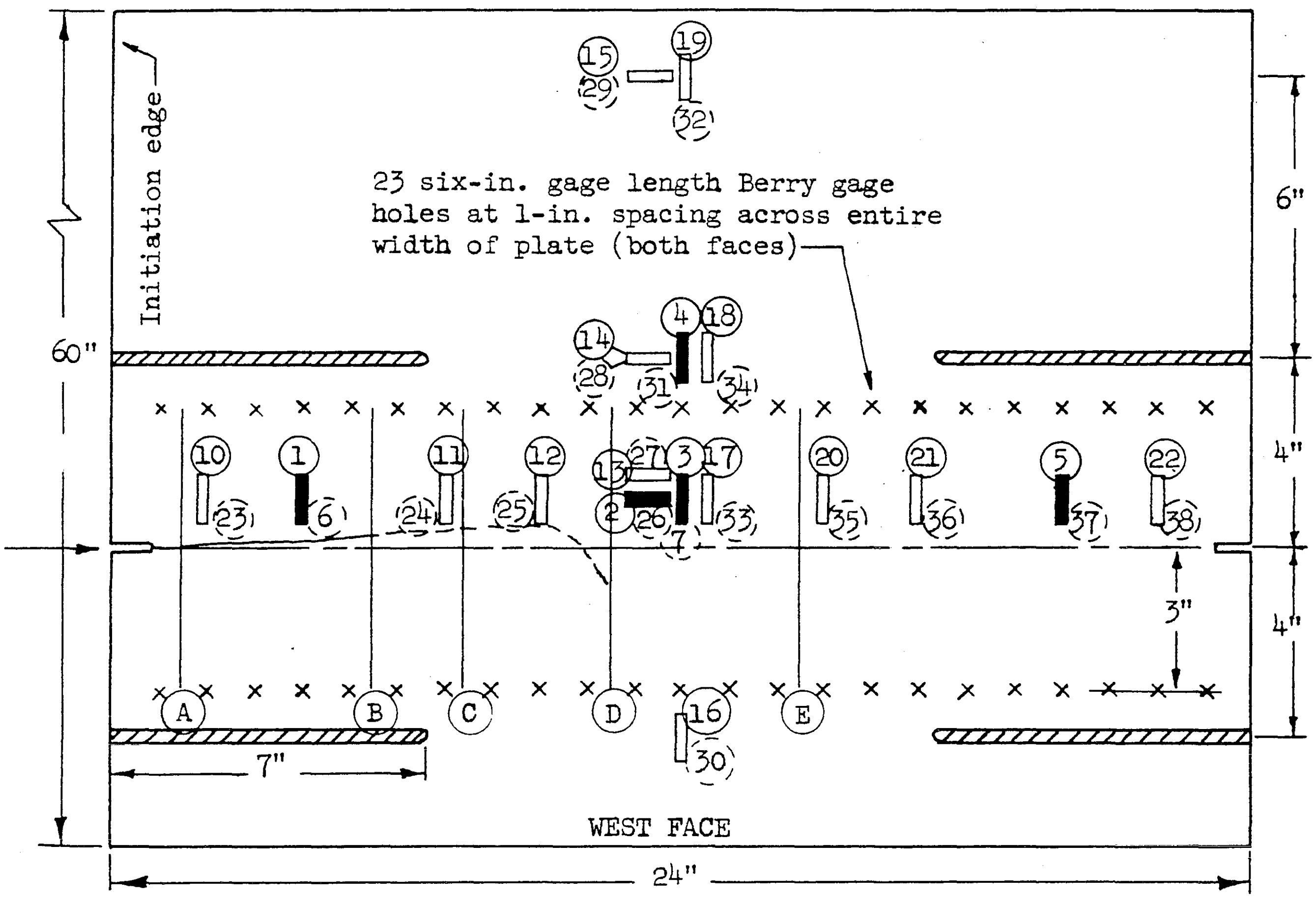


FIG. 21 CLOSEUP OF FRACTURE REGION -- TEST 42



23 six-in. gage length Berry gage holes at 1-in. spacing across entire width of plate (both faces)

Detectors* | (A-9)		
A	at	1.5"
B	at	5.5"
C	at	7.5"
D	at	10.5"
E	at	14.5"
(East Face)		

Static Strain Gages* ▯				
10	and	23	at	2.0"
11	and	24	at	7.0"
12	and	25	at	9.0"
		26	at	11.25"
13	and	27	at	11.25"
14	and	28	at	11.25"
15	and	29	at	11.25"
16	and	30	at	12.0"
		31	at	12.0"
19	and	32	at	12.0"
17	and	33	at	12.5"
18	and	34	at	12.5"
20	and	35	at	15.0"
21	and	36	at	17.0"
		37	at	20.0"
22	and	38	at	22.0"
(E)		(W)		

Dynamic Strain Gages* ▮		
1 and 6	at	4.0"
2	at	11.25"
3 and 7	at	12.0"
4	at	12.0"
5	at	20.0"

○ East Face

◌ West Face

* All distances measured from initiation edge

FIG. 22 INSTRUMENTATION LAYOUT AND FRACTURE PATH -- TEST 42

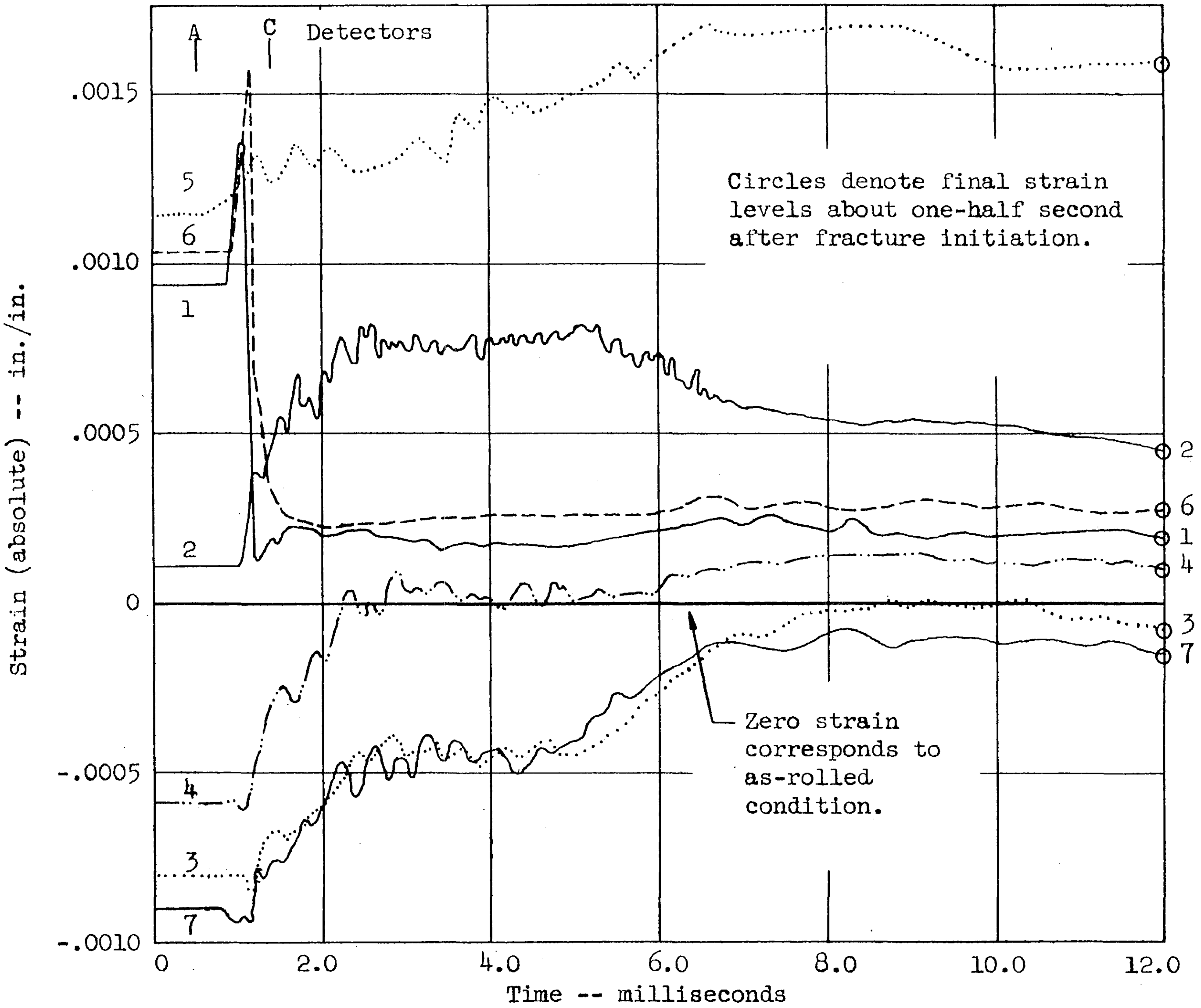


FIG. 23 STRAIN-TIME RECORD -- TEST 42

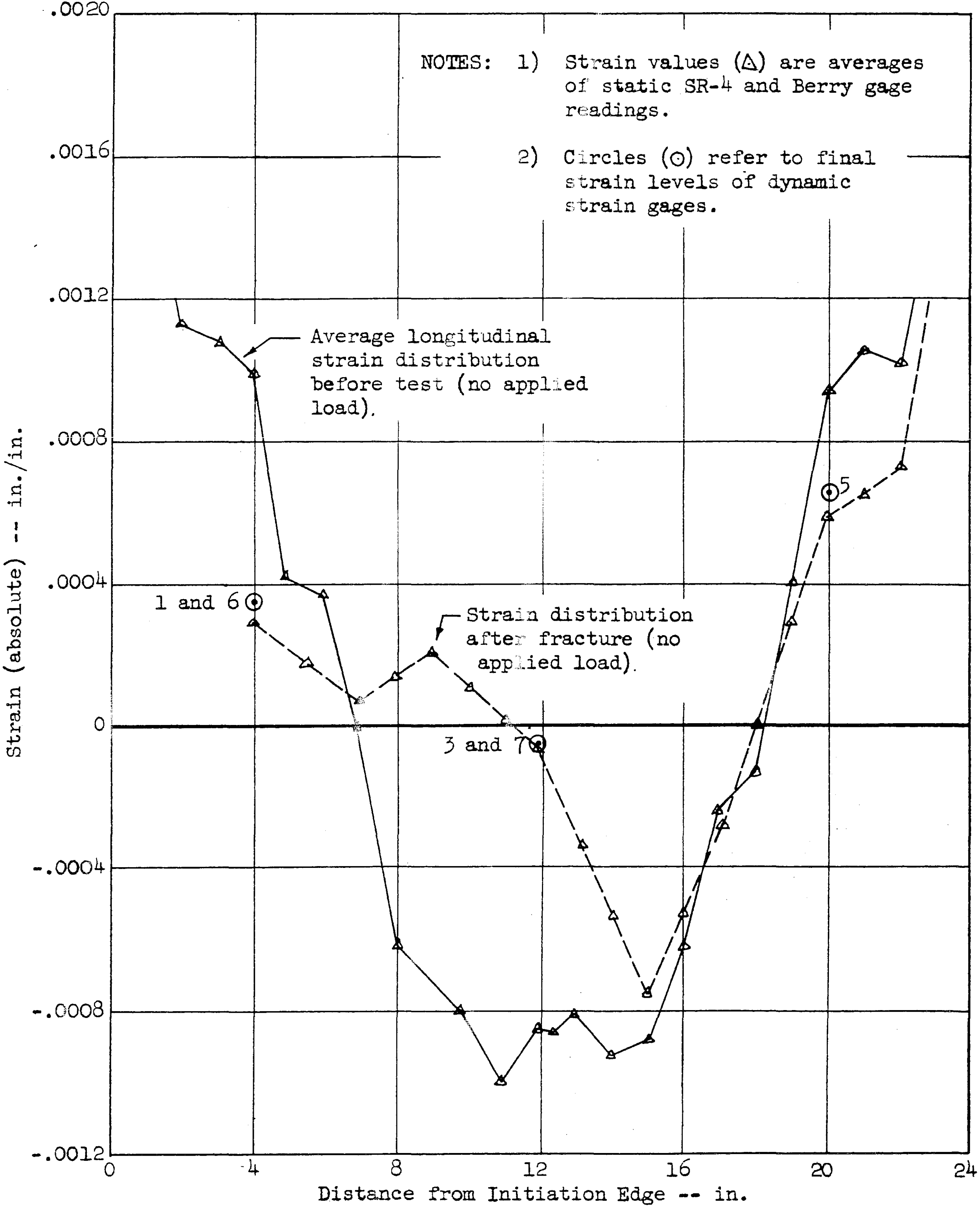
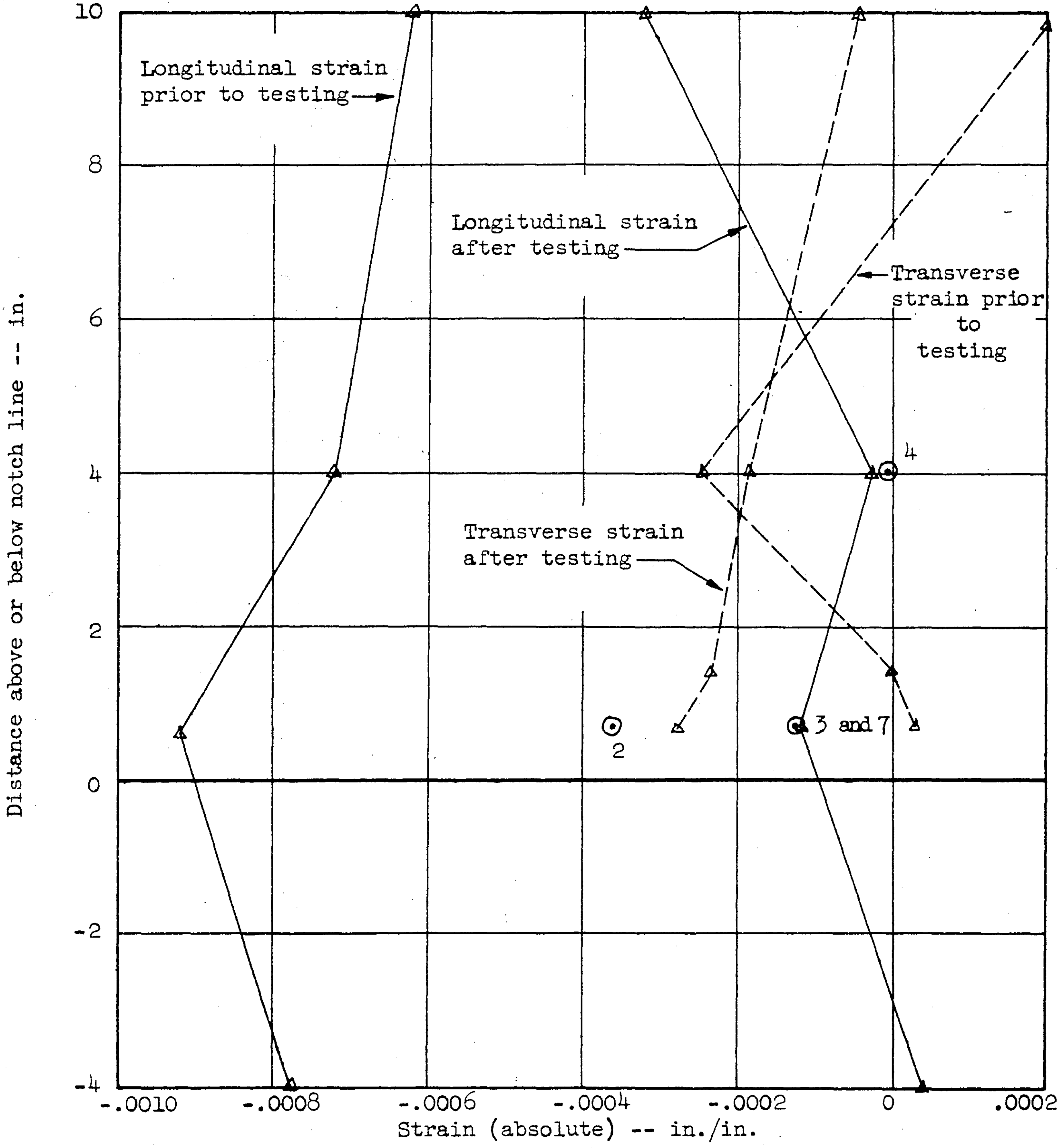


FIG. 24 AVERAGE LONGITUDINAL STRAIN DISTRIBUTION ACROSS PLATE AT NOTCH LINE -- TEST 42



Note: (1) Strain values (△) were taken with no applied load on the specimen and are average of back-to-back gages.

(2) Circles (⊙) refer to final strain levels of dynamic gages.

FIG. 25 AVERAGE STATIC STRAIN DISTRIBUTION ALONG VERTICAL CENTER-LINE OF SPECIMEN 7 (TEST 42)