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STUDIES OF BRITTLE FRACTURE PROPAGATION

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Final Report of Project SR-155
to the
SHIP STRUCTURE COMMITTEE
under the
BUREAU OF SHIPS, U.S. NAVY
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ABSTRACT

A summary of the most significant observations arising from experimental studies of brittle fracture propagation in wide steel plates conducted as a part of SSC Projects SR-137 (Fracture Mechanics) and SR-155 (Low Velocity Fracture) is presented in this report. In these studies three general types of wide plate specimens were employed in which measurements of crack speed and strain distribution were made during crack propagation.

Six-foot wide plain plate specimens were tested at an average applied stress of about 20 ksi, 0°F., and with the notch-wedge-impact method of initiation, in order to study fracture propagation under relatively steady state conditions; the fracture speeds in these tests were in the range of 2000 to 4000 fps and from recorded strain data it was possible to depict the surface strain field associated with the advancing fracture.

Six-foot wide prestressed steel plates with a region of high tensile residual strain at each edge, and a region of residual compression in the central portion, were tested at zero or 3 ksi average applied stress, at 0°F., and with impact initiation, to study low-velocity fracture propagation; fracture speeds of 6000 fps were recorded in the tensile zone near the initiation source, but speeds as low as 50 fps were recorded in the central portions of the plate. The change in the strain field associated with the propagating fracture as it traveled at these reduced speeds also was studied.

Two-foot wide centrally notched and welded specimens fabricated in different ways were utilized to study fracture propagation under conditions of static initiation and with fracture speeds of intermediate magnitude. A majority of these specimens fractured at an average applied stress of about 10 ksi and a temperature of -40°F; speeds within 1 1/2 inches of the initiation source, in a region of high residual tensile stress, were as high as 5000 fps whereas speeds

throughout the remainder of the specimen, which initially possessed a low compressive residual stress, were on the order of 1800 fps. A number of observations concerning fracture texture and the effects of thermal strain cycling, and notch geometry as they affect fracture initiation and propagation also are presented.

STUDIES OF BRITTLE FRACTURE PROPAGATION

1. INTRODUCTION

In the recent University of Illinois fracture mechanics investigations sponsored by the Ship Structure Committee, primary emphasis has been placed on studies of brittle fracture propagation in wide steel plates. Because of the considerable fundamental information amassed in these investigations in recent years, it was decided that one of the final tasks of Project SR-155 would be the preparation of this short report summarizing the most significant observations arising from work conducted as a part of Projects SR-137 and SR-155; this report also serves as the final report on Project SR-155.

Project SR-137 dealt primarily with studies of fracture propagation in six-foot wide plain plate specimens. The fractures studied as a part of the latter investigation were generally of a high speed nature (2000-4000 fps); the study provided considerable information about the average fracture speed and the strain field surrounding the tip of propagating fractures as measured by instrumentation located on the surface of the plate. In one of the later phases of Project SR-137, pilot studies were made with wide plates in which a residual strain field had been introduced. These tests indicated that brittle fractures could propagate at extremely low velocities (recorded as low as 50 fps) when propagating through regions where the initial residual strain perpendicular to the crack path was of a compressive nature. The differences noted between high and low speed fracture propagation raised many questions about the role of the various parameters affecting propagation, and in order to study this problem more fully, Project SR-155 was undertaken to examine various aspects of low-velocity fracture propagation. Such a study was of particular interest because results from this investigation, when combined with the results from Project SR-137, would provide a rather complete picture of brittle fracture propagation in six-foot wide steel plates over a wide range of fracture speeds.

Another major phase of Project SR-155 involved the testing of 2-ft and 3-ft wide plates containing a centrally located transverse notch and a longitudinal butt weld. Because of the high residual tensile stress in the region of the prepared notch, brittle fractures could be consistently initiated under static load conditions without the aid of impact. The results of these studies were deemed of great importance because they provided speed and strain data from statically initiated fractures which could be compared with the earlier impact-initiated fracture data, and because they represented an intermediate fracture speed level.

It is to be noted that none of the plate specimens tested on Projects SR-137 or SR-155 were stress relieved.

The remainder of the report is devoted to a summary of the most pertinent observations arising out of the major areas of experimental investigation of Projects SR-137 and SR-155. Whenever appropriate, comparisons of the various findings are presented. More detailed discussions of the various phases of the investigation reported herein may be found in the theses, reports and published papers listed in the Bibliography at the end of this report.

2. SUMMARY OF EXPERIMENTAL STUDIES

2.1 Wide Plain Plate Tests

All tests of plain plate specimens were conducted as a part of Project SR-137 and with the exception of initial exploratory tests, all specimens were 3/4 in. thick and 6 ft. wide. Including the early exploratory studies, a total of thirty-nine brittle fracture tests were conducted as a part of Project SR-137. The primary purpose of the investigation was to study the fracture speed and transient strain field surrounding the tip of a propagating fracture.

The specimens were tested at an average applied stress of 15 to 20 ksi, at a temperature of approximately $0^{o}F$, and with the notch-wedge-impact method for fracture initiation. Speed measurements and surface strain response as determined from strain gages mounted on the surface of the plate were obtained during fracture propagation.

A typical instrumentation layout and strain-time records from gages mounted on the surface of a specimen are shown in Fig. 1. In this series of tests the majority of the strain and speed measurements were made in the immediate vicinity of the fracture path. Although fracture speeds as high as 7550 fps were recorded, in over seventy-five percent of the tests the speeds were in the range of 2000 to 4000 fps. Peak strain magnitudes of 800 to 3000 microin./in. (one value as high as 5000 microin./in. was noted) were recorded on the plate surface near the fracture with negligible permanent set remaining after fracture, i.e., the exhibited response was elastic from gages even as close as one-quarter inch to the fracture. Preliminary tests had indicated that, outside of the immediate initiation region, surface strains were not materially affected by the impact used for initiation.

In a later phase of this study, rectangular strain rosettes were utilized to provide sufficient data to establish the characteristics of the strain field surrounding a propagating fracture. A typical instrumentation layout and a photograph of the fractured portion of a test specimen in which rosettes were used is shown in Fig. 2. Strain-time traces for the component gages of three rosettes of this same specimen are presented in Fig. 3. As may be noted from this figure, the strain-time pulse is very sharp for gages located close to the fracture (in some cases strains as high as 5000 microin/in. were noted); for gages further away, the peak strain is of a lower magnitude and the pulse extends over a longer time.

From strain data obtained from rosettes it was possible to calculate maximum and minimum principal strains, and typical principal strain-time plots for three rosettes are shown in Fig. 3 to the right of the component gage traces. In general the major principal strain trace for each rosette has essentially the same shape as the corresponding vertical component gage trace, which indicates that the direction of major principal strain is essentially normal to the fracture.

In order to portray the strain distribution on a plate surface during the time a crack was propagating, data from several tests conducted under identical conditions were superimposed to permit the plotting of contours of major principal strain for various crack lengths. It was found that for six-foot wide plates the magnitude and extent of the strain field associated with the moving crack tip increased from its original size near the fracture source to a steady state condition after traversing approximately one-quarter of the plate width. A set of typical major principal strain contours for a crack length greater than one-quarter of the plate width is presented in Fig. 4.

The fracture texture of all plain plate specimens was quite rough, and the usual chevron markings were easily visible. A photograph of the fracture texture of a typical specimen is shown in Fig. 5.

2.2 Wide Prestressed Plate Tests

All of the tests described in the preceding section were conducted as a part of Project SR-137 on specimens in which the major applied stress was that resulting from the externally applied machine load. The last series of tests of Project SR-137, and the initial area of study on Project SR-155, were conducted on both 2-ft and 6-ft wide plates in which residual stresses were present. The purpose of these tests was to investigate the effects of residual stress on the initiation and propagation characteristics of a brittle fracture and if possible to utilize the residual compressive stress field as a means of obtaining low-velocity brittle fractures.

Preliminary studies established that the most satisfactory method for introducing a residual stress pattern across the width of a specimen was by welding tapered slots cut above and below the expected fracture path on each edge of the plate. The position of the slots may be seen in the plate layout shown in Fig. 6(a). The major phase of this investigation involved brittle fracture tests of eight plate specimens 3/4 in. thick and 6 ft. wide, seven of which were prestressed by the welding of tapered slots, and one of which was a plain plate specimen tested to aid in evaluating the effect of the initiation procedure. Although there was some variation in the magnitudes of residual strain resulting from the prestressing procedure, the pattern was similar for all specimens and consisted of high residual tensile strain approaching or exceeding the yield level at the edges of the plate and a fairly uniform compressive strain region across the central portion of the plate. The measured longitudinal residual strain distribution in a typical prestressed specimen is shown in Fig. 6(b).

Brittle fractures were successfully initiated by the notch-wedge-impact procedure in all prestrained specimens tested, even those in which no external load was employed. In three tests, in which a small load of 3000 psi was applied to maintain the specimen taut in the machine, complete brittle fracture of the specimens occurred; in the other four prestrained specimens, the fractures arrested in the compressive strain region. Of these latter four specimens in which the fracture arrested, three were tested with zero applied load as just noted. Apparently, the residual compressive strain normal to the crack path and the lack (or small amount) of stored energy in the specimen-machine system was a factor in causing the arrest of the brittle fracture. The fact that the fracture arrested in one of the specimens with a small applied load would seem to indicate that the fractures in all such specimens may have been on the verge of arrest.

In the earlier 6-ft wide plain plate tests in which there was no residual strain field, an average applied stress in excess of 15,000 psi was necessary to insure fracture initiation under similar test conditions. The fact that brittle fractures could be consistently initiated in the prestressed specimens with little or no external applied stress indicates that a high residual tensile strain field materially aids in the initiation process.

While the residual tensile stress aided fracture initiation and propagation, the residual compressive stress field in the central portion of the test specimen had just the opposite effect. The most significant effects were that high fracture speeds were recorded near the initiation edge where high residual tensile strains were present, while greatly reduced speeds were recorded in the central portion of the plate in the area of residual compression; the latter speeds were considerably lower than those recorded earlier in tests of 6-ft wide plain plate specimens. In specimens in which complete brittle fractures occurred, the highest fracture speeds recorded were in the range of 5500 to 6500 fps near the initiation source, and the lowest speeds were in the range of 50 to 300 fps in the central region.

A comparison of the fracture speeds in the plain plate and prestressed plate specimens considered in this report are presented in Fig. 7 along with data for a centrally notched specimen to be discussed later. In this figure the breaking time of a detector gage, or the time of peaking of a strain gage, is plotted versus distance along the crack path; the slope of these curves represent the speed. Typical speed values are noted for purposes of comparison.

The effect of the residual strain field on the propagation characteristics was apparent from the dynamic strain records obtained during the tests. Except for two tests in which rectangular strain rosettes were employed, the major portion of the dynamic strain data was recorded from individual vertical gages. The strain-time traces recorded from vertically oriented gages were similar for all tests and typical strain-time traces from Test 46 are shown in Fig. 8. The traces shown are for vertically oriented strain gages located at the positions indicated in Fig. 6.

A typical instrumentation layout for a specimen in which strain rosettes were used is shown in Fig. 9. Strain-time traces for the component gages of two rosettes of the specimen shown in Fig. 9 are presented in Fig. 10; the major and minor principal strains, and maximum shear strain, all versus time, are shown to the right in Fig. 10. Most of the peak strain values recorded were in the range of 500 to 1500 micrcin./in.; this range is lower than that recorded from the tests of plain plate specimens.

From an analysis of the recorded strain data, it was evident that the strain field associated with the tip of propagating fracture was considerably reduced in magnitude and extent by the residual compressive strain in the central portion of the specimens. This was evident in all tests and may be observed from the strain data shown in Fig. 8. Also the pulse width (time base) increased as the fracture passed through the compressive zone; in some cases the pulse lengths were as long as 5 milliseconds. Gage 5, which was located in an area of residual tension showed a peak strain response of approximately 1700 microin./in., while Gage 10, located much closer to the fracture but in a zone of initial residual compression, showed a peak strain response of only 800 microin./in. This reduction of the transient strain field in the residual compressive strain region was observed to occur in all tests of prestrained specimens, even those in which the fracture arrested. Strain redistribution during propagation may be noted from the traces for Gages 12 and 14 in Fig. 8. The redistribution mechanism is complicated by the fact that it involves the redistribution of both external load and internal residual strain.

Another interesting feature noted from the strain-time records was the behavior of component gages of rosettes located extremely close to the fracture path. From previous tests it had been observed that the vertical gage of a rosette always peaked in tension as the fracture passed the gage while the horizontal gage peaked in compression. If, however, the rosette is located within approximately 1/2 in. of the fracture both the vertical and horizontal gages peaked in tension, although the magnitude of the vertical strain peak was considerably higher. These observations are illustrated by the strain records shown in Fig. 10 and 3. This pronounced biaxial state of tensile strain extremely close to the fracture path was observed in tests of all type specimens in which gages were located sufficiently close to the fracture.

In both the plain plate specimens and the notched and welded plate specimens (to be described), the fracture path was essentially straight, which would be expected since the direction of the principal stress, and any major applied stress or strains were in the vertical direction. In the prestressed plate tests, however, in which transverse edge slots were welded, the direction of the major principal stress varied considerably throughout each specimen. In these specimens the path of the fracture was observed to deviate noticeably from a straight line as may be noted in Fig. 6(a) and 9, and a study of the principal strain directions existing at the time of test indicated that the fracture generally propagated in a direction normal to the direction of the major principal strain.

The texture of the fracture surface was noticeably different as it passed through regions of tensile and compressive residual stress. Near the initiation edge, where the initial longitudinal residual stress was tensile and where the highest fracture speeds were recorded, the fracture texture was rough and exhibited the familiar chevron pattern observed in most brittle fractures. This coarse texture was similar to that noted in the earlier tests of 6-ft wide plain plate specimens. In the initial residual compressive stress region, however, where the recorded fracture speeds were extremely low, the fracture texture was noticeably smooth but still brittle in appearance; in the smooth textured region, there was no clearly discernible chevron pattern. Photographs of typical fracture textures in regions of both initial residual tension and residual compression are shown in Fig. 11. The fracture texture toward the far edge of the plate in the initial tensile zone was smooth as contrasted to the rough texture in the corresponding tensile strain zone at the initiation edge; this difference in texture was not unexpected, because of the stress redistribution accompanying the fracture.

2.3 Centrally Notched and Welded Plate Tests

In all previous brittle fracture tests conducted thus far as a part of this investigation, fracture initiation was produced by the notch-wedge-impact technique. To avoid any possibility of having unknown impact effects included in the recorded data, and at the same time, to obtain brittle fractures which could be made to initiate and propagate at fairly low values of applied stress, a series of tests were conducted on centrally notched plates containing a longitudinal butt weld. By virtue of the low stress level for fracture, it was expected that the resulting fracture speeds would be in the low to intermediate range. The presence of the weld produced high residual tensile stresses in the region of the prepared notch and consequently made it possible to initiate brittle fractures statically at a low average applied stress.

The purpose of this series of tests was to study fracture propagation in plate specimens with special emphasis on fracture velocity and surface strain during propagation. Because the fractures were initiated statically, some consideration was necessarily given to certain aspects of fracture initiation and this area of the study also is included in the discussion presented herein.

A total of nineteen tests were conducted as a part of this phase of the investigation; with the exception of two exploratory tests, all specimens were prepared from 3/4-in. semi-killed steel plate. The majority of the specimens were 2 ft. wide and contained either a complete or interrupted butt weld down the center of the plate. Variations in the fabrication procedure were utilized in a few cases to facilitate the study of certain parameters. For convenience in discussion, all specimens have been classified as Types A through E according to the particular fabrication procedure employed. A sketch of the various specimen configurations employed and details of the notches are shown in Fig. 12.

The majority of the specimens (15 out of 19) contained either a complete (Type A) or interrupted (Type B) butt weld, and both static and dynamic strain measurements were made on selected specimens from these two groups. During preparation of Type B specimens both strain and temperature measurements were recorded on the plate surface at a point immediately adjacent to the notch tip. Strain measurements this close to the notch tip were possible because an unwelded gap, which resulted in low temperatures, existed in the vicinity of the central notch; temperature at the notch tip never exceeded approximately 200°F. The strain measurements indicated that the material on the plate surface at the notch tip underwent a cyclic strain of as much as 2000 microin./in. range per weld pass. A plot showing the strain and temperature variations during welding for a typical gapped specimen is presented in Fig. 13. In this figure, one pass consists of laying one bead from one end of the specimen to the termination at the gap followed by an identical bead on the other half of the plate, all on the same side; this procedure gives rise to two compressive strain peaks per cycle.

It was found that the residual strain pattern across the notch line resulting from welding was essentially the same for both Type A and Type B specimens and a plot of a typical residual strain pattern for a Type B specimen is shown in Fig. 14.

Four exploratory specimens were prepared by a different fabrication procedure than that just discussed, which resulted in different conditions of strain cycling and residual strain. Two specimens (Type C) were identical to the Type A and B specimens except that no weld joined the two plate halves; one specimen (Type D) contained short transverse welds located above and below the notch, and one specimen was a plain plate (Type E) containing only the central Vee-notch. Thus, the Type C and Type E specimens were not subjected to strain cycling or temperature changes, and contained no residual strain, while the Type D specimen underwent very little strain cycling; however, the latter specimen contained extremely high residual tensile strains (as much as 6000 microin./in.) in the vicinity of the notch.

All plate tests were conducted at a temperature of approximately $-40^{\circ}F$. Statically initiated brittle fractures at low average applied stress were obtained only in the Type A and B specimens. All other specimens fractured at yield stress or above after undergoing considerable general yielding.

In general, either a partial or complete brittle fracture at a low applied stress was obtained in tests of Type A and B specimens. In the few cases in which the first fracture occurred at or near yield stress, the unusually high stress necessary for fracture could be attributed to variations in the plate geometry, such as misaligned notch, different notch geometry or a longer unwelded gap.

Fracture speeds were determined in these tests from crack speed detectors and dynamic strain gage data. Since a complete fracture could propagate only 12 in., the amount of speed data that could be obtained was limited; however, sufficient information was obtained to provide a reasonable indication of the fracture velocity of statically initiated fractures. Measured average speeds were found to vary from a high of 5000 fps near the point of initiation to approximately 1800 fps for the major portion of fracture travel, which was through a region of low residual compression. This velocity variation is indicated in Fig. 7. Speed measurements in these tests represent the first time fracture velocity has been obtained within 1 1/2 in. of the initiation source. The measured speeds also are consistent with data from previous tests with regard to the correspondence between speed and total stress level.

In all tests conducted high fracture speeds in excess of 2000 fps were observed to occur in regions where the tensile stress resulting from applied loads or the stress resulting from residual tensile strains were high. In regions of initial compressive residual strain the fracture speeds recorded were much lower with the lowest fracture speeds being associated with the highest initial residual compressive strain.

Dynamic strains were recorded during fracture propagation in selected specimens containing a weld (Type A and B). The strain-time records from vertically oriented gages were similar in shape to those recorded in the compressive strain region of the tests of the six-foot wide prestressed plates, although the pulse times for the strain peaks were somewhat shorter. Typical strain-time records are shown in Fig. 15 for the specimen whose residual strain pattern is given in Fig. 13. In Fig. 15 the zero strain level corresponds to the strain level of the gage at the time of fracture and does not include the additional strain arising from loading or the residual strain. If the total strain is considered, the strain peaks decrease in magnitude as the fracture moves toward the edge of the plate, and do not increase as the traces in Fig. 15 would seem to indicate. This behavior is consistent with previous results, which indicate that the highest strain peaks occurred in regions where the fracture speed was highest. Comparison of these strain time records with those for higher and lower speeds will show the pulse width and height to be about that which would be expected. Thus, at distances from the source of initiation the strain field associated with a propagating brittle fracture was ascertained to be of the same nature irrespective of whether the fracture initiation was of a statical type or of the notch - wedge - impact method.

Because of the particular instrumentation and recording procedure employed, it was impossible to statically monitor the strain gages used for dynamic recording once loading of the specimen had commenced; thus, the actual strain level of a gage at the time the dynamic records were obtained was not known precisely. For this reason, in these tests employing rectangular strain rosettes, principal strain values were not calculated; records from strain rosettes were used only to obtain the dynamic response of the component gages.

In all of the tests described in this section, the fracture texture appeared to be directly related to the stress level in the specimen at the time of fracture. For specimens which fractured at a low average applied stress, the texture was smooth, comparable to that observed in the compressive strain region of the wide prestressed plates. The texture was noticeably rougher, however, for fractures which occurred at or near yield stress. Typical fracture textures for the two conditions noted are shown in Fig. 16 along with the stress values at fracture.

2.4 Fracture Initiation in Small Notched Specimens

A separate but related study, conducted concurrently with the wide plate studies was concerned with the initiation of brittle fractures in small notched specimens of mild steel. Some of the results of this study are described herein because of their relationship to the wide plate studies. Specifically, the purpose of this study was to determine the general state of stress associated with the initiation of a brittle fracture, and in particular to determine the critical tensile stress necessary for fracture initiation. Also included as a part of this investigation was a study of the effects of certain parameters on fracture behavior. The results were obtained from both experimental tests of notched specimens and an analytical stress analysis.

An approximate elastic-plastic stress analysis was developed utilizing the model notch configuration shown in Fig. 17. The analysis accounted for limited plastic deformation in the immediate vicinity of the notch tip, and provided a theoretical relationship between the average applied stress and the principal stresses existing along the minimum section of the notched specimen. The maximum axial tensile stress at the notch tip as a function of the average applied stress, as determined from this analysis and which indicates the nature of the stress concentration effect, is shown in Fig. 18.

To predict the actual stresses existing in a notched specimen whose geometry is similar to that of the model used in the stress analysis, the average applied stress at fracture and the yield stress must be known. These values were determined from tests of 2-in. wide plate-type specimens of varying thicknesses containing 1/2-in. deep edge notches. Specimen thickness was varied from 1/4 to 1 in. and tests were conducted at temperatures of +78°F (room), -100°F and -320°F.

Application of the analytical stress analysis to the results obtained from the experimental studies provided a theoretical prediction of the state of stress at the location of fracture initiation and provided an indication of the position of the elastic-plastic boundary in the specimens. For the material and specimens employed in this investigation, it was estimated that a brittle fracture would initiate when the maximum axial tensile stress, $(\sigma_y)_{max}$, reaches a critical value of approximately 245,000 psi; the remaining two principal stresses, $(\sigma_x)_{max}$ and $(\sigma_z)_{max}$, were found to be approximately 125,000 psi and 110,000 psi respectively at the time of fracture initiation. The position of the elastic-plastic boundary at fracture, as predicted by the theoretical analysis, was approximately 0.01 in. beneath the notch root along the minimum cross section;

this position of the yield zone also was qualitatively verified by results from experimental work. The noted value of critical stress of 245,000 psi was obtained from both analytical and experimental procedures and thus represents a predicted, rather than measured quantity, but interestingly enough is quite close to values predicted earlier by Clark and Wood*. A more striking comparison, however, exists between the theoretical critical stress predicted by this study and the stress at the tip of a propagating fracture as determined from the experimental propagation studies made at the University of Illinois in recent years. As noted in Section 2.1 of this report, a considerable amount of dynamic strain data was obtained from tests of 6-ft wide plain plates as a part of Project SR-137; in Fig. 19 are presented values of vertical and horizontal peak dynamic strains measured during fracture propagation plotted as a function of gage distance from the fracture. By extrapolation of the data from the plain plate tests, approximate values of horizontal (ϵ_x) and vertical (ϵ_y) strains at the crack front can be obtained; as indicated in the figure, these strains are found to be approximately +1900 microin./in. and +7200 microin./in., respectively. Since the strains were measured on the surface of the test specimens, the corresponding stresses can be computed from the plain stress relationships. Calculated in this manner, the maximum tensile stress at the tip of a propagating fracture was found to be approximately 255,000 psi, which compares favorably with the predicted value of 245,000 psi.

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* Hendrickson, J. A., Wood, D. S. and Clark, D. S., "The Initiation of Brittle Fracture in Mild Steel," Third Interim Technical Report under Office of Ordinance Research, OOR Project No. 1235, Contract No. DA-04-495-Ord-171, California Institute of Technology, April 1957.

Also shown in Fig. 19 are the peak vertical strain values versus gage distance from the fracture for the 6-foot wide prestressed plates for gages located in the central region of the plate which initially possessed a residual compressive strain. Although these strain values are apparently of a lower magnitude this is likely a result of both a lower applied stress and the initial residual compression present in the plate. Although data is lacking for points very close to the fracture, it is likely that the vertical strains increase sharply at close-in distances as a result of the extremely high strain rates associated with a propagating fracture.

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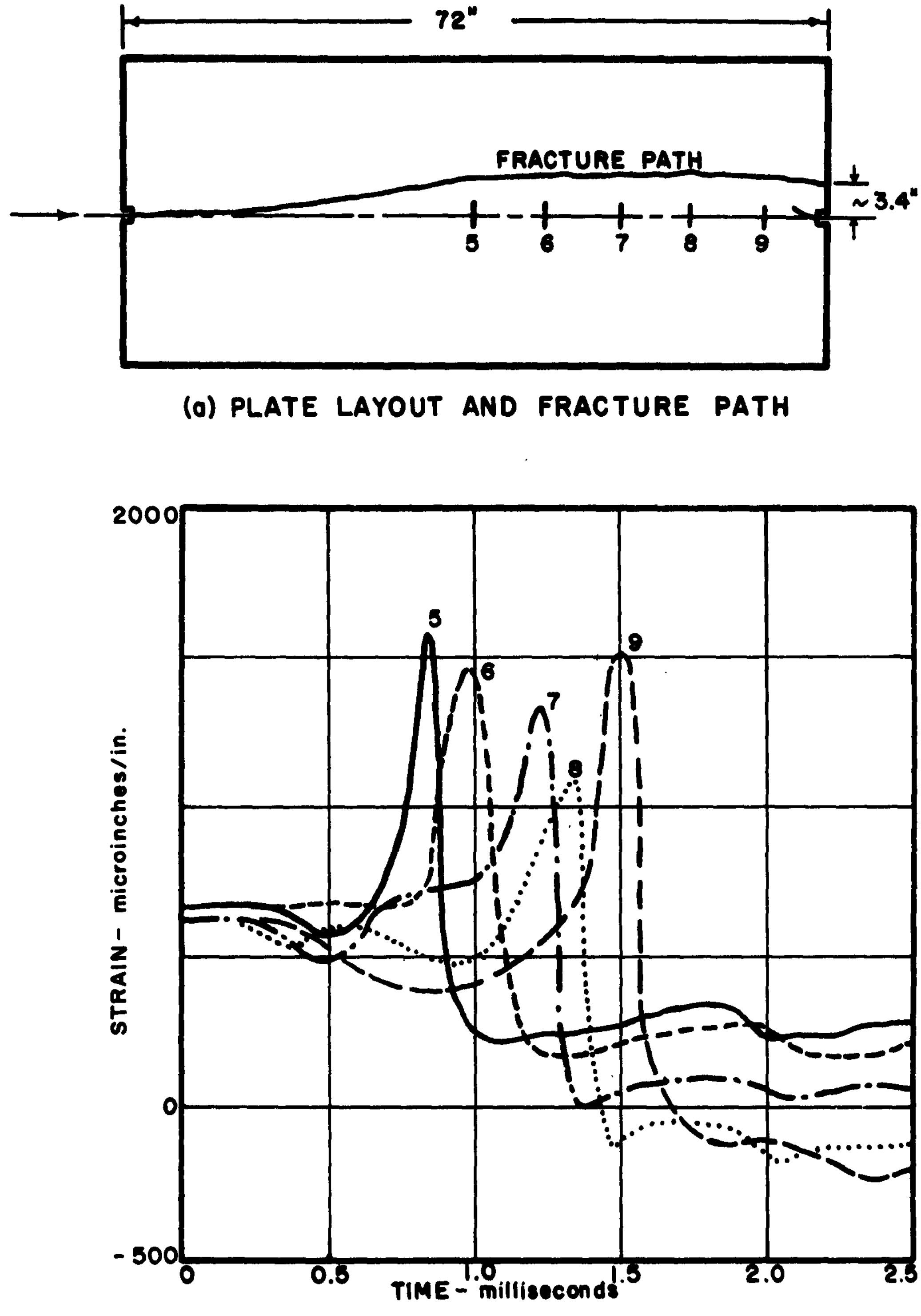
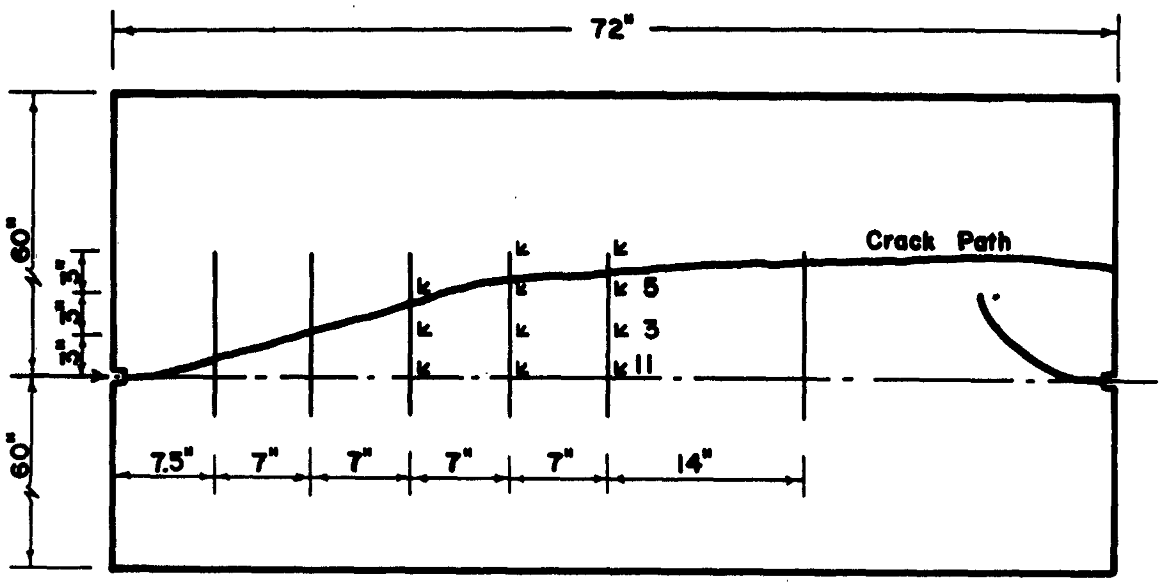


(a) PLATE LAYOUT AND FRACTURE PATH

(b) STRAIN-TIME RECORDS

FIG. 1 PLAIN PLATE--TEST 23



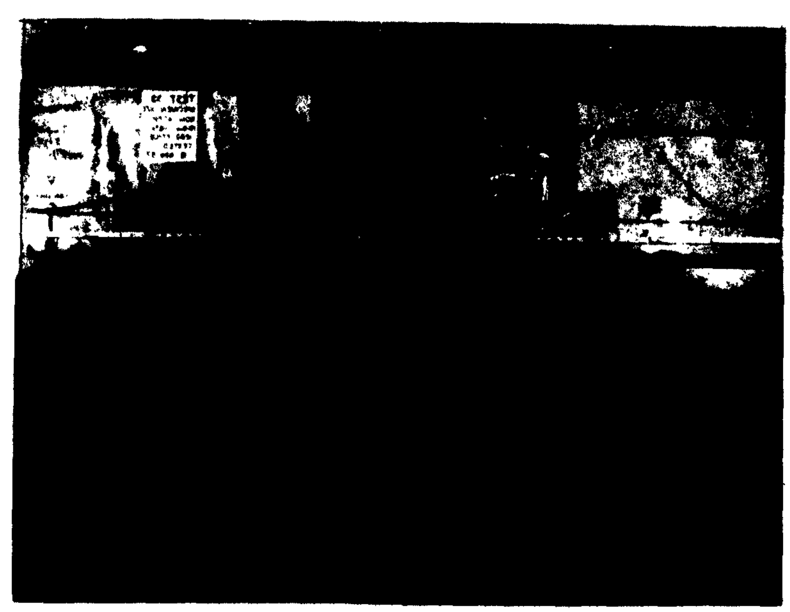


FIG. 2 PLAIN PLATE--TEST 39

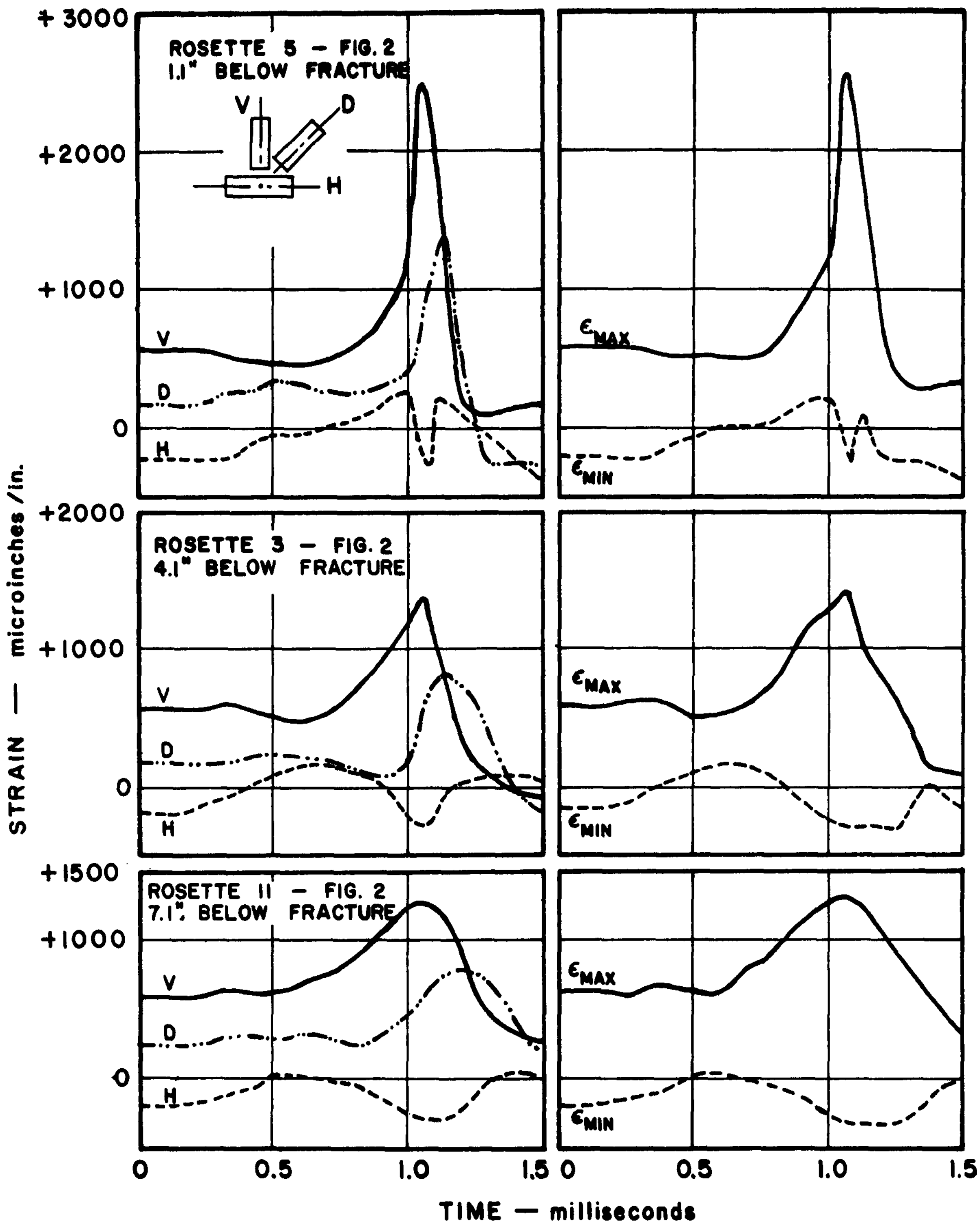


FIG. 3 STRAIN-TIME TRACES AND COMPUTED PRINCIPAL STRAINS FOR ROSETTES LOCATED AT VARIOUS DISTANCES FROM THE FRACTURE -- TEST 39

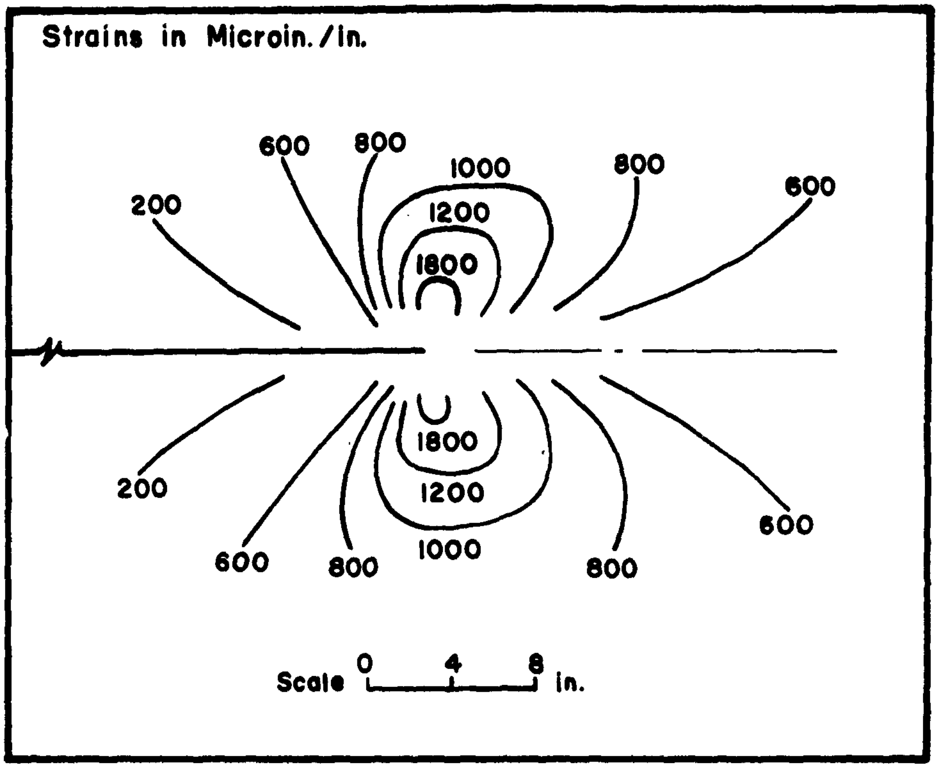


FIG. 4 MAJOR PRINCIPAL STRAIN CONTOURS

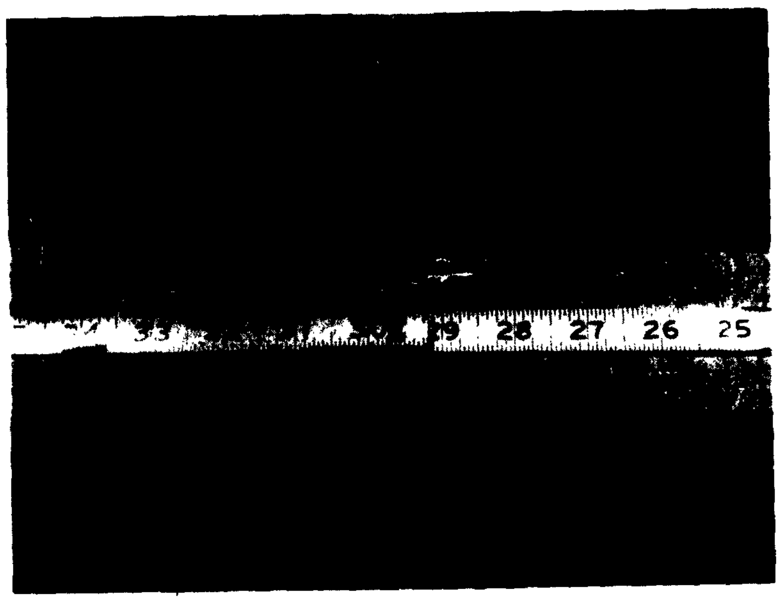
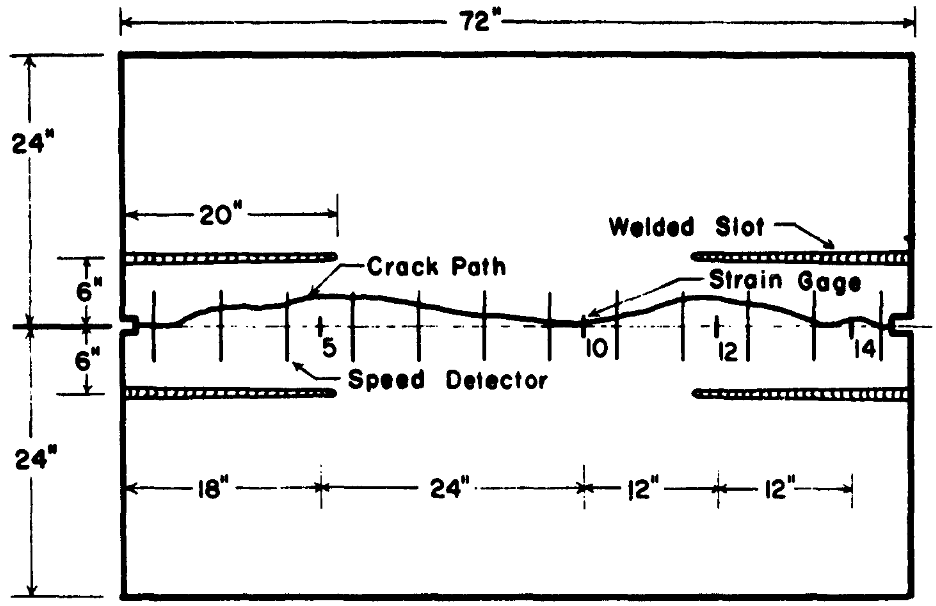
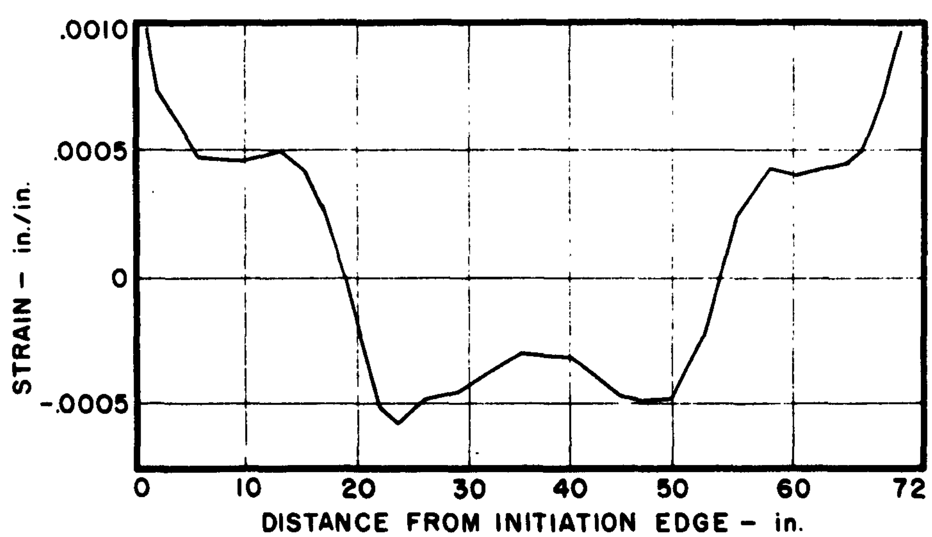


FIG. 5 FRACTURE TEXTURE--TEST 38



(a) PLATE LAYOUT AND FRACTURE PATH



(b) AVERAGE LONGITUDINAL RESIDUAL STRAIN

FIG. 6 PRESTRAINED PLATE --TEST 46

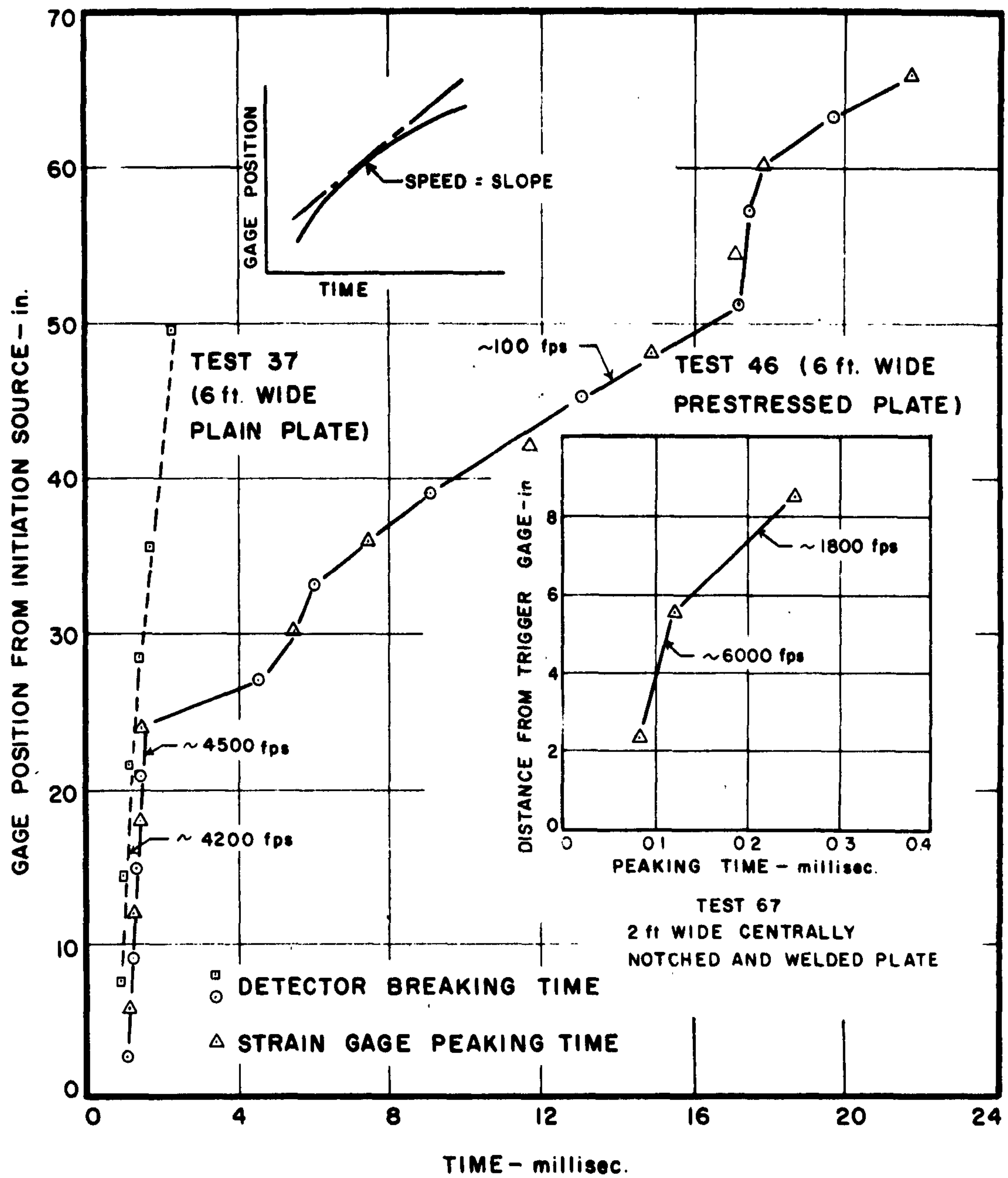


FIG. 7 FRACTURE SPEEDS ACROSS PLATE WIDTHS --TESTS 37, 46, AND 67

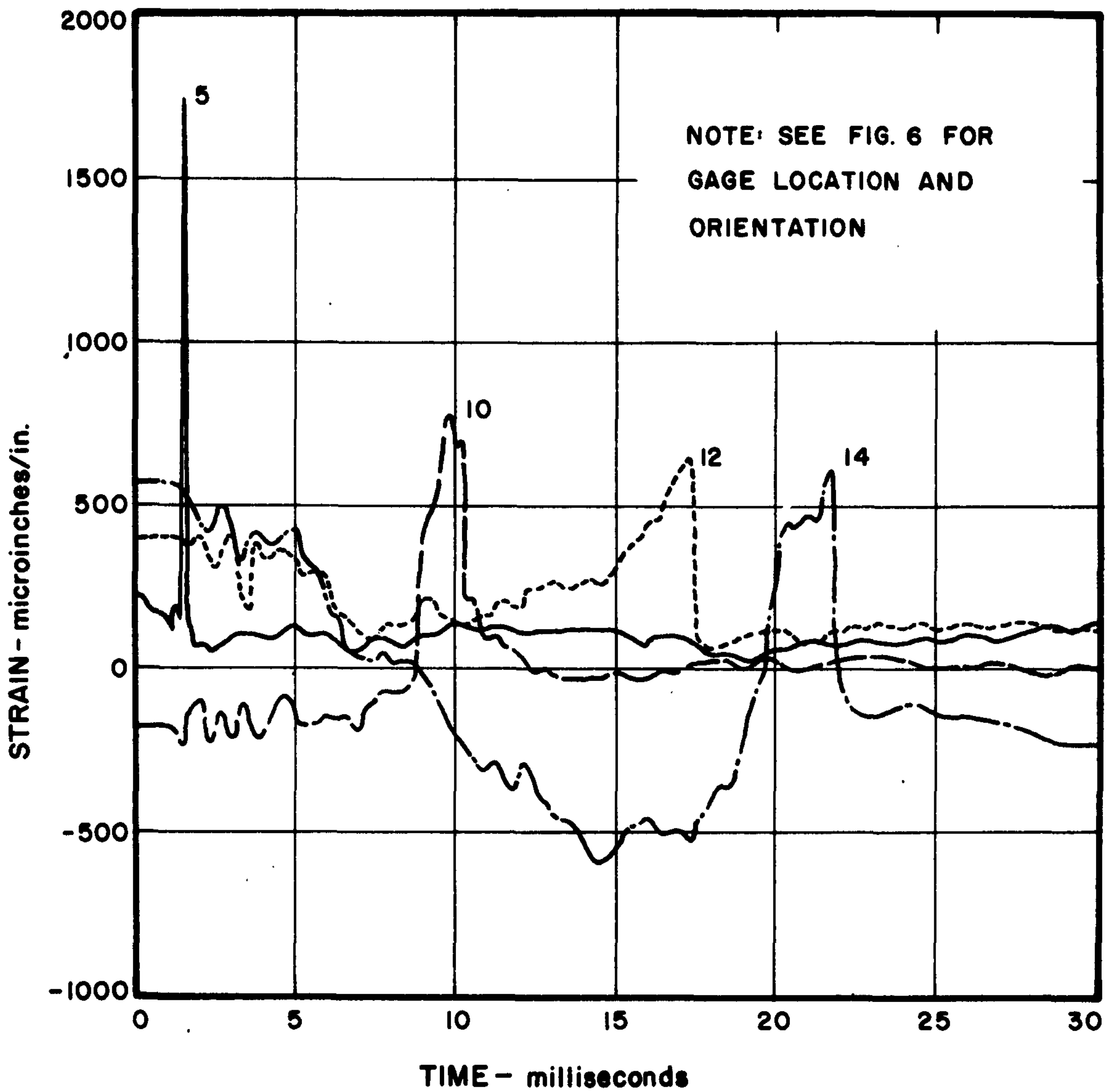


FIG. 8 TYPICAL STRAIN-TIME RECORDS-- TEST 46

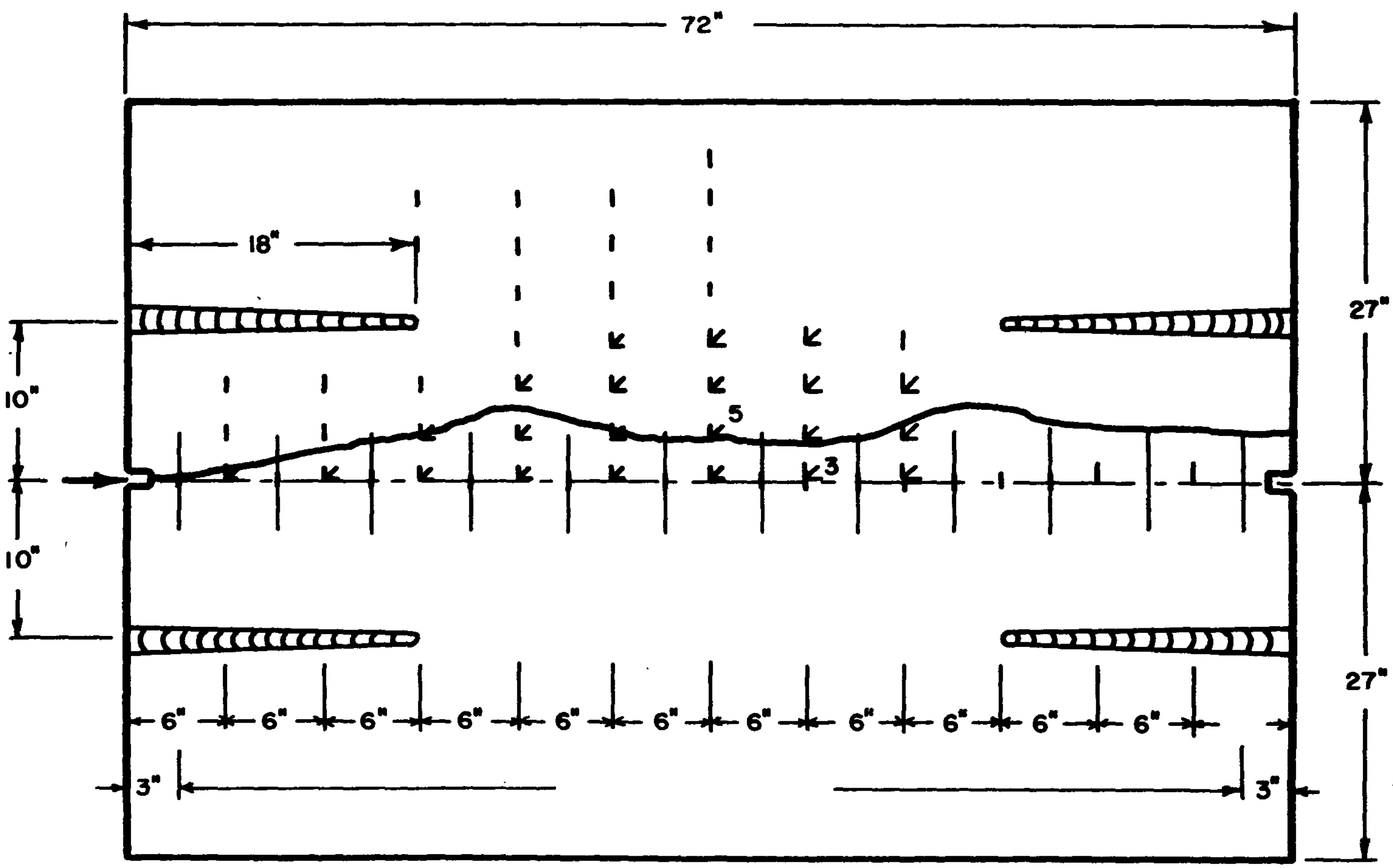


FIG. 9 PLATE LAYOUT -- TEST 50

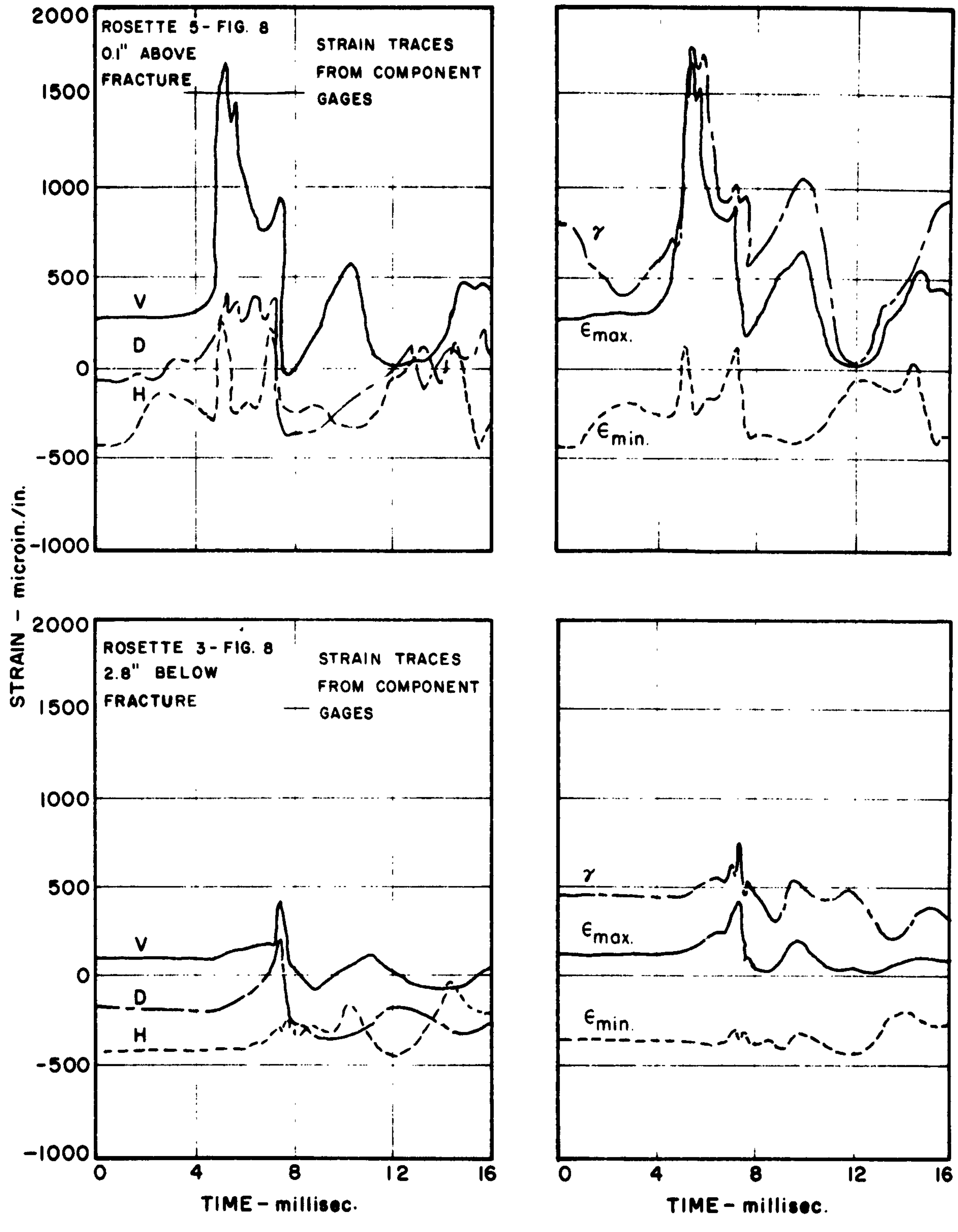
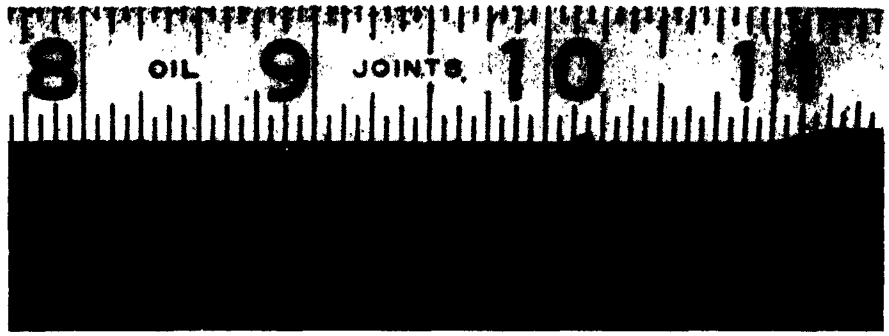


FIG. 10 STRAIN-TIME TRACES AND COMPUTED PRINCIPAL STRAINS -- PRESTRESSED PLATE TEST 50



HIGH SPEED REGION

LOW SPEED REGION

FIG. 11 FRACTURE TEXTURE-- TEST 50

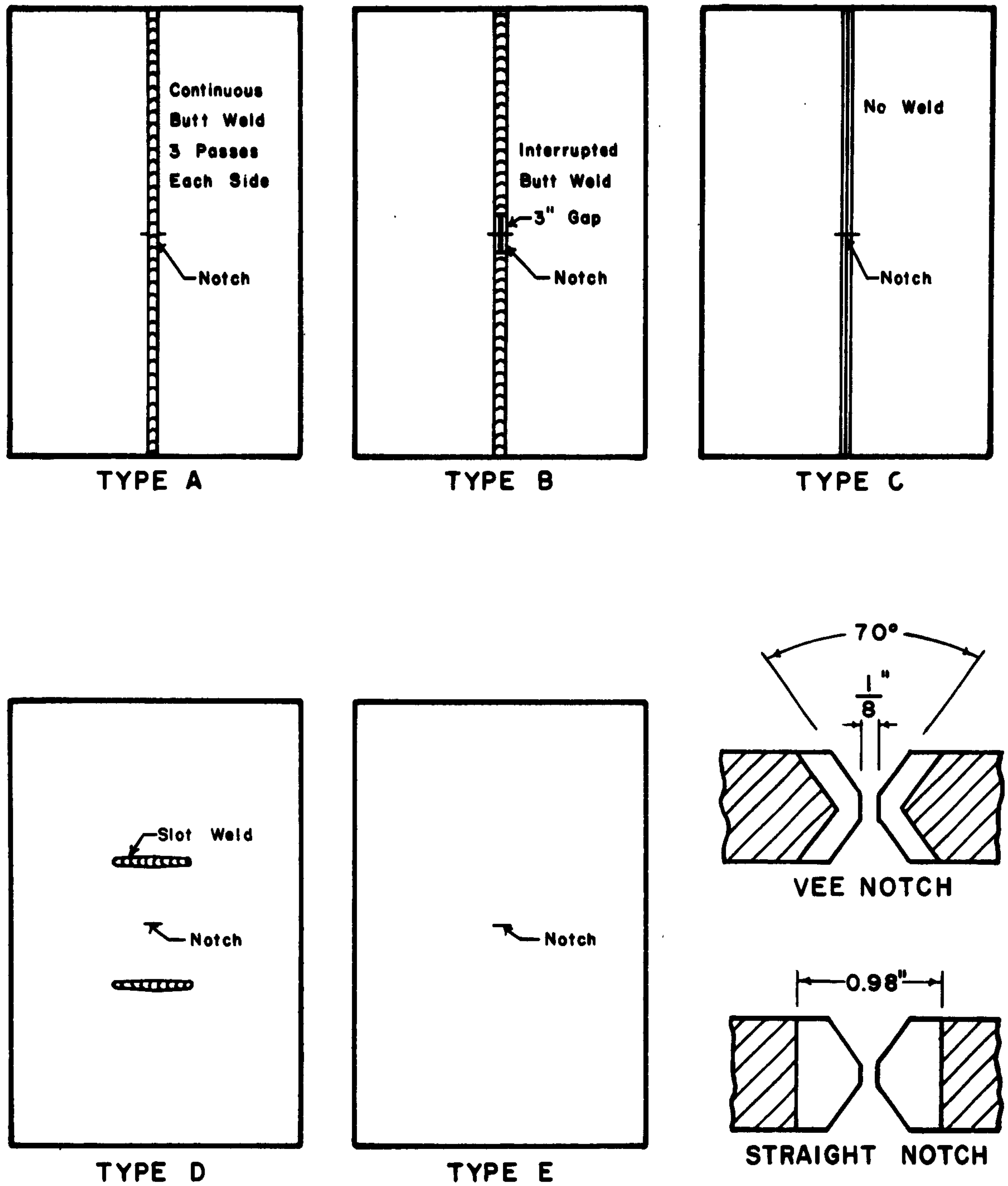


FIG. 12 SPECIMEN TYPES AND NOTCH DETAILS

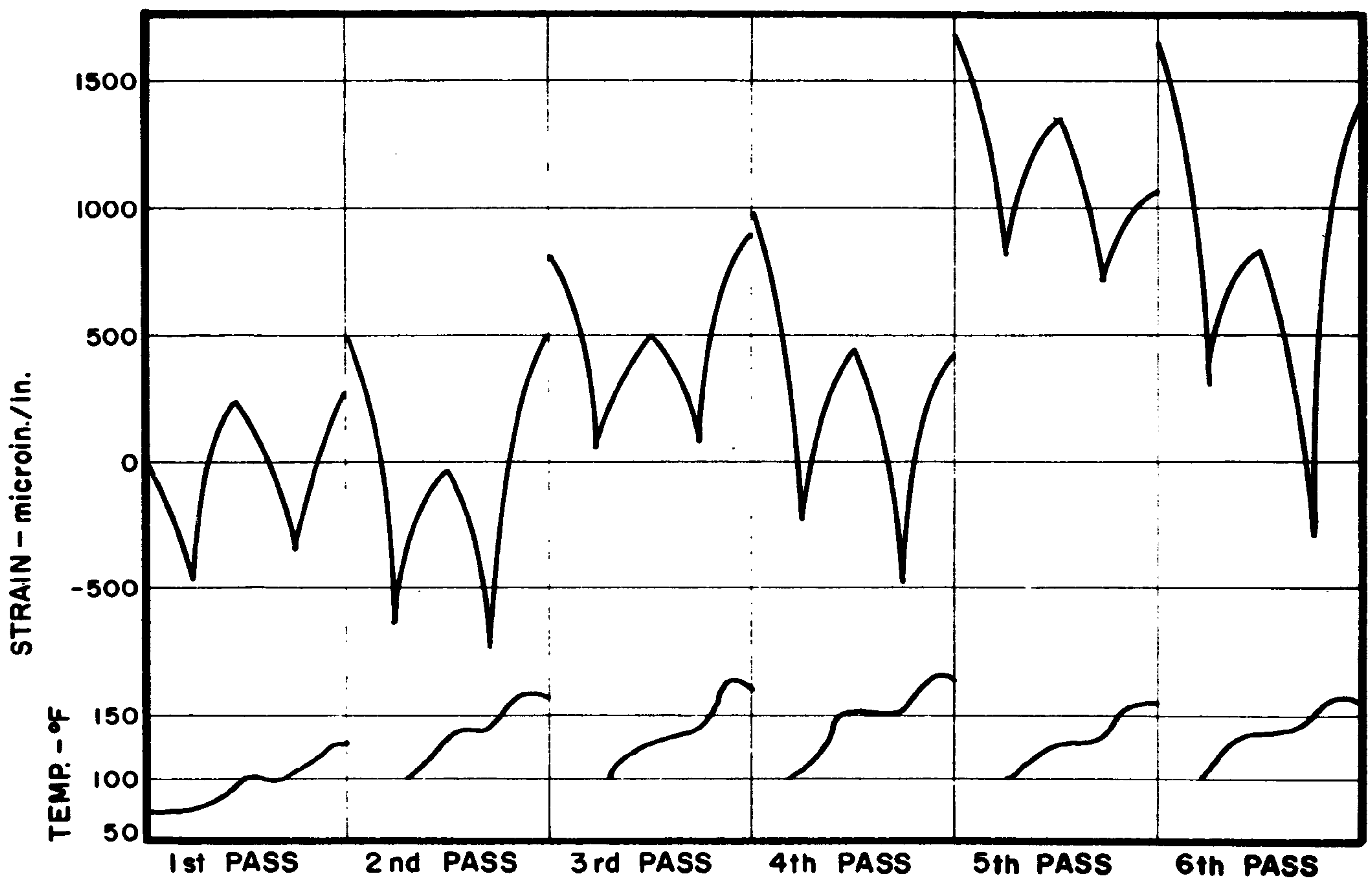


FIG. 13 STRAIN AND TEMPERATURE VARIATION DURING PREPARATION OF TYPE B SPECIMEN

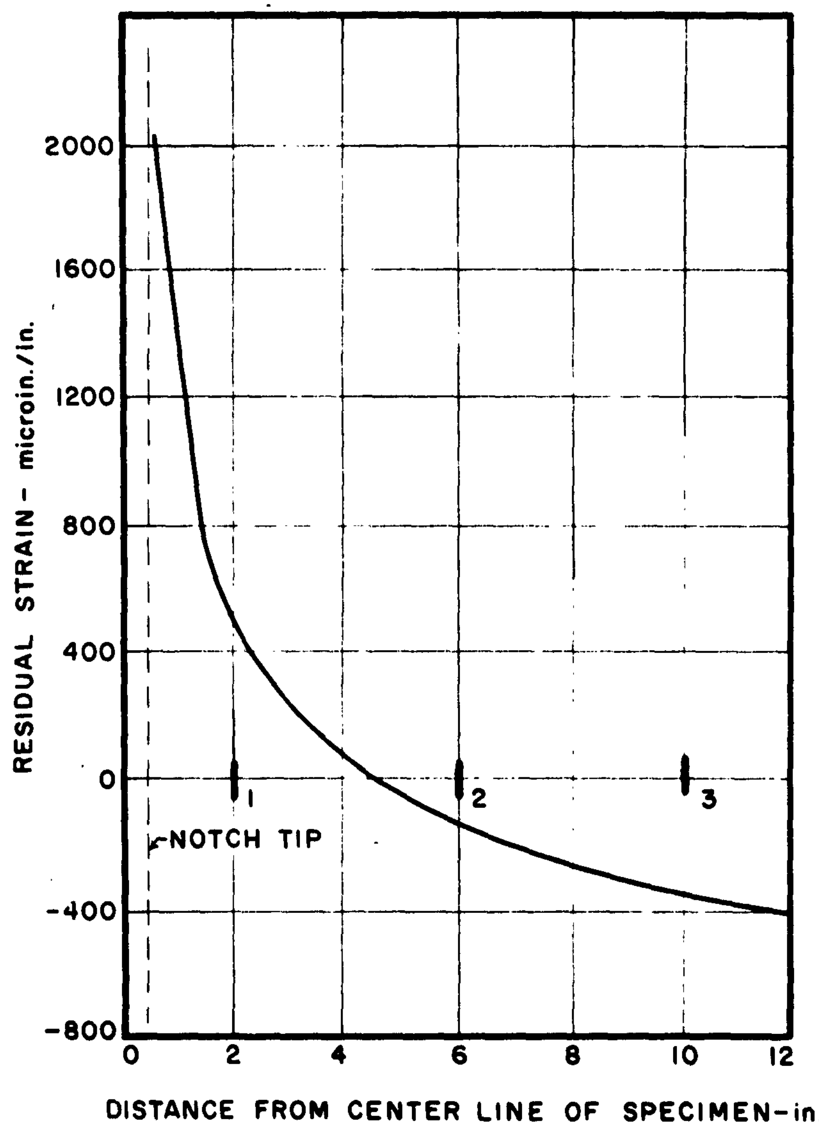


FIG. 14 RESIDUAL STRAIN DISTRIBUTION ACROSS SPECIMEN--TEST 56

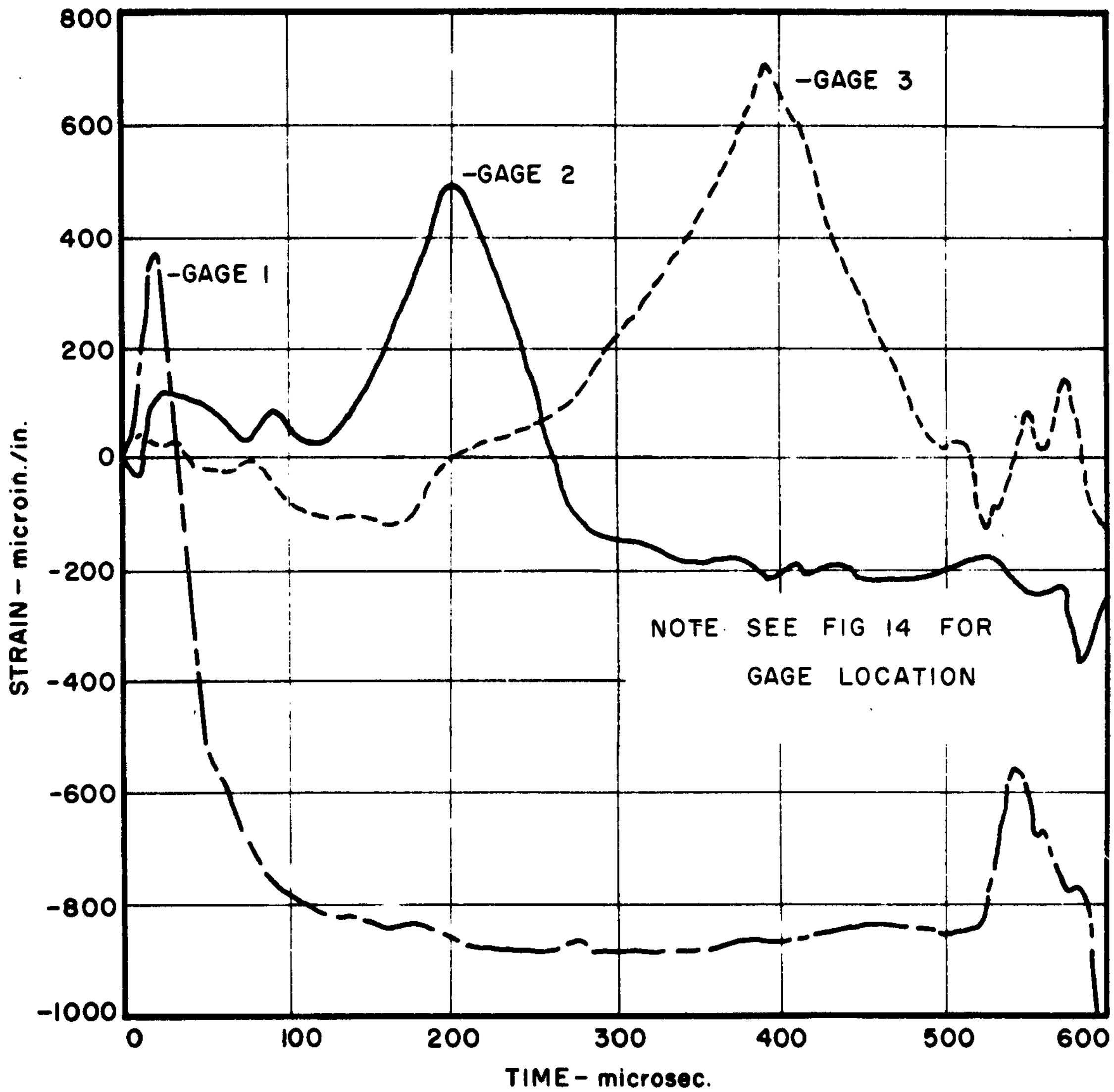
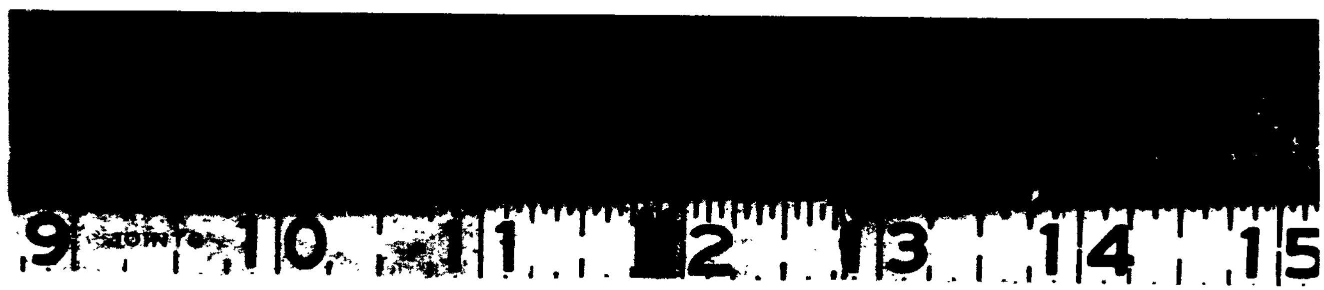


FIG. 15 STRAIN-TIME RECORDS --TEST 56



TEST 53
(FRACTURE STRESS = 10 ksi)

TEST 51
(FRACTURE STRESS = 40 ksi)

FIG. 16 FRACTURE TEXTURES--TESTS 51, AND 53

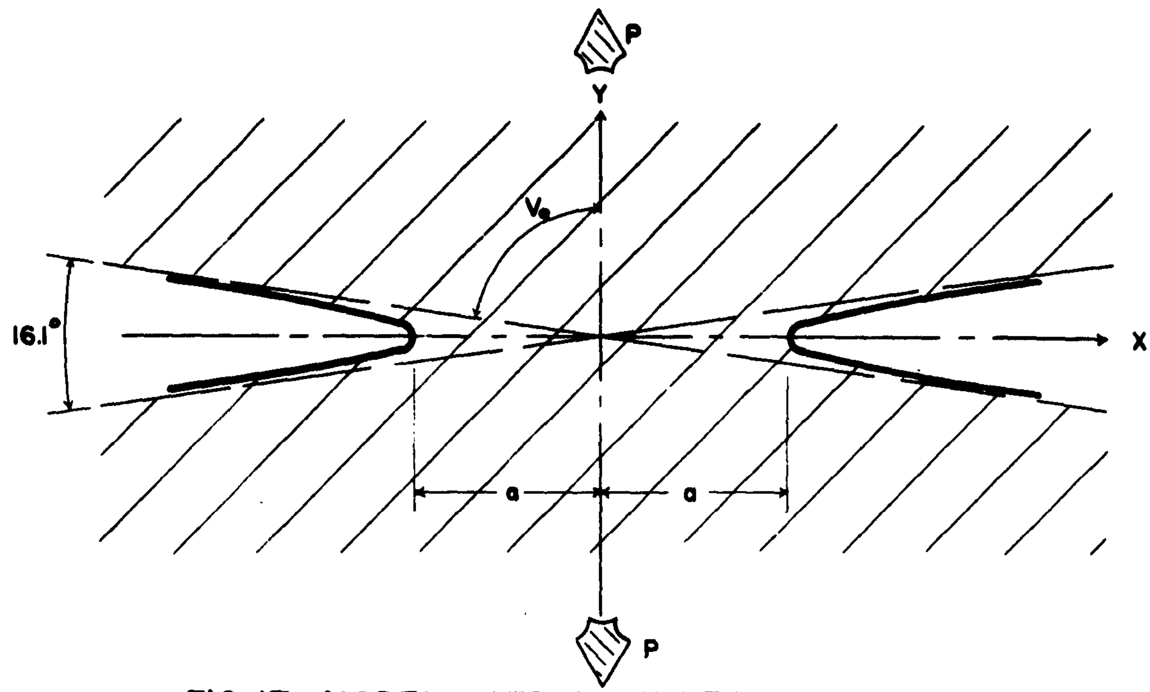


FIG. 17 MODEL USED IN STRESS ANALYSIS

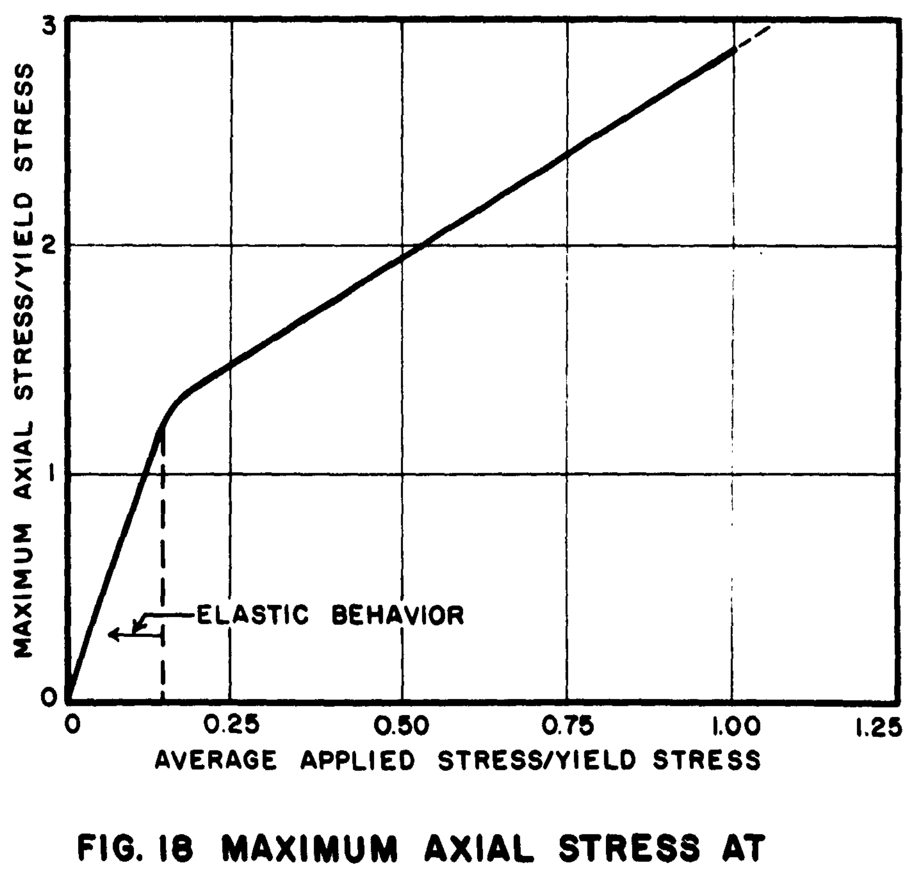


FIG. 18 MAXIMUM AXIAL STRESS AT NOTCH TIP VS. APPLIED STRESS

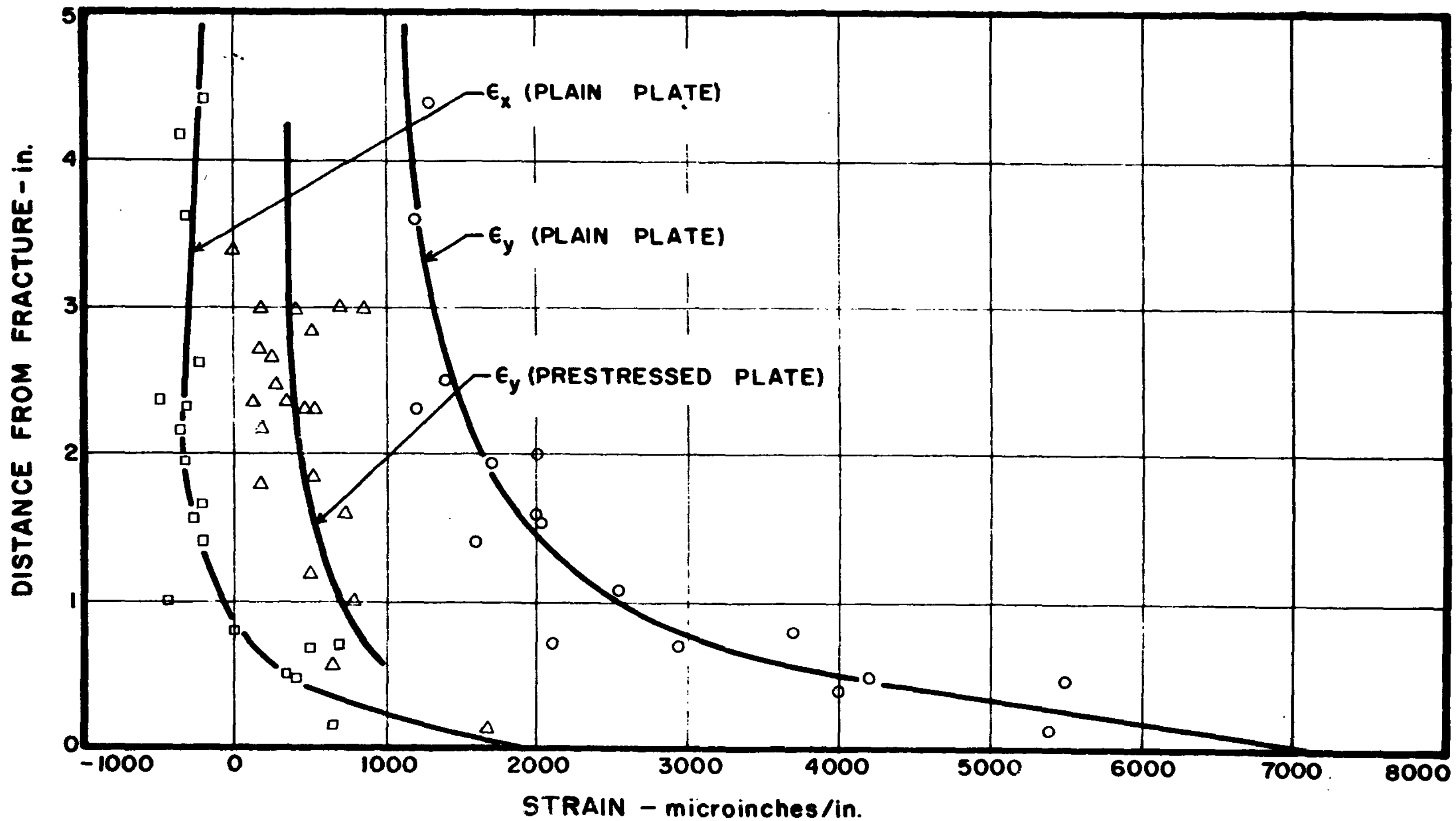


FIG. 19 PEAK STRAIN VS. DISTANCE FROM PROPAGATING FRACTURE