FATIGUE TESTS OF WELDED HYBRID PLATE GIRDERS UNDER CONSTANT MOMENT

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PREFACE

This is the second and the final report in a series of reports covering the work of this project. The reports are:

Report No. 1 — "Fatigue Testing of Ribbed Orthotropic Plate Bridge Elements" by H. L. Davis and A. A. Toprac; this report covers only the work performed on the orthotropic plate portion of the project concerned with the "Fatigue Strength of Plate Girder Webs Under Constant Moment."

Report No. 2 — "Fatigue Strength of Hybrid Plate Girders Under Constant Moment" by H. S. Lew and A. A. Toprac; this report covers the experiments carried out on the hybrid plate girders under repeated load.

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.

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ABSTRACT

Two series of fatigue tests on welded hybrid plate girders are described. The first series consisted of fourteen panel specimens and the second series consisted of six full length specimens. In both series, the center test panel (or panels) was subjected to pure bending moment. The test specimens had ASTM A514 steel flanges and ASTM A36 steel webs. Flange dimensions and web depth were kept constant in all test specimens. The web thicknesses used were 1/8, 1/4, and 3/8 inch. The maximum stresses applied to each of the two groups of specimens were 20, 30, 40 and 50 ksi with stress ranges of 10, 15, and 25 ksi.

The primary objectives of the investigation were: (1) to determine the manner in which thin web hybrid girders fail when subjected to repeated loads and (2) to determine what factors influence the fatigue strength of thin web girders.

The test setup and test procedures are described and the test results are analyzed and discussed. It is concluded that, regardless of the web thickness, for the specimens subjected to applied stress below the yield point of the web material, no cracks were found within two million cycles. However, when applied stresses exceeded the yield point of the web steel, the web flexing action coupled with the membrane stress caused the development of fatigue cracks along the toe of the compression flange to web fillet weld and near the end of the transverse stiffener. Various fatigue cracks caused by fabrication irregularities were also found in the specimens stressed beyond the web yield point. In all cases the final failure of the specimen was accompanied by a fracture in the tension flange.

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1. INTRODUCTION

1.1 Background and Scope

In recent years, the use of high strength alloy steels in civil engineering structures has become popular, particularly in highway bridge design. The combination of higher allowable stresses and suitable welding procedures is chiefly responsible for this growing popularity. Since the high allowable stress enables a reduction in cross-sectional area, the use of high strength alloy steel enables a significant reduction in the dead load of large structures.

In flexural members such as bridge girders, the flanges carry most of the bending moment. Hence, it is logical to make the flanges of high strength alloy steel. Such an idea was conceived by design engineers and hybrid girders consisting of high strength steel flanges welded to low carbon steel webs were created.

While the static load tests on such hybrid girders revealed that straining the web beyond its yield point has little adverse effect on the behavior of the girder(1) insufficient data are available on the fatigue strength of such girders.

In addition, although an increase in ultimate tensile strength in steel does not bring an equivalent increase in fatigue strength(2, 3), no generalized conclusion can be drawn on the fatigue strength of hybrid girders made in the aforementioned combination of steels. Testing must be undertaken to determine the fatigue characteristics of hybrid girders when subjected to repetitive loading.

To establish design rules based on experimental work, a test program was planned for investigating full size girders. The test specimens were subjected to various maximum stresses and stress ranges to obtain an S-N diagram similar to that used for metals. In establishing the S-N curve, a "fail safe" criterion was adopted. Instead of attempting to establish an endurance limit, that is, to find the fatigue limit, this investigation aimed at a finite life rather than an infinite life of such plate girders. Furthermore, emphasis was placed on the initiation of cracks in determining the life of a specimen. This condition is chosen because, according to a previous investigation[5], those cracks found in the tension side of a girder section propagated relatively at a faster rate than those found in the compression side and eventually led to the failure of the specimens as a result of fractures in the tension flange. Also, it had been observed that fewer number of cycles were required to cause a crack to reach a complete fracture than to initiate a crack.

1.2 Objective

The objectives of this investigation were: (1) to determine the manner in which thin web hybrid girders fail when subjected to constant moment fatigue loading, and (2) to determine the factors that influence the fatigue strength of this type of girder when subjected to cycles of constant stress. Both the maximum stress levels and the stress ranges were altered for each specimen.

The specimens were subjected to two million cycles if no fractures appeared so as to cause a reduction of stiffness or an increase in deflection beyond the stroke capacity of the hydraulic jacks. The number two million was chosen because it was considered to be the maximum number of cycles that any member in a bridge will experience during its useful life time.

This investigation was limited to specimens made of ASTM A514 steel for flanges and ASTM A36 steel for web.

1.3 Definitions and Nomenclature

Definitions

Endurance Limit (or Fatigue Limit)	the limiting value of the stress below which a material can presumably endure an infinite number of stress cycles, that is, the stress at which the S-N diagram becomes horizontal.
Fatigue Strength	the greatest stress causing failure at a given number of cycles under a prescribed loading condition.
Maximum Stress	the highest algebraic value of the stress in the stress cycle. In this report, the maximum stress corresponds to the extreme fiber stress of the flanges at the instant of maximum load.
Minimum Stress	the lowest algebraic value of the stress in the stress cycle. In this report, the minimum stress was the stress in the extreme fiber at the instant of minimum load.
Stress Range	the algebraic difference of the maximum and minimum stress in a stress cycle.
S-N Diagram	the graphical relationship between stress and number of cycles to failure.

Nomenclature

ϵ_1	the strain at the extremities of web corresponding to the maximum stress.

ϵ_2	the strain at the extremities of web corresponding to the minimum stress.
α	ratio of panel length to web depth (aspect ratio).
β	ratio of web depth to web thickness (slenderness ratio).
σ_{MAX}	maximum stress.
σ_{MIN}	minimum stress.
σ_R	stress range.
σ_Y	static yield stress.
σ_{Yf}	yield stress of flange.
σ_{Yw}	yield stress of web.
σ_u	ultimate tensile stress.

2. DESCRIPTION OF TESTS

2.1 Design Consideration

Previous investigations made on hybrid girders subjected to repeated load revealed that the fatigue strength depends on the magnitude of applied stresses and the web slenderness ratios[4]. It was noted that if the web was too thin with respect to the depth of the girder, excessive lateral deformations of the web under the fatigue load caused the development of fatigue cracks along the web boundaries.

In order to study further the manner in which the behavior of the web will affect fatigue strength, all geometric configurations of a girder that may influence the test results were kept constant for the test specimens except the web slenderness ratio.

A wide range of slenderness ratios were used in this test series. Various web thicknesses were selected so that two groups would be below and one above the maximum slenderness ratio of 170, specified by the AASHO bridge specifications for 33 ksi yield point steel. Such a program then would encompass all practical ranges of ratios that could be encountered in bridge design. The ratios selected for this investigation series were 96, 144 and 288 which correspond to 3/8 in., 1/4 in., and 1/8 in. thick web, respectively. In all specimens, the web depth and the flange dimensions were kept constant and equal to 36 in. for the web and 8 in. x 1/2 in. for the flanges.

Since the purpose of this investigation was to obtain fatigue strength with respect to a number of cycles rather than to establish an endurance limit, it was decided that the specimens be subjected to various maximum stress levels; namely, 20, 30, 40 and 50 ksi. Thus, it was necessary that the specimens be tested both above and below the web yield point. The stress ranges were chosen as 10, 15, and 25 ksi.

A schematic array of the stress levels and the corresponding stress ranges are given for each test specimen together with the nominal web slenderness ratios in Table I.

2.2 Test Program and Test Specimens

The test program was divided into two parts: Series A and Series B. Series A consisted of fourteen specimens and Series B consisted of six specimens which were duplicates of a part of Series A as shown in Table I.

In order that the test results could be compared with previous investigations,[4] [5] it was decided to use ASTM A514 steel for the flanges and ASTM A36 steel for the web.

All test panels had 8 in. x 1/2 in. flanges and a web depth of 36 in. Transverse stiffeners were placed 36 in. apart giving the panel an aspect ratio of one. The stiffeners were cut short 2 in. from the tension flange to reduce possible premature fatigue damage to the flange. All specimens were fabricated by the manual arc welding process with E7018 electrode for the fillet weld between the flange and web and E7010 for the fillet weld between the web and the stiffeners.

To prevent tilting of a girder, during the test, a sufficient number of lateral supports were used. The bracing system was designed so that it only allowed vertical movements.

2.2.1 Series A

The test set up for this series consisted of three major parts: two loading fixtures and a test panel (Figure 1). The loading fixtures and specimens were fabricated so that they could be bolted together thus permitting reuse of the same fixtures for all fourteen panel specimens.

It has been shown by laboratory tests that friction type joints with high strength steel bolts are superior to others and that the fatigue strength of such bolted joints approach the yield strength of the connected material.[(6)] Based on this test result, the flange and web friction type connections were designed using 1 1/8 in. and 7/8 in. diameter ASTM A490 bolts, respectively.

Figure 2 shows the dimensions of the specimens which were eight feet long and had a single test panel. To prevent the possibility of fatigue cracks initiating at bolt holes, all holes were drilled. All reentrant corners of the bottom flanges were ground smooth to minimize fractures in the tension flange caused by stress concentration.

2.2.2 Series B

After observing some undesirable fractures in the tension flange near the bolted connection, it was decided to alter the test set up from using panel specimens to using full length specimens. Figure 3 shows the dimensions of these girders together with the shear and bending moment diagrams. The geometry and crossectional dimensions of the Series B girder were the same as the Series A girder except that the Series B specimens had two test panels.

There were a total of six specimens fabricated, five of which had a 1/8 in. thick web and one had a 1/4 in. thick web. All specimens had the same thickness of web plate throughout except one with 1/8 in. thick web which was to be subjected to a stress range from 25 ksi to 50 ksi. For this specimen a 3/16 in. web plate was used in the shear span to increase shear capacity and to minimize vertical deflection.

2.3 Material Properties

In order to keep the physical properties of the steel plates used for fabrication as uniform as possible, all plates of the same thickness came from one heat.

Both chemical and physical properties of each component plate used for the girder specimens are presented in Table II. The chemical properties were supplied by the fabricator and the physical properties were determined in the laboratory by means of tensile coupon tests using the same plate as used in fabrication of the specimens. It should be noted that the yield stresses given in Table II were obtained under zero strain rate and are referred to as the static yield stress. Typical stress vs. strain diagrams for A36 steel and A514 steel are shown in Figures 4 and 5, respectively.

2.4 Reference Loads

All reference loads used for testing were computed based on the actual measured dimensions given in Table III and the static yield stresses obtained from the tensile coupon tests given in Table II.

Whenever the maximum stress did not exceed the yield point of the web, the usual Mc/I formula was used in computing the reference loads. However, for those specimens that were subjected to a stress above the static yield point of the web material, reference loads were computed assuming an elasto-plastic stress distribution based on the linear stress distribution. All tests loads used for the fatigue test were corrected for the inertia effect on the dynamic response of the girder even though it was very small.

2.5 Instrumentation

In order to observe the general behavior of a girder under static load, vertical deflections were measured at the center and at the points where the load was applied by means of an engineer's level reading 1/100 in. graduated scales secured on a specimen.

To study the behavior of the web panel, lateral web deflections were measured at 3 in. by 3 in. grid points as shown in Figure 6. The measurements were made using a special rig with a 1/1000 in. dial gage attached to a movable block that could be positioned at any desired level (Figure 7).

Electrical resistance strain gages (SR-4) were mounted on both surfaces of the web plate and on the flanges to check the response of the girder to the applied static load. No attempt was made to evaluate stress distributions in the web panel using the data from these SR-4 gages.

Slip gages, each consisting of a 1/1000 in. dial gage, were placed at the load points and at the center line of the specimens in the hope of obtaining an indication of the loss of girder stiffness due to the formation of cracks.

2.6 Designation of Specimens

Each specimen was numbered with respect to the thickness of web, stress range and test series:

Series A	Series B
21020A	21020B
21530A	21530B
21540A	21540B
22540A	22540B
22550A	22550B
41020A	none
41530A	none
41540A	none
42540A	none
42550A	42550B
61530A	none
61540A	none
62540A	none
62550A	none

The first number designates the thickness of the web in multiples of 1/16 in. The next four numbers designate the stress range with the first two as the minimum stress and the last two as the maximum stress. The letter shows pertinent series.

As an example, 41530A represents the specimen which had a 1/4 in. web and was subjected to the stress range from the minimum of 15 ksi to the maximum of 30 ksi at the extreme fibers of flanges and belongs to Series A.

3. TESTING OF SPECIMENS

3.1 General Testing Procedure

The testing procedure of a girder consisted of three phases: first, the initial static load test, wherein the load was increased up to the maximum load that was to be applied in the fatigue test; second, the fatigue test in which the loads were fluctuated between a positive minimum and a positive maximum load; third, the static test to the ultimate load after completion of the fatigue test.

The first phase of testing of a girder was initiated by taking readings on all instruments at zero load. After the initial readings were taken, the loads were then applied gradually to the next designated load level at which measurements were again taken. The increment between each load level was predetermined as a fraction of the total load to facilitate the test procedure.

Upon reaching the maximum test load, a thorough inspection of the entire girder was made. All yield lines were noted by observing hairline cracks on the whitewashed surfaces and welds were carefully examined visually with the aid of a magnifying glass to see that no cracks were present. The load was then reduced to zero to measure residual deformations. In all tests, the lateral deflections of the web were taken only at zero load and at the load levels corresponding to the minimum and maximum fatigue test load.

The second phase of testing was followed immediately after the static load test. Pulsating load was applied to the specimen by means of two hydraulic jacks each having 120 kip capacity under dynamic load. The pulsating load was achieved by oil pressure supplied to the jacks by a Riehle-Los pulsater producing the sinusoidal load application to the specimen at about 300 cpm.

Throughout the fatigue test, a visual inspection of all welds and the heat affected areas due to welding was made with the aid of a magnifying glass at 3 hours intervals (about 54,000 cycles). However, a more frequent observation was made after the first crack was noted and continued until the end of the fatigue testing. Slip gage readings were recorded at each inspection period to check the loss of stiffness due to the presence of cracks.

To observe the crack propogation, growth of cracks were marked and measured at each inspection period. A typical example of such growth is shown in Figure 8. When cracks occurred on the outside of the test section proper, the fatigue testing was stopped temporarily to repair the cracks. Following the repair, the testing was resumed until two million cycles were reached unless detrimental reduction in the girder stiffness was noted due to the fracture of the repair or cracks occurred in the test panel.

The third phase of testing, i.e., the ultimate static load test, was carried out on some of the fatigued specimens.

3.2 Repair of Fatigue Cracks

The cracks were separated into two categories: the one formed in the test section proper, the other on the outside of the test section.

If cracks were observed within the test section, no repairs were made. However, if cracks were found on the outside of the test section, the cracks were repaired immediately by first gouging out the cracks by the "arc-air" method and then depositing fresh weld. Both low hydrogen electrodes and regular "shield arc" electrodes were used in repairing the cracks. AWS E11018 electrodes were used for the repairs made on the flange, E7018 electrodes were used for the fillet weld at the juncture of flange and web, and E7010 electrodes were used at the juncture of web and stiffener. All E11018 and E7018 electrodes were kept in an oven until their use.

After the welding, all welds on the tension flange were ground smooth to the surface and polished with an electric sander to eliminate rough surfaces which could have been detrimental to fatigue life because of stress concentration. All other repairs were left untreated.

3.3 Testing of 1/8 inch web specimens

No fatigue cracks were observed in Specimens 21020A, 21530A, 21020B and 21530B within 2 million cycles and will not be discussed. The specimens which had cracks are discussed briefly below:

3.3.1 Specimen 21540A

The first crack was found along the toe of the fillet weld in the heat affected zone in the web at the juncture of the compression flange and web at 294,000 cycles. (Figure 9). It was noted that the crack was already 3 inches in length when found but appeared only on one side of the web. Since the crack occurred in the test section, the testing was continued without repair until it penetrated through the web. At this point the testing was terminated (295,500 cycles).

3.3.2 Specimen 21540B

Due to premature cracks in the shear span at 71,000 cycles the testing was stopped to replace the shear spans with thicker web sections. Splices were made by butt welding the webs and flanges. However, reoccurrance of cracking in the butt weld joint compelled the termination of the testing at 277,400 cycles.

3.3.3 Specimen 22540A

At 1,310,600 cycles the first crack was located in the tension flange at one of the reentrant corners (Figure 10). This crack which had initiated at the edge of the tension flange propagated 3/4 in. into the flange. Immediate repair of the crack followed according to the procedures mentioned previously. The crack reappeared at 1,333,000 cycles. When testing was stopped for repair, this crack had propagated 5 in. across the tension flange and 3 1/2 in. upward into the web (Figures 11,12). The crack was again repaired but, at this time, all repaired welds were radiographed to check flaws in the repaired area. The results indicated that the repaired area had some slag inclusion.

Notwithstanding the defects in the repair, the specimen was retested. At 1,722,450 cycles a new crack was found along the toe of the compression flange to web fillet weld in the test section. The crack was already 5 inches long and appeared on both sides of the web when it was found. The testing was terminated at this point.

3.3.4 Specimen 22540B

The first crack was found within the test section proper along the toe of the compression flange to web fillet weld at 1,588,000 cycles (Figure 13). The crack had already grown to 3 1/2 in. in length and had appeared on both sides of the web. The testing was terminated at 1,709,000 cycles.

3.3.5 Specimen 22550A

Two cracks were observed at 617,000 cycles within the test panel. One crack was found in the compression part of the web along the toe of the fillet weld and had a length of 3/4 in. while the other was discovered at the bottom of the transverse stiffener and had propagated 3 in. downward to the tension flange (Figure 14).

Since eventual fracture of the tension flange similar to that shown in Figure 7 would occur due to propagation of the latter crack, the testing was terminated.

3.3.6 Specimen 22550B

As mentioned previously, this specimen had a 3/16 in. web section in the shear spans. As anticipated, the first crack appeared at the bottom end of the spliced section at 217,500 cycles. The crack was repaired and testing was resumed until the first crack was noted in the test panel at 672,300 cycles. The crack was located in the compression side of the web along the fillet weld similar to that shown in Figure 15.

3.4 Testing of 1/4 inch web specimens

No fatigue cracks were observed in Specimens 41020A and 41530A and they will not be discussed further. The following specimens had cracks are discussed briefly below:

3.4.1 Specimen 41540A

A crack which initiated in the bottom flange under the flange-web juncture within the test panel was found at 630,000 cycles (Figure 16). When the crack was discovered, it had already penetrated into the web 1 3/4 in. The testing was discontinued to avoid complete fracture in the tension flange as it will be retested under static load for the ultimate capacity.

3.4.2 Specimen 42540A

No crack was observed within the test panel. At 947,200 cycles a crack was found at the reentrant corner in the tension flange (Figure 17). The crack had already penetrated 2 1/4 in. into the web and had propagated 6 1/4 in. across the flange. The crack was repaired and radiographed. Similar flaws as observed in 22540A were found in the repaired weld. When a crack reappeared in the repaired area at 2,118,100 cycles, the testing was discontinued.

3.4.3 Specimen 42550A

A crack in the tension flange at the reentrant corner was located at 639,500 cycles (Figure 18). The crack was repaired and radiographed. This repair also had some slag inclusions. As it was observed in Specimen 42540A that the defective weld sustained more than a million cycles of load repetition, the testing was continued even after observing a possible minute crack in the repaired area. However, this time a wide crack appeared within 20,000 cycles and the entire tension flange was fractured by 760,400 cycles.

3.4.4 Specimen 42550B

This specimen was a duplicate of specimen 42550A. At 421,000 cycles a crack was found near the cut-off end of the transverse stiffener along the toe of the weld (Figure 19, 20). When this crack was found, it was 2 5/8 in. long and had propagated 1/8 in. below the end of the transverse stiffener. At 500,000 cycles, the crack had penetrated into the bottom flange and by 563,000 cycles, the bottom flange was completely fractured (Figure 7, 21).

3.5 Testing of 3/8 inch web specimens

No cracks were noted in Specimens 61530A and 62540A and they will not be discussed. The following specimens had cracks and will be discussed briefly:

3.5.1 Specimen 61540A

Three cracks were found within the test section at 1,394,800 cycles. Two cracks occurred near the cut-off end of the transverse stiffener and one occurred at the tension flange to web juncture (Figure 22). A close examination of the latter crack revealed that the crack had initiated at the point where manual welding operation was interrupted in making the continuous longitudinal fillet weld (Figure 23). Since further cycling would have caused complete fracture in the tension flange, the testing was discontinued.

3.5.2 Specimen 62550A

A crack was initiated at the edge of the tension flange due to the presence of a small notch caused by the flame cutting process. When it was found at 479,000 cycles the crack had propagated 4 1/4 in. into the tension flange and penetrated 3/4 in. upward into the web (Figure 24). The testing was terminated at this point.

4. TEST RESULTS

4.1 Fatigue Cracks

The total number of cycles to which each specimen was subjected are presented in Figures 25 through 28. In each figure, the fluctuating stresses for each specimen are depicted at pertinent minimum and maximum stress levels to indicate their relative positions with respect to the stress range spectrum. The arrow marks shown on each stress cycle curve denote the number of cycles at which the first crack was observed. The numerical values corresponding to the arrow marks are listed in the fourth column of Table IV. It can be seen from these values that all specimens subjected to a maximum stress below 30 ksi sustained two million cycles without any cracks in the test specimens. However, for those specimens which were strained beyond the yield strain of the web, fatigue cracks developed in both the compression and tension side of the girders. The actual magnitudes of the strains at the extremities of the web corresponding to the minimum and maximum test stresses are shown in the second and third column of Table IV as ratios of the extreme web fiber strain to the yield strain of the web. The values larger than 1.0 imply that the extreme web fibers were strained beyond the elastic limit.

The comments given in the last column of Table IV describe the types of crack observed. They are divided into three types according to the location of cracks for the sake of convenience: Type 1, cracks found in the compression part of the web along the toe of the flange to web fillet weld; Type 2, cracks found in the web at the end of the vertical stiffener to web boundary; and Type 3, cracks initiated at stress concentrated areas, at the notch along the edges of the tension flange, at discontinuities in the fillet weld or at the juncture of the tension flange and the web. These types of cracks are shown in Figure 29.

4.1.1 Type 1 Crack Specimens: 21540A, 22540A, 22550A, 22540B, 22550B

It is seen from Table IV that Type 1 cracks were found only in 1/8 inch web specimens. A Type 1 crack is shown in Figure 30. Formation of this type of crack can be attributed to excessive lateral movements of the web under a pulsating load.

A typical example of such lateral movements of the web at a cross section taken through the crack is given in Figure 31, together with a contour diagram showing the buckling pattern. The shaded portion of the diagram represents the range of lateral movements of the web between P_{min} and P_{max}.

4.1.2 Type 2 Crack Specimen: 22550A, 61540A, 42550B

Type 2 cracks were those found near the bottom of the transverse stiffener either in the heat affected area of the web along the toe of the fillet weld or in the weld itself. For all cases, the cracks were found when they were already 2 to 3 inches long and had propagated in both directions, upward along the toe of the fillet weld and downward into the tension flange. Figure 32 shows a typical crack of this type. In this figure, the numbers represent a sequence of crack propagation and the corresponding cycles are presented at the bottom. It is important to note that in all cases, the Type 2 cracks led to fractures in the tension flange which in turn led to final failure.

4.1.3 Type 3 Crack Specimens: 21540A, 41540A, 42540A, 42550A, 61540A, 62550A

Type 3 cracks include all those which initiated in the tension flange. For clarity, the Type 3 crack is subdivided into 3 groups according to where it originated.

The first group, Type 3a, includes those cracks which initiated at the flange to web juncture. Such a crack is mainly due to incomplete penetration of the fillet weld leaving an internal stress concentration point or to discontinuities on the weld surface as a result of manual welding operation. Photographs illustrating these cases are shown in Figures 33 and 23, respectively.

The second group, Type 3b, includes those cracks which initiated at the edge of the tension flange. The cause of such a crack was due to the presence of notches at the edge of the plate as a result of the flame cutting process. Such notches are generally formed by a sudden increase in oxygen pressure to the cutting torch or an uneven travel speed of the cutting torch.

The third group, Type 3c, includes those cracks which originated at the reentrant corners of the tension flange. This type of crack was not intended to be studied in this test program; however, because they did appear, their results are presented herein.

Repairs made on these cracks were found to be unsuccessful, and this was the prime reason for changing from the panel specimens to the full length specimens.

4.2 Web Deflections

Three different patterns of initial web lateral deflections were observed (Figure 34). The magnitude of the initial web deflection varied from an almost neglible amount in the 3/8 in. web specimen to as much as twice the web thickness in the 1/8 in. web specimens.

The initial web deflections influenced both patterns and magnitudes of web deflection as load increased. Diagrams in Figure 34 reveal that increase in load simply distorted and changed the amplitude of the buckles. The change in amplitude occurred mainly in the compression part of the web where the amplitudes of the initial buckles were increased but kept the same deflected configuration.

5. DISCUSSION OF TEST RESULTS

5.1 Effect of Web Behavior on Fatigue Life

Web lateral deflections at x=0 and y=9 in. for 1/8 in. web specimens are listed in Table V. In order to compare the measured values on a common basis the deflections are presented in ratios of the web thicknesses. The coordinate point x=0 and y=9 in. was chosen because, in most cases, the maximum lateral web deflections were observed at this point under the maximum load. The web lateral deflection values at zero, minimum, and maximum load are presented in the first three columns after the specimen numbers. The web movements between the minimum and the maximum load are listed in the next column. In the last column, the numbers of cycles to initial crack are listed for each specimen.

Judging from the values listed in the last column of Table V, it is apparent that the fatigue behavior was influenced by the web deflections. Two influencing factors were evident from the test results. One factor is the initial deflections and the other factor is the web flexing action between the minimum and the maximum load. The extent to which these factors affected the fatigue behavior was dependent upon the magnitude of the initial web deflections and the magnitude of the web flexing action in the compression part of the web panels.

When a web panel has a relatively large initial web deflection, it is expected that additional lateral movement of the web takes place upon increasing the load. As a result, the edges of the web tend to move toward one another. However, since both edges are anchored to relatively stiff flanges, the edge of the web cannot move freely. As a consequence, tensile membrane stresses are induced in the web due to the effect of the elongations in the web. Therefore, it is expected that fatigue cracks may initiate as a result of the membrane stress.

From the previous paragraph it is obvious that a web panel with larger initial deflections develops larger tensile membrane stress than a web panel with smaller initial deflections. Since the membrane stress is in tension, it has a stabilizing effect on further lateral deflection of the web due to additional loads. Hence, it can be said that the range of lateral deflections between any two given loads is inversely proportional to the magnitude of the initial web deflections. In this respect, the web flexing action is controlled to a certain extent by the initial web deflections. Therefore, greater web flexing action is expected to occur only with a moderate magnitude of the initial deflection. As a result, the fatigue cracks which occurred in specimens 21540A and 22550B were due to a large magnitude of the web flexing action with a relatively small amount of initial deflection. In contrast to the fatigue cracks due primarily to the web flexing action, a crack found in Specimen 22550A was caused mainly by the tensile membrane stresses. As may be seen in Table V, this specimen had an initial web deflection 1.75 times its thickness.

In summary, based on the foregoing discussion, it is evident that the fatigue cracks found in the compression part of the web along the toe of the fillet weld are produced, in general, by a combination of two major factors: the initial web deflection and the web flexing action. The effect of these factors on the development of the fatigue cracks are not well defined. Furthermore, the magnitudes of initial deflections vary from girder to girder with the fabrication procedures.

5.2 Stress Level

The fatigue cracks were found only in those specimens whose maximum applied strains exceeded the yield strain at the extremities of the web. A consistant relationship between the number of cycles to initial crack and the maximum applied strain in the web can be seen in Table IV. Regardless of the web thickness, all specimens sustained more than two million cycles when they were subjected to a maximum stress not exceeding 30 ksi. This test result establishes a possible lower bound on applied stresses if no fatigue crack is desired within two million cycles.

For the specimens subjected to a higher stress than the yield point of the respective web materials, the fluctuating stresses in the flange and web followed different paths during the stress cycles. In Figure 35, an idealized stress-strain relationship of the fluctuating stress in the flanges and the extremities of the web are illustrated. Since the maximum applied stress was less than the flange yield point, the fluctuating stress in the flange remained elastic. However, due to yielding in the web, the maximum stress in the web remained constant at its yield point, and the stresses fluctuated below the yield point but equal in magnitude to the stress range in the flange. In Figure 35, the points A and D correspond to the stress range in the flange and the points C and E correspond to the stress range in the web.

5.3 Stress Range

The number of cycles to initial cracks versus stress ranges for each specimen is presented in Figure 36 in the form of a bar chart. The number of cycles are scaled as the ordinate and the stress ranges to which each specimen was subjected are layed out as the abscissa. To have a uniform basis of comparison, the height of the bar describing the number of cycles are cut off at two million cycles as this point was considered as the minimum expected fatigue life under a given stress condition for this investigation. Based on this postulation, the average number of cycles to initial crack of each stress range group is presented as $\bar{x}$. A comparison of $\bar{x}$ values shows clearly that the stress range is a definite factor affecting fatigue strength.

The effect of the stress range on the fatigue strength is particularly reflected on the Type 1 cracks. The values listed in the last column of Table V are plotted in Figure 37. The ordinate is denoted by σ_R , and the number of cycles is the abscissa. In an attempt to establish an S-N relationship, a solid line is fitted in the test data with an assumption that no Type 1 failure would take place if the stress range is below 15 ksi.

5.4 Type 2 cracks

Type 2 cracks were developed primarily due to the tensile membrane stresses coupled with the web flexing action. The extent to which the membrane stress affected a Type 2 crack cannot be clearly determined. However, the test results seemed to indicate that the membrane stress played a major role in developing the Type 2 crack because the crack appeared not only in 1/8 inch web specimens but also in 1/4 and 3/8 in. web specimens where extremely little web flexing action occured.

Since no strains were measured to evaluate the actual stress condition, it is difficult to pin point the effect of the membrane stresses on the fatigue crack. However, from the known information the following analysis can be made to explain the stress condition at the end of the transverse stiffener. Two stress components that constituting the membrane stress can be considered. One component is that of stress concentration at the end of the transverse stiffener causing localized magnification of stresses. The other component is the locked in stress caused by the welding process. This stress is commonly known as welding residual stress. As both of these stress components are additive to each other in the region near the bottom of the transverse stiffener, it is expected that premature yielding near the end of the transverse stiffener would result. Since any process which causes yielding of a material will reduce its fatigue strength, it is expected that a fatigue crack would develop at the end of the transverse stiffener.

The test results of Type 2 cracks are presented in Figure 38, as a function of the ratio of the maximum applied stress, σ_{max} to the yield point of the web material, σ_{yw}. It is seen that only a small change in the ratio of σ_{max} to σ_{yw} results in a considerable increase in the fatigue life. When the ratio was reduced to 0.8, no Type 2 crack was observed in any of the test specimens.

5.5 Type 3 Cracks

As mentioned before, the Type 3 crack was formed mainly due to fabrication irregularities. Since these imparing factors are, in general, difficult to control and predict, a scatter in the test results would be expected. In Figure 39, the number of cycles to the first crack are presented according to the group described previously in Section 4.1. It is seen in this figure that the fabrication irregularities reduced the fatigue life considerably.

To aid in interpreting the test data the results were compared with the results of a test program on axially loaded T-specimens connected with a fillet weld(7) as this test condition simulated the bottom flange of a girder. The comparision indicated that the test results reported herein fell between the S-N curves of R = 1/2 and 1/8 of the T-specimen tests where R is the ratio of σ_{min} to σ_{max}. This means that the fatigue strength of girders are slightly lower than that of the T-specimens. This difference could be attributed to the fact that the T-specimens were fabricated by the automatic submerged arc welding process under a controlled condition, whereas the specimens of this test series were fabricated following commercial shop practices.

6. SUMMARY AND CONCLUSIONS

6.1 Summary

The objectives of this investigation were to determine the manner in which thin web hybrid girders of ASTM A514 steel flange and ASTM A36 steel web fail when subjected to repeated loads and to determine what factors influence the fatigue strength of this type of girder. In particular, the study was directed to the effect of web slenderness ratios on fatigue behavior in which the extremities of the web are subjected to a strain beyond the yield strain. Attention was also given to the effect of girder details and to fabrication irregularities.

Web slenderness ratios of the test specimens were 96, 144 and 288 for the 36 in. deep web section. To ascertain the effect of yielding in the web, the extreme fibers of the flanges were subjected to four different stress levels, namely, 20, 30, 40 and 50 ksi. The stress ranges were varied from 10 ksi to 25 ksi. The loading arrangements were such that the test sections experienced only pure bending moment.

The testing was divided into two series. Of twenty specimens investigated, fourteen specimens were tested in the first series (Series A) and the remaining six specimens were tested as duplicates of the first in the second series (Series B).

The test results led to the conclusion that fatigue cracks occurred within 2 million cycles if applied stress exceeded the yield point of the web material. Three types of cracks were observed according to their location: Type 1 cracks were those found in the compression part of the web along the toe of the flange to web fillet weld; Type 2 cracks were those in the heat affected area of the web which initiated near the end of the transverse stiffeners; Type 3 cracks were those initiating within the tension flange.

The test results indicated that whereas both Type 2 and 3 cracks propagated fast and led to final failure of the girder, Type 1 cracks propagated relatively slow and often stabilized. The stiffness of the girders was not greatly reduced due to a Type 1 crack although the crack extended to as much as 6 inches.

6.2 Conclusions

The conclusions drawn from the results of the investigation reported herein may be summarized as follows:

1. The fatigue strength of welded hybrid plate girders cannot be related directly to that of the homogeneous girders because of yielding in the web at its extremities. For the specimens subjected to an applied stress below the yield point of the web material, no cracks were found within two million cycles.

2. In general, Series A (panel specimens) test results were in agreement with Series B (full length specimens). In particular, whenever no cracks were found in Series A, the Series B specimen exhibited the same characteristic.

3. Two factors caused fatigue failures in thin web hybrid girders. One factor was that of the web flexing action and the other was the fluctuating membrane stresses. For 1/8" web specimens in which the web flexing action was in the order of the web thickness or more, a crack initiated at the flange to web boundary in the compression side (Type 1 crack).

4. Within the limitations of this investigation, it can be said that the stress range had definite effect on the fatigue strength of the hybrid girders although it is difficult to assess its absolute effect on fatigue behavior.

5. Cracks initiating at the stiffener to web boundary in the tension side of the web (Type 2 crack) led to a fracture in the tension flange when enough cycles were applied. In all cases, Type 2 cracks were found in those specimens which were subjected to the maximum stress higher than the yield point of the web.

6. The test results indicated that reducing fabrication irregularities will improve the fatigue life.

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3. Krauchevko, P. Ye., "Ustalostuaya Peochnost", Vysshaya Shkola, Moscow, 1960. (English Translation by the Pergamon Press).

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7. Reemsnyder, H. S., "Fatigue Strength of Longitudinal Fillet Weldments in Constructional Alloy Steel", Welding Journal, October, 1965.

TABLE I

STRESS LEVELS AND STRESS RANGES FOR EACH TEST SPECIMEN

Specimen No. Series A	Specimen No. Series B	Nominal Web Thickness	Slenderness Ratio	Stress Levels (Min-Max)	Stress Ranges (ksi)
21020A	21020B	1/8 inch	288	10-20	10
21530A	21530B			15-30	15
21540A	21540B			15-40	25
22540A	22540B			25-40	15
22550A	22550B			25-50	25
41020A	--	1/4 inch	144	10-20	10
41530A	--			15-30	15
41540A	--			15-40	25
42540A	--			25-40	15
42550A	42550B			25-50	25
61530A	--	3/8 inch	96	15-30	15
61540A	--			15-40	25
62540A	--			25-40	15
62550A	--			25-50	25

TABLE II

CHEMICAL AND PHYSICAL PROPERTIES OF GIRDER COMPONENT PLATES

Series	ASTM DESIG.	Thickness (In.)	CHEMICAL PROPERTIES (IN %)										PHYSICAL PROPERTIES		
			C	Mn	P	S	Cu	Si	Mo	Cr	Ti	B	σ_y (ksi)	σ_u (ksi)	ϵ (%)*
A-Series	A514	1/2	.19	.64	.013	.018	.24	.32	.23	1.04	.07	.002	104.711	116.372	11.910
	A36	3/8	.22	.52	.010	.020		.06					41.540	64.676	33.710
	A36	1/4	.19	.45	.011	.013		.05					36.660	59.040	29.518
	A36	1/8											33.874	45.898	30.434
B-Series	SSS100A	1/2	.17	.58	.010	.018	.28	.35	.20	1.03	.06	.002	104.00	110.40	13.680
	A36	1/4	.20	.38	.006	.014		.03					40.888	66.068	27.835
	A36	1/8	.13	.64	.008	.029	.26	.022					32.350	45.000	31.200

*Elongation in 8 in. Gage Length.

TABLE III

CROSS SECTIONAL DIMENSIONS

SPECIMEN NO.	NOMINAL DIMENSIONS Flange	Web	MEASURED DIMENSIONS Flange	Web
21020A	8"x1/2"	36"x1/8"	8.043 x 0.526	36 x 0.121
21530A			8.031 x 0.527	36 x 0.122
21540A			8.042 x 0.526	36 x 0.121
22540A			8.0156 x 0.528	36 x 0.124
22550A			7.950 x 0.528	36 x 0.122
21020B	8"x1/2"	36"x1/8"	8.028 x 0.526	36 x .1337
21530B			8.020 x 0.532	36 x .1337
21540B			8.003 x 0.528	36 x .1337
22540B			8.018 x 0.522	36 x .1337
22550B			8.016 x 0.522	36 x .1337
41020A	8"x1/2"	36"x1/4"	8.085 x 0.528	36 x 0.257
41530A			7.969 x 0.527	36 x 0.254
41540A			7.948 x 0.529	36 x 0.252
42540A			8.042 x 0.527	36 x 0.261
42550A			8.093 x 0.529	36 x 0.256
42550B	8"x1/2"	36"x1/4"	8.007 x 0.522	36 x .2448
61530A	8"x1/2"	36"x3/8"	7.950 x 0.527	36 x 0.379
61540A			7.9275 x 0.529	36 x 0.388
62540A			8.042 x 0.527	36 x 0.388
62550A			8.0104 x 0.525	36 x 0.389

All dimensions are in inches

TABLE IV
FATIGUE TEST RESULTS

Specimen	β^*	$\frac{\epsilon_1}{\epsilon_{YW}}$	$\frac{\epsilon_2}{\epsilon_{YW}}$	Cycles to Initial Crack	Type of Crack
21020A	295	0.584	0.292	2,927,000	No Crack
21530A	295	0.875	0.437	2,000,000	No Crack
21540A	295	1.168	0.437	294,000	1
22540A	295	1.168	0.730	1,318,700	3c
				1,722,400	1
22550A	295	1.470	0.730	617,800	1,2
21020B	269	0.603	0.301	2,233,000	No Crack
21530B	269	0.905	0.452	2,137,300	No Crack
21540B	269	1.206	0.447	277,400	Testing Discontinued
22540B	269	1.206	0.749	1,588,000	1
22550B	269	1.500	0.749	672,000	1
41020A	141	0.525	0.262	2,311,200	No Crack
41530A	141	0.798	0.399	2,000,000	No Crack
41540A	141	1.060	0.399	630,000	3a
42540A	141	1.060	0.662	947,200	3c
42550A	141	1.325	0.662	639,500	3c
42550B	147	1.208	0.604	421,000	2
61530A	93	0.700	0.350	2,000,000	No Crack
61540A	93	0.935	0.350	1,394,800	2, 3a
62540A	93	0.935	0.584	2,530,000	No Crack
62550A	93	1.168	0.584	479,000	3b

* Based on actual measured dimensions.

TABLE V

WEB LATERAL DEFLECTIONS
AT X=0 and Y=9 INCHES FOR 1/8 INCH WEB SPECIMENS

Specimen	Initial $\frac{\delta_0}{t}$	Min. Load $\frac{\delta_1}{t}$	Max. Load $\frac{\delta_2}{t}$	$\frac{\lvert\delta_1 - \delta_2\rvert}{t}$	Cycles to Initial Crack
21020A	0.318	0.608	0.927	0.319	2,927,000*
21530A	1.550	1.980	2.438	0.458	2,000,000*
21540A	0.433	0.209	1.536	1.327	294,000
22540A	0.201	1.865	2.255	0.390	1,722,400
22550A	1.750	2.263	2.680	0.417	617,800
21020B	1.560	1.722	1.862	0.140	2,235,000*
21530B	0.084	0.142	-0.035	0.177	2,137,300*
21540B	0.220	0.382	1.240	0.858	277,390**
22540B	0.735	1.318	1.704	0.386	1,588,000
22550B	0.085	1.170	2.160	0.990	672,260

*No Cracks Observed
**Testing Terminated due to failure in outside of test section

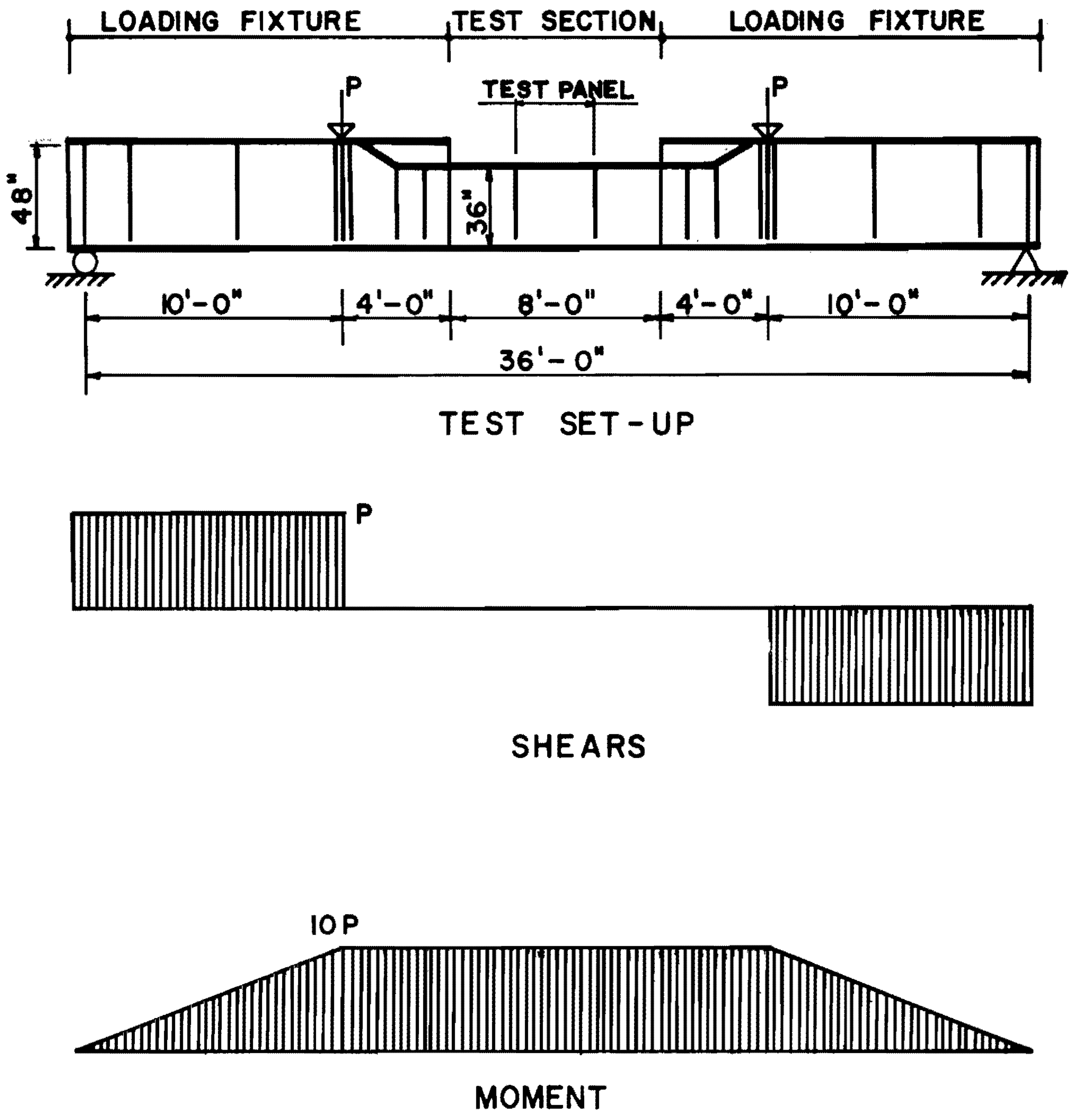


FIG. 1 TEST SETUP FOR A-SERIES

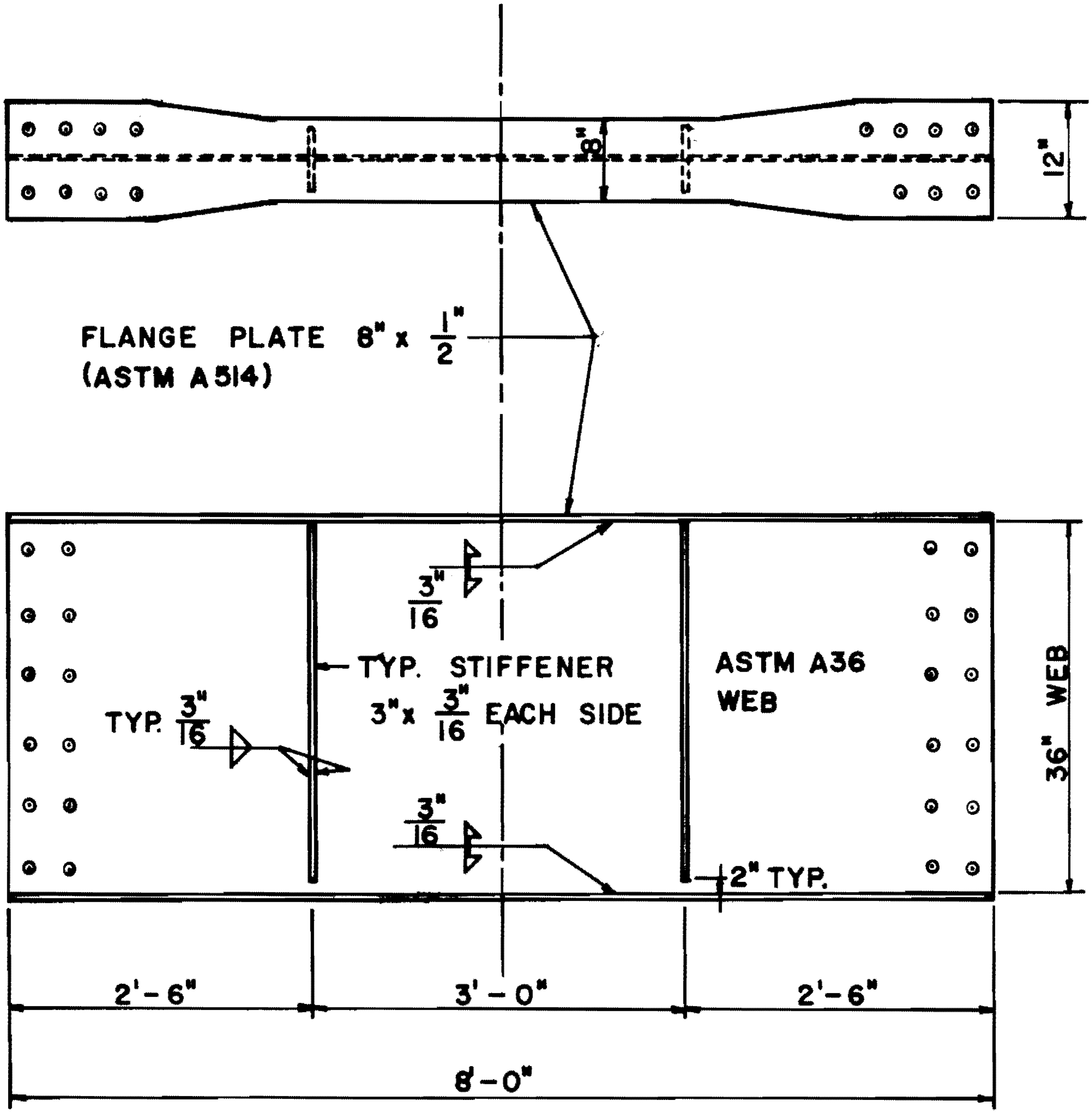


FIG. 2. DIMENSIONS OF A-SERIES SPECIMENS

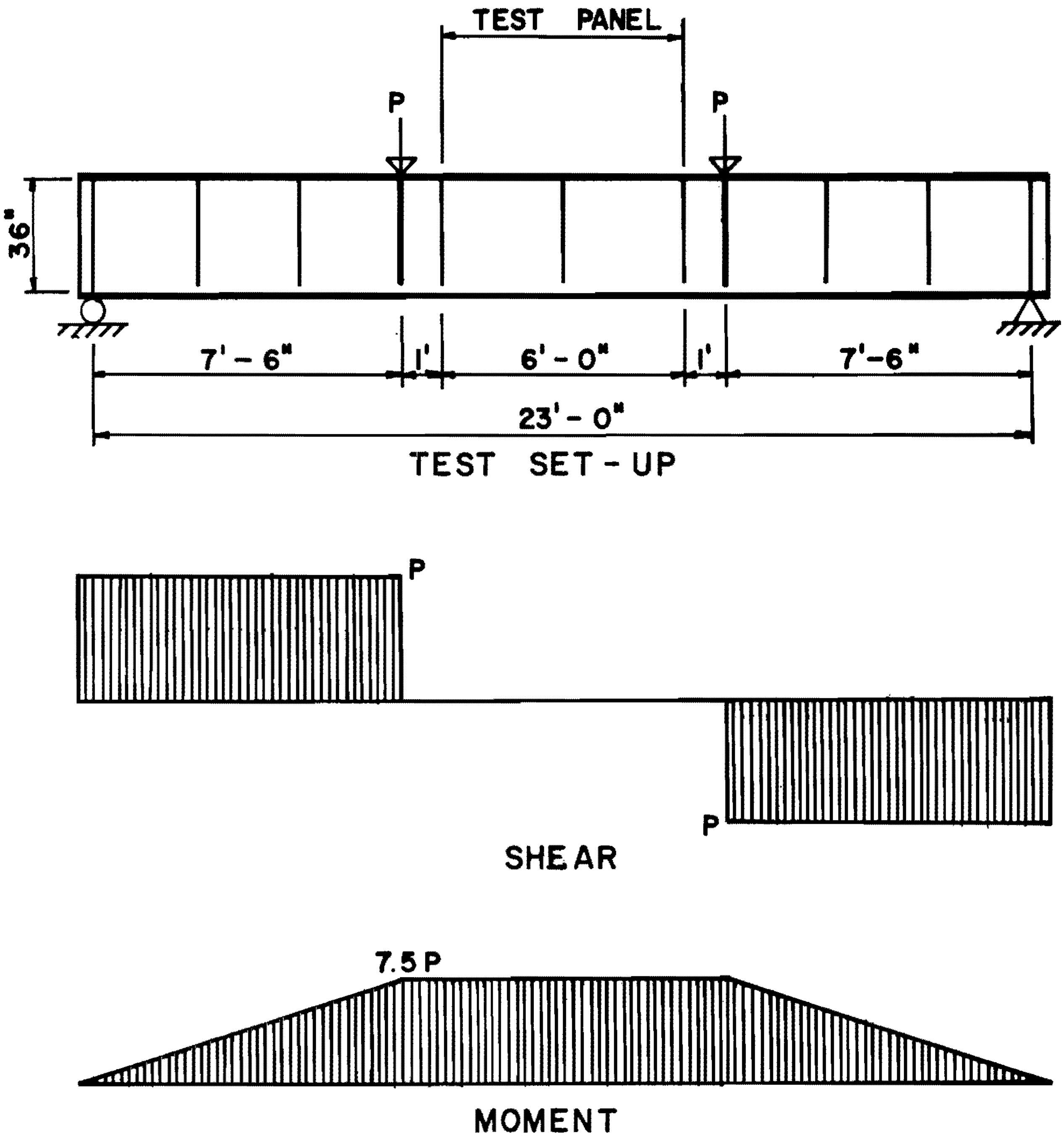


FIG. 3 TEST SETUP FOR B-SERIES

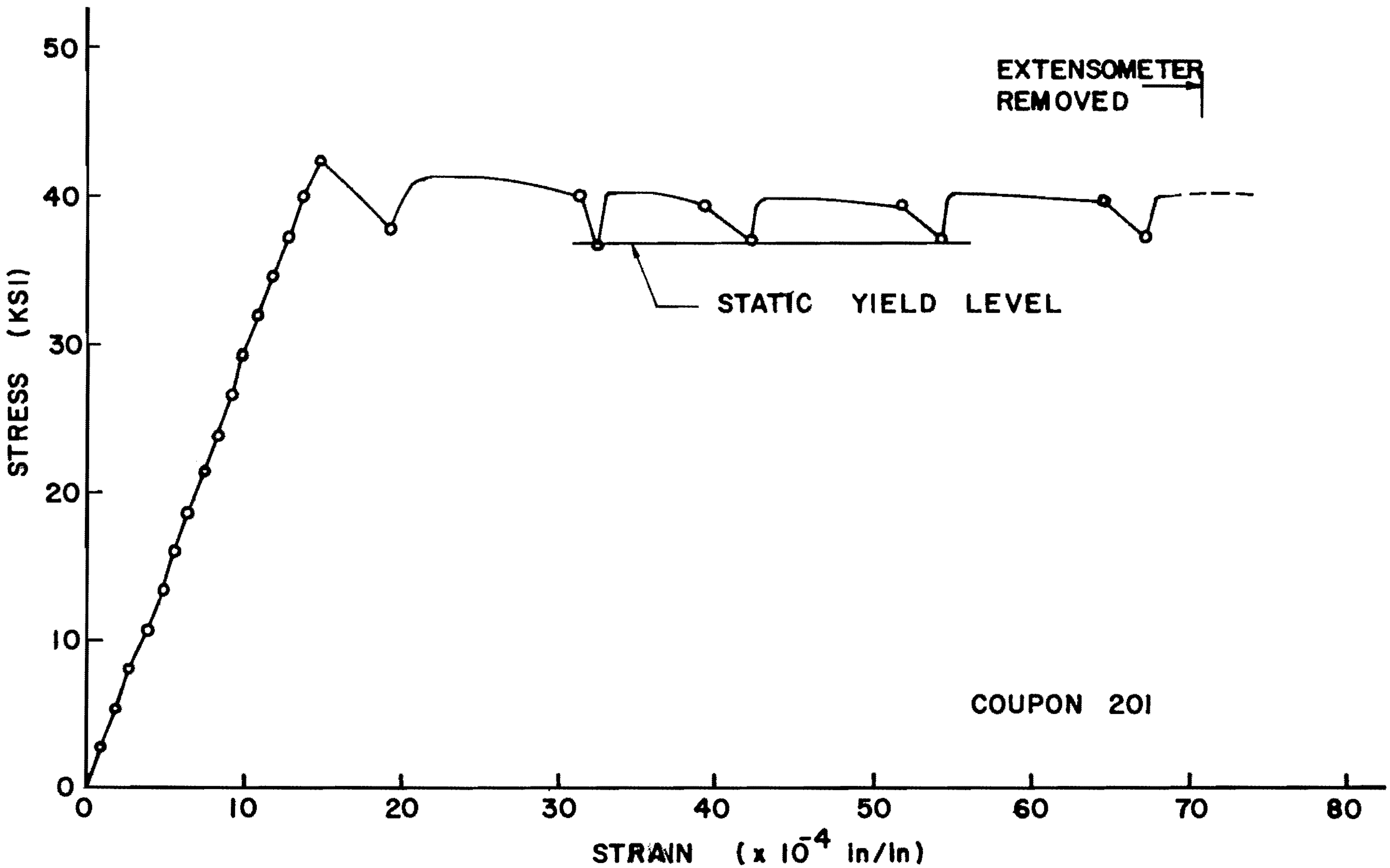


FIG. 4 STRESS-STRAIN CURVE FOR ASTM A-36 STEEL

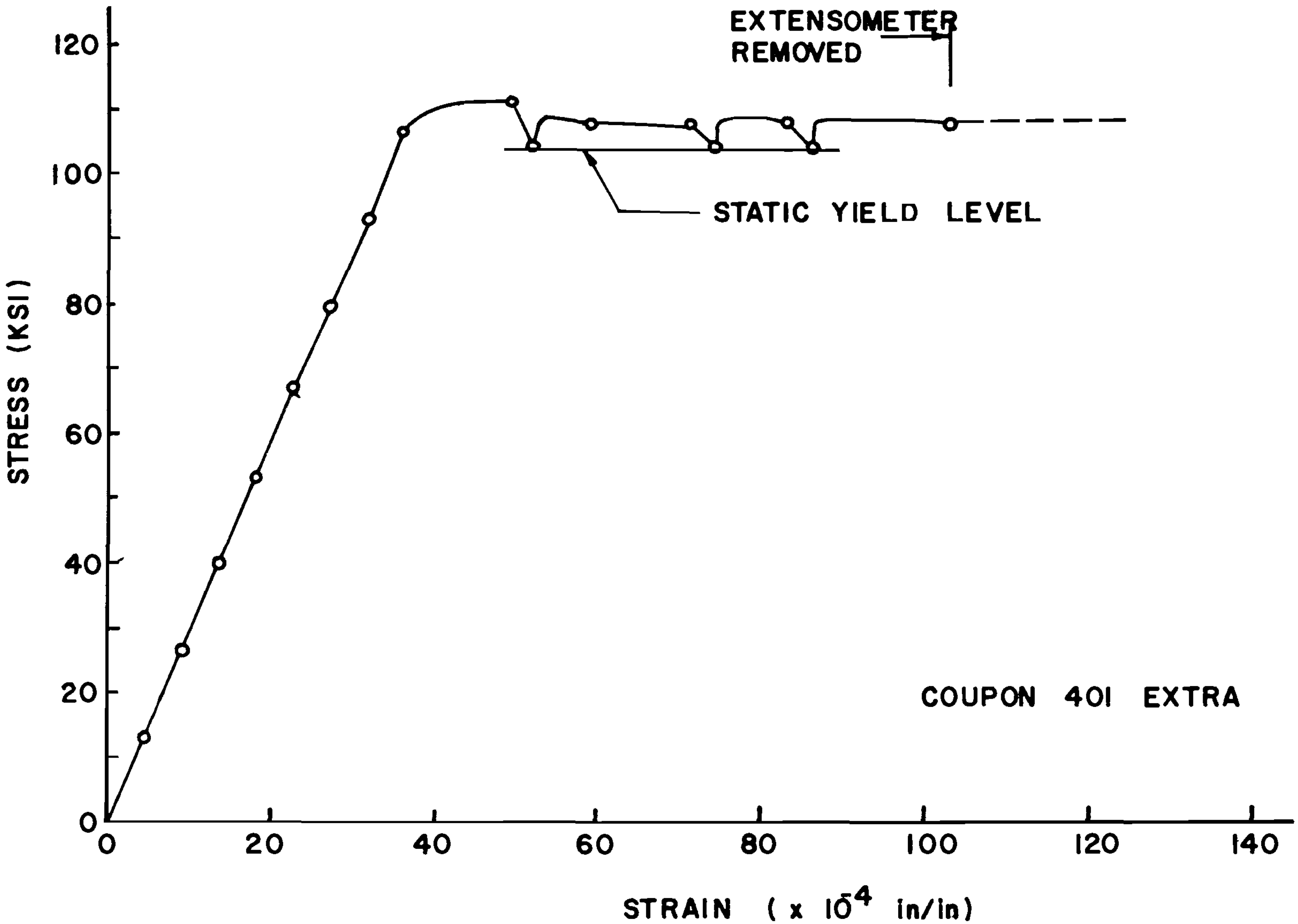


FIG. 5 STRESS-STRAIN CURVE FOR ASTM A- 514 STEEL

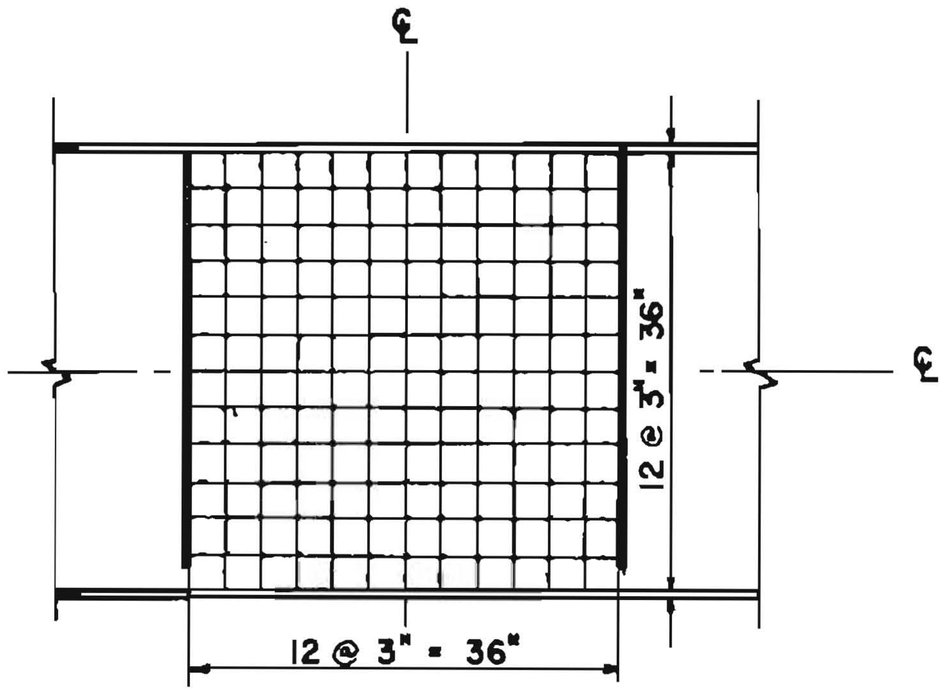


FIG. 6 LOCATIONS OF LATERAL WEB DEFLECTION MEASUREMENTS

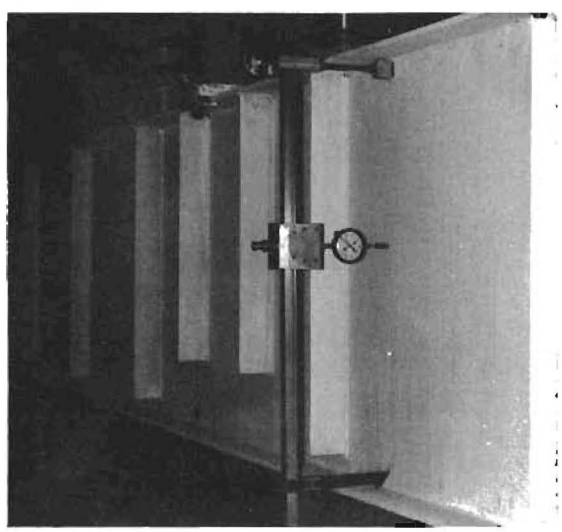
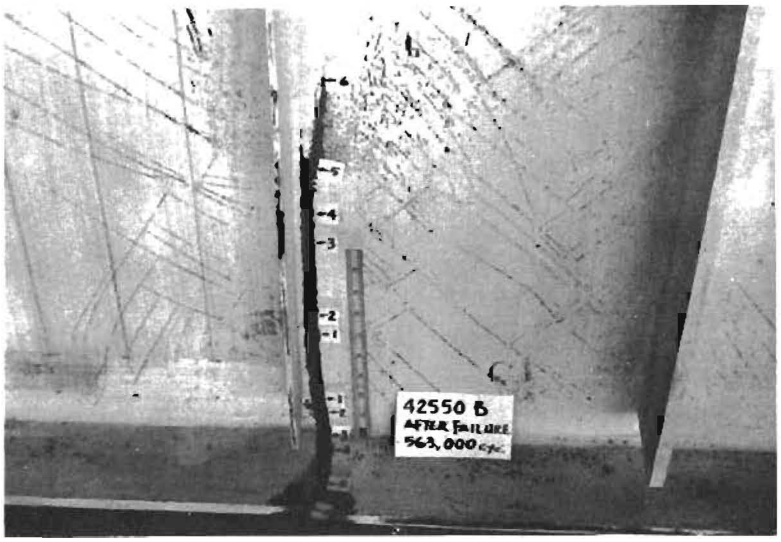


FIG. 7 MOVABLE HEAD DIAL RIG



SPECIMEN 42550 B

1. 421,000 cycles
2. 448,500 cycles
3. 499,000 cycles
4. 536,900 cycles
5. 541,000 cycles
6. 563,000 cycles

FIG. 8 CRACK PROPAGATION - FROM WEB TO FLANGE

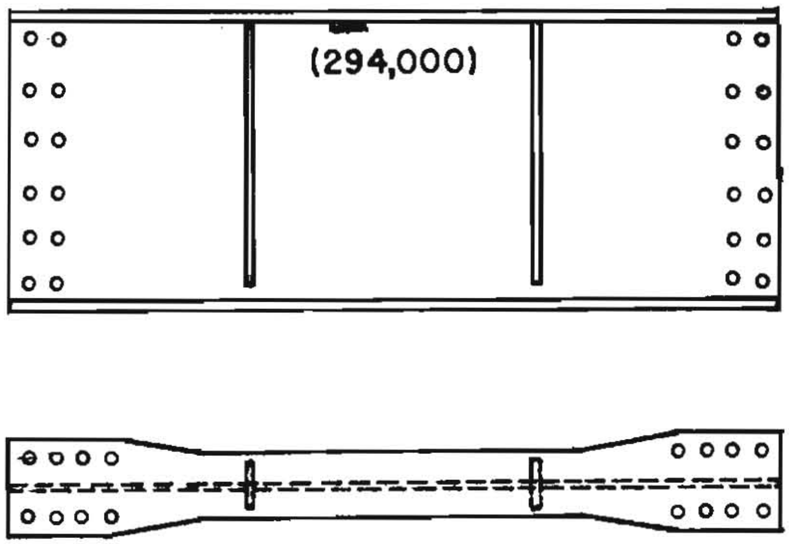


FIG. 9 CRACK LOCATION OF GIRDER 21540 A

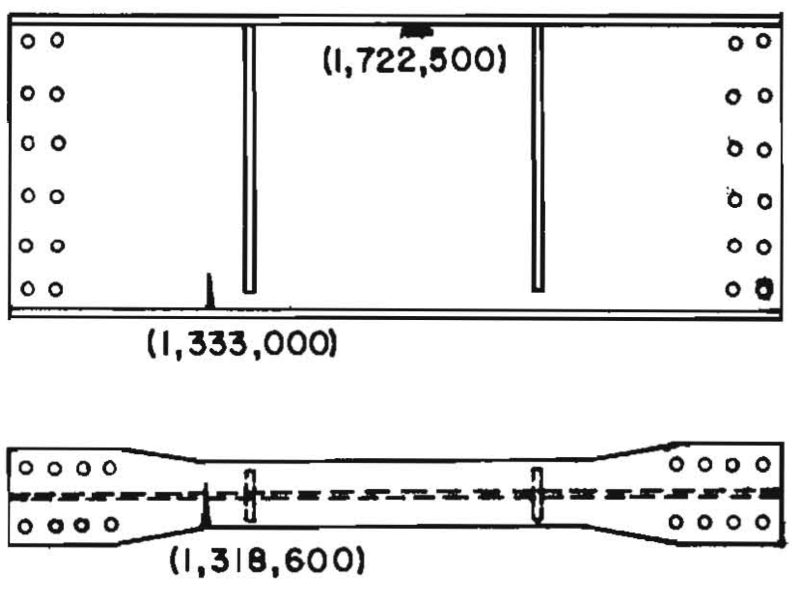


FIG. 10 CRACK LOCATIONS OF GIRDER 22540 A

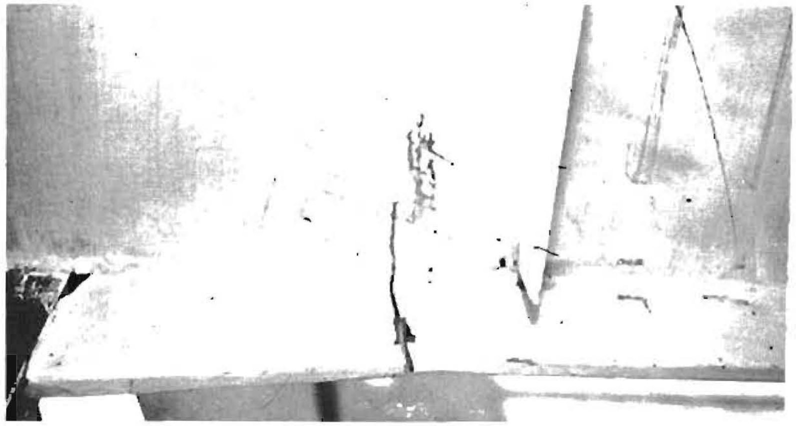


FIG. 11 INITIATION OF CRACK AT REENTRANT CORNER

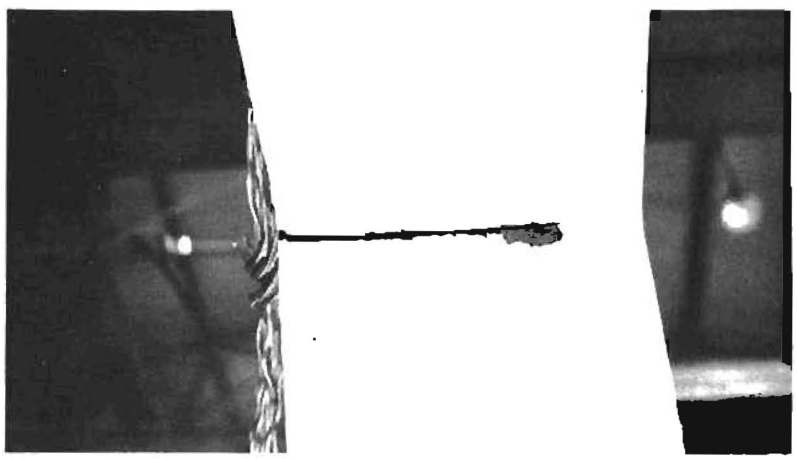


FIG. 12 COMPLETE FRACTURE IN TENSION FLANGE

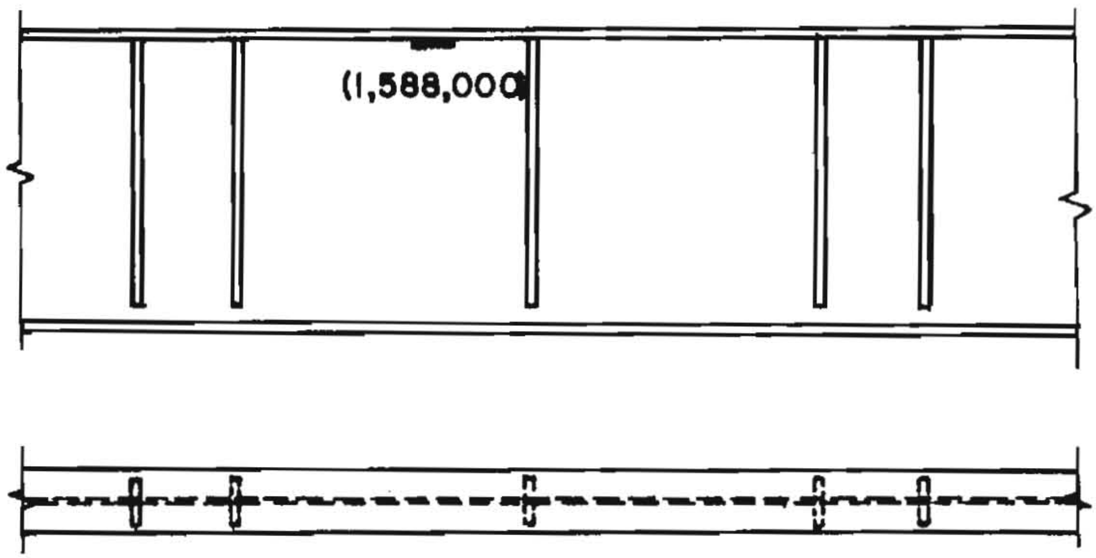


FIG. 13 CRACK LOCATION OF GIRDER 22540 B

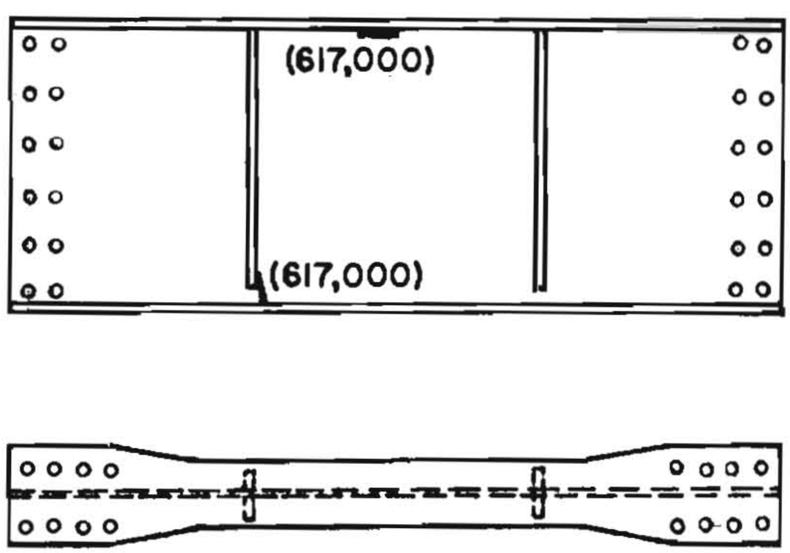


FIG. 14 CRACK LOCATIONS OF GIRDER 22550 A

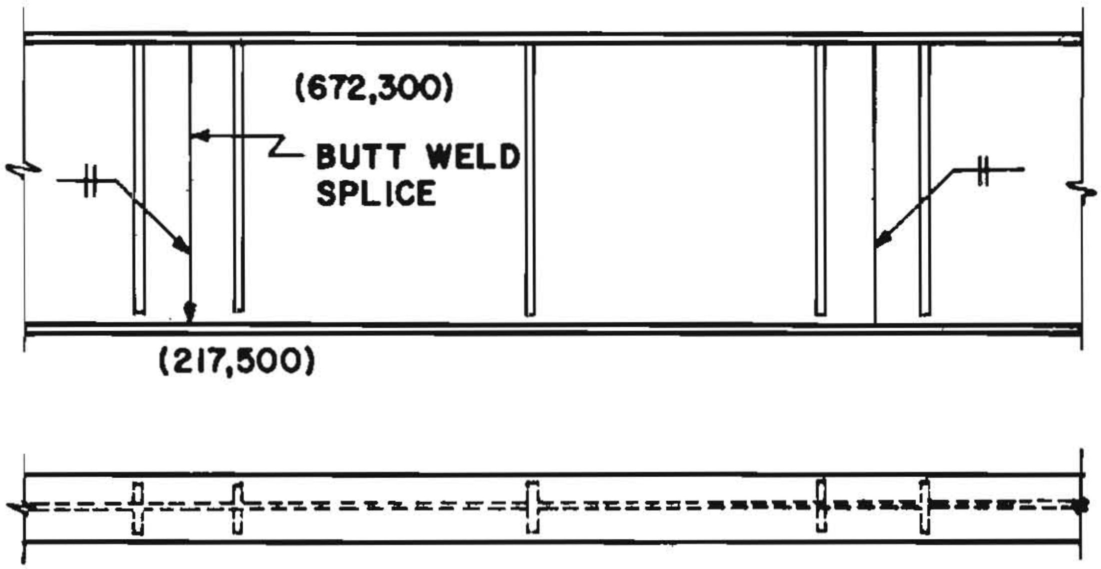


FIG. 15 CRACK LOCATIONS OF GIRDER NO. 22550 B

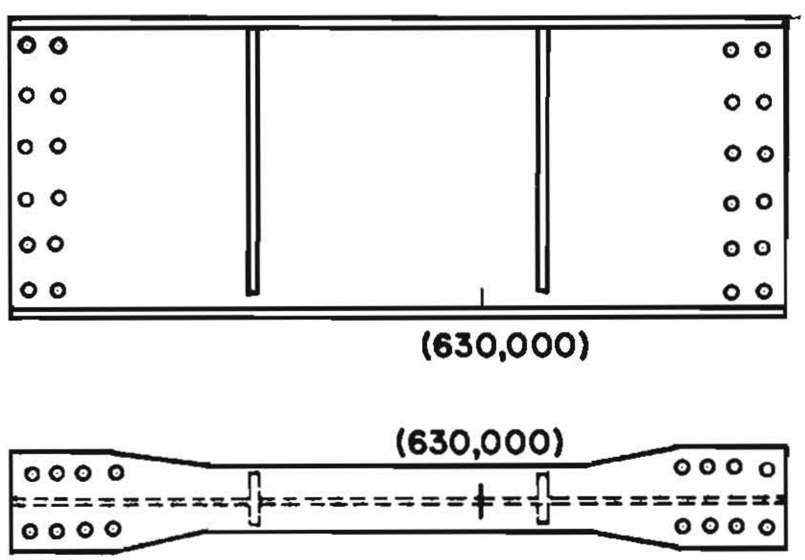


FIG. 16 CRACK LOCATION OF GIRDER NO. 41540 A

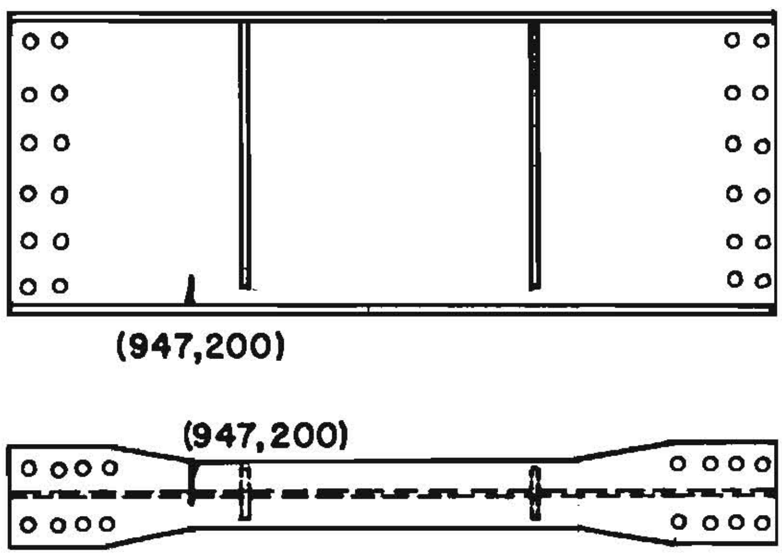


FIG. 17 CRACK LOCATION OF GIRDER 42540 A

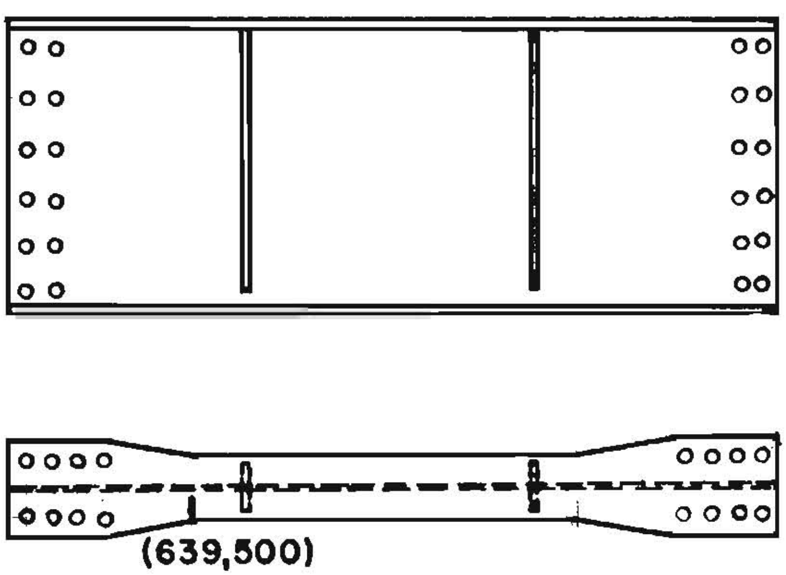


FIG. 18 CRACK LOCATION OF GIRDER 42550 A

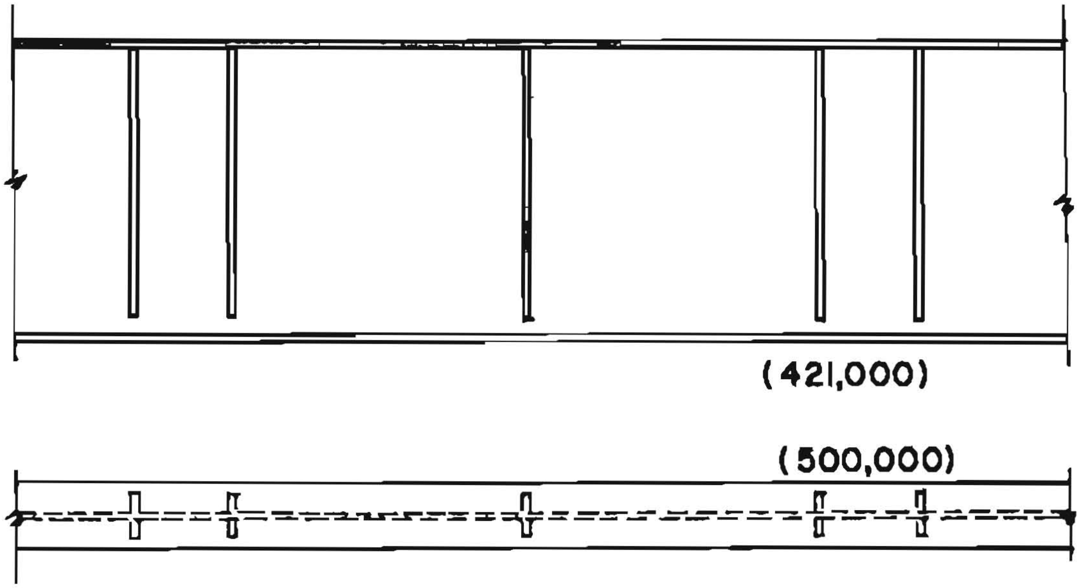


FIG. 19 CRACK LOCATION OF GIRDER NO. 42550 B

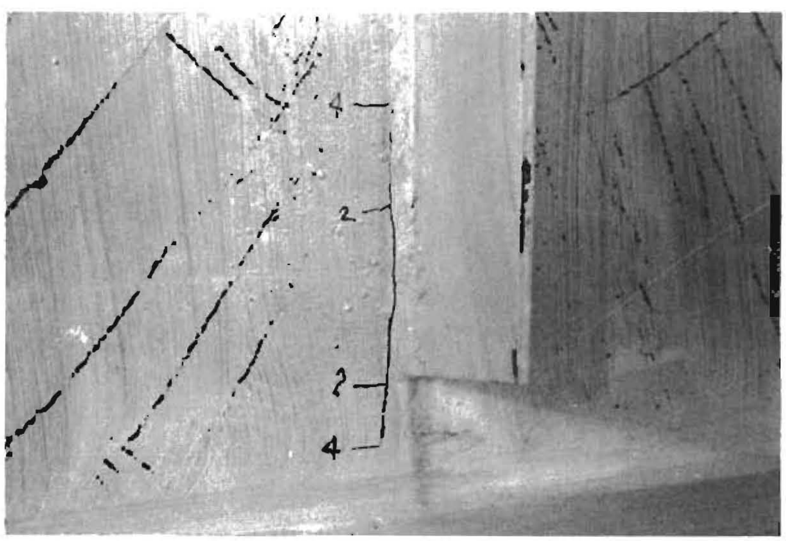


FIG. 20 INITIATION OF CRACK NEAR CUT-OFF END OF VERTICAL STIFFENER

FIG. 21 FRACTURE IN TENSION FLANGE AS A RESULT OF PROPAGATION OF CRACK INITIATED NEAR CUT-OFF END OF VERTICAL STIFFENER

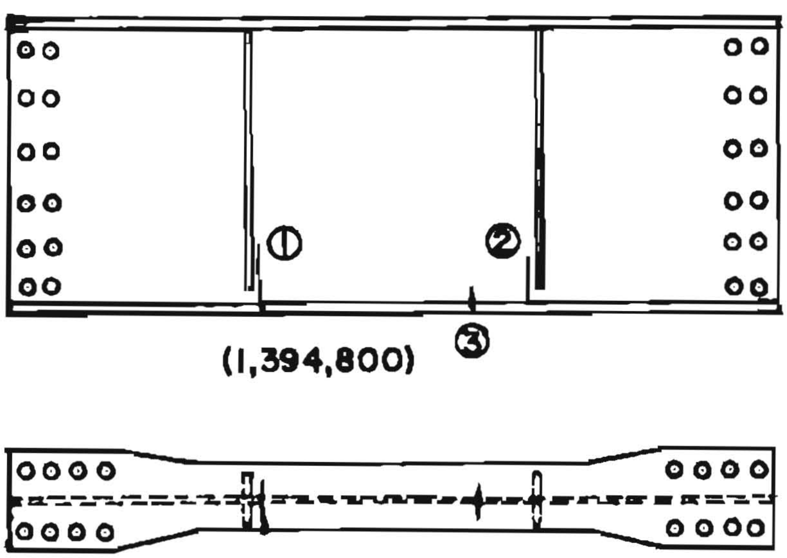


FIG. 22 CRACK LOCATIONS OF GIRDER NO. 61540 A

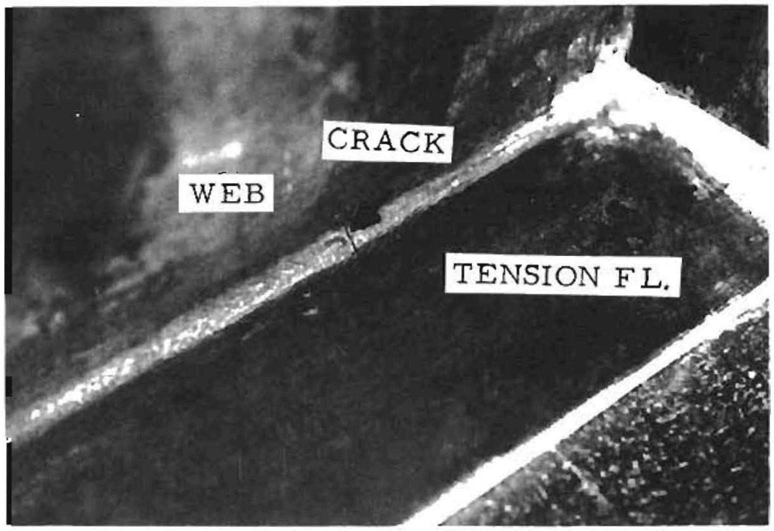


FIG. 23 DISCONTINUITY IN WEB TO TENSION FLANGE FILLET WELD

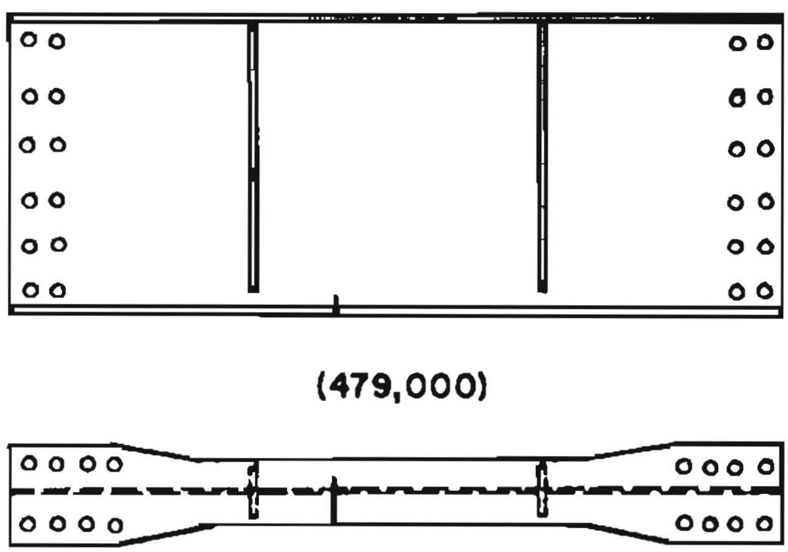


FIG. 24 CRACK LOCATION OF GIRDER 62550 A

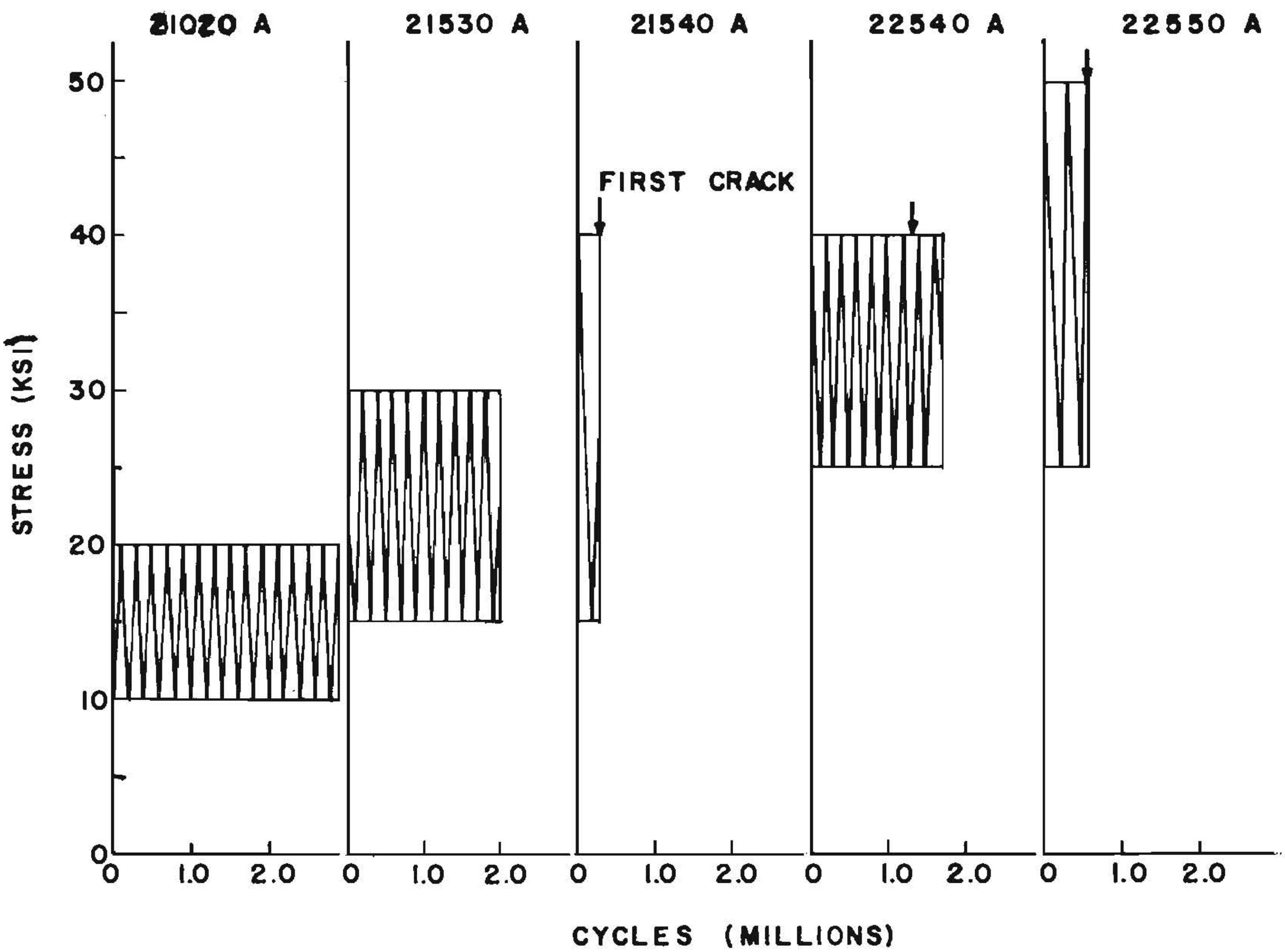


FIG. 25 SUMMARY OF FATIGUE TEST OF 1/8 in. WEB SPECIMENS - A SERIES

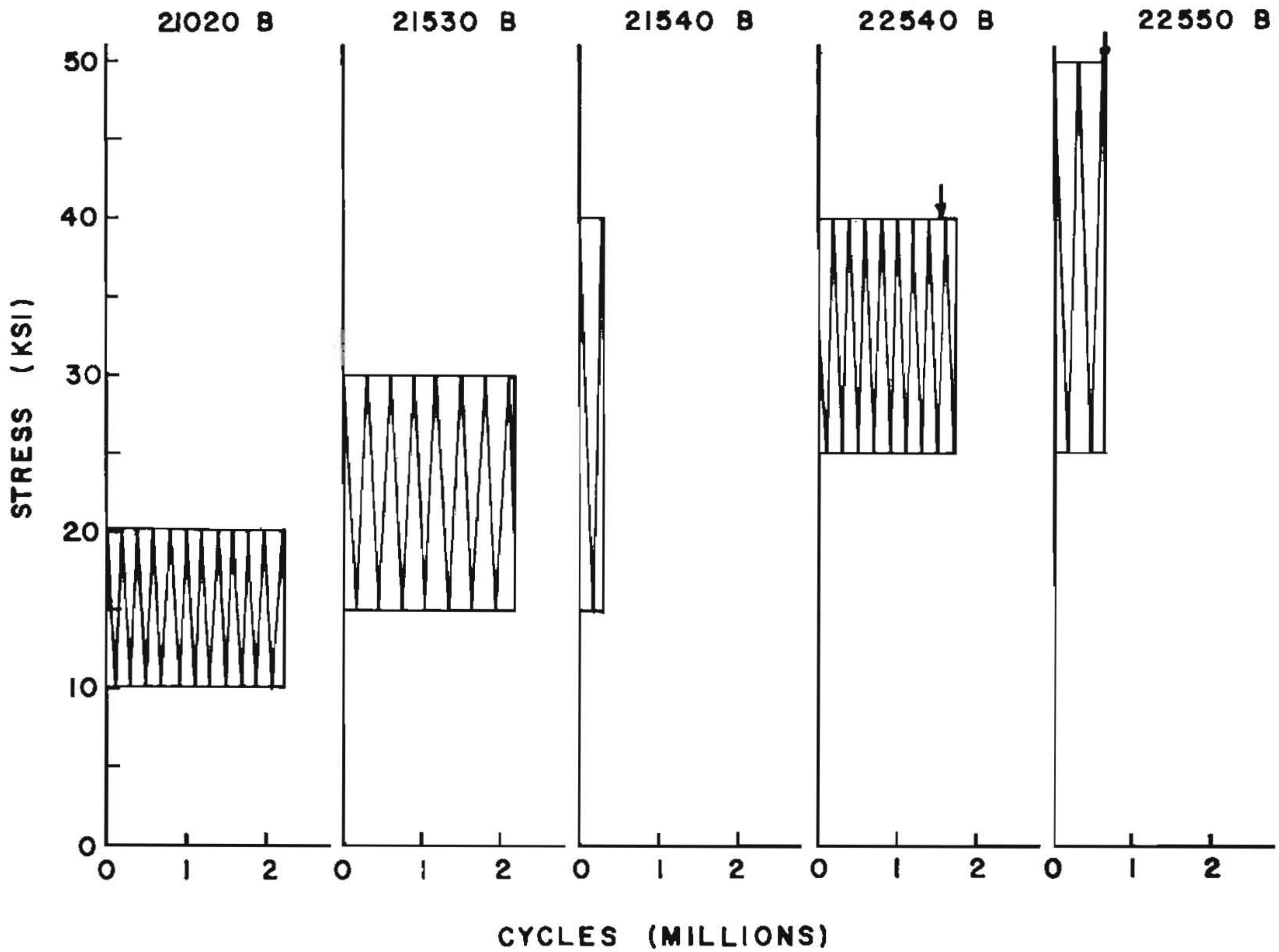


FIG. 26 SUMMARY OF FATIGUE TESTS OF 1/8 in. WEB SPECIMENS - B SERIES

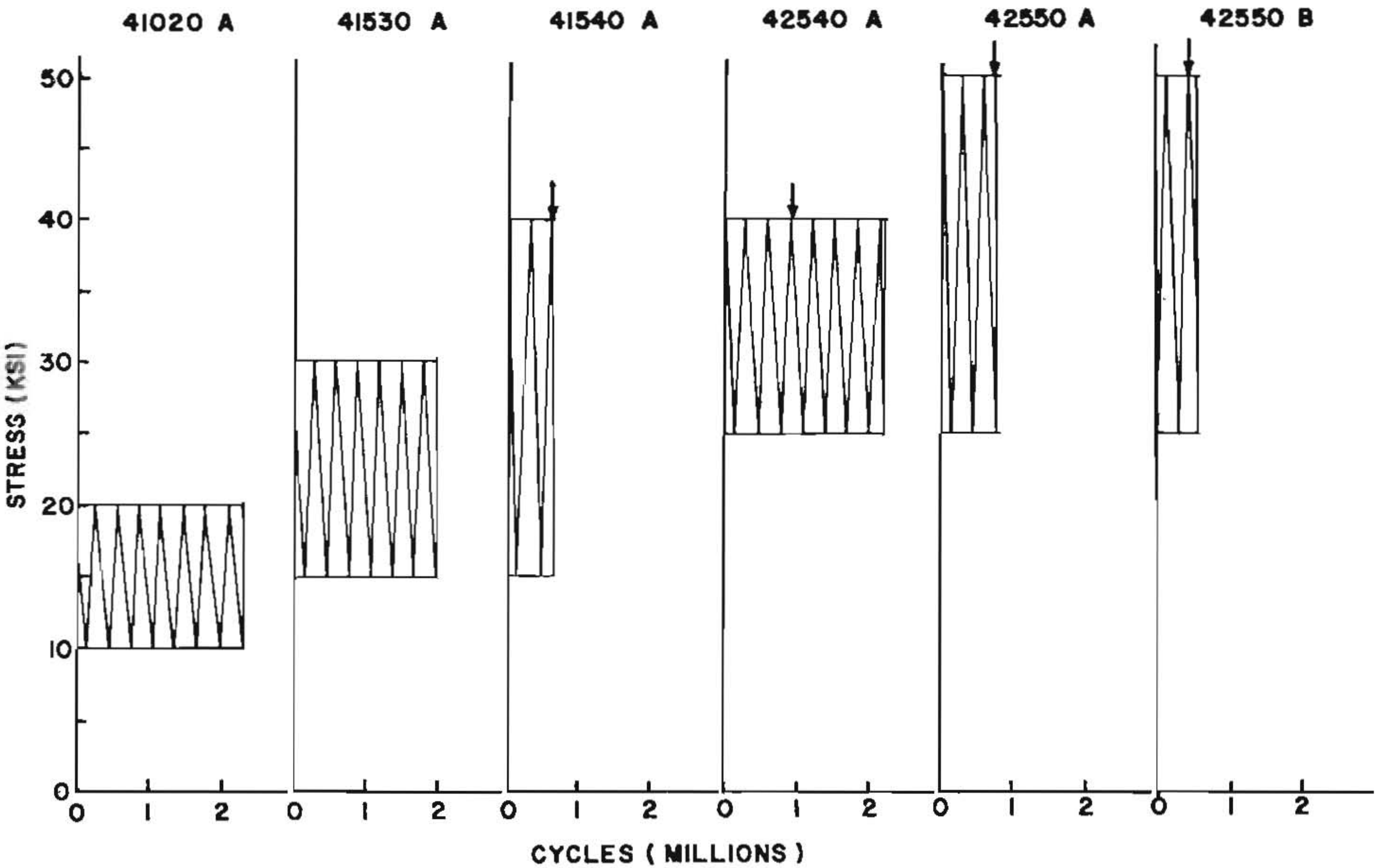


FIG. 27 SUMMARY OF FATIGUE TESTS OF 1/4 IN. WEB SPECIMENS - SERIES A&B

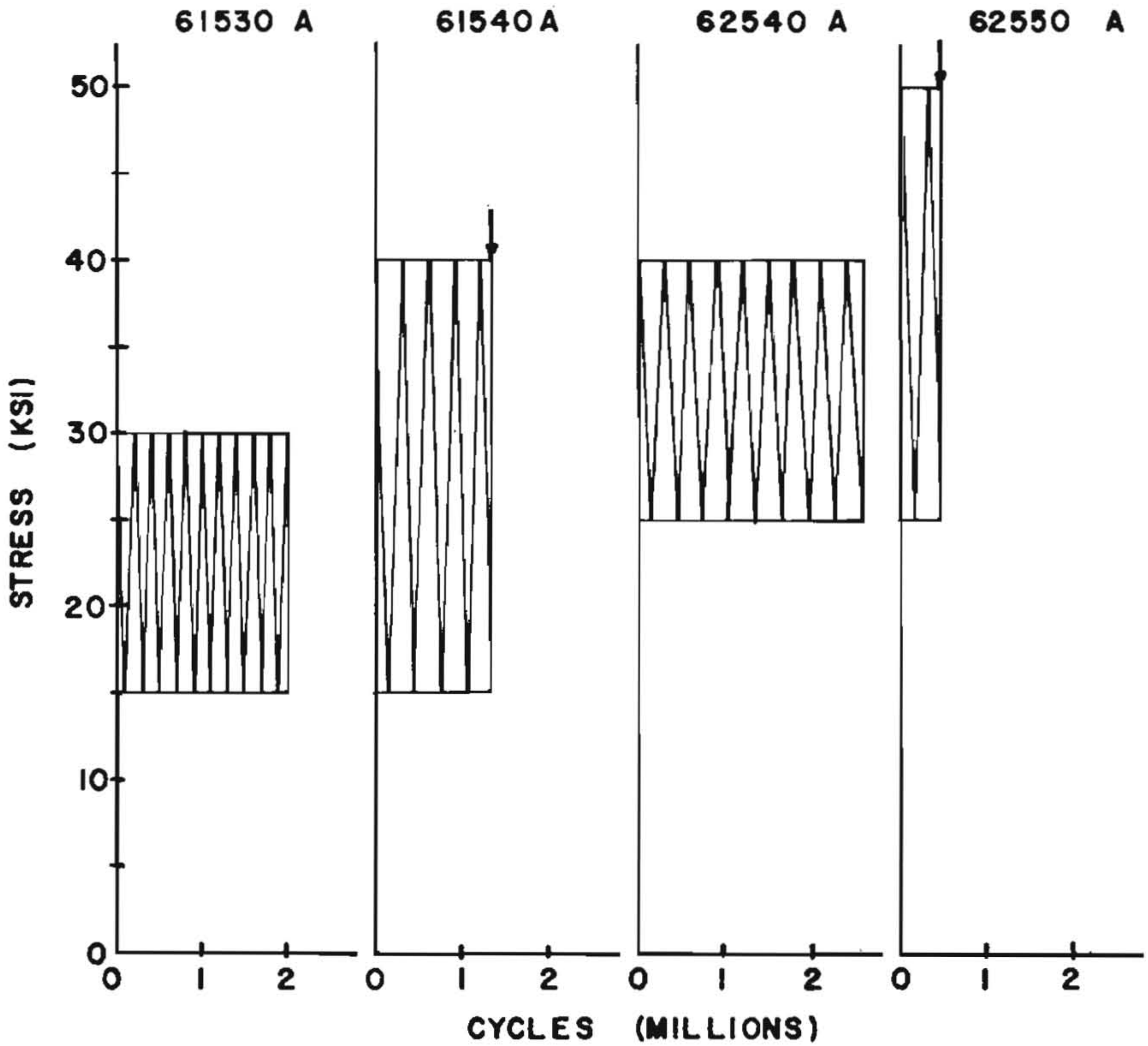


FIG. 28 SUMMARY OF FATIGUE TESTS OF 3/8 in. WEB SPECIMENS - A SERIES

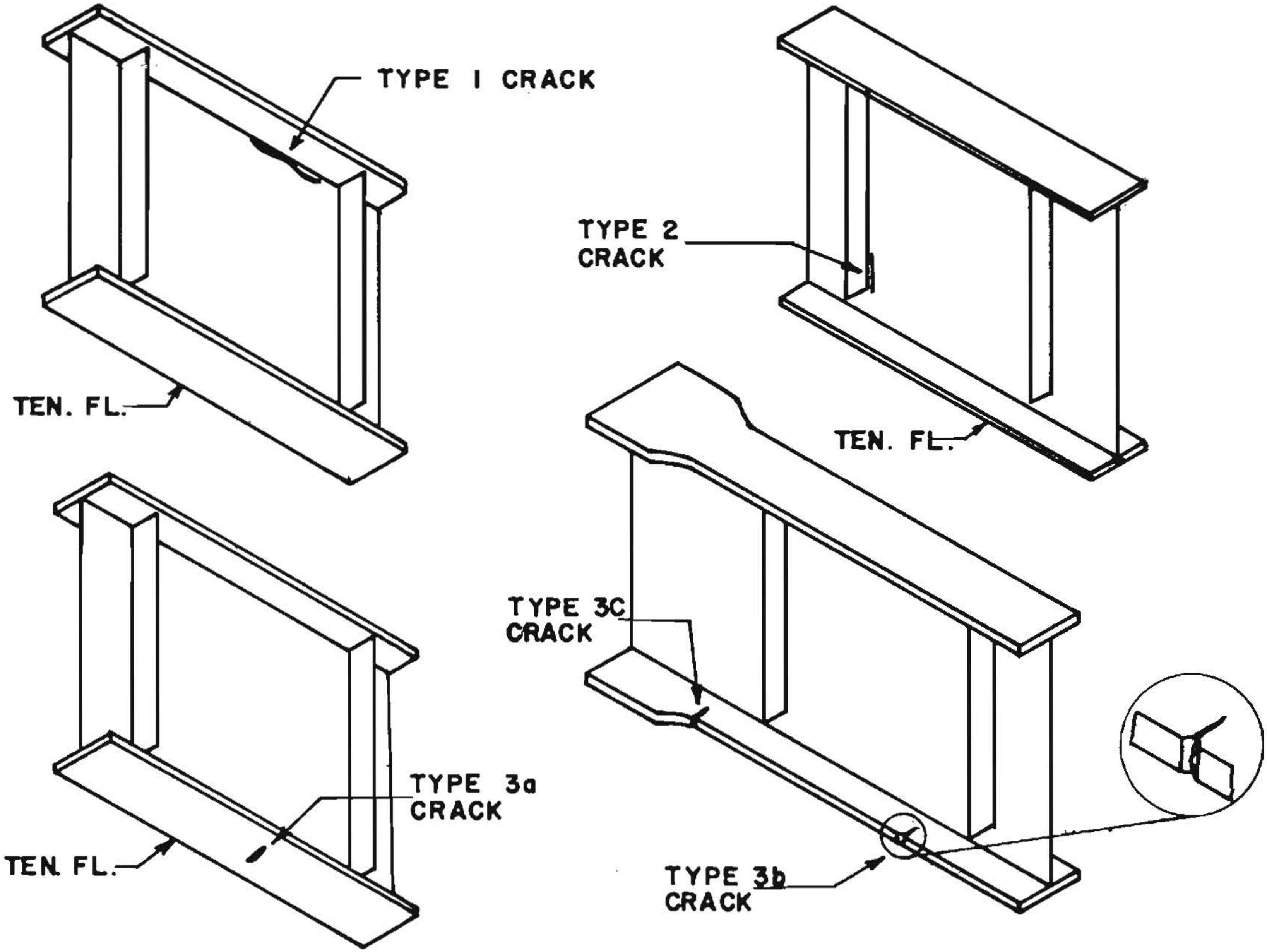


FIG. 29 TYPES OF FATIGUE CRACK

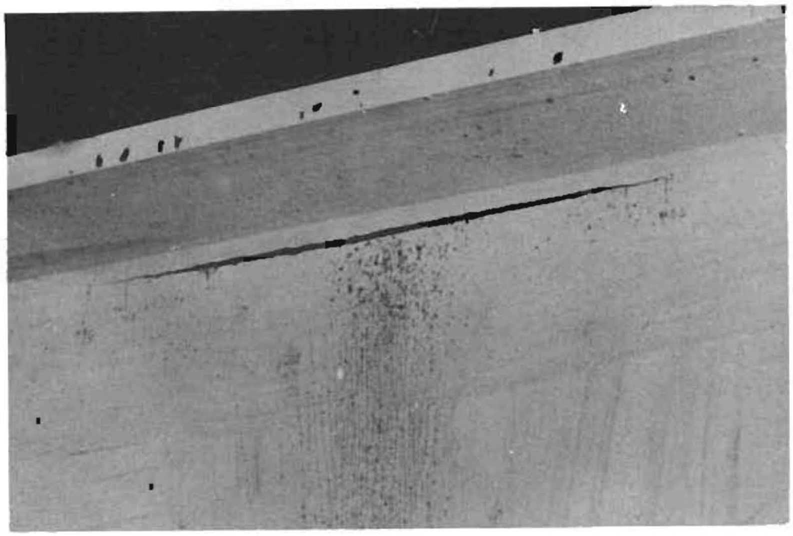


FIG. 30 CRACK IN COMPRESSION SIDE OF WEB ALONG THE TOE OF WEB TO FLANGE FILLET WELD

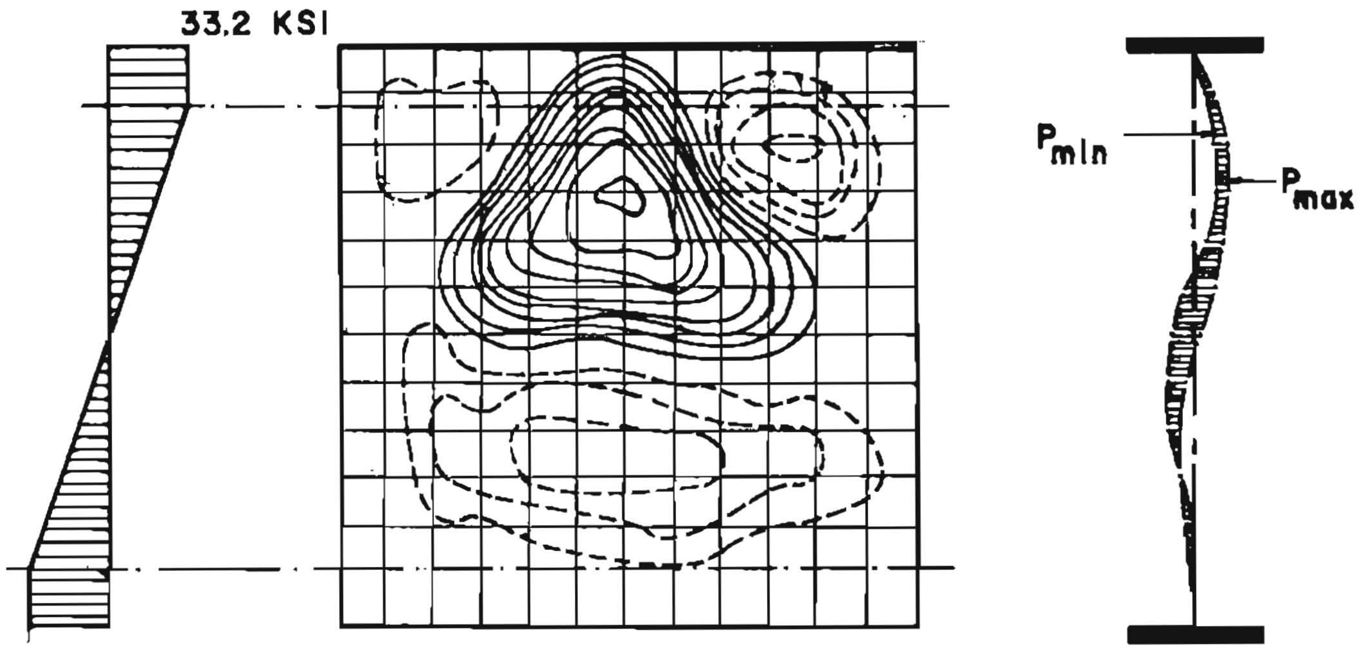
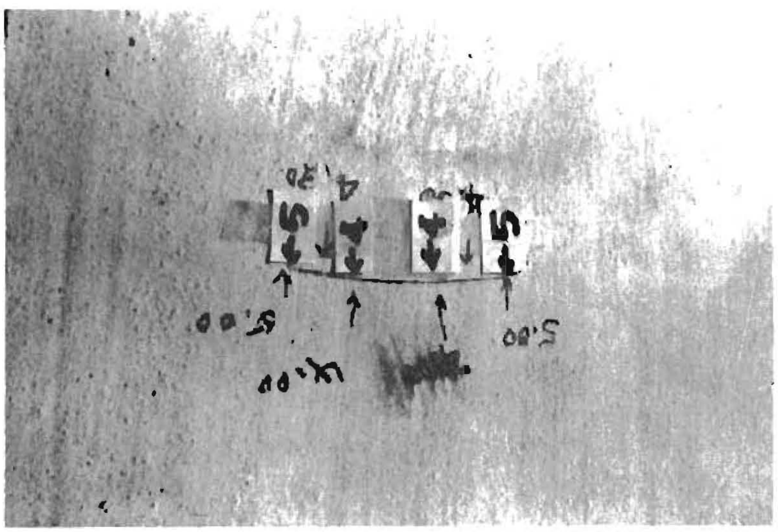


FIG. 31 WEB DEFLECTION OF SPECIMEN NO. 21540 A

1. 878,000 cycles
2. 973,000 cycles
3. 1,024,600 cycles
4. 1, 064,400 cycles
5. 1,075,000 cycles

a. Crack on web and bottom flange



b. Crack on bottom face of tension flange

FIG. 32 PROPAGATION OF TYPE 2 CRACK

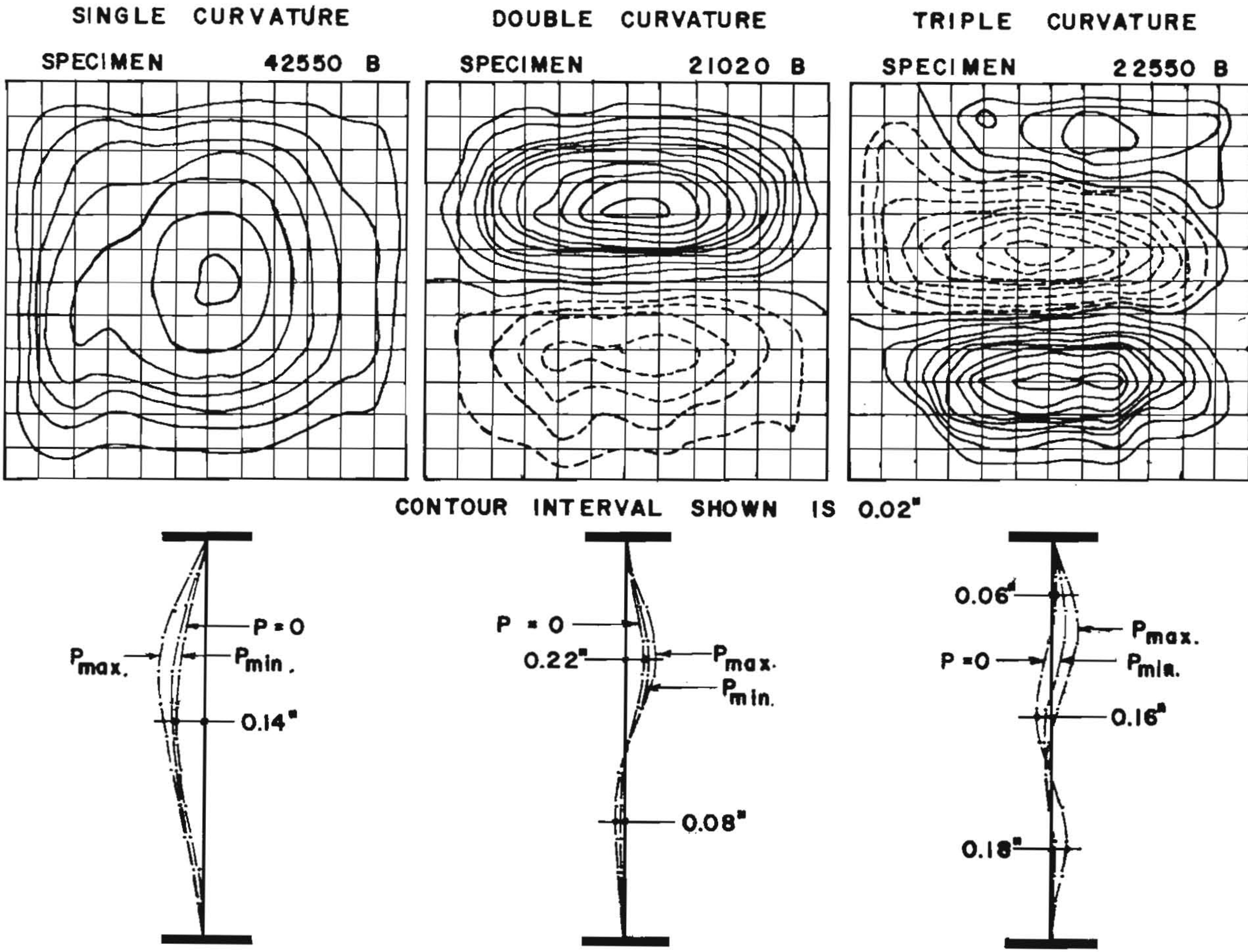


FIG. 34 INITIAL WEB CONFIGURATIONS

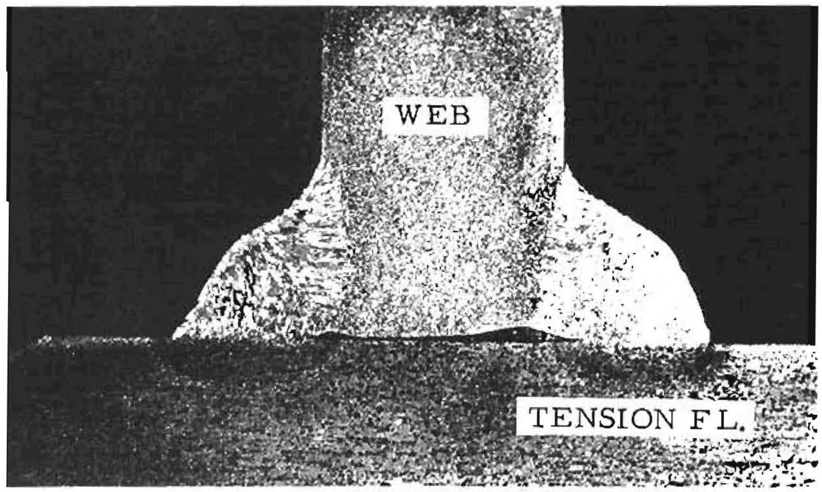


FIG. 33 INCOMPLETE PENETRATION OF TENSION FLANGE TO WEB FILLET WELD

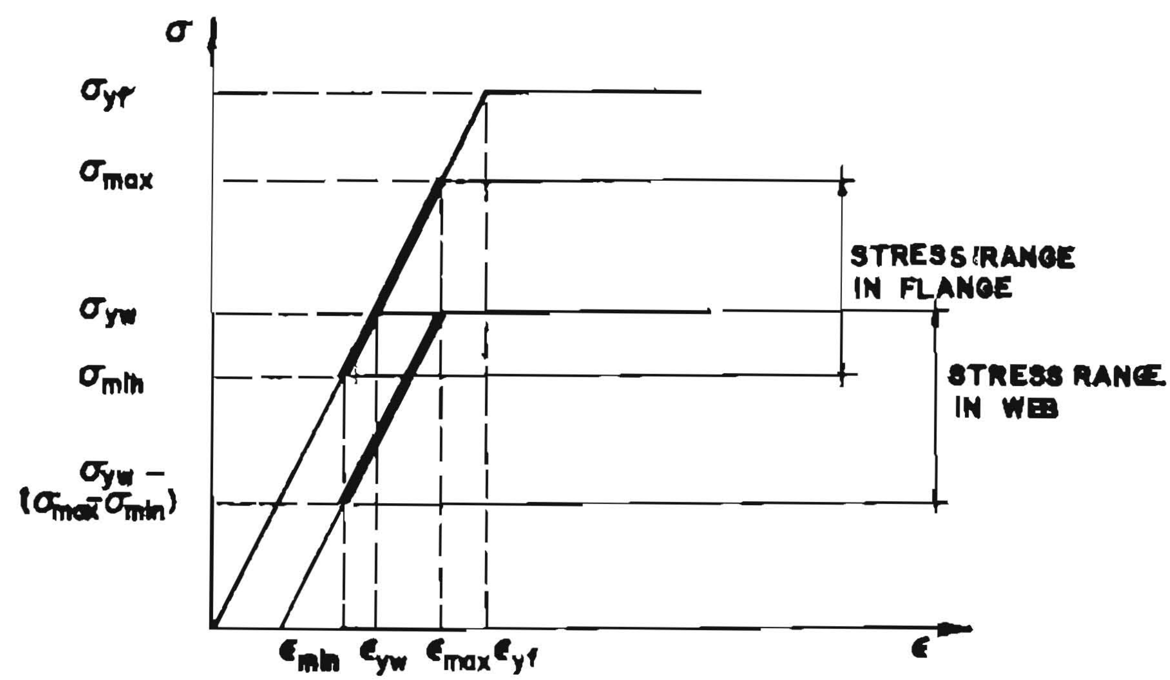


FIG. 35 FLUCTUATING STRESS LEVELS IN FLANGE AND WEB

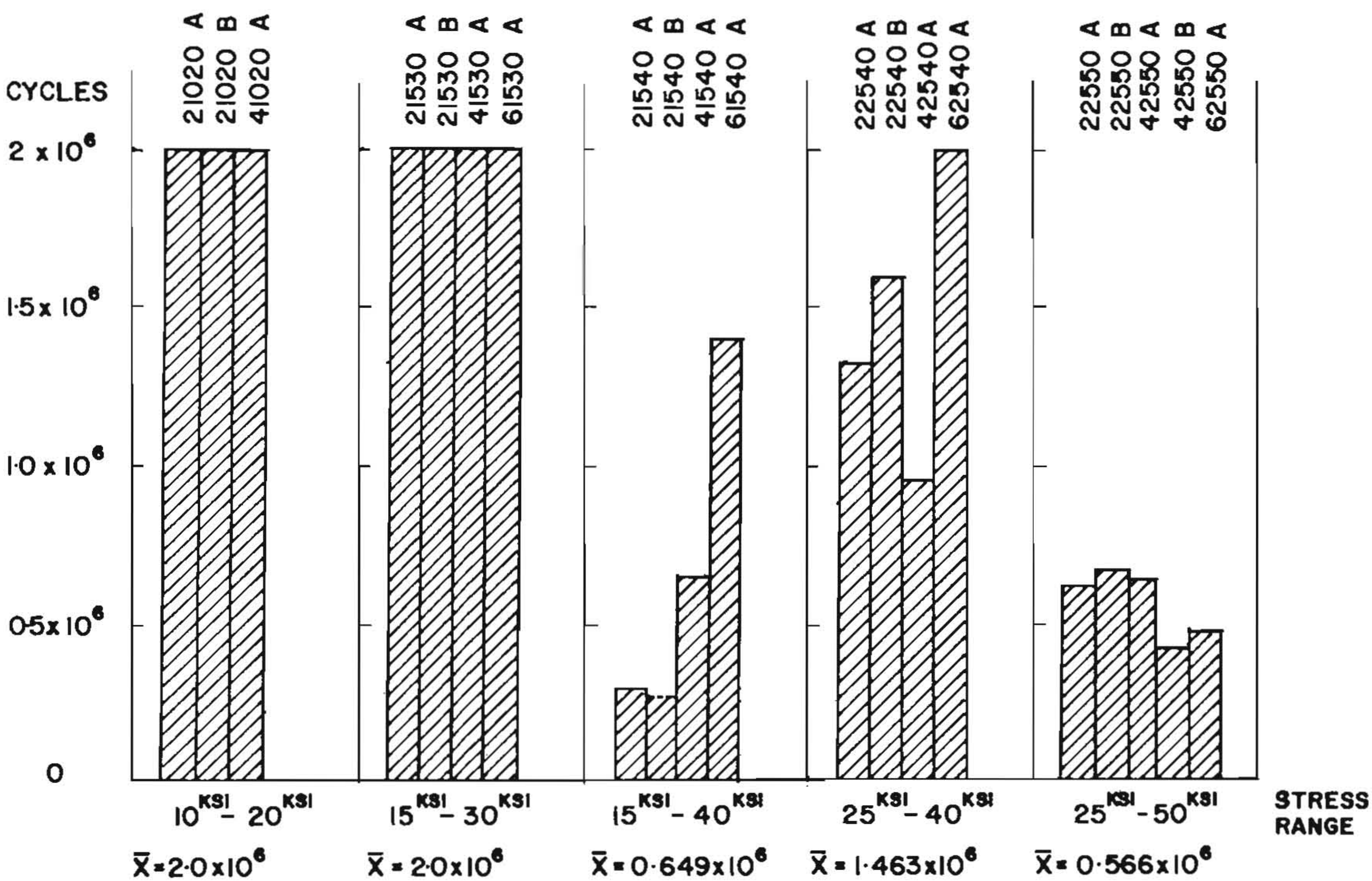


FIG. 36 NUMBER OF CYCLES TO INITIAL CRACKS

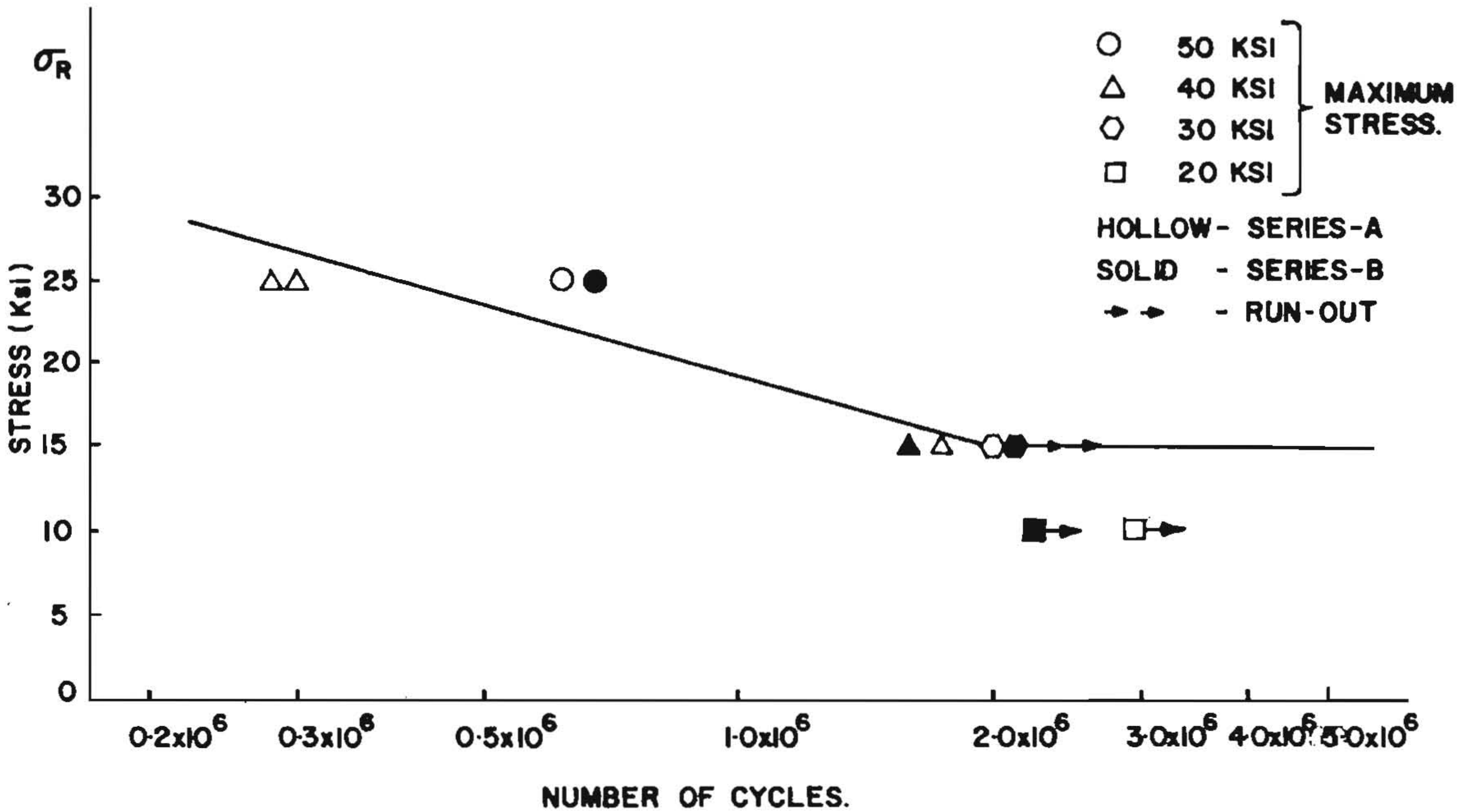


FIG. 37 TEST RESULTS OF TYPE 1 CRACK

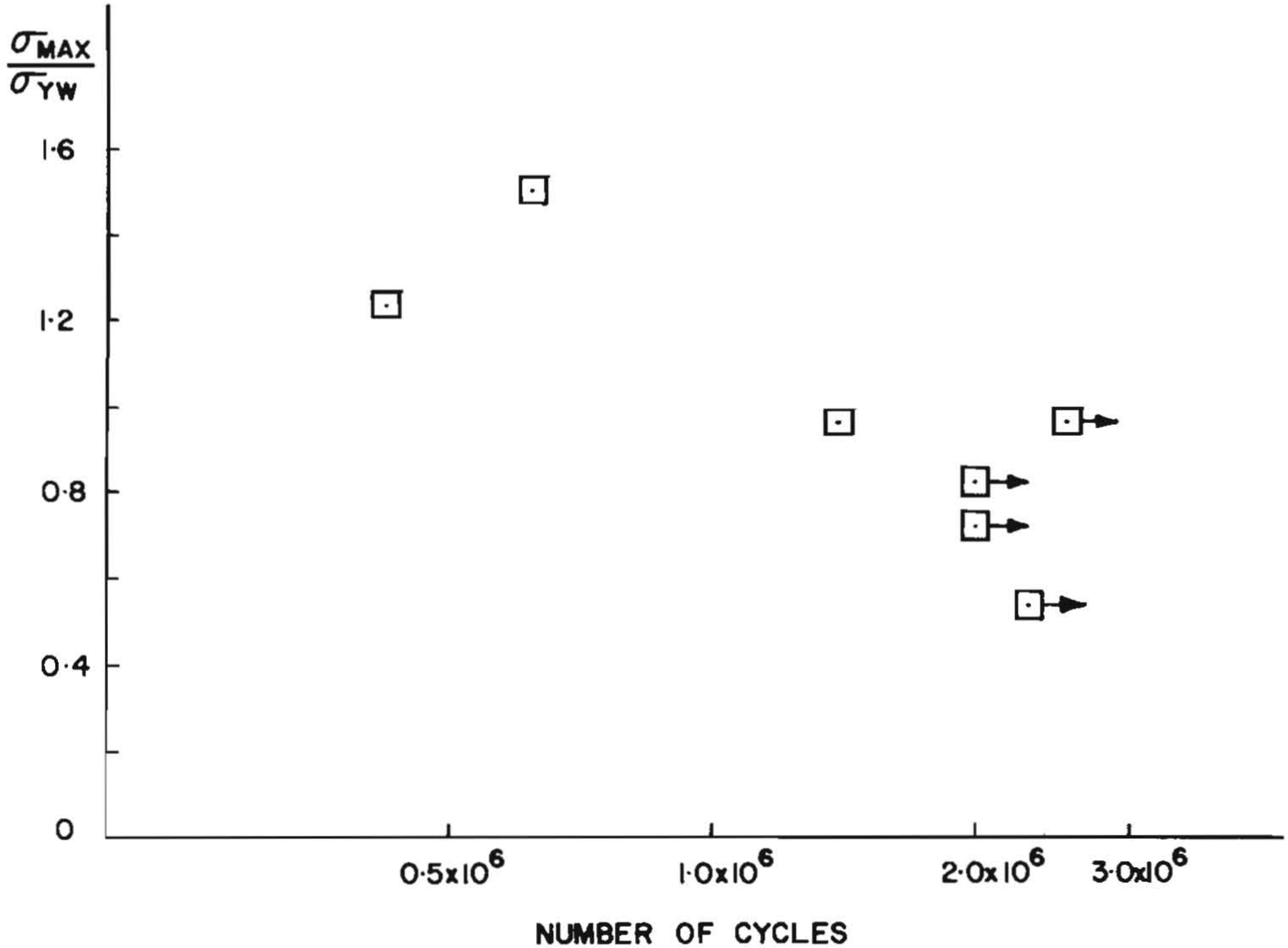


FIG. 38 TEST RESULTS OF TYPE 2 CRACK

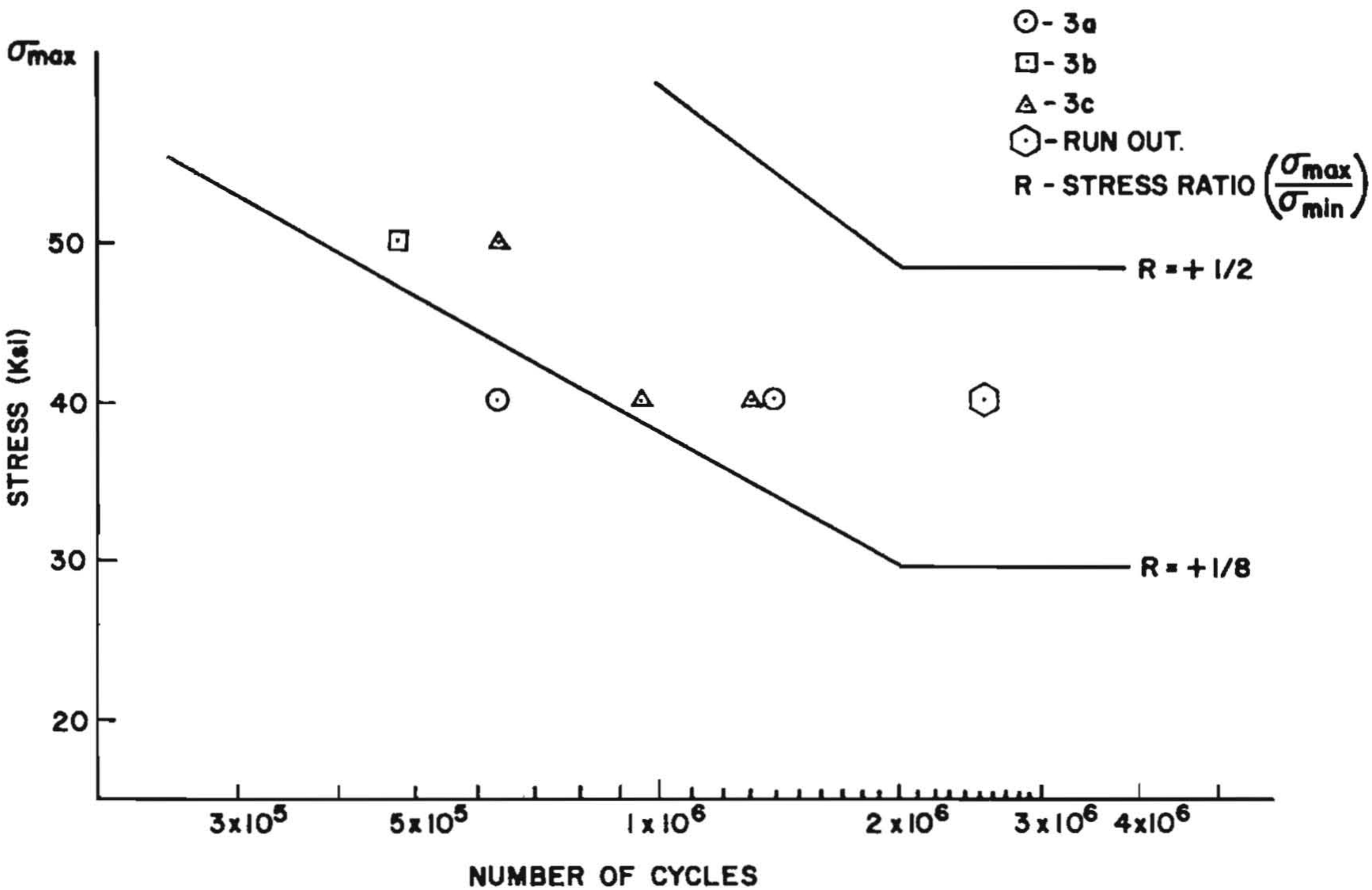


FIG. 39 TEST RESULTS OF TYPE 3 CRACK