ADDITIONAL FATIGUE TESTS OF HYBRID PLATE GIRDERS UNDER PURE BENDING MOMENT

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Plate Girders under Shear

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

The present report is the first of three under Project 3-5-66-96 "Fatigue Strength of Hybrid Plate Girders Under Shear." The second report under this project is entitled "Hybrid Plate Girders Under Combined Bending and Shear," and will be issued shortly. The third, and final report will pertain to the fatigue strength of hybrid plate girders under constant moment.

ABSTRACT

Six fatigue tests were conducted on welded hybrid plate girders. The flange steel was A441 and the web steel was A36. Web slenderness ratios of 144 and 192 were investigated. A sequential test program was devised to determine the maximum permissible stress range that will give a life of two million cycles.

The objectives of this investigation were to obtain fatigue data for hybrid plate girders and to determine the fatigue strength at two million cycles.

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1. INTRODUCTION

Since 1961 both static and fatigue behavior of hybrid plate girders have been studied at The University of Texas. Prior to the investigation described here, both static - and fatigue - test results from a number of research projects have been reported. For these tests the specimens consisted of ASTM A514 steel flanges and A36 steel webs. (1), (2), (3) Since there was no data available on the fatigue strength of plate girders with A441 flanges and A36 webs, an investigation of this type of hybrid sections was thought to be useful.

Hybrid girders with A514 flanges and A36 webs, when subjected to cyclic loads of pure bending type, developed three types of fatigue cracks, (2), (3) referred to as Types 1, 2, and 3.

Type 1 cracks are those which occurred in the compression side of the web plate along the toe of the flange-to-web fillet weld. The thin web plates of hybrid girders deform laterally as the load increases, producing larger deflection in the compression side of the web panels than in the tension side. It was inferred that the fluctuating stress at the compression edge of the web due to this web movement is pertinent to this type of crack formation. In general Type 1 cracks were observed in the girders with very slender webs (web slenderness ratio greater than 192).

Type 2 cracks are those which initiate at the stiffener-to-web boundary near the cut-off end of the stiffener, a few inches above the tension flange. The major cause for this crack initiation was considered to be the tensile primary bending fiber stress coupled with a stress concentration due to the abrupt termination of vertical stiffeners near the tension flange. Type 2 cracks were found in most groups of test girders, regardless of the web thickness. These cracks extend both upward and downward along the toe of the web-to-stiffener fillet weld. When this crack reaches the tension flange, it propagates into it and eventually fractures the flange. The propagation of these cracks is much faster than the propagation of Type 1 cracks.

Type 3 cracks are those which occurred in the tension flange or in the web-to-flange fillet weld at points where notches existed. These notches were produced by defective welding and cutting operations.

In the tests reported previously [3] no cracks in the bending panels were found within two million cycles if the applied maximum stress in the flanges was less than 30 ksi and the stress range was less than 15 ksi. For the specimens which were subjected to a flange stress of more than 40 ksi, the three types of cracks described above were observed.

The tests presented here are an extension of the investigation reported in Ref. 3. The specific purpose of this project is to secure test data on the fatigue behavior of hybrid girders under pure bending when the section is composed of A441 steel flanges and an A36 web. In this test series the maximum flange stress was kept at 30 ksi (60 percent of the specified yield point of the flange material), and the stress range was varied (see Table 3).

Information was sought as to the stress range within which the bending panels can survive approximately two million cycles. This number of cycles was chosen because this was considered to be the largest number of cycles of maximum load that any member in a bridge would ever experience during its service life.

2. TEST PROGRAM AND SPECIMENS

To study the fatigue strength of the girders at two million cycles a sequential test plan as described below was adopted.

The first specimen was tested with extreme fiber stress fluctuating between 10 ksi and 30 ksi. If the specimen failed before two million cycles the next specimen was to be tested with a stress range 5 ksi less than the previous stress range, keeping the maximum stress constant at 30 ksi. If the first specimen did not fail before two million cycles, the second specimen was to be tested with a stress range 5 ksi greater than the previous one.

If the second specimen failed, the stress range was decreased by 5 ksi; if the second specimen did not fail, the third specimen was tested at the same stress level as before to make sure that another specimen with the same stress range would not fail within two million cycles. The maximum stress was kept at 30 ksi for all the specimens. This proposed sequence of fatigue testing is shown in Fig. 1.

Six specimens were tested of which three had 3/16 inch and three had 1/4 inch web thickness. This gave slenderness ratios of 192 and 144, respectively. These web slenderness ratios are above and below the maximum ratio of 170 specified by the AASHO bridge specifications for A7 steel. The objective here was to use practical ratios that are encountered in bridge design.

All the specimens had the same dimensions except the web thickness. The web was 36 inches deep and was stiffened by pairs of transverse stiffeners 36 inches apart giving a panel-aspect ratio

(ratio of panel width to depth) of 1.0. The stiffeners were cut short two inches above the tension flange to reduce the possibility of premature fatigue damage to the tension flange. Both the tension and compression flanges had the same dimensions, and had uniform width and thickness along the length of the specimens. The actual measured dimensions of each specimen are shown in Table 1, along with the nominal dimensions.

Figure 2 shows the specimen configuration. The specimens had two central test panels, a narrow panel on each end of the test section, and three panels between the loading jacks and the supports. The purpose of having the narrow panel between the load point and the test panel was to provide a transition section to reduce the local effect of load application. Automatic submerged arc welding was used at the flange to web juncture resulting in a full-penetration weld. For all other welds E 7018 electrodes were used.

Each specimen was numbered with respect to the thickness of the web, the minimum and maximum stresses, and the test series designation. For example, in 31030H the first number designates the thickness of the web in multiples of 1/16 inch, 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 H indicated this series of tests.

For the specimens, all plates of the same thickness were taken from the same heat. Both the chemical and physical properties of the flanges and the webs are presented in Table 2. The physical properties in this table were measured by means of standard tensile tests on coupons from the same plates used in the specimens. It should be noted that the yield stresses given in Table 2 were obtained at zero strain rate and are referred to as static yield stresses.

3. TEST SET-UP, MEASUREMENTS, AND TESTING PROCEDURE

The girders were tested in a simply supported condition with two equal concentrated loads symmetrically applied with respect to the center line. The test panels, therefore, were subjected to constant bending moment (Fig. 2). A hydraulic pulsator and hydraulic jacks of 120 kips capacity were used to apply the cyclic loads. To prevent tilting of the girders, a sufficient number of lateral braces, designed to allow only vertical movements, were used.

In order to observe the general behavior of the girders, vertical deflections were measured at the center, at the points of load application, and at the supports, using dial gages. Lateral web deflections were measured at 3 inch by 3 inch grid points as shown in Fig. 3. These latter measurements were made using a special rig with a dial gage attached to a movable block that could be positioned at any desired level (Fig. 4). Electrical resistance-strain gages were mounted on the flanges and on both sides of the web to check the longitudinal strain under the applied bending moment.

During the fatigue test, a slip-deflection gage was placed at the center of a specimen to obtain an indication of the loss of girder stiffness as a result of crack development.

Preceding the fatigue test of each girder, a static test was performed. Load was increased up to the maximum load that was to be applied in the fatigue test, and then removed. At the maximum and minimum stress levels and zero load, the measurements mentioned above were made. Typical curves for vertical deflections, lateral web deflections, and strains in the flanges and the webs are shown in Figs. 5, 6, and 7, respectively. Web deflections at the center line of two typical test panels, with 1/4 inch and 3/16 inch web respectively are shown in Fig. 6. For the 1/4 inch web, the deflections changed very little up to the maximum test load P_{max}. For the 3/16 inch web the deflections increased between P_{min} and P_{max}. The reason for this behavior is that P_{max} for the 1/4 inch web is less than P_{cr} (the load to cause web buckling); whereas, for the 3/16 inch web P_{max} is larger than P_{cr}. The actual ratios of P_{max}/P_{cr} are indicated on Fig. 6. When the maximum test load had been reached, a thorough inspection of the entire girder was made. All yield lines were noted by observing cracks in the white-washed surfaces. Welds were carefully examined visually with the aid of a magnifying glass to see that no cracks were present.

The maximum and minimum stresses for the fatigue testing were computed by beam theory based upon the actual dimensions. All test loads used for the fatigue test were determined from these stresses and corrections were made for the effect of the inertia force on the dynamic response of the girder. The fatigue test followed immediately after the static-load test. The pulsating loads were applied at a rate of about 250 to 300 cycles per minute. Throughout the fatigue test visual inspections of all welds and heat affected areas (due to welding) were made with the aid of a magnifying glass at 3-hour intervals (about 54,000 cycles). However, more frequent observations were made after the first crack was noted. Slip-gage readings were recorded at each inspection period.

To observe crack propagation, the growth of cracks was marked and measured at each inspection period. The initiation and growth of the first crack, as well as of any other crack forming later, are described in the following section. If cracks were found outside the test section, fatigue testing was stopped temporarily and the cracks were repaired by first gouging out the cracks by the "arc-air" method and then depositing fresh weld. Following the repair, testing was resumed until two million cycles were attained, unless either a detrimental reduction of the girder stiffness was noted due to the fracture of the tension flange outside the test panels or cracks were found in the test panels. Whenever testing was stopped, the girder was loaded with the maximum test load so that cracks would be more easily seen and so that a check could be made to insure that no cracks had been overlooked.

4. FATIGUE CRACKS

All cracks found in this series of tests were Type 2 cracks, namely, those occurring along the toe of the web-to-stiffener fillet weld near the cut-off end of the stiffener. The fatigue cracks discussed here are only those observed inside the test section, along the three stiffeners nearest the middle of the span. In order to avoid confusion, the cracks appearing outside the test section are not discussed here, but they are included in the figures showing crack locations.

Testing of 3/16-inch Web Specimens

Specimens 31030H (Fig. 8) - According to the test sequence adopted, the minimum and maximum stresses in the flanges for this test were 10 ksi and 30 ksi, respectively. The first crack was found along the toe of the web-to-stiffener weld at 1,842,000 cycles. This crack was 1 inch long, extended vertically above the cut-off end of the stiffener, and was observed on one side only. At 1,868,000 cycles, the second crack was found along another stiffener. This crack was 1/2 inch long extending upward from the cut-off end and was observed on one side only. The testing was discontinued at 2,015,000 cycles. The cracks had propagated vertically; the first crack was 2 3/16 inches long reaching a point 1 1/4 inches above the tension flange; the second crack was 1/2 inch long reaching a point 1 7/8 inches above the tension flange. Both of them were seen only on one side of the girder.

Specimen 31530H (1) - Since the first specimen developed fatigue cracks within two million cycles, the minimum and maximum stresses for the second specimen were 15 ksi and 30 ksi. No cracks were found within two million cycles. The testing was terminated at 2, 941, 000 cycles.

Specimen 31530H (2) - Since no cracks were found within two million cycles in the second specimen, the third specimen was tested at the same stress level as specimen 31530H (1). Again no cracks were found within two million cycles. Testing was terminated at 2, 360, 000 cycles.

Testing of 1/4-inch Web Specimens

Specimen 41030H (Fig. 9) - According to the test program, the minimum and maximum stresses in the flanges of this specimen were 10 ksi and 30 ksi, respectively. No cracks were found within two million cycles. Testing was stopped at 2, 041, 000 cycles and final inspection was made under a static load to be certain that no cracks were present. On this occasion, a crack was found along the toe of the web-to-stiffener fillet weld extending from the cut-off end of the stiffener. It was 2 inches long and was seen on one side only.

Specimen 40530H (1) (Fig. 10) - Since no cracks were found within two million cycles in the first specimen, the stress range was increased. The minimum and maximum stresses for this spcimen were 5 ksi and 30 ksi, respectively. A crack similar to Type 2 cracks appeared along the stiffener outside the test section at 577, 000 cycles. The crack was repaired three times, but each time it reappeared at the repaired area. The test was finally terminated at 888, 000 cycles. However, during the final inspection at 888,000 cycles, a crack was observed within the test area. It was 1 1/4 inches long extending upward from the cut-off end of the stiffener, and was observed only on one side of the girder.

Specimen 40530H (2) (Fig. 11) - Although the second specimen developed a fatigue crack in the test section within two million cycles, the third specimen was tested at the same stress level as the second specimen (Specimen 40530H (1)) as a check on the results. Two cracks were found along the two stiffeners at 862,000 cycles. One was 6 1/2 inches long extending along the toe of the weld and reaching a point 1/2 inch above the tension flange. The other was 2 inches long extending along the toe of the weld above the cut-off end of the stiffener. Both of tem were observed only on one side of the girder. The testing was stopped at 934,000 cycles because a crack which occurred outside the test section reached the tension flange.

A summary of the fatigue test results is shown in Table 3.

5. DISCUSSION OF TEST RESULTS

It was noticed in a previous investigation [3] that Type 2 cracks always propagated into the tension flange as the number of the applied cycles of loads increased, finally resulting in complete failure of girders due to fracture of the tension flange. Therefore, the initiation of Type 2 cracks is regarded in this study as fatigue failure for a girder.

Flexural membrane (fiber) stresses in the web around the cut-off end of the stiffener can be estimated by simple beam theory. As shown in Fig. 7 the strains measured by strain gages and the strains computed by beam theory show some difference. A more thorough investigation [4] of the membrane stresses in the webs near the vertical stiffeners gave the conclusion that the difference is small. These stresses are of course different from the stresses present at the toes of the welds where the Type 2 cracks appeared, because of the localized stress disturbance due to welding.

Figure 12 shows the relationship between the extreme fiber stress range in the flange (right hand scale) and the number of cycles when the first crack developed in all tests of this series. In the tests of series A and B reported previously, [3] Type 2 cracks developed regardless of the web thickness, and the S-N diagram indicated a curve which is typical of S-N curves in the fatigue of metal structures. The stress in the flange is proportional to the membrane stress in the web regardless of the web thickness. Therefore, it is considered that the flexural membrane stress is one of the important factors influencing the development of Type 2 cracks.

The membrane stress in the web at the cut-off end of the stiffener was about 86 percent of the stress in the flange according to beam theory. The stress in the web at this point was 26.0 ksi when the stress in the flange was 30 ksi. The stress range of the web at this point is indicated in Fig. 12 as the ordinate in the stress-range scale to the left. The configuration and the state of stress around the area at which the Type 2 cracks were found seem to be fairly similar to those of a plate with fillet-welded attachments as shown in Fig. 13. According to Fig. 8.4 of Ref. 5 the median fatigue strength of the plate with the fillet-welded attachments at two million cycles is about 26 ksi and 10 ksi in terms of the maximum and the minimum stresses. This fatigue strength is close to the stress level of the web-membrane stress at the cut-off ends of the stiffeners where cracks were found at about two million cycles (Fig. 12). The S-N Curve in Fig. 12 was obtained from Ref. 5 assuming a linear log S versus log N relationship between 10^5 and 2×10^6 cycles. There are many factors which can influence the occurrence of Type 2 cracks. A comparison which was made in the above reference with a simple tension specimen considered only the effect of the fiber stresses in the web. More investigation of the factors that influence the initiation of Type 2 cracks is necessary.

A sequential test as described in Section 2 was adopted to determine the fatigue strength of the hybrid girders under pure bending moment at two million cycles. The maximum stress in the flanges was kept at 30 ksi for all the specimens and the stress range in the flanges was changed depending on whether or not the preceding specimen failed within two million cycles. The test results are shown in Fig. 14, where O indicates no failure and X indicates failure. The available test results are still too few to estimate the fatigue strength for a certain percentage of survival at two million cycles from the statistical viewpoint. According to the S-N relationship shown in Fig. 12, however, the approximate fatigue strength (at 2×10^6 cycles) is considered to be about 20 ksi flange stress range for a maximum flange stress of 30 ksi. The results of these tests are shown again in Fig. 15 with the S-N Curve presented in Ref. 3. The results of this investigation agree quite well with the previous tests.

6. SUMMARY

A series of fatigue tests of hybrid plate girders under pure bending moment was performed. ASTM A441 steel was used for the flanges and A36 steel was used for the webs. Two groups of girders (three specimens for each group) were tested. These two groups differ only in the web thickness; the one had a web slenderness ratio of 144, and the other had a web slenderness ratio of 192.

Although the objective of this investigation was to compile data on the fatigue strength of hybrid girders, special emphasis was placed on estimating the fatigue strength of the bending panels at two million cycles. To estimate the fatigue strength at two million cycles, a sequential series of response tests was adopted. The maximum flange stress was kept at 30 ksi (60 percent of specified yield point of A441 steel) and the stress range was varied.

For all the specimens tested, the fatigue cracks occurred in the web along the toe of the web-to-stiffener fillet weld near the cut-off end of the stiffeners. It was noted that the initiation of this type of crack was related to the tensile fiber stress range in the web. The difference in web thickness apparently was not significant in the tests carried out. The stress magnitude at the points where the cracks appeared was found to be comparable with the median fatigue strength of tension specimens with fillet-welded attachments. For the bending panels tested, the approximate fatigue strength at two million cycles was found to be a stress range of 20 ksi for a

maximum stress of 30 ksi. However, more tests are considered necessary to establish the fatigue strength more precisely and to carry out a statistical analysis. The S-N curve presented in Fig. 15 provides a slightly conservative estimate of the fatigue strength of the girders in this test series.

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(1) A. A. Toprac and R. A. Engler, "Plate Girders with High-Strength Steel Flanges and Carbon Steel Webs," 1961 Proceedings, National Engineering Conference AISC, New York, N. Y.

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(3) H. S. Lew and A. A. Toprac, "Fatigue Strength of Hybrid Plate Girders Under Constant Moment," Highway Research Record No. 167, Highway Research Board, Washington, D. C., 1967.

(4) B. T. Yen and J. A. Mueller, "Fatigue Tests of Large-size Welded Plate Girder," Fritz. Engrg. Lab. Report, 303.10 (June 1966).

(5) W. H. Munse, "Fatigue of Welded Steel Structure," Welding Research Council (1964).

Specimen No.	Nominal Dimensions		Web Slenderness Ratio	Measured Dimensions		Moment of Inertia ($in.^4$)
	Flg. Wdth. X Flg. Th.	Web Depth X Web Th.		Flg. Wdth. X Flg. Th.	Web Depth X Web Th.	
31030 H	8" x 1/2"	36" x 3/16"	192	8.003" x 0.5097"	36.0" x 0.1972"	3485
31530 H (1)	"	"	"	8.020" x 0.5100"	"	3493
31530 H (2)	"	"	"	7.995" x 0.5083"	"	3475
41030 H	"	36" x 1/4"	144	8.007" x 0.5093"	36.0" x 0.2617"	3735
40530 H (1)	"	"	"	7.983" x 0.5072"	"	3716
40530 H (2)	"	"	"	8.006" x 0.5112"	"	3745

TABLE 1 Cross Sectional Dimensions of Test Panels

PLATE	1/2"(A441)	1/4"(A36)	3/16"(A36)
Thickness (in.)	0.514	0.261	0.197
Static Y. P. (ksi)	52.7	43.3	40.4
Tensile Str. (ksi)	74.2	66.3	54.7
Elong. (% in 8 in.)	24	29	28
Chem. Comp.			
C	0.16	0.20	0.20
Mn	1.08	0.45	0.45
P	0.010	0.012	0.006
S	0.019	0.027	0.014
Si	0.25	0.10	----
Cu	0.28	----	----
V	0.061	----	----

TABLE 2 Chemical and Physical Properties

of Girder Plates

Specimen Nos.	Stress Level (ksi)		Cycles to Initial Crack	Remarks
	Min.	Max.		
31030 H	10	30	1,842,000	Second crack at 1,867,000 cycles
31530 H (1)	15	30	-------	Run out; Stopped at 2,941,000 cycles
31530 H (2)	15	30	-------	Run out; Stopped at 2,360,000 cycles
41030 H	10	30	2,041,000	
40530 H (1)	5	30	888,000	
40530 H (2)	5	30	862,000	Two cracks were found at 862,000 cycles

TABLE 3 Summary of Fatigue-Test Results

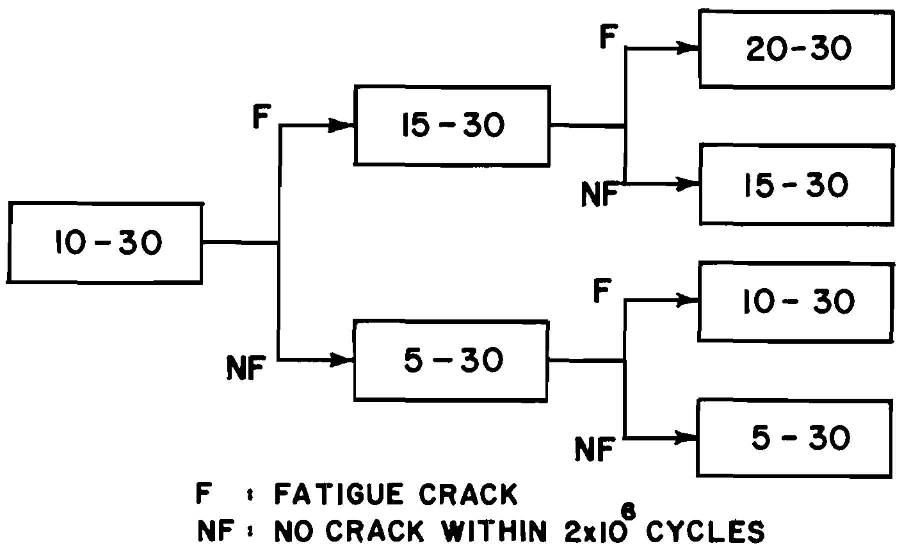

FIG. 1 TESTING SEQUENCE

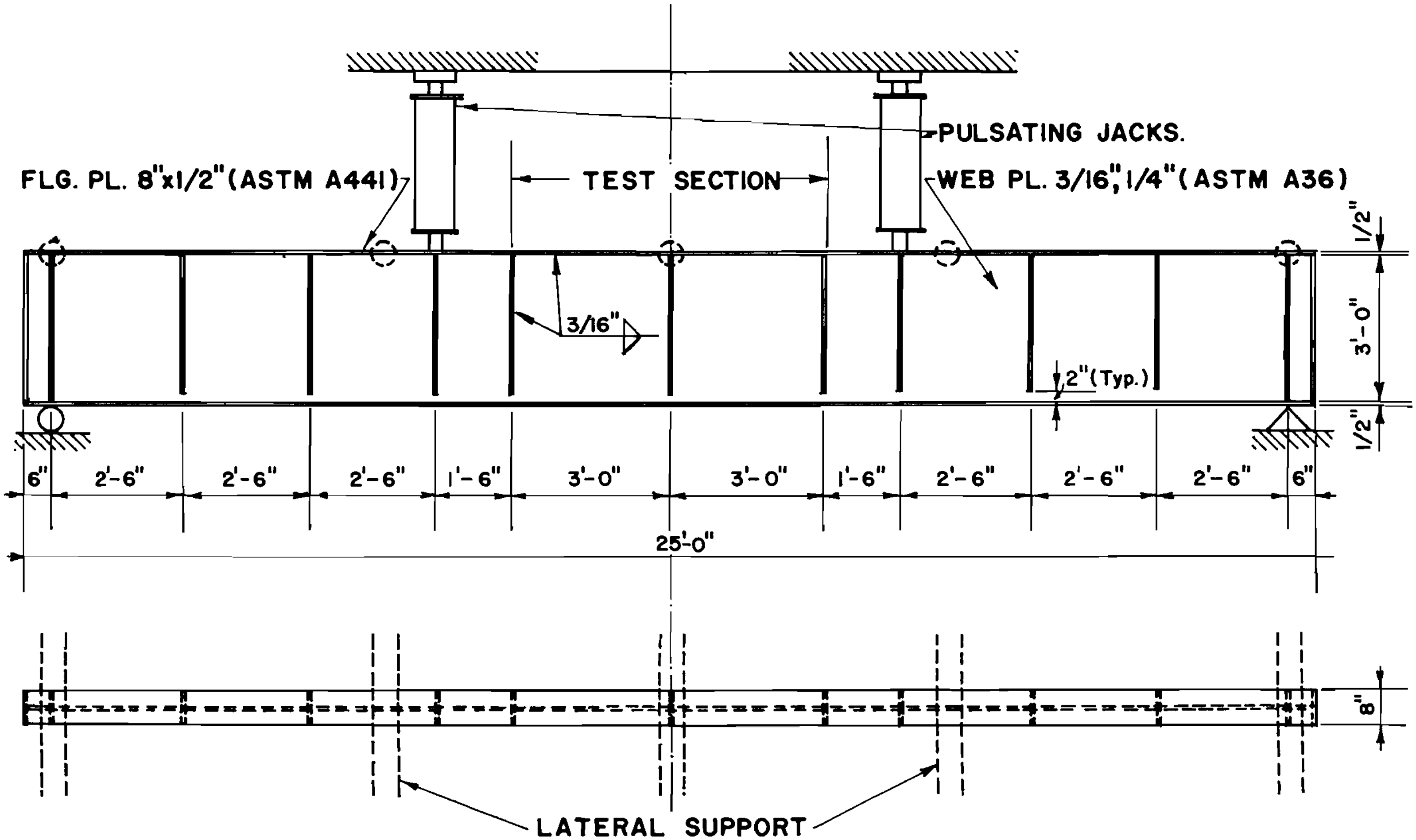

FIG. 2 SPECIMEN AND TEST SET-UP.

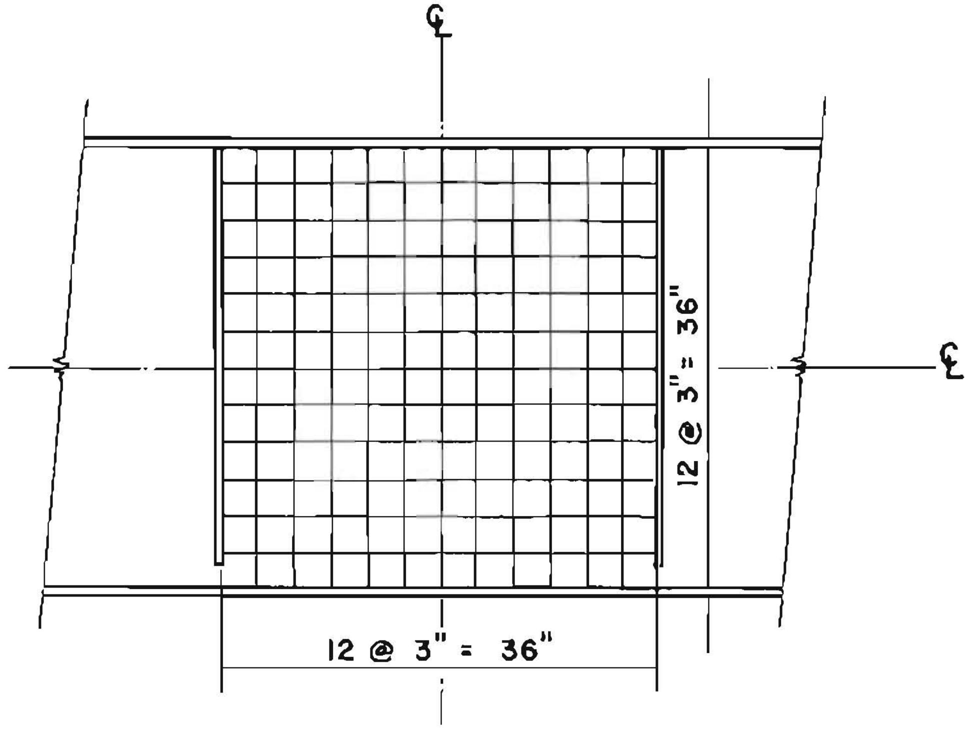

FIG. 3 LOCATIONS OF LATERAL WEB DEFLECTIONS MEASUREMENTS.

FIG.4 MOVEABLE HEAD DIAL RIG

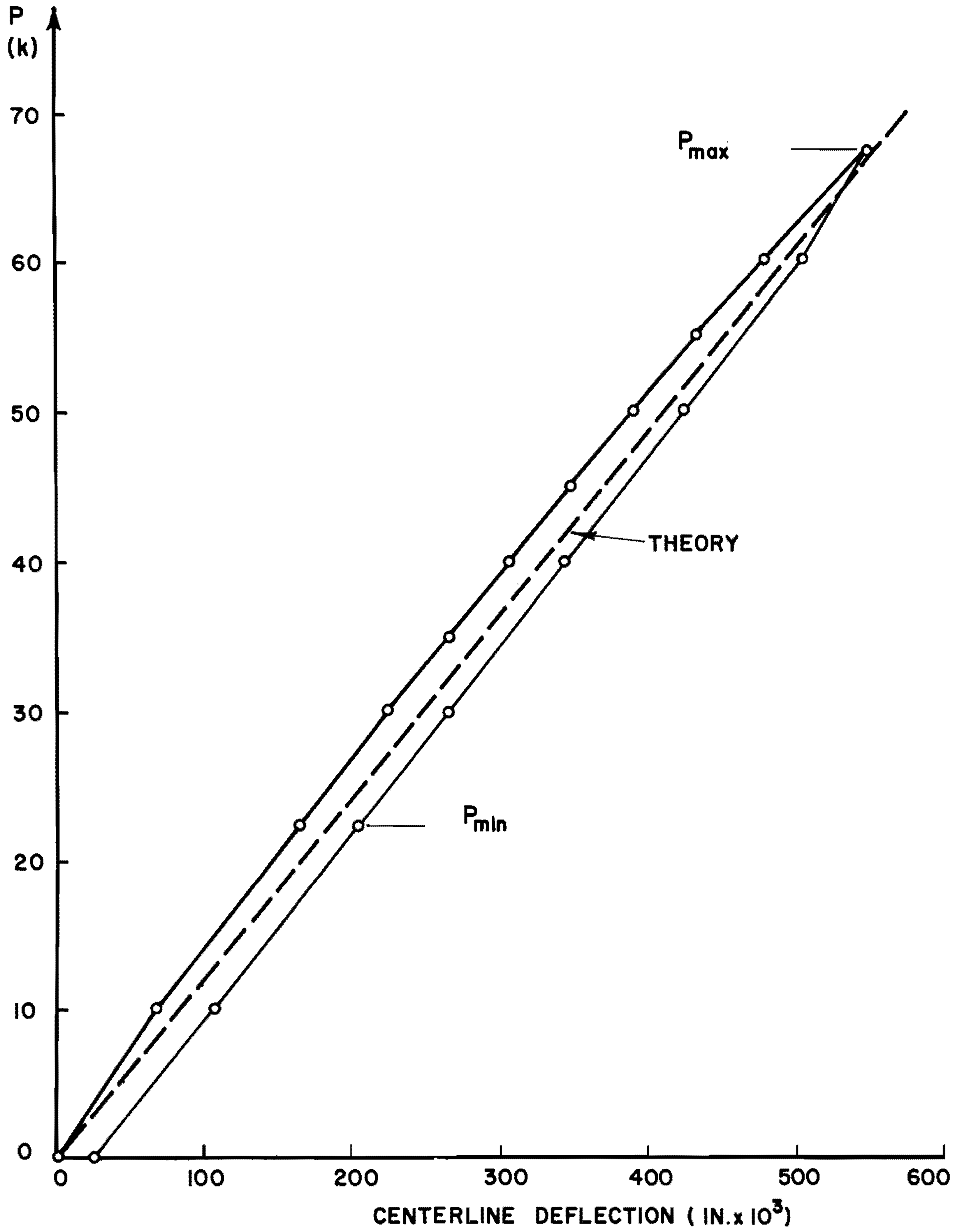

FIG. 5 LOAD Vs CENTERLINE DEFLECTION (41030 H)

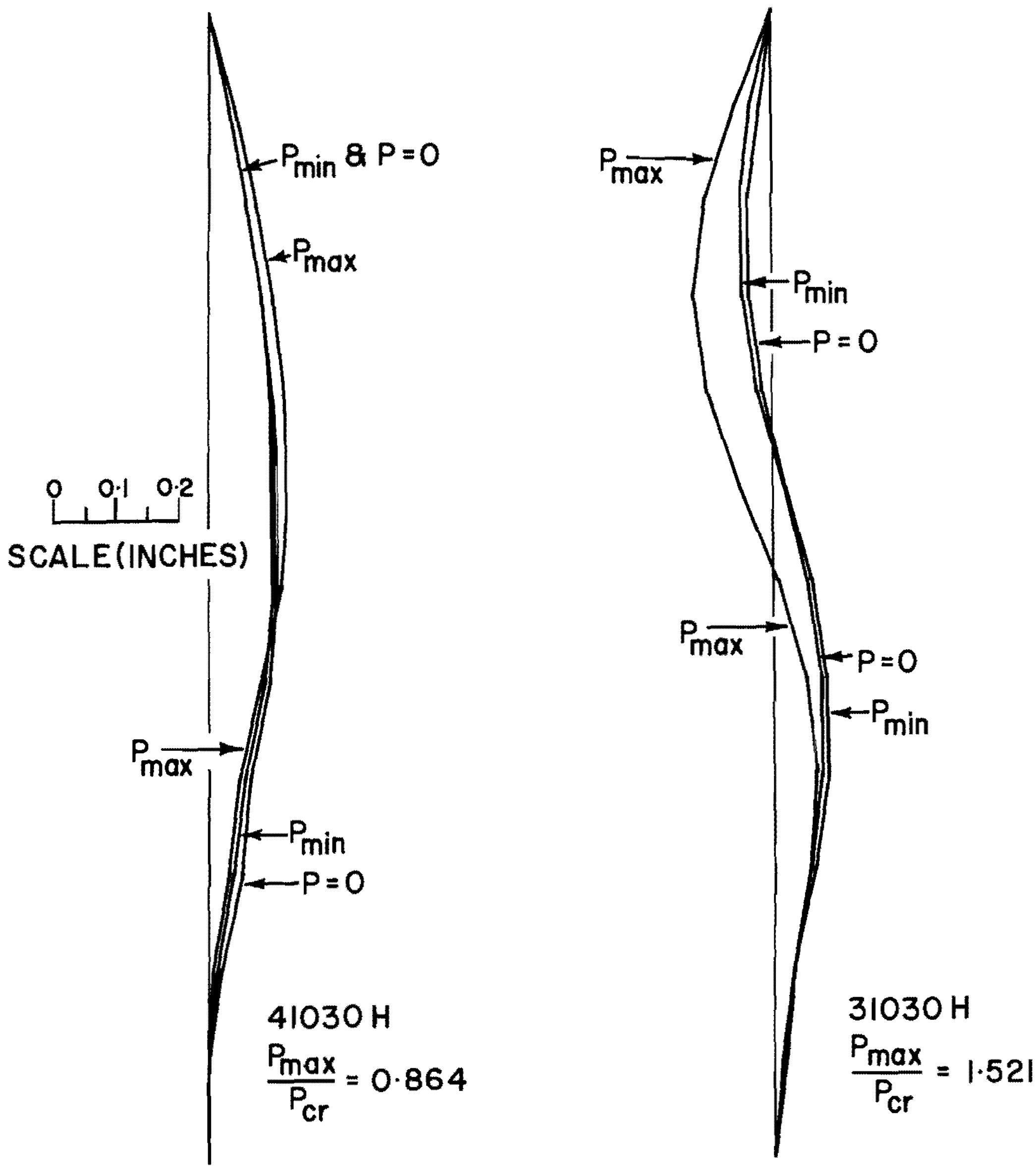

FIG. 6 WEB DEFLECTIONS (CENTERLINE OF TEST PANEL)

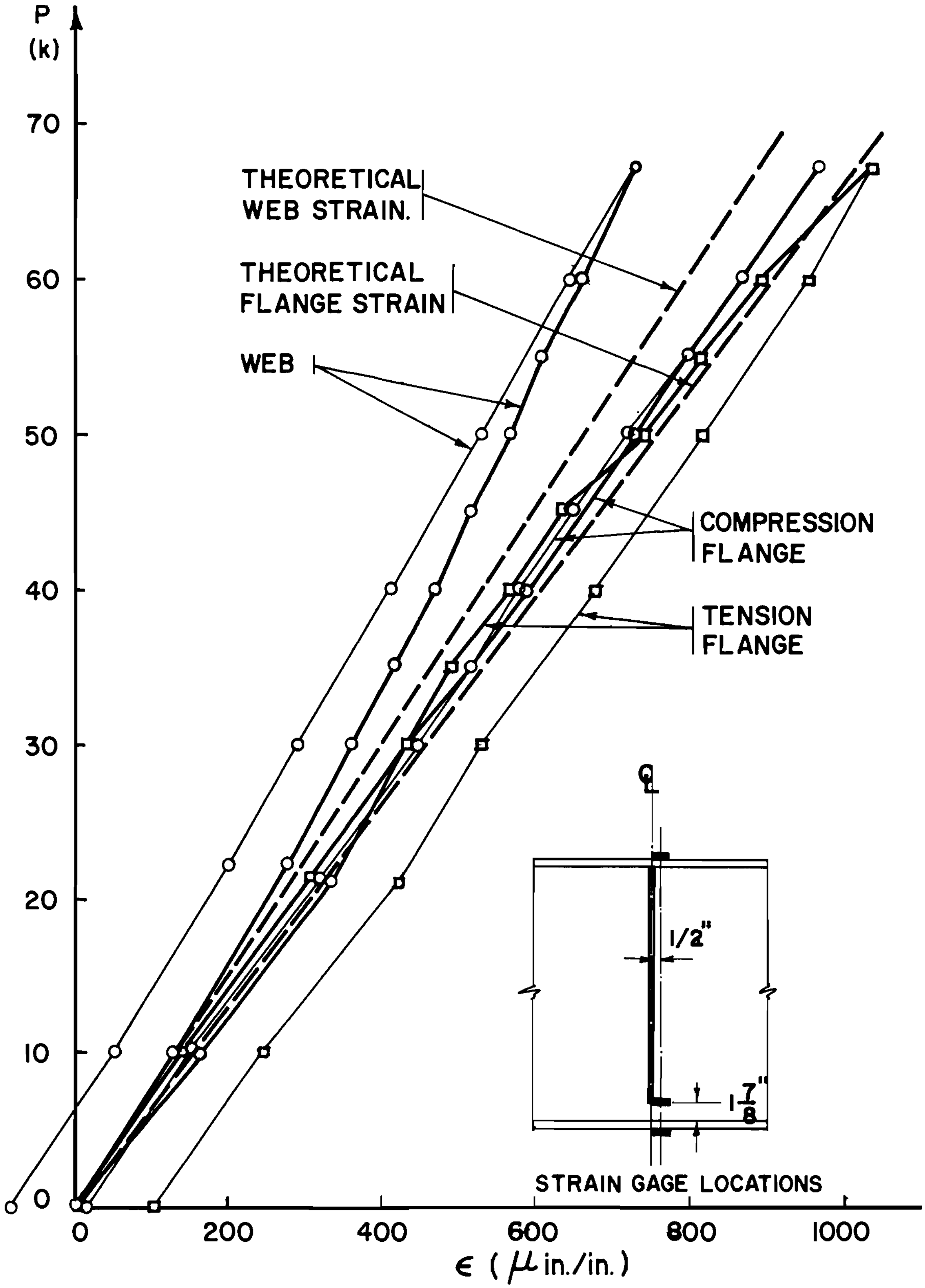

FIG. 7 LOAD Vs STRAIN (41030 H)

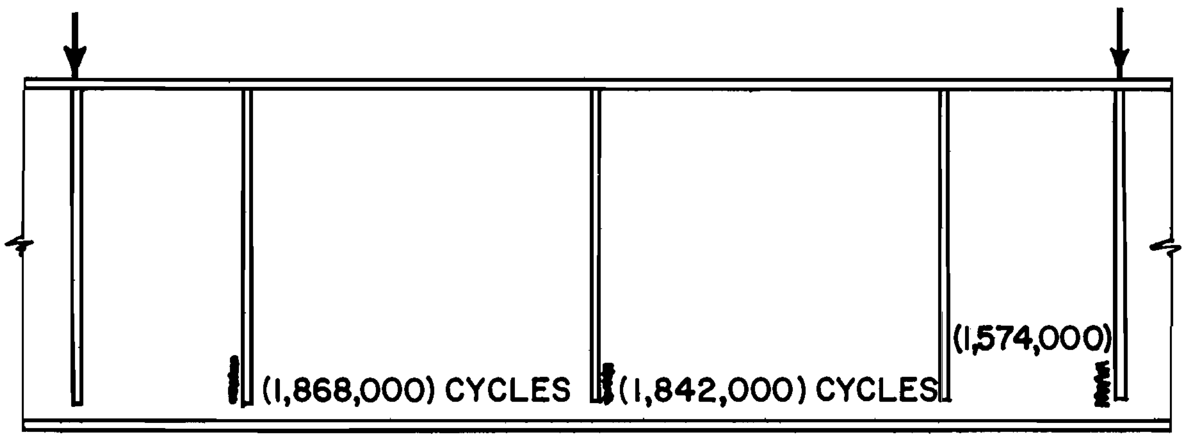

FIG. 8 CRACK LOCATIONS AND CYCLES TO CRACK INITIATION FOR SPECIMEN 31030 H

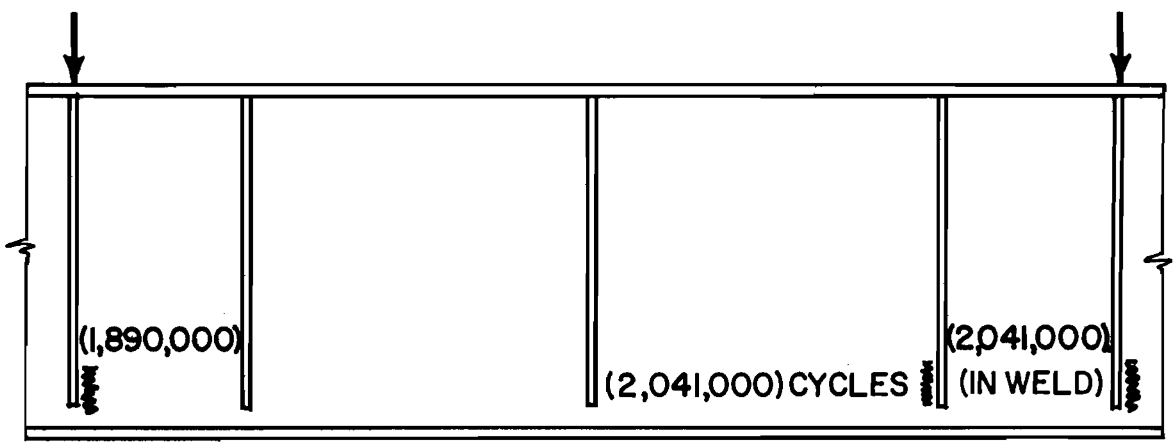

FIG. 9 CRACK LOCATIONS AND CYCLES TO CRACK INITIATION FOR SPECIMEN 41030 H

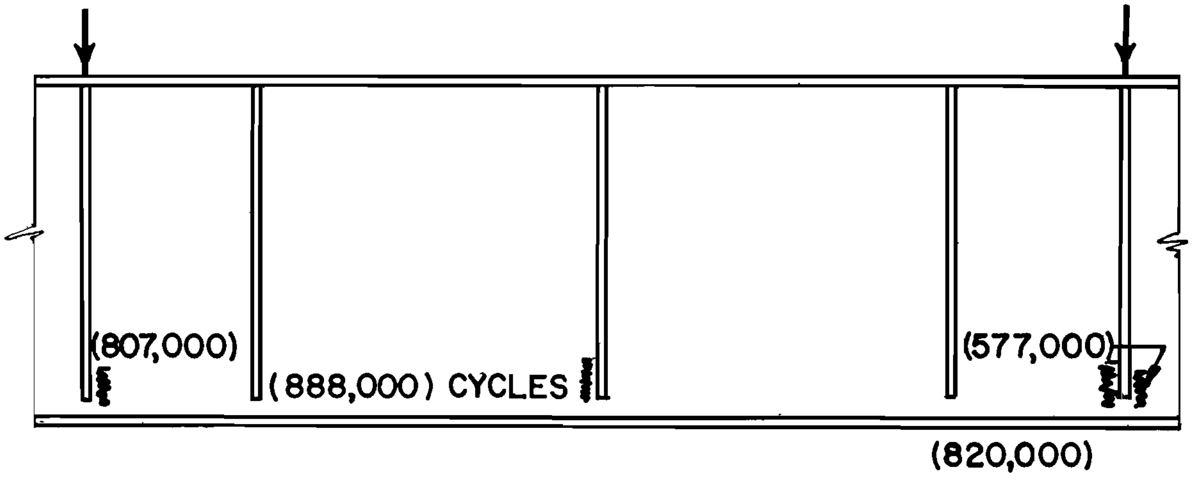

FIG. 10 CRACK LOCATIONS AND CYCLES TO CRACK INITIATION FOR SPECIMEN 40530 H(1)

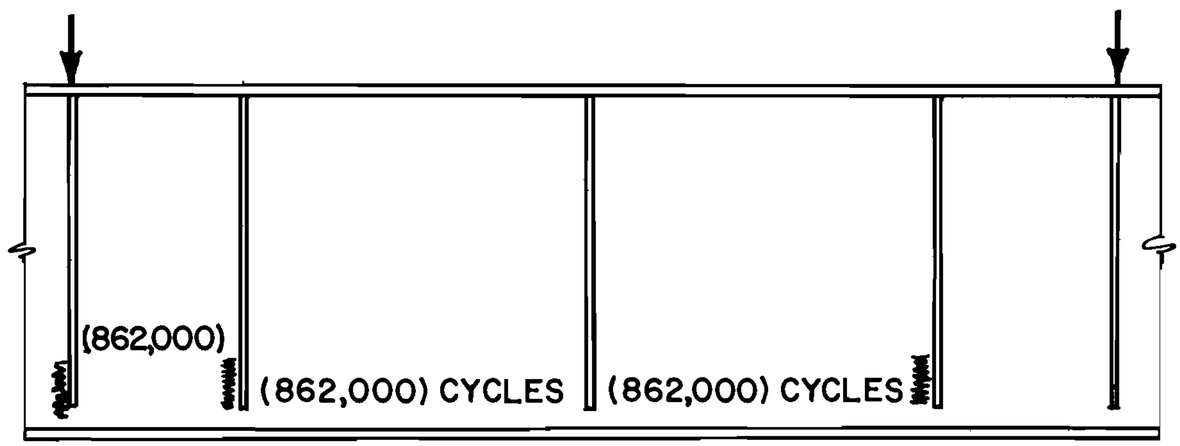

FIG. 11 CRACK LOCATIONS AND CYCLES TO CRACK INITIATION FOR SPECIMEN 40530 H (2)

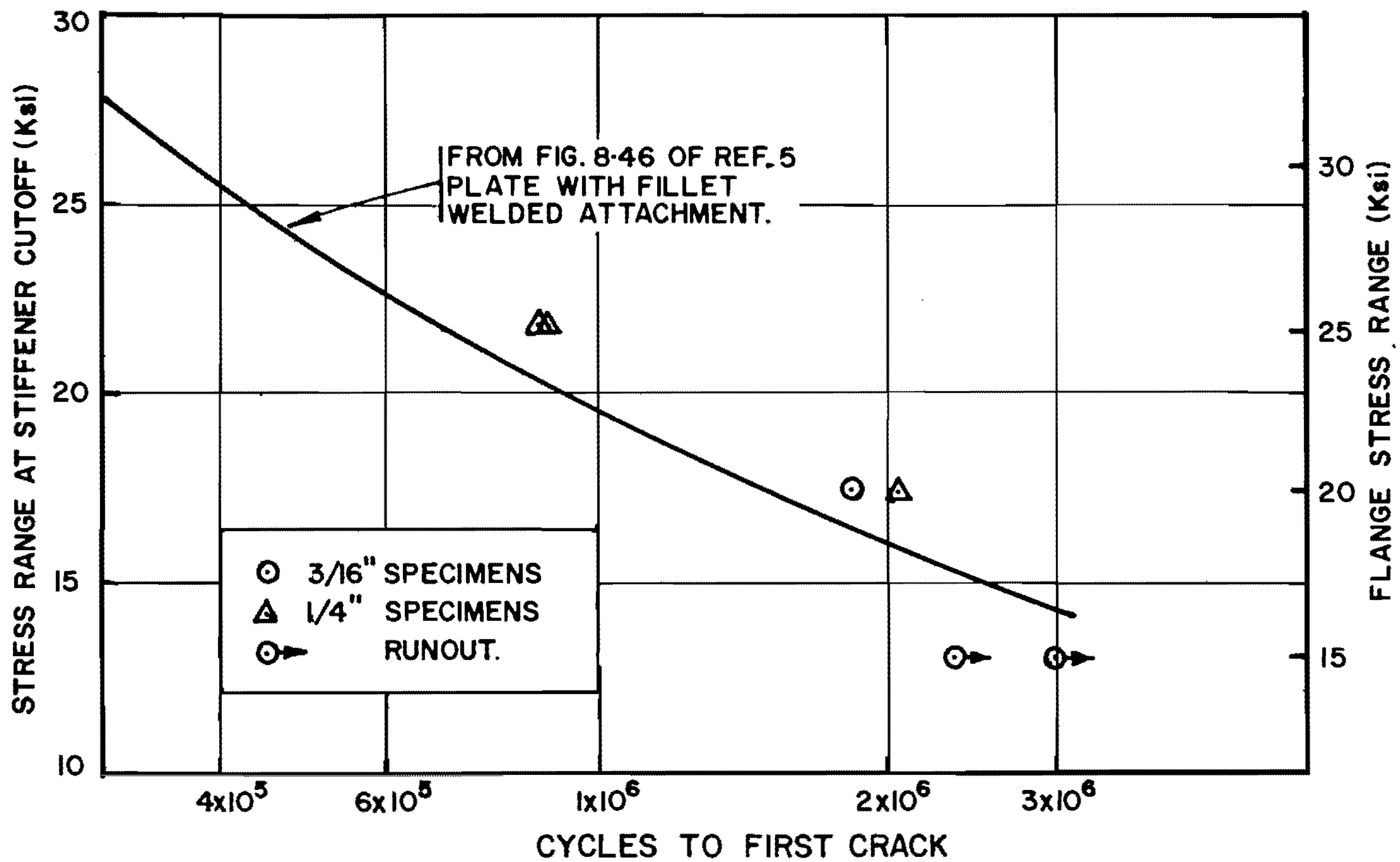

FIG 12. STRESS RANGE — CYCLES TO FIRST CRACK.

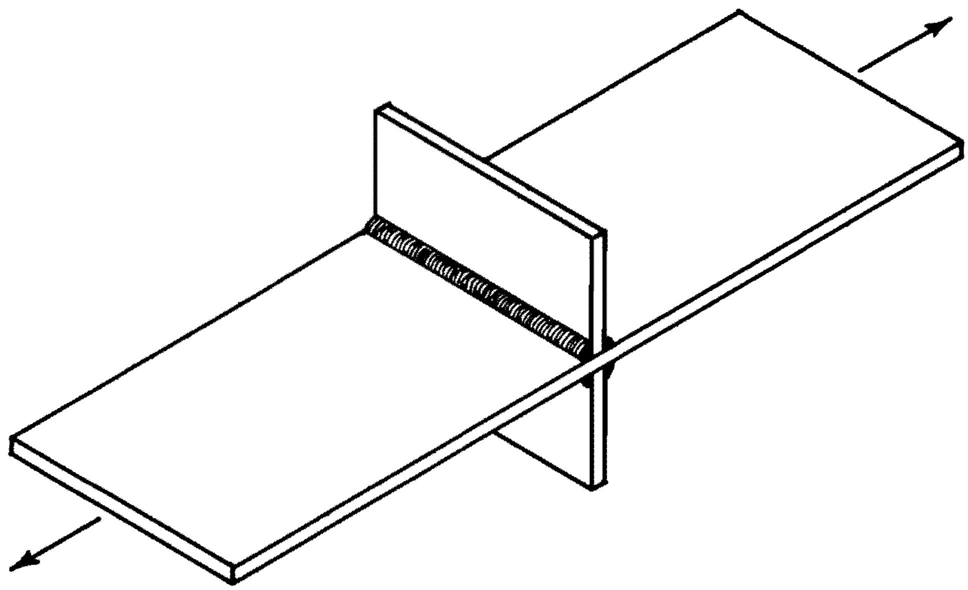

FIG. 13 TENSION SPECIMEN WITH FILLET-
WELDED ATTACHMENT (5)

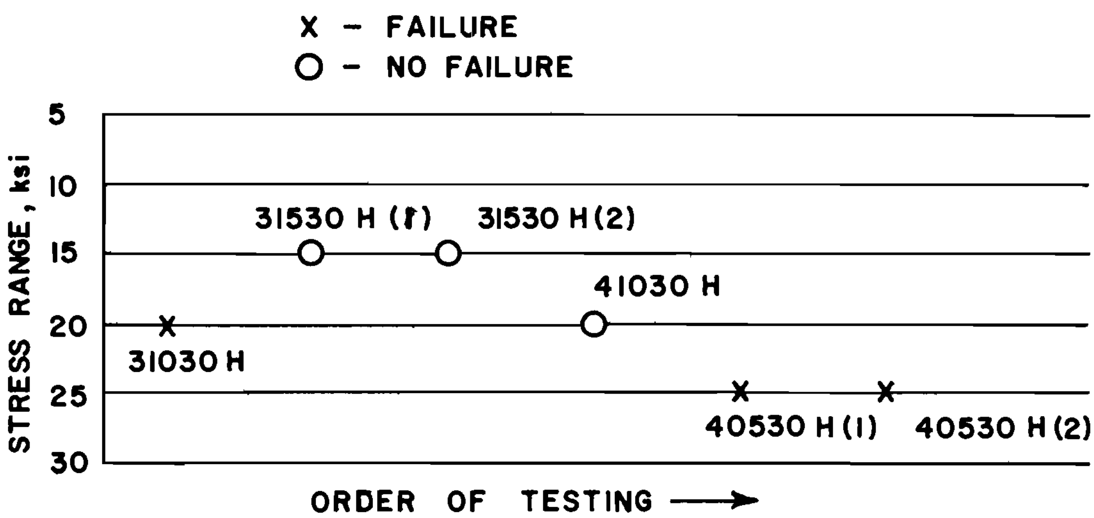

FIG. 14 STAIRCASE ILLUSTRATION OF RESULTS

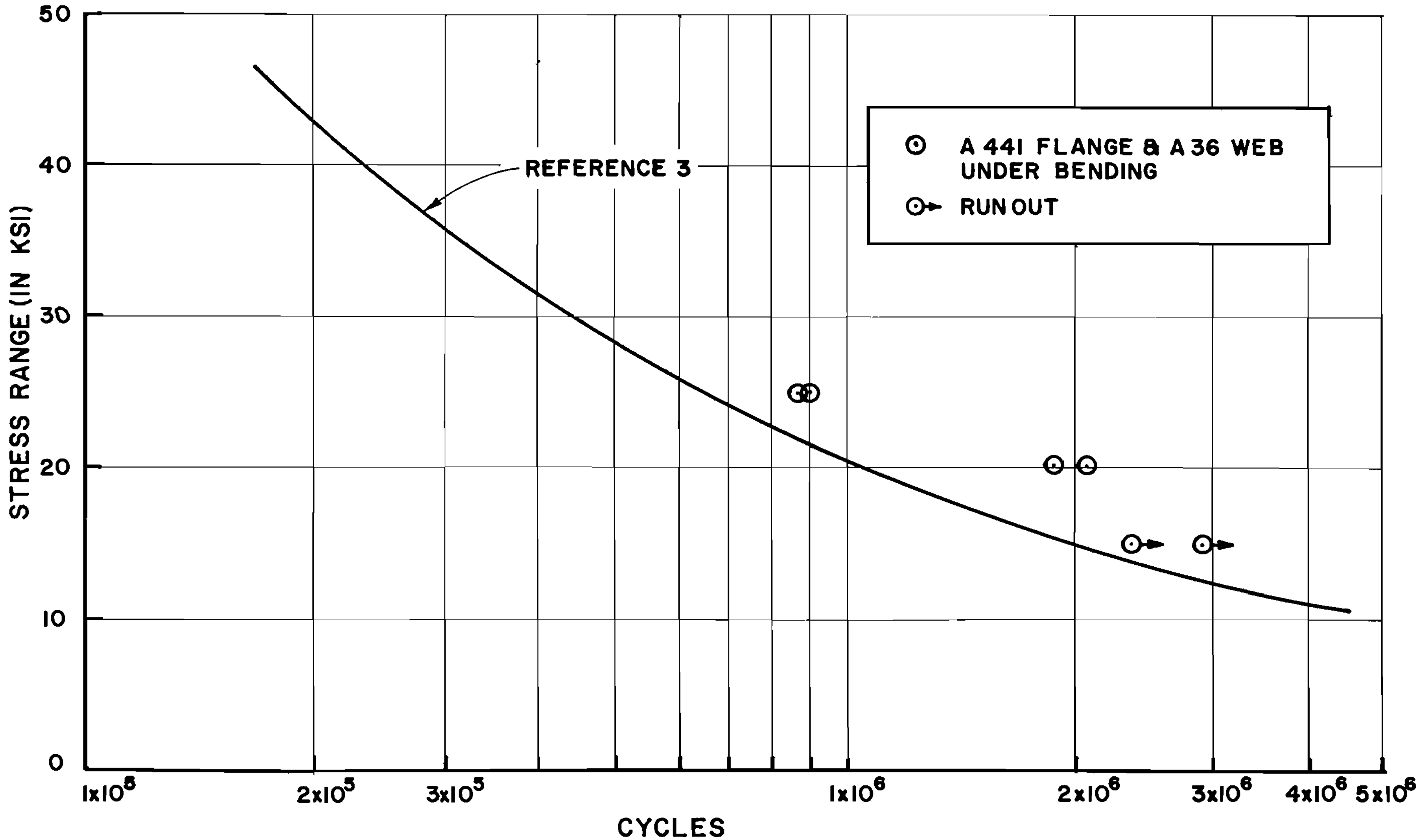

FIG. 15 S-N CURVE FOR PREVIOUS TESTS