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TUBULAR JOINTS UNDER ALTERNATING LOADS

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Interim Report to the Sponsors: Standard Oil Company of California, San Francisco, California

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STRUCTURAL ENGINEERING LABORATORY
COLLEGE OF ENGINEERING
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BERKELEY CALIFORNIA

Structures and Materials Research
Department of Civil Engineering
Division of Structural Engineering
and Structural Mechanics

TUBULAR JOINTS UNDER ALTERNATING LOADS
(Phase II, Part 1)

A Report of an Investigation

by

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San Francisco, California

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ACKNOWLEDGMENT

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I. INTRODUCTION

To develop vitally needed knowledge to improve the design of tubular joints subjected to alternating loads, a general program of research has been carried out. The first phase of this program was designed to obtain information regarding the relative efficiency of a number of tubular connections as encountered in typical off-shore construction. Based upon the results of this first phase[1], the second phase was basically designed to obtain information regarding the life expectancy of certain selected joints under different levels of alternating loads. The joints to be studied in this second phase were selected because of their relatively superior performance observed during the Phase I studies. The second phase of this program was to be carried out in two parts. The first part was to investigate a number of joints of a design identical, or closely similar, to those studied in Phase I, while the second part of the Phase II program was to study modified joint arrangements of connections investigated in the first part of Phase II. Consequently, the selection of the joints for study under Phase II, Part 2, was made following the outcome of the first part.

The results to date are presented herein and cover the findings of three of four types of joints which were to be studied in the first part of Phase II.

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1. Bouwkamp, J. G., "Tubular Joints Under Static and Alternating Loads," Report No. 66-15, June 1966, Structures and Materials Research, Department of Civil Engineering, University of California, Berkeley.

II. OBJECTIVE AND SCOPE

The objective of Phase II of this program was to investigate under complete reversals of load, the fatigue strength of four basic types of tubular connections. A total of seven specimens have been examined to date under different levels of alternating nominal stress. Three basic types of joints were tested. The joints--Type 1 with a thick-wall column section as shown in Figure 1, and Type 3 as shown in Figure 3--were identical to those tested in Phase I[1]. The Type 2 joint, as shown in Figure 2, was a modification of the Type 2 joint tested previously in Phase I. This modified Type 2 joint had a negative eccentricity e of 0.40 D rather than 0.25 D as tested before. In addition, Type 1 joints with thin-walled column sections were to be tested in Phase II. These connections were different from those tested in Phase I because of an anticipated cement-grout fill of the column members. These specimens were scheduled to be tested last. It is anticipated that the results from these tests will be available within three months.

As a result of Phase I findings, it was concluded that under the extremely high local stress levels as applied in this program of testing, the influence of the corrosive must have been of minor significance. Therefore, all of the specimens in Phase II were tested under in-air conditions.

III. TESTING PROCEDURE

The testing of each of the specimens was carried out in air under alternating loading conditions. However, the second of the Type 2 joints tested was first subjected to a series of cyclic, step-wise increased static loads in order to compare the strains for the initial load cycle with those resulting after a limited number of cycles of loading had been applied. The purpose of this static load sequence was to determine if a truly elastic state of stress did develop after a certain number of cycles.

Due to an improved mounting arrangement, it was possible to reduce the tolerance in the test frame considerably. As a result, it was possible to raise the cycling speed from about 15 cycles per minute, as applied in Phase I, to about 30 cycles per minute. The alternating loads were applied until failure of the joint was observed or until at least 350,000 cycles of load had been applied to the specimen.

In order to subject each specimen to the alternating load, the joints were assembled in a test frame as shown in Figure 4. In all instances, a required dead load producing a practically constant compressive stress of 11 ksi in the column section was applied. A more complete description of the test assembly was presented earlier[1] and will not be repeated here.

During the Phase I tests, each specimen was extensively instrumented, and detailed information was obtained with regard to strain levels in the joints. In this series of tests only one Type 2 joint, being a modified version of the Phase I tested Type 2 joint, was instrumented with five three-element rosettes to determine the effect of the larger branch member overlap and the material linearity at both the initial loading and after several cycles of loading had been applied. The location of these gages is shown in Figure 5.

IV. RESULTS OF STATIC TESTS

IV-1. General

For the study of the strains and stresses in the modified Type 2 joint, a number of presumably critical locations were selected and instrumented. The maximum load applied to the horizontal branch member was 50 k in either direction. The nominal stress in the diagonal member for a load of 50 k is approximately 28 ksi, or about 1.33 times the commonly allowable stress of 22 ksi. The applied force and the subsequent reactions were superimposed on the precompression load of the column member.

To check the alignment of the modified mounting arrangement in the loading frame, the first specimen tested--Type 1 joint--was instrumented with strain gages on the diagonal at 90° intervals around a section half way between joint and mounting plates. Strain readings up to a statically applied load of + and - 50 k clearly indicated that the alignment for all practical purposes was excellent.

IV-2. Detailed Test Results

IV-2-1. Joint Type 2 - Modified

This type of joint is a modified version of the original Type 2 joint as tested in the first phase of this program. In this case, the overlap of the diagonal member has been increased to achieve a design with approximately the same weld lengths between the diagonal and horizontal and the diagonal and column member. This arrangement, which causes a joint eccentricity of $e = 0.4$ D (D = O. D. column member), was expected to result in a more uniform load transfer and a reduced stress level near the weld between the two web members, which, as could be concluded from the fatigue failures observed in Phase I, was the critically stressed area in this joint.

Under the initial tensile load of 50 k, which was reached in 10 k intervals and was applied to the horizontal tube, the diagonal member underwent considerable yielding in the region of the intersection of the diagonal and the column member. The strain reading at gage 11 was some 2220 micro in./in. in compression. The complete tabulation of the strain readings under the initial tensile and compressive loading of 50 k is given in Table I.

The residual principal stresses and directions are shown in Figure 6. They indicate that the maximum and minimum stresses at gage locations 10, 11, and 12 were +21.5 ksi and -21.4 ksi, which would substantiate the fact that significant yielding had occurred under the initial loading condition.

After this first initial loading sequence, the gages were zero balanced to eliminate the first cycle residual strain pattern, and the specimen was cycled for 20 complete load reversals. Strain readings under step-wise increased loads were taken, and it was noted that a consistently linear plot was obtained. The specimen was again loaded for an additional 50 complete load reversals with readings being taken in intervals of 10 k up to 50 k after each 10 cycles. The results indicated that the joint was responding in an entirely linear fashion. Table II shows the strains at ±50 k at the end of 70 cycles of loading. The readings at the final 0 k load level show very small residual strain. Figures 7 and 8 show the principal stresses and directions after 70 cycles of complete load reversal had been applied. The results seem to indicate that the original objective of balanced load transfer has been met. However, it becomes evident that the tube wall near the weld between the column member and diagonal seemed to be stressed more than the wall along the weld between the diagonal and horizontal web members. This would indicate that the overlap was increased too much from the Phase I version of this joint. Furthermore, if the shear yield point is taken as $F_y/\sqrt{3}$, or for this material 27.7 ksi, the strains recorded some 0.25 in. away from the welds seem to indicate that the joint might have yielded in shear immediately adjacent to the weld at the intersection of the diagonal and horizontal members whenever the horizontal member was undergoing the maximum tensile load. The actual maximum shear stress some finite distance from the weld at this point was 18.9 ksi on one side and 17.8 ksi on the other. The shear stress determined some finite distance from the weld between the diagonal and column members was 21.8 ksi on one side and 21.4 ksi on the other side of the joint. From the principal stresses obtained, it would indicate that the ratio of maximum principal stress to the tensile yield stress is about 0.590. However, the ratio of the maximum shear stress to the shear yield stress is some 0.788.

TABLE I--STRAINS IN DIAGONAL - JOINT TYPE 2

INITIAL LOADING OF ±50 k

Gage No.	Strain Micro in./in.			
	+50 k	0 k	-50 k	0 k
1	-256	0	+204	+4
2	-972	+144	+1092	+212
3	+120	+204	+360	+228
4	-516	-232	+16	-236
5	-1616	-576	+376	-464
6	-208	-12	+208	+12
7	+260	+36	-140	+380
8	-16	+40	+264	+64
9	-308	+16	+584	+40
10	-252	-48	+136	0
11	-2220	-1116	+132	-968
12	-228	-96	+124	-4
13	+16	0	-104	-116
14	-888	-144	+824	-60
15	-260	-136	+180	-60

TABLE II--STRAINS IN DIAGONAL - JOINT TYPE 2

AFTER 70 CYCLES OF 50 k LOAD REVERSAL

Gage No.	Strain Micro in./in.		
	+50 k	-50 k	0 k
1	-244	+216	+4
2	-1116	+936	0
3	-44	+128	+8
4	-252	+260	-8
5	-1072	+912	+4
6	-192	+212	+8
7	+236	-168	+8
8	-56	+180	+20
9	-300	+528	+24
10	-188	+212	+8
11	-1092	+1088	+4
12	-80	+184	+12
13	+96	+8	+4
14	-804	+880	+4
15	-168	+216	+12

V. RESULTS OF ALTERNATE LOADINGS

V-1. General

The alternating lateral forces acting on off-shore structures produce alternative web member forces. In these studies, the member forces are represented by alternating loads acting on the specimens. These loads are introduced similarly as in Phase I by a double acting hydraulic cylinder with a maximum capacity of ±80 k. For the alternating load tests, the horizontal branch members were subjected to cylinder loads varying between ±20 k and ±50 k. The load in the diagonal under these conditions ranges from 35 k to 87.5 k.

As was pointed out earlier, all tests in this second phase were carried out under in-air conditions.

V-2. Detailed Test Results

V-2-1. Joint Type 1

The thick-walled Type 1 joint was the first to be tested. Under an alternating load of ±20 k, or an alternating nominal stress of ±11.2 ksi in the diagonal, the first of these joints passed through 382,192 load cycles without joint failure. At this point, the testing was discontinued as the specimen had cracked and failed for the second time along the attachment plates of the pin connection of the diagonal member. This area was repaired and rewelded first at 162,640 cycles but again failed after 382,192 cycles. Because the number of cycles recorded to that stage was so large as compared to the 9,900 cycles recorded during Phase I for the same type of joint under an alternating load of ±50 k, it was decided to stop this test and to continue the program with the testing of two other Type 1 specimens at intermediate load levels of ±40 k and ±30 k. Based on the fatigue life of this type of joint under intermediate loads, the significance of the approximately 382,000 cycles at ±20 k could be determined and the need to continue that test be established.

The second thick-walled Type 1 joint was subjected to an alternating load of ±40 k producing a nominal alternating stress of ±22.4 ksi in the diagonal. The first crack, the location of which is shown by a heavy dot in Figure 9, was noted at 16,100 cycles immediately above the weld on the diagonal member at the intersection with the column member and nearest to the horizontal member. This crack had propagated around the diagonal member approximately 4 inches when the test was stopped at 27,700 cycles. At 17,700 cycles a crack developed immediately above the weld in the horizontal member at the intersection with the column member nearest to the diagonal member. This crack propagated around the horizontal member about 3 inches after an additional 3,500 cycles had been placed on the specimen.

The third thick-walled Type 1 joint was subjected to an alternating load of ±30 k, producing a nominal alternating stress in the diagonal of 16.8 ksi. After 27,500 cycles, the first crack developed in the horizontal branch immediately above the weld between this member and the column member nearest to the diagonal member. This crack had propagated around the horizontal member for approximately 2 inches when the test was stopped at 75,860 cycles of loading. Figure 10 shows the crack progression for this test.

Considering the low fatigue life of this type of joint for alternating loads of ±40 k and ±30 k, the continuation of the fatigue test on the first specimen at ±20 k was deemed unnecessary.

V-2-2. Joint Type 2 - Modified

Two thin-walled Type 2 joints have been tested under a cyclic loading of ±50 k. The first joint tested developed, after 1,800 cycles of loading, practically instantaneous cracks in the wall of the diagonal member immediately adjacent to the welds. These cracks occurred on the far side only and were noticed at two locations. One crack, as shown in Figure 11, was 3 inches long and ran along the weld between the diagonal member and the horizontal member. Based on the symmetry of the subsequently noticed initial crack propagation, it seems that this crack must have been initiated at a point in the center of this crack length or approximately 2-1/2 inches up from where this weld meets the column member. The other crack was 2 inches long and occurred along the weld between the diagonal member and column member. The point of crack initiation must have been located approximately 2 inches from the point of the common intersection of the welds between the three members. Both cracks propagated initially symmetrically in both directions. In addition to those cracks, a third crack developed at the near side of the diagonal member, again along the weld between the two branch members. This crack started at about 2,200 cycles at which time the far side cracks had already weakened the diagonal cross-section considerably. The test was stopped after 3,020 cycles of loading.

The second joint tested developed a crack at 3,130 cycles in the far side wall of the diagonal member immediately along the weld between the intersection of the diagonal and the column member. This first crack, as shown in Figure 12, started probably at about 1-3/4 inches from the point of common intersection of the welds between the three members. At 3,480 cycles a second crack developed in the wall of the diagonal on the side opposite to the first crack. Finally, at 3,800 cycles a third crack developed in the wall of the diagonal on the side of the first crack along the weld between the diagonal and horizontal members. This crack started at a point about 2-1/2 inches up from the common point of intersection of the welds between the three members. All cracks propagated in both directions to maximum lengths between about 2 and 4 inches until the test was stopped at 6,000 cycles of loading.

V-2-3. Joint Type 3

The first gusset plate joint was tested at an alternating load level of ±30 k. At 6,480 cycles the first hairline crack was noted in the wall of the horizontal branch tube on the side of the diagonal member just above the weld between the gusset plate and the horizontal member. This hairline crack, as shown in Figure 13, had not propagated more than 5/8 inches even after 39,000 cycles. The second crack to be noted was at 23,900 cycles and occurred in the wall of the diagonal member to the side of the top of the weld between the gusset plate and the diagonal member on the column side of the diagonal tube. This crack had propagated through the weld just above the top of the gusset plate and around the diagonal tube approximately 5-1/2 inches when the test was stopped after 39,000 cycles. A third crack started at 34,500 cycles in the diagonal tube wall just above the weld with the gusset plate. This crack had propagated about 1 inch when testing was terminated.

The second of the Type 3 joints was loaded with a ±20 k alternating load. The first crack originated in the diagonal member on the side nearest the column member and approximately 1/2 inch above the 1/4-inch gusset plate. The crack occurred at 14,600 cycles of load and propagated as shown in Figure 14. The second crack started in the horizontal member immediately above the center of the 1/4-inch gusset plate on the side nearest the diagonal member and about 1/2 inch above the gusset plate. This crack occurred after 26,300 cycles of loading and did not propagate noticeably. The total number of cycles of load on this specimen was 43,700.

VI. CONCLUSIONS AND RECOMMENDATIONS

The static load study on the one Type 2 joint indicated that the welded joint contains considerable residual stresses due to welding. Under the initial loading cycle of ±50 k the diagonal member exhibited considerable yielding. However, after this initial plastic deformation of the joint, the specimen essentially acted in an elastic manner. Increasing the negative eccentricity of the joint from 25% to 40% of the O. D. of the column member seemed to produce a rather balanced stress transfer.

The alternating load studies undertaken in this phase of the project provided additional information as to the alternating load life under various load levels. The results of these tests are presented in Figure 15 and plotted as applied load versus the number of cycles at which the first crack was initiated.

It can be concluded that the modified thin-walled Type 2 joint with a 40% negative joint eccentricity showed no improvement over the fatigue life observed in Phase I for the 25% negative eccentricity joint. To the contrary, it seems that the added stiffness of the joint due to the larger overlap of the branch member caused a general restraint within the joint which resulted in a slightly lower fatigue life than recorded before in Phase I. In general, it can be concluded that interwelded branch members of the type tested in this program, despite their effectiveness under static loads, should not be used in alternatingly loaded joints. It should be noted again that thin-walled joints as tested earlier in Phase I with non-interwelded branch members and a column member wall thickness of less than 3% of the outer diameter of the column section, will have a life expectancy of only a fraction (less than 10%) of that which can be expected for the above mentioned interwelded joints. The recommendation is, therefore, against the use of thin-walled tubular joints.

The gusset-plate joints tested showed little increase in the fatigue life under lower load levels. This seems to indicate clearly that the stress concentration near the points of penetration of the gusset-plate and the branch members are invariably high and therefore remain the prime cause of failure. The only structural improvement which can lead to an increased fatigue life seems to be the application of tapered gusset-plates which will reduce stress and strain concentrations. It is therefore recommended to include in the second part of this Phase II program a number of tapered gusset-plate joints. Possibly two types of joints should be considered--one with a gusset plate scalloped within the perimeter of those tested so far and a second joint with gusset-plate which would be more gradually tapered and extend beyond the present gusset-plate perimeter.

The results regarding the thick walled Type 2 joint again indicate the relatively superior performance of this connection. It seems that between the applied load levels of ±20 k and ±30 k a significant change in the strain pattern must have occurred. The considerable improvement of the fatigue life under a cyclic load of ±20 k might have resulted from the absence of critical yield strains at this lower load level. It is recommended to investigate the possible further improvement of this joint type by increasing the column wall thickness as well as possibly the wall thickness of the web members. However, a study of the state of stress through numerical analysis is recommended before the design of these joints. Also, the aspect of different diameter ratios of branch member and column section could be studied. Again, such experimental studies should be preceded by an analytical investigation.

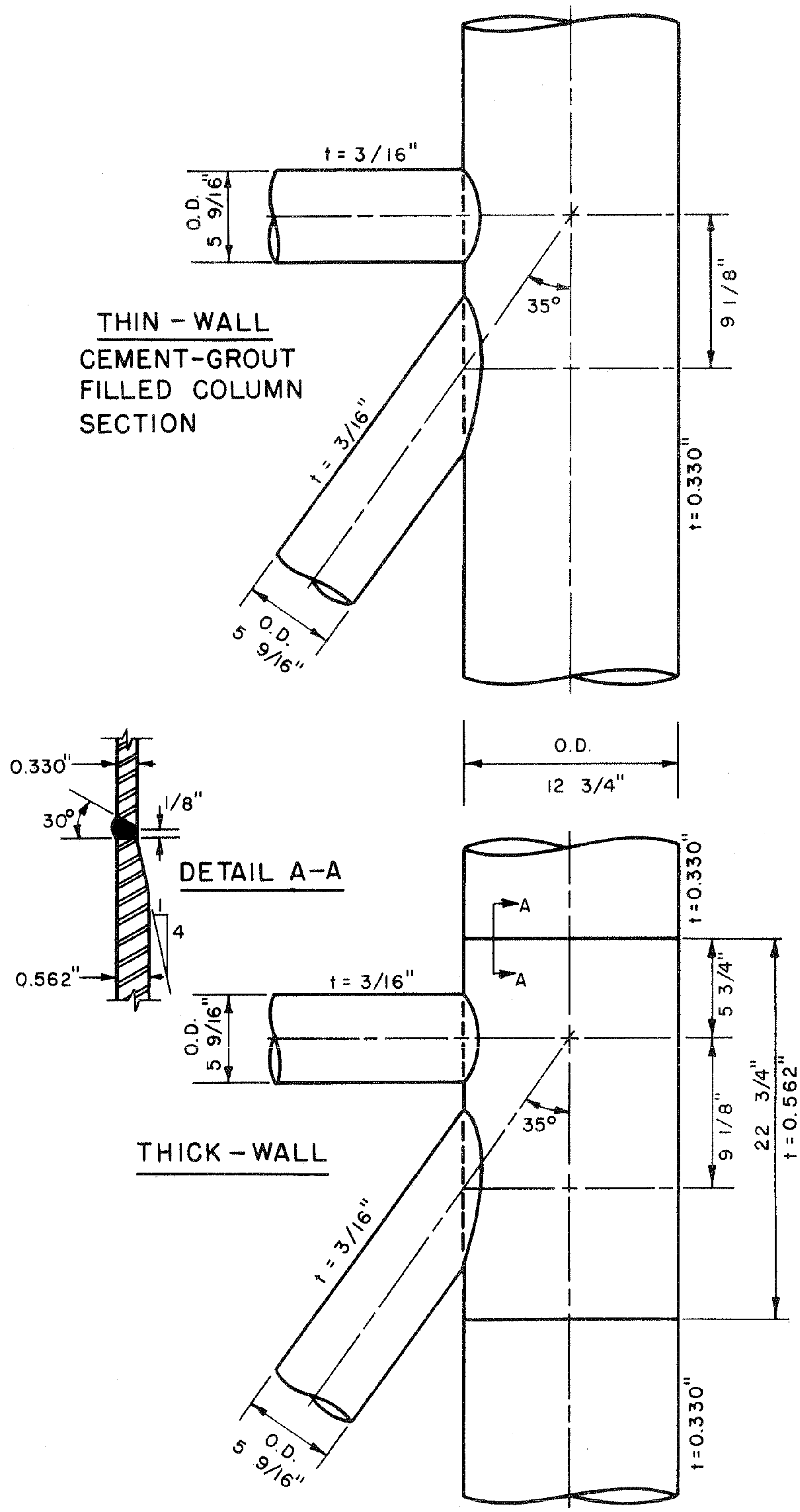


FIG. 1 JOINT TYPE 1 (ZERO-ECCENTRICITY)

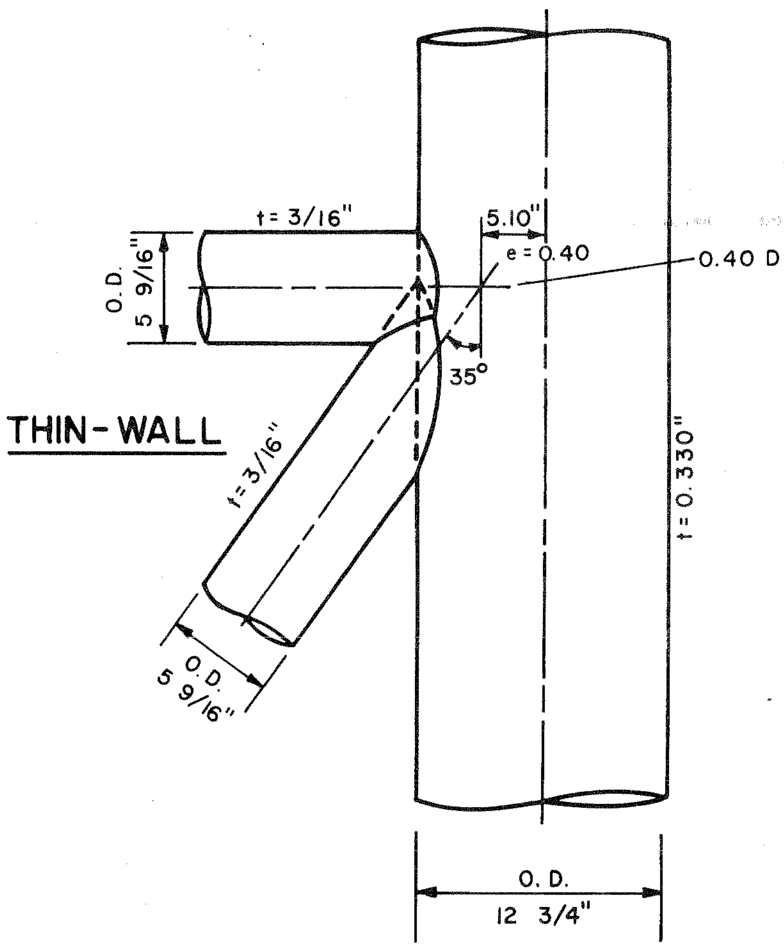


FIG. 2 JOINT TYPE 2 (NEGATIVE-ECCENTRICITY)

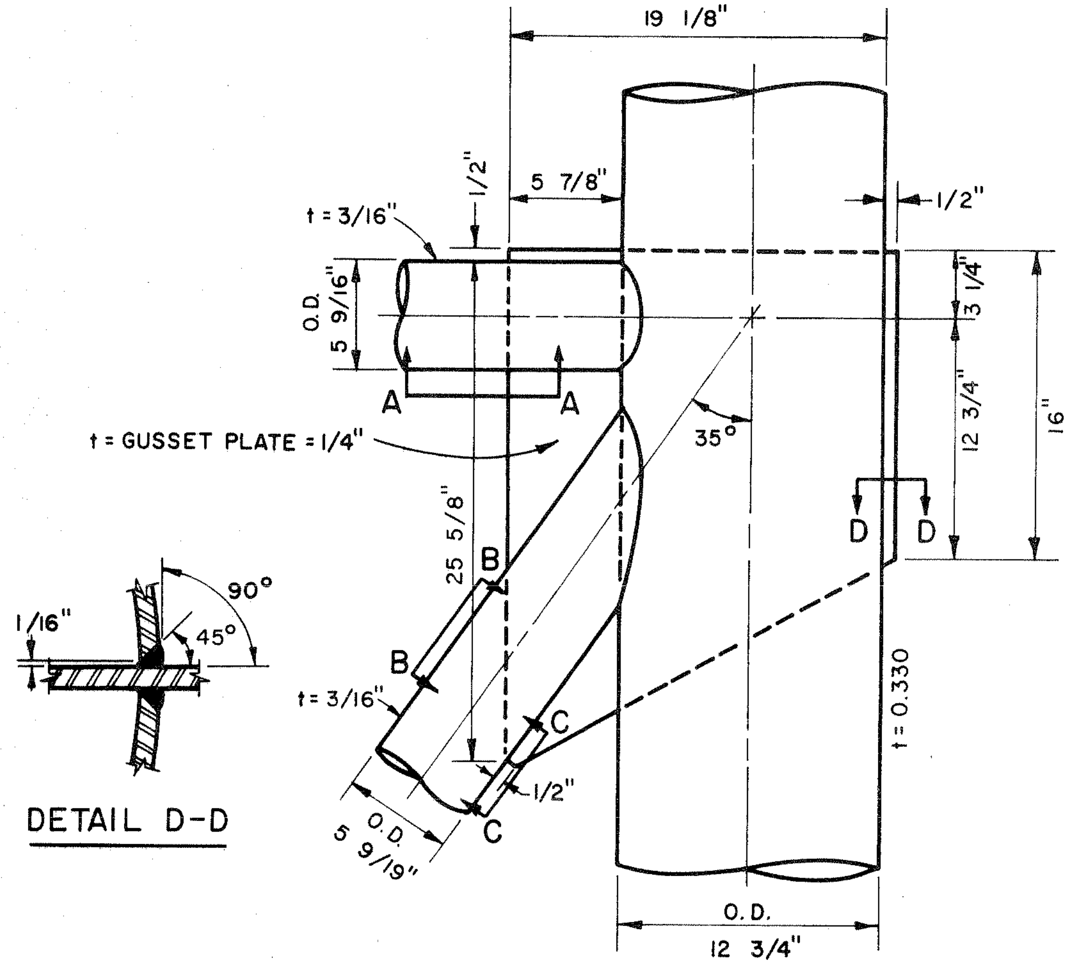


FIG. 3 JOINT TYPE 3

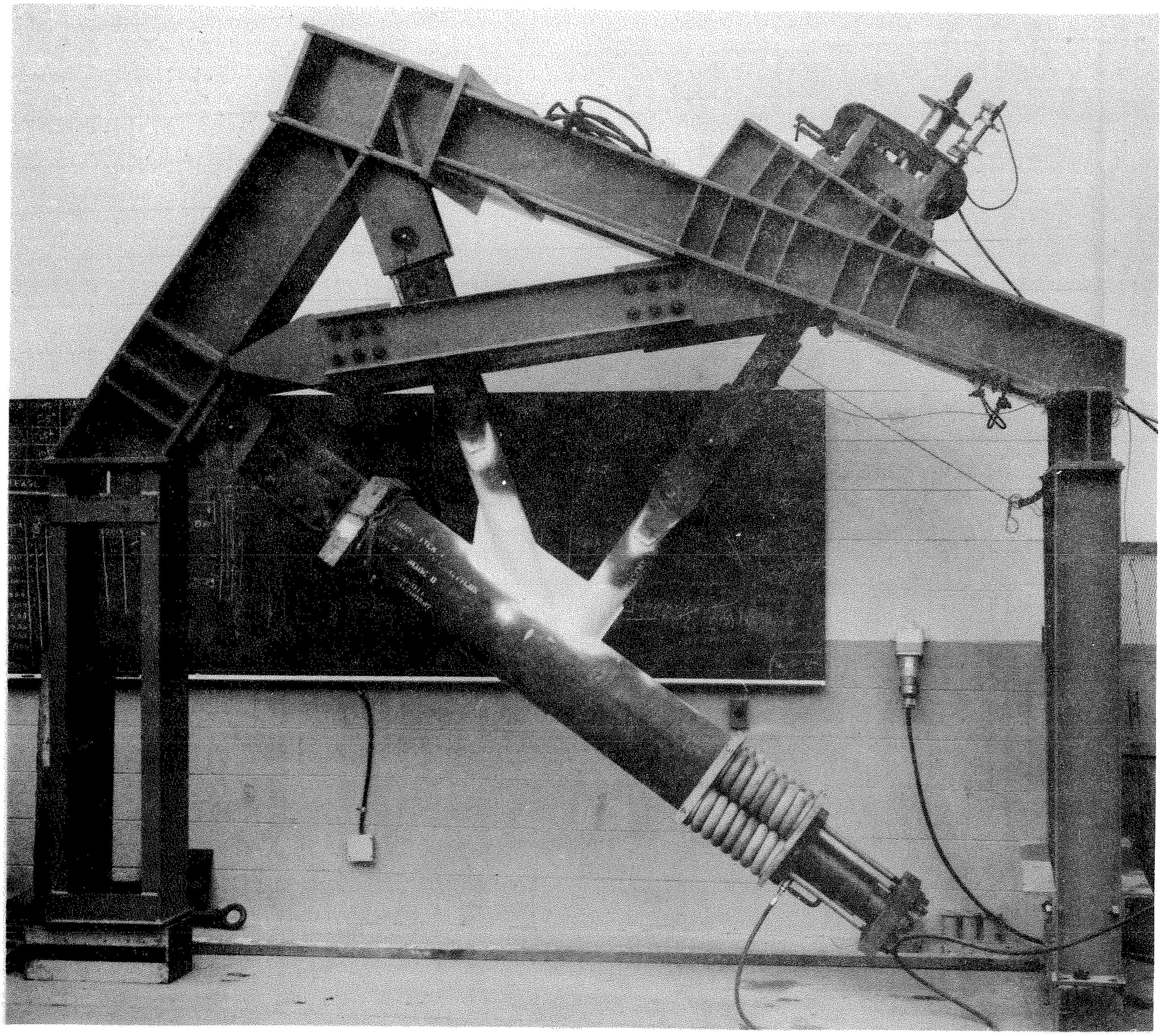
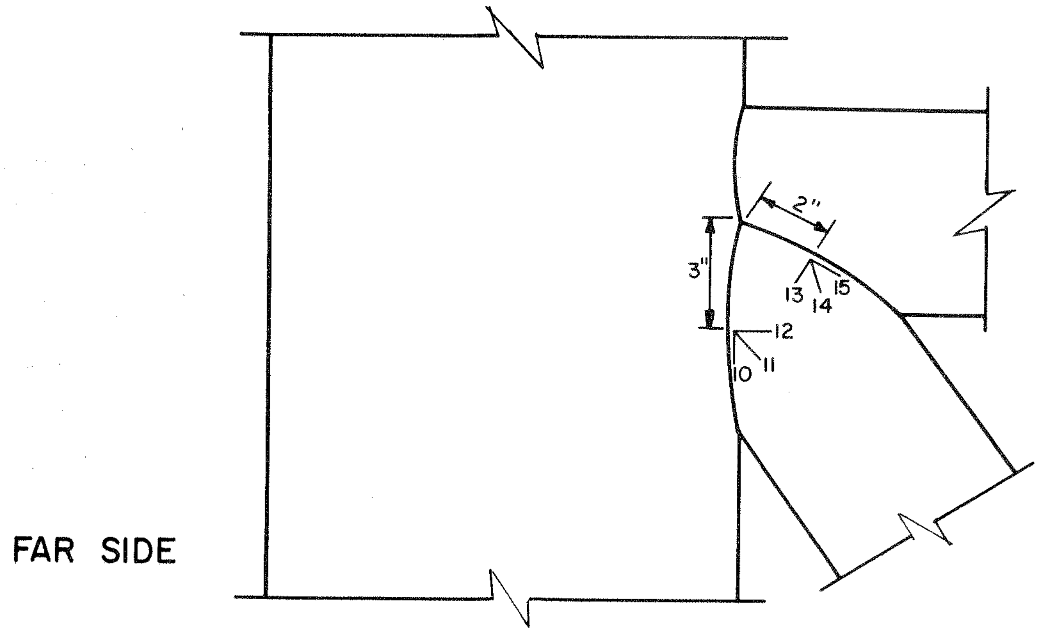
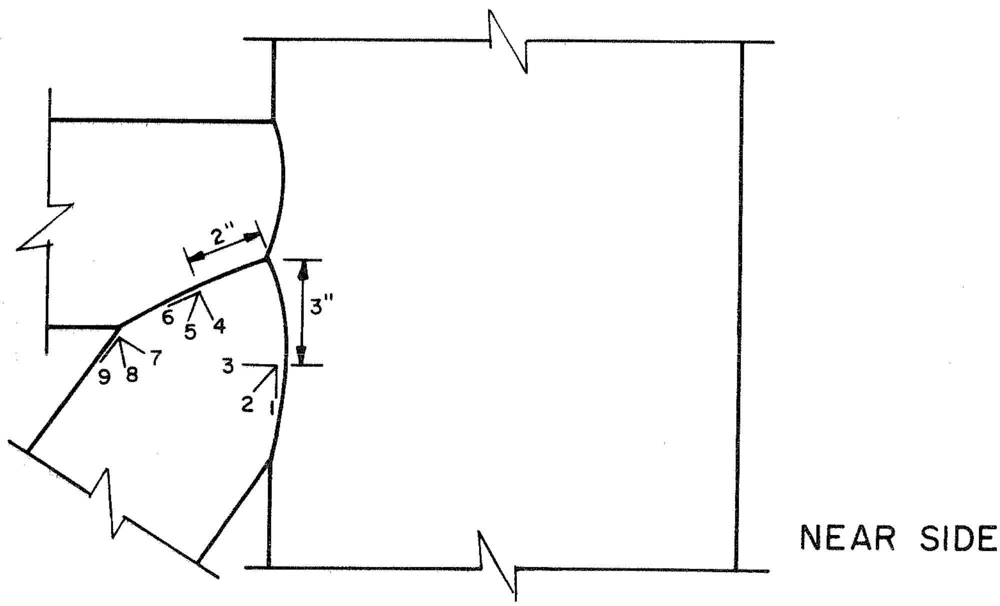


FIG. 4 TEST FRAME WITH MOUNTED SPECIMEN

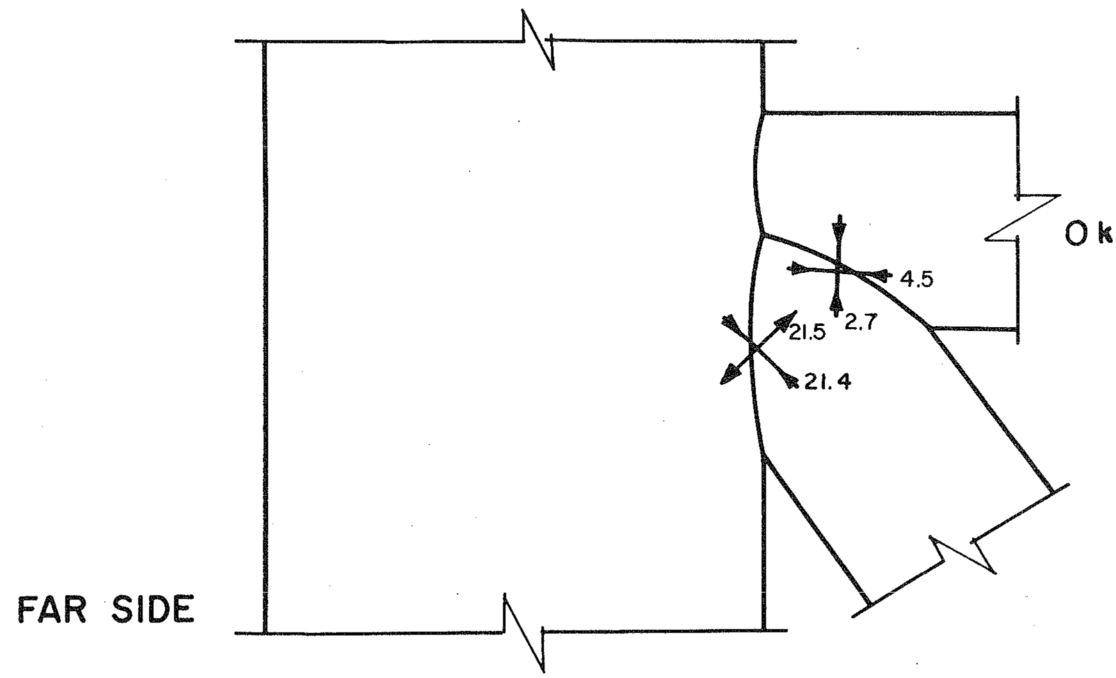


JOINT TYPE 2 THIN WALL



JOINT TYPE 2 THIN WALL

FIG. 5 STRAIN GAGE INSTRUMENTATION



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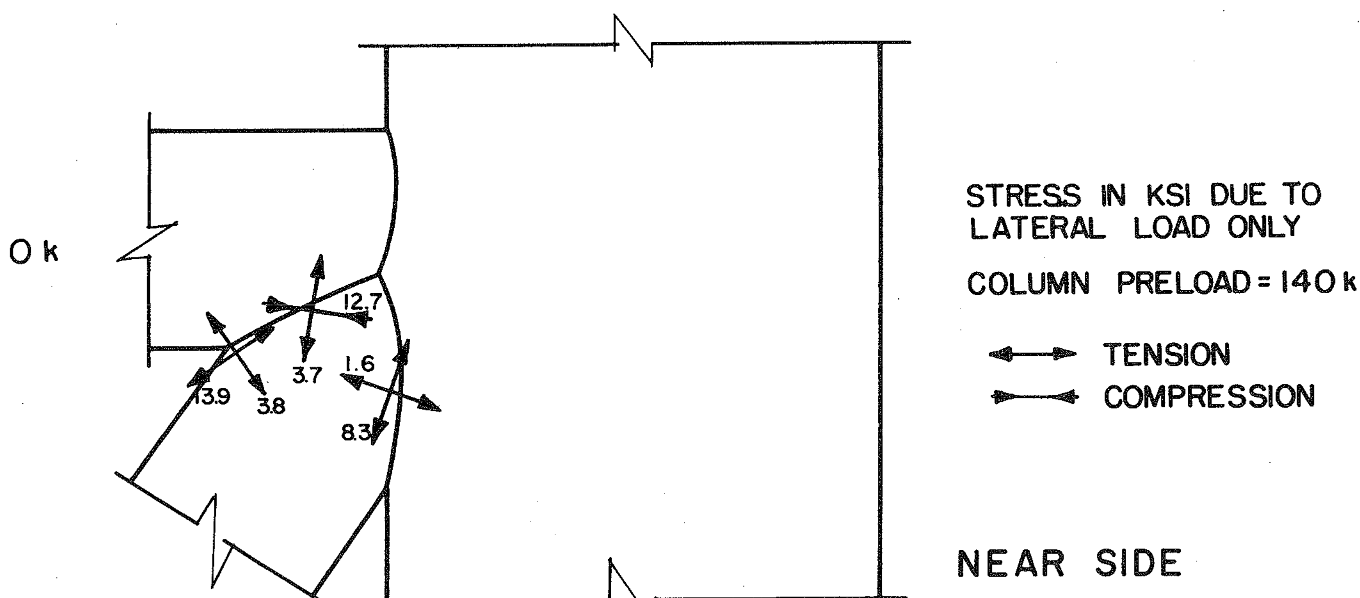
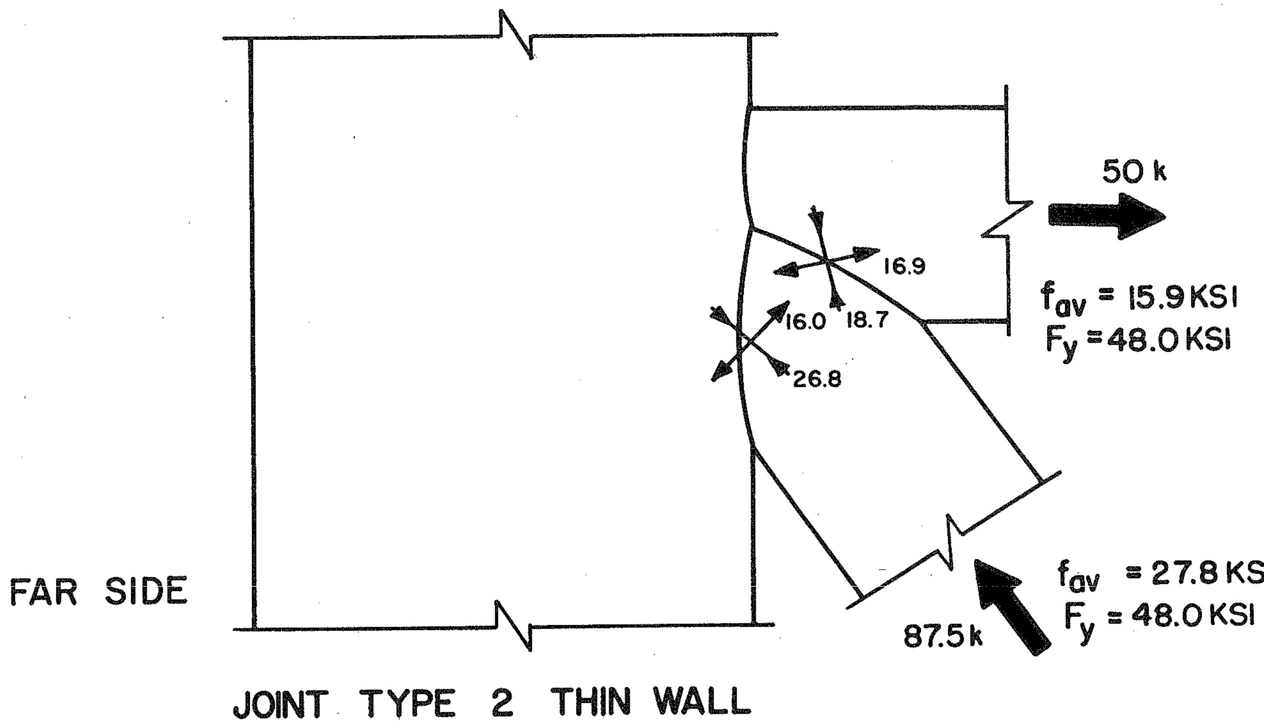


JOINT TYPE 2 THIN WALL

FIG. 6 RESIDUAL PRINCIPAL STRESSES AFTER INITIAL ±50 k LOAD



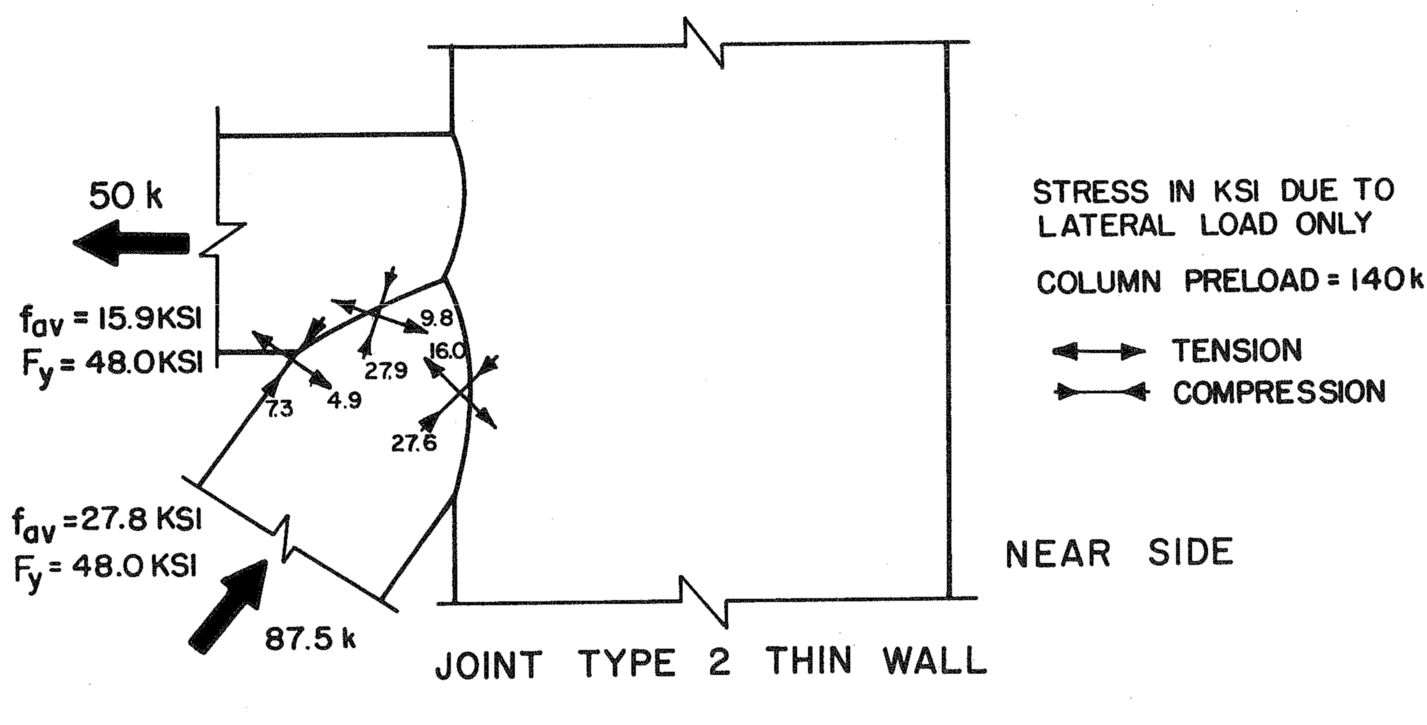


FIG. 7 PRINCIPAL STRESSES - TENSION LOAD IN HORIZONTAL TUBE AFTER 70 CYCLES OF LOAD

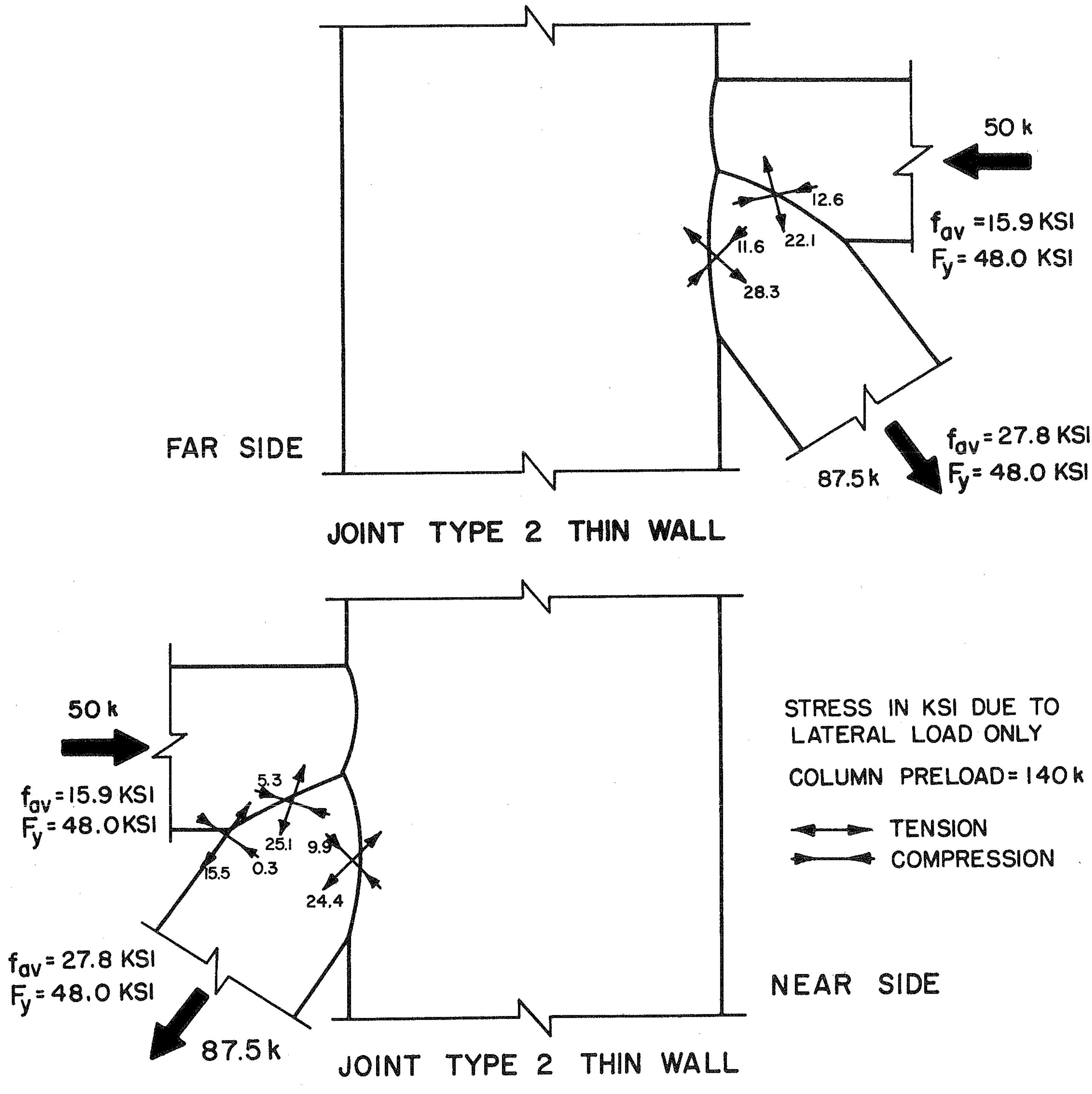
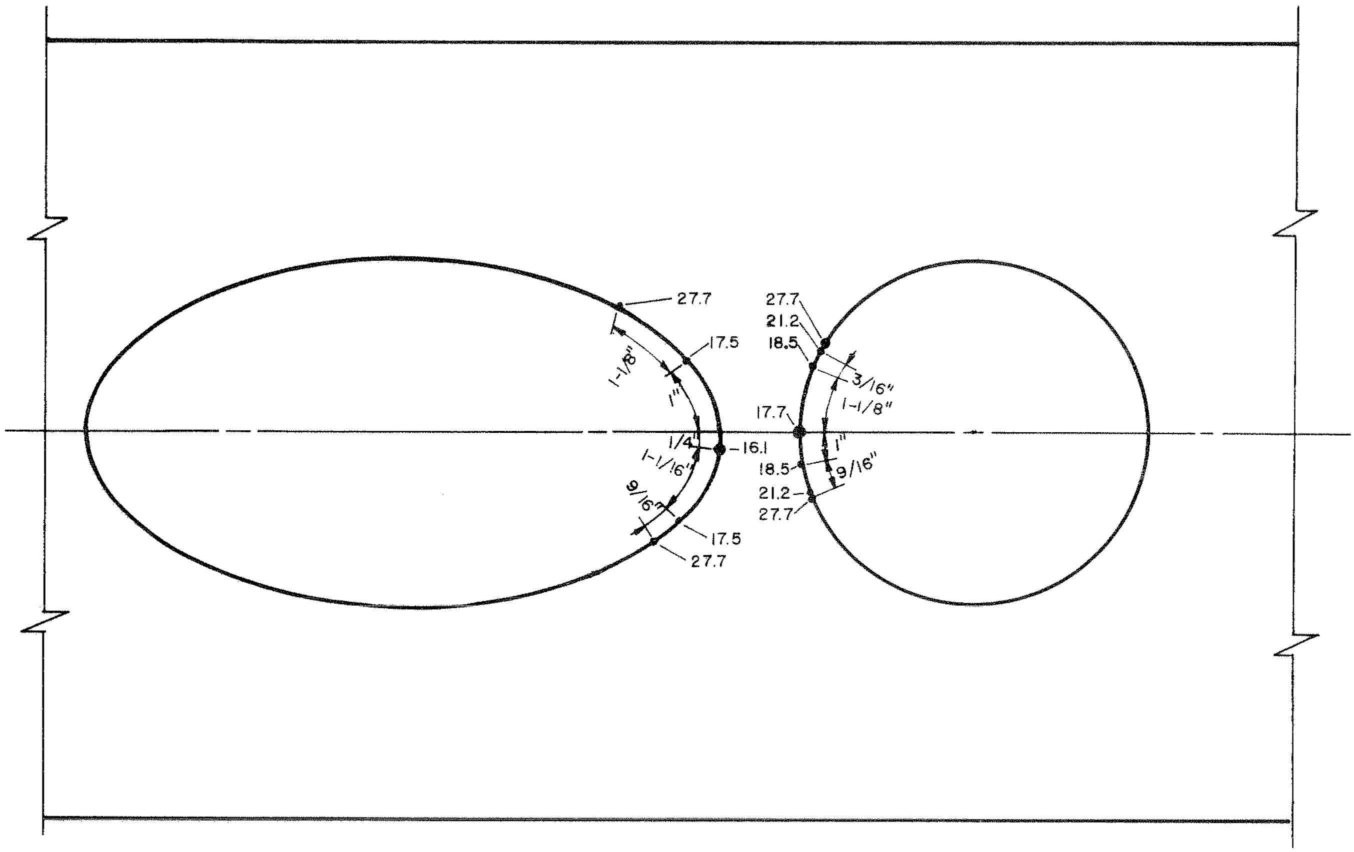
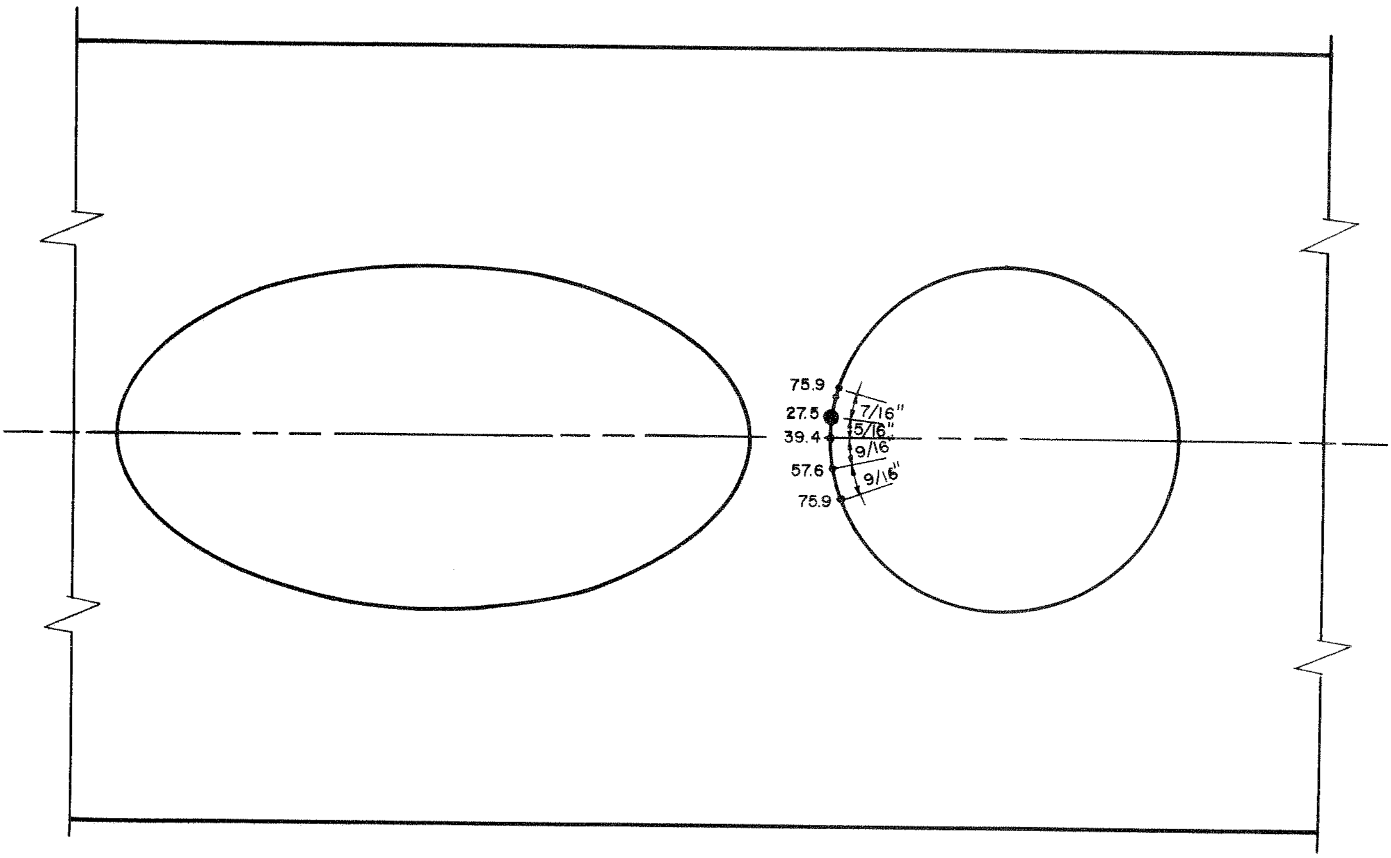


FIG. 8 PRINCIPAL STRESSES - COMPRESSION LOAD IN HORIZONTAL TUBE AFTER 70 CYCLES OF LOAD



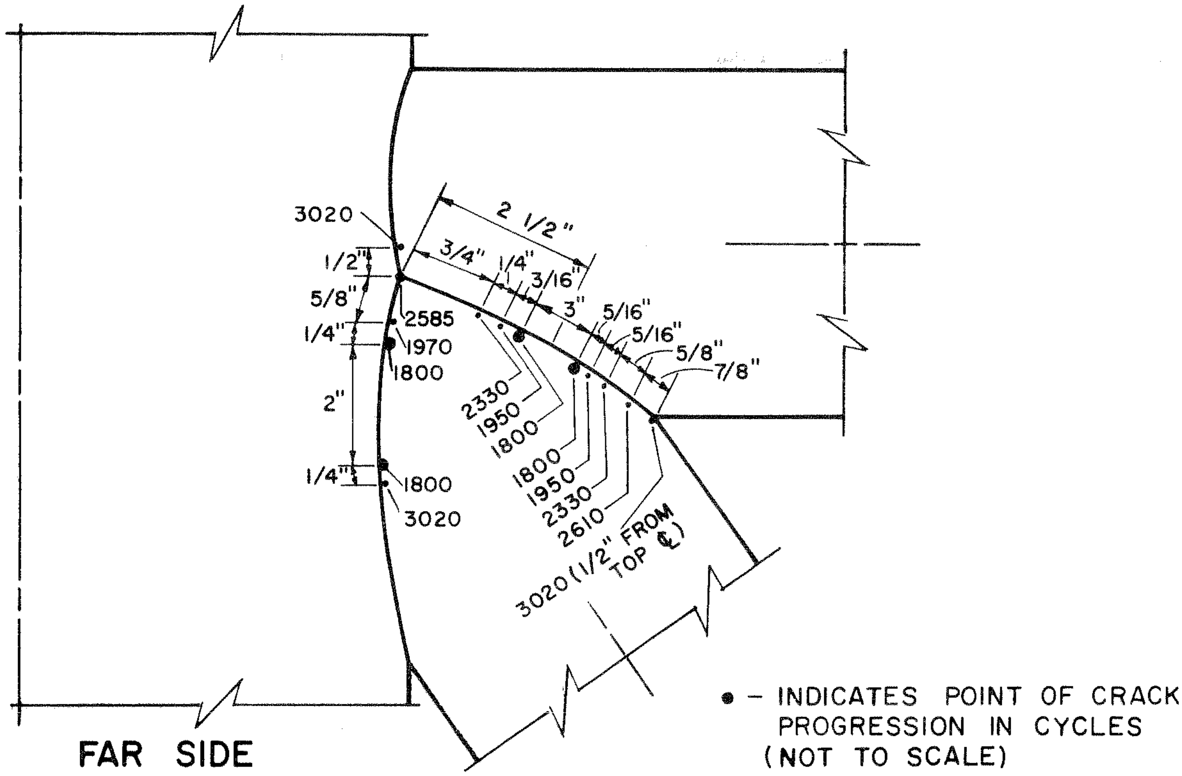
● INDICATES POINT OF CRACK PROGRESSION IN 1000 CYCLES

FIG. 9 CRACK PROPAGATION IN TYPE I JOINT LOADED AT ±40K IN HORIZONTAL MEMBER



● INDICATES POINT OF CRACK PROGRESSION IN 1000 CYCLES

FIG. 10 CRACK PROPAGATION IN TYPE I JOINT LOADED AT ± 30K IN HORIZONTAL MEMBER



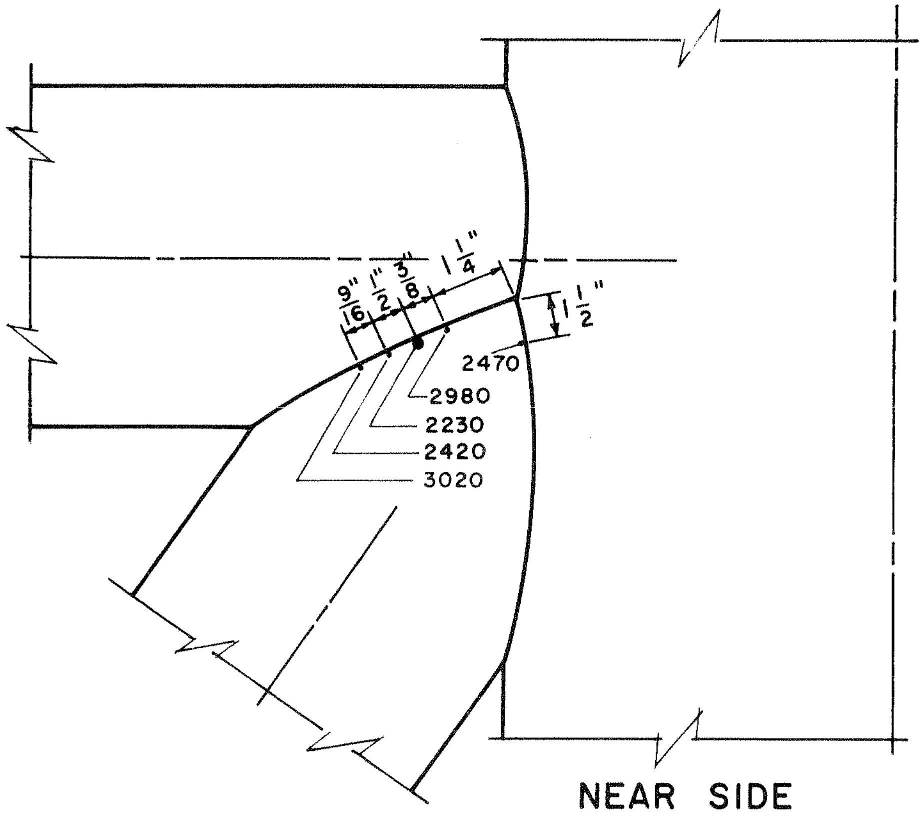


FIG. 11 CRACK PROPAGATION IN TYPE 2 JOINT LOADED AT ± 50 K IN HORIZONTAL MEMBER

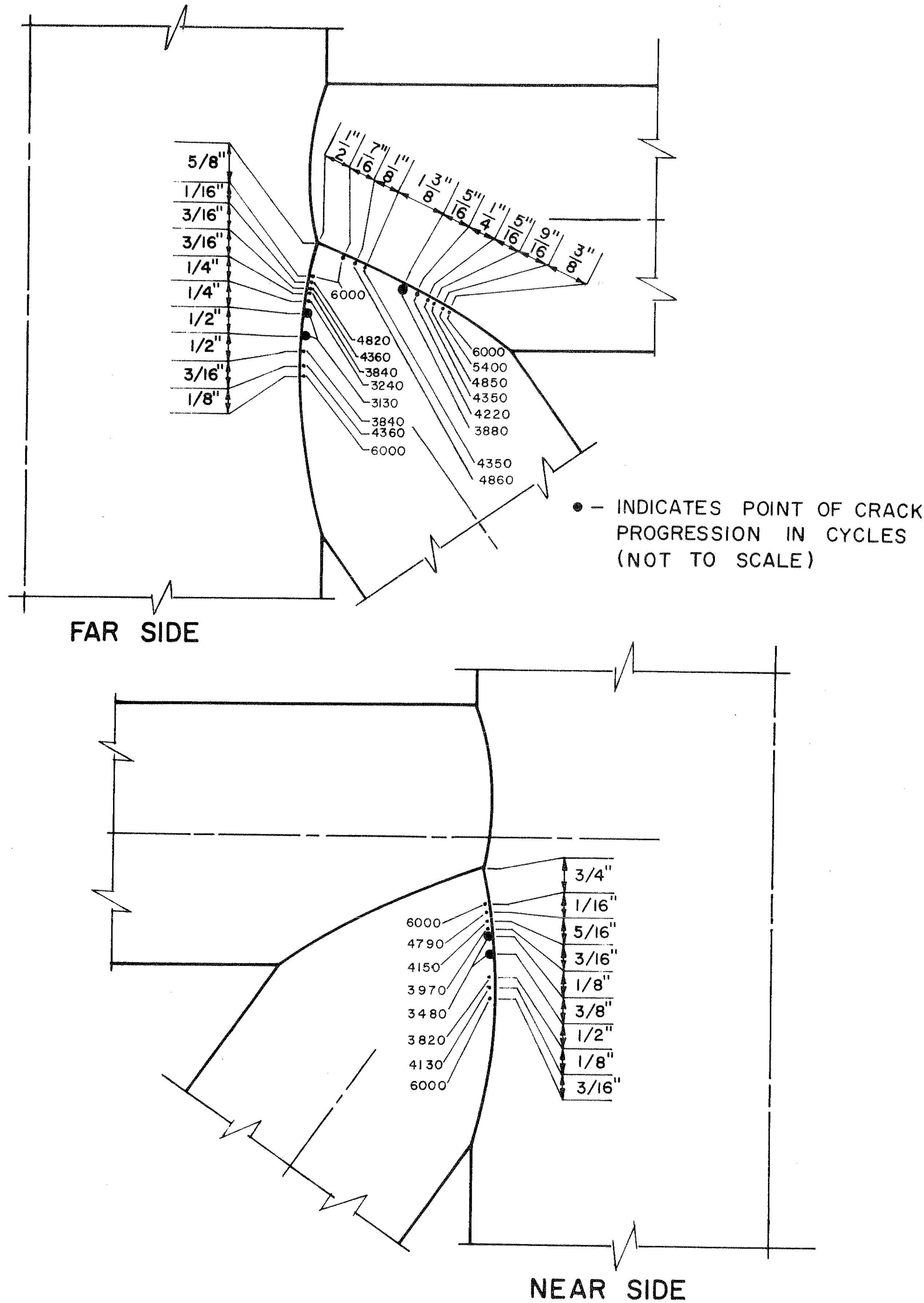
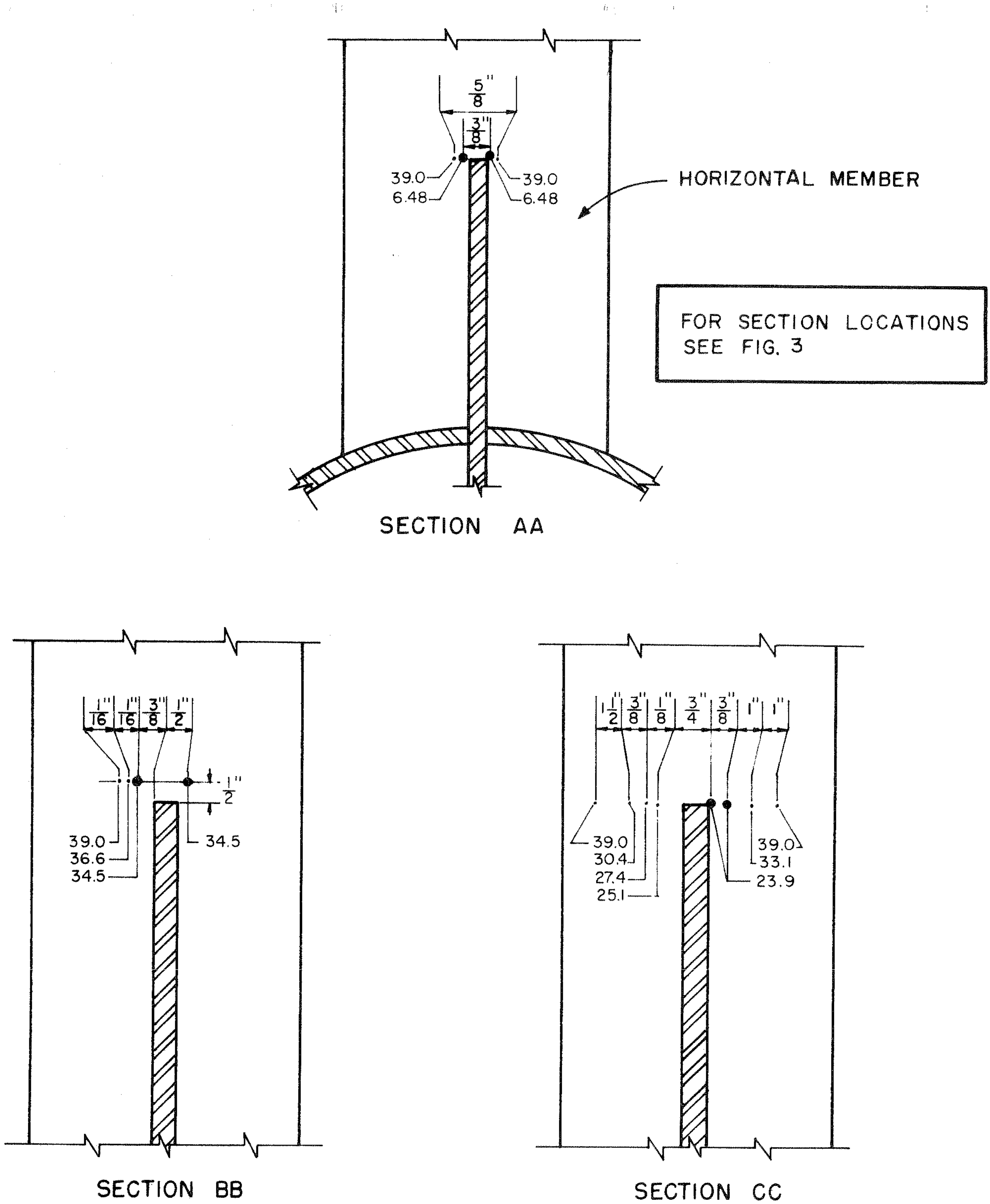
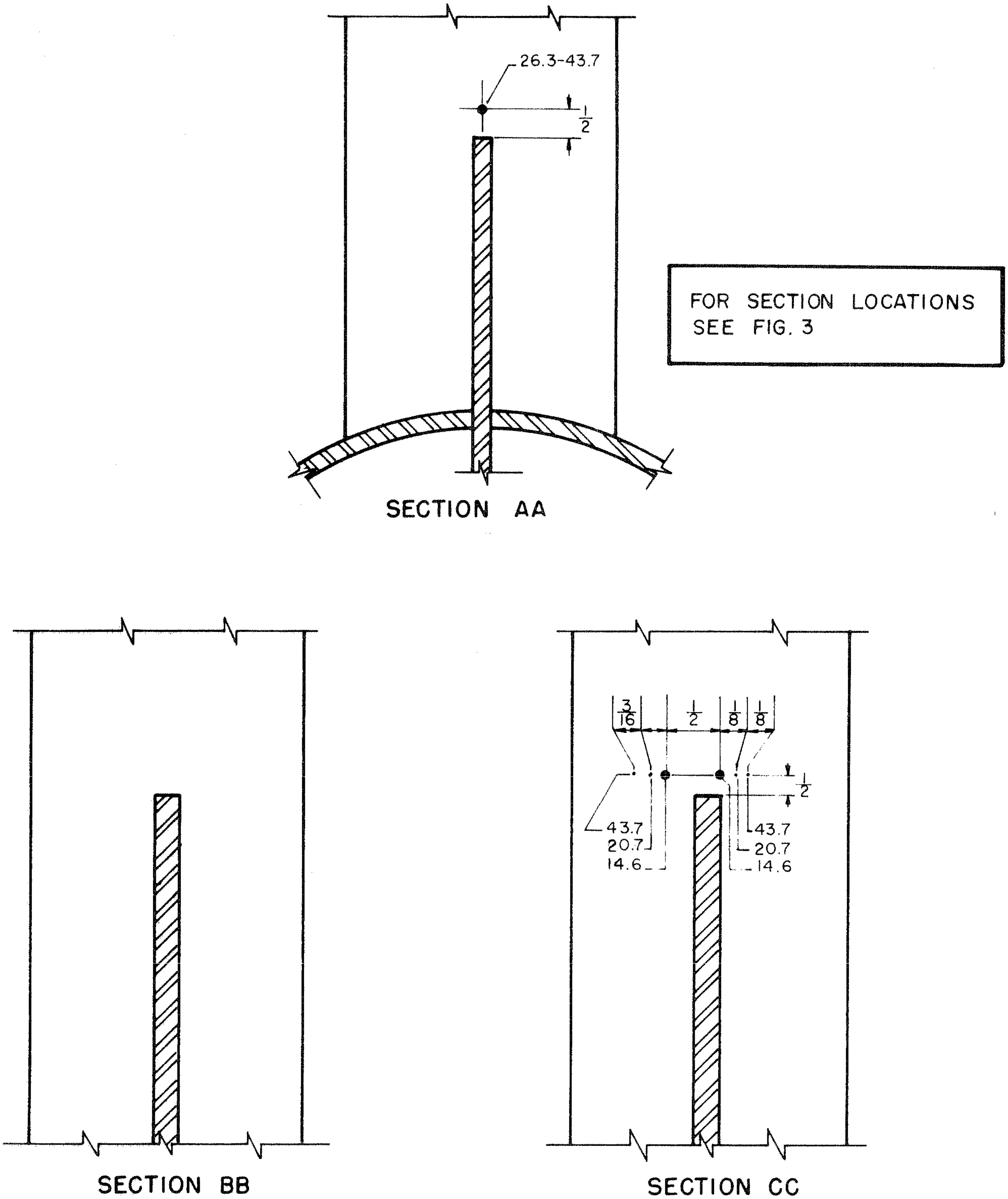


FIG. 12 CRACK PROPAGATION IN TYPE 2 JOINT LOADED AT ± 50 K IN HORIZONTAL MEMBER



• —— INDICATES POINTS OF CRACK PROGRESSION IN 1000 CYCLES
(NOT TO SCALE)

FIG. 13 CRACK PROPAGATION IN TYPE 3 JOINT LOADED AT ±30K IN HORIZONTAL MEMBER



•—— INDICATES POINTS OF CRACK PROGRESSION IN 1000 CYCLES
(NOT TO SCALE)

FIG. 14 CRACK PROPAGATION IN TYPE 3 JOINT LOADED AT ±20K IN HORIZONTAL MEMBER

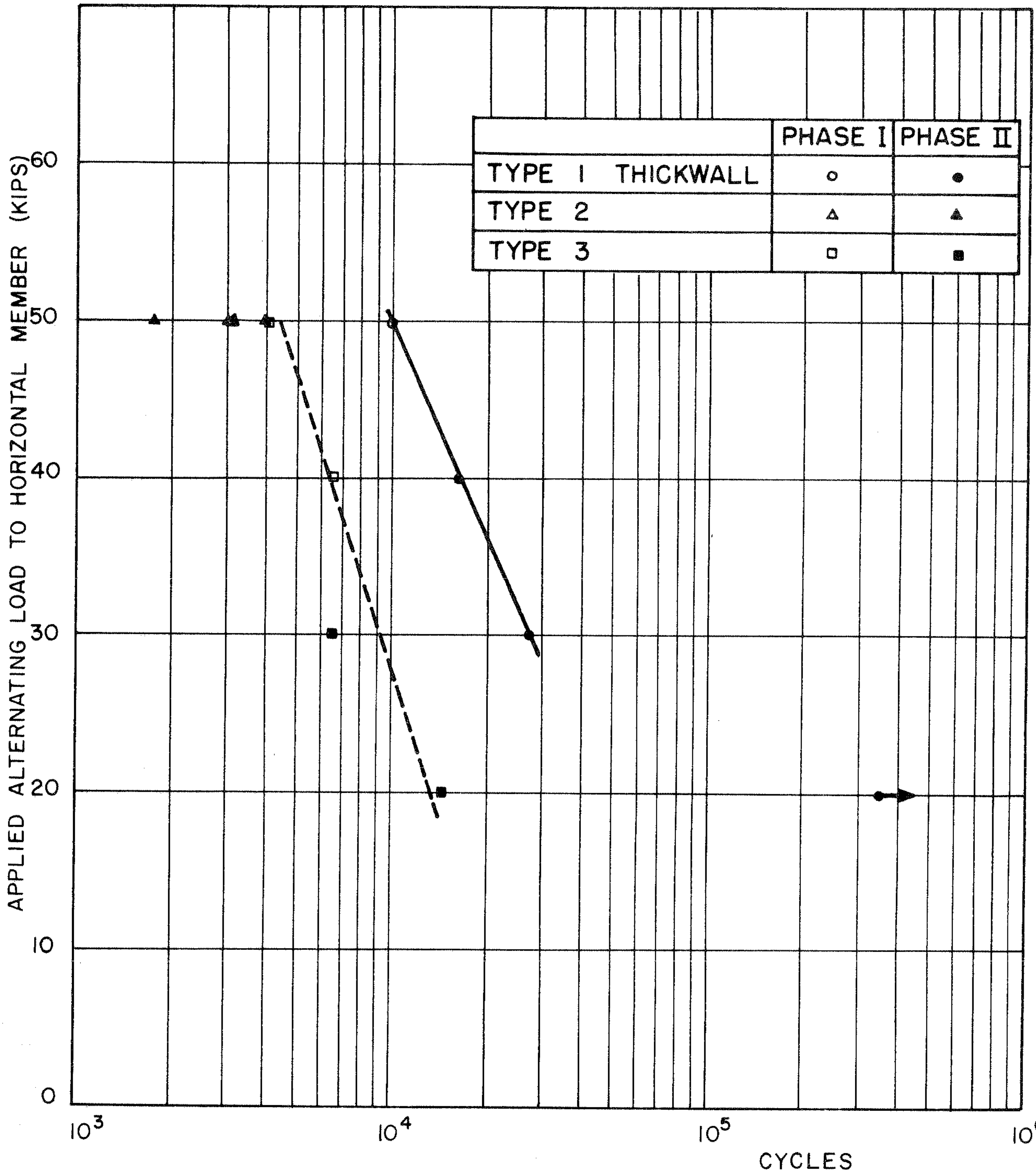


FIG. 15 ALTERNATING LOAD LIFE OF THREE TYPES OF TUBULAR CONNECTIONS