Title
Tubular Joints Under Alternating Load

Authors
Bouwkamp, Jack
Stephen, Roy

Publication Date
1970-03-01

REPORT NO.
70-4

STRUCTURES AND MATERIALS RESEARCH
DEPARTMENT OF CIVIL ENGINEERING

TUBULAR JOINTS UNDER ALTERNATING LOADS

PHASE II PART 2

BY

J. G. BOUWKAMP
R. M. STEPHEN

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

MARCH 1970

STRUCTURAL ENGINEERING LABORATORY
COLLEGE OF ENGINEERING
UNIVERSITY OF CALIFORNIA
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 2)

A Report of an Investigation

by

J. G. Bouwkamp
Professor of Civil Engineering

and

R. M. Stephen
Senior Development Engineer

to

Standard Oil Company of California
San Francisco, California

College of Engineering
Office of Research Services
University of California
Berkeley, California

July 1971

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONTINUED)

ACKNOWLEDGEMENT

The work reported herein was conducted in the Structural Research Laboratory, and Davis Hall, Division of Structural Engineering and Structural Mechanics, Department of Civil Engineering, University of California, Berkeley. The program was co-sponsored by several companies with interest in off-shore structures. The United States Steel Corporation, Pittsburgh, Pennsylvania, donated the joint-specimens. The Standard Oil Company of California, San Francisco, acted as industry representative. The research grant was administered by the Office of Research Services, College of Engineering, University of California.

A number of persons made significant contributions to the work described in this report, and the authors wish to thank them all. Particularly, the contribution by Mr. A. D. Lawrence of the Laboratory staff is gratefully acknowledged.

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 at the University of California, Berkeley.

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 the second phase were selected because of their relatively superior performance observed during the Phase I studies.

The second phase of this program was 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. The main objective of this part was to evaluate the fatigue life under different levels of alternating stress. The second part of the Phase II program was to study modified joint arrangements of connections investigated in the first part of Phase II. The selection of the joints for study under Phase II, Part 2, was made following the outcome of the first part and the evaluation of extensive analytical studies.

---

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.

The results of the specimens tested under the first part of Phase II were reported earlier[2,3], except for one thick-walled Type 1 joint which was extensively instrumented in an attempt to correlate a theoretical, finite-element solution with the results obtained in this experimental program[4].

The pipe material used for all joint specimens tested in this program was API Spec 5L-Grade B.

---

2. Bouwkamp, J. G., and Stephen, R. M., "Tubular Joints Under Alternating Loads," Structures and Materials Research Report No. 67-29, November 1967, Department of Civil Engineering, University of California, Berkeley.
3. Bouwkamp, J. G., and Stephen, R. M., "Cement-Grout Filled Tubular Joints Under Alternating Loads," Structures and Materials Research Report No. 68-16, Department of Civil Engineering, University of California, Berkeley.
4. Greste, Ojars, "Finite Element Analysis of Tubular K Joints," Report No. UCSESM 70-11, June 1970.

II. OBJECTIVE AND SCOPE

The objective of Phase II was to investigate under complete reversals of loads and under different stress levels the fatigue strength of two basic types of tubular connections, namely non-gusset plate joints with or without an intersecting web member, and gusset plate joints.

In the second part of the Phase II program, reported herewith, a total of twelve joint specimens along with one thick-walled specimen remaining from the first part of Phase II and having non-intersecting web members, were examined under different levels of alternating nominal stress. Six of the twelve specimens were Type I joints with non-intersecting web members as shown in Figure 1. The wall thickness of the web members was increased from 0.188 in., as tested earlier, to 0.258 in. The chord members had in two cases an increased wall thickness of 0.625 in. (versus 0.562 in.). The objective of this particular series was to study the possible beneficial influence of increased wall thicknesses on the fatigue life of these types of joints. Earlier studies[1] had indicated that increasing the chord wall thickness increases the fatigue life. These studies also indicated that failure in those instances normally occurred in the web member walls, immediately above the welds connecting the web to the chord member, rather than in the chord member wall. Hence, increasing the wall thickness of the web members only over a limited length near the joint between web and chord members could well increase the joint fatigue life. Furthermore, increasing the chord member wall, in turn, would further improve the state of stress and, hence, probably the fatigue life. The selection of the member sizes, as shown in Figure 1, was based on the stress calculations obtained from a finite element computer solution as described in reference 4.

A second series of six specimens were tested with tapered and scalloped gusset plates as shown in Figure 2. These Type-3 joints were designed on the basis of experimental model studies[5]. Results of these photoelastic studies indicated an improved balanced stress distribution in the gusset plates, particularly for joints with tapered gusset plates. Since a rather uniform state of stress in the tips of the gusset plates indicates a relatively uniform force transfer from the web member walls into the gusset plates, an improved fatigue behavior could be expected. To study this aspect, four tapered and two scalloped gusset-plate joints were fabricated and tested under different levels of alternating stress.

---

5. Bouwkamp, J. G., "Recent Trends in Research on Tubular Connections," Journal of Petroleum Technology, November 1966.

III. TESTING PROCEDURE

The testing of each of the specimens was carried out in air under alternating loading conditions.

In order to subject each specimen to the required loading, the joints were mounted in a specially designed test frame as described in reference 2. The member forces due to lateral loads on a prototype structure were introduced through a double-acting load cylinder applying a load to the horizontal branch member. In all instances, a required dead load producing a compressive stress of 11 ksi in the column section was applied. Since this load was applied through a set of soft springs, this load remained virtually constant during the test. After the static lateral loading had been applied in each case, the alternating load at a rate of about 30 cycles per minute was applied until failure of the joint was observed.

Each of the joints tested under Part 2, except the first specimen, was first subjected to a series of cyclic, static loads in order to compare the maximum strains for the initial load cycle with those recorded after a limited number of cycles of loading had been applied. Following these initial load cycles, the specimens were subjected to alternating loads to determine the fatigue life of these joints. Failure was considered the instance of crack initiation as observed visually through a magnifying glass.

Eleven of the twelve joints under Part 2 were instrumented with strain gages in order to determine the magnitude of the strains at a number of selected locations on the joint and also to study the joint response at both the initial loading cycle and after several cycles of loading had been applied.

For the Type-1 joints the strain gage locations are shown in Figure 3. As the number of gages located on each joint was not the same, the table in Figure 3 indicates the specific gages for each of the specimens tested. Similarly, the location of the strain gages on the Type-3 joints is shown in Figure 4. The location of the gage on the gusset plates differs between the tapered and scalloped gusset and is indicated in the figure.

In order to establish the accuracy of a finite element computer program which was developed to determine the stress distribution in a simple tubular joint (Type 1), the one remaining thick-wall specimen on the Phase II, Part-1 Series was extensively instrumented and subjected to a series of cyclic step-wise increased static loads to determine the strain distribution in the joint and to compare the results with analytical values derived from the finite element analysis. The location of the strain gages for this joint is shown in Figure 5. It should be noted that these gages were located predominantly in the immediate vicinity of the welds between the web and column members.

The results of this comparative study proved to be unsatisfactory. Particularly due to the closeness of the gages to the welds, the inherent local effects of insufficient continuity (lack of weld penetration) resulted in experimental strain values considerably different than those evaluated analytically for an ideal tubular system. Hence, an additional check on the accuracy of the theoretical solution was considered necessary. Therefore, it was decided to extensively instrument also one of the six Type-1 thick-walled joints tested in this part of the program. Hence, specimen No. 5 was instrumented with 24 two-element rosettes and 22 three-element rosettes at the locations shown in Figure 6. To prevent the influence of local effects, the gages are located several inches away from the welds. To improve the accuracy of the strain data, the gage length of the individual elements was only 5 mm or about 1/5 inch. The results of this study have been published in reference 4.

Since the general objective of the cyclic load studies of the joints was to determine the fatigue life and its possible correlation with strain values near the cracked zones (along the welds), the strain gages in all specimens were located, with the exception of the Type-1 specimen No. 5, as close to the toe of the weld or the edge of the gusset plate, as the case may be, as was practically possible.

IV. RESULTS OF STATIC TESTS

IV-1 General

Under the static loading condition the maximum load applied to the horizontal branch member in all cases was 50 k in either direction. Hence, the nominal stress in the basic diagonal member (t = 0.188 inches) for this load was approximately 28 ksi, or about 1.33 times the commonly allowable stress of 22 ksi for an ASTM A-36 grade steel. The applied force and the subsequent reactions were superimposed on the precompression load of the column member which produced a stress of 11 ksi in this member. For the six Type-1 specimens with locally thickened web members (t = 0.258 inches), the nominal stress in this portion of the diagonal member was only 20 ksi.

As noted before, an initial attempt to correlate the stress results of a theoretical finite element solution with those obtained from the experimental study of a thick-wall tubular joint did not prove to be very satisfactory because of the close location of the gages near the welds. Therefore, an additional Type-1, thick-wall, specimen from the Part 2 test sequence, joint specimen No. 5, was instrumented with gages placed a distance away from the welds, and tested subsequently. The results in that case showed a much closer correlation. The correlative studies are reported elsewhere(4), and are not repeated here. Only the results showing the magnitude and direction of the principal stresses for these two specimens are reported herein.

IV-2 Detailed Test Results

IV-2-1 Joint Type 1 - Thick-Wall (Part-1 Specimen)

This extensively instrumented joint was loaded step-wise up to a maximum load of + and - 50 k. The maximum strains observed were about $\pm$ 1250 micro in/in. These strains were essentially constant from the 1 to the 50th cycle and were observed at gages 34 and 36 located in the area of the toe of the diagonal member. (See Figure 5 for gage location.) In general, the strain gage data showed a virtually linear load-strain relationship even for gages located near the welds in areas of concentrated force transfer.

The principal stresses for the + and - 50 k loads are plotted in Figures 7 and 8 respectively. The maximum stress obtained was + 40.4 ksi at gage location 36. Since this stress was constant for 50 cycles, it indicates that the region of the toe of the diagonal at some finite distance from the weld between the diagonal and column member behaved linearly elastic.

IV-2-2 Joint Type 1 - Part-2 Specimens

Specimen No. 1 was not instrumented, and, therefore, no static loading was applied. For specimens Nos. 2, 3, 4, and 6, the strains for + 50 k, 0 k, -50 k, and 0 k are tabulated in Tables I, II, III, and IV respectively. The readings were generally taken on the first cycle and after a number of cycles had been applied and it had been noted that the peak strains had stabilized. However, on specimen No. 4 this procedure was not followed and a large number of cycles were applied prior to the taking of the strain readings. Therefore, for this specimen the readings were taken on the 2255th and 2256th cycles of loading and tabulated in Table III.

Since the gage locations for specimen No. 5 (see Figure 6) were selected in order to allow a comparative study of analytical and experi-

TABLE I STRAINS IN TYPE 1 JOINT-SPECIMEN NO. 2

Gage No.	1st Cycle Strain in Micro in./in.				6th Cycle Strain in Micro in./in.			
	-50 k	0 k	+50 k	0 k	-50 k	0 k	+50 k	0 k
1	700	*	-660	40	750	30	-740	0
2	720		-720	-60	700	10	-680	0
5	1010		-920	60	1040	30	-1030	0
6	-70		150	50	-110	0	+70	0
7	-630		860	100	-730	-10	670	-10
8	-160		190	30	-150	0	120	0

*Not recorded

TABLE II STRAINS IN TYPE 1 JOINT-SPECIMEN NO. 3

Gage No.	1st Cycle Strain in Micro in./in.				10th Cycle Strain in Micro in./in.			
	+50 k	0 k	-50 k	0 k	+50 k	0 k	-50 k	0 k
1	-700	-20	670	0	-690	-20	670	0
2	-640	0	680	10	-660	-20	680	0
5	-920	10	850	30	-950	-10	830	0
6	130	10	-50	10	120	0	-60	0
7	810	10	-710	-20	790	0	-680	0
8	210	0	-150	20	210	0	-160	0

TABLE III STRAINS IN TYPE 1 JOINT-SPECIMEN NO. 4

Gage No.	2255th Cycle Strain in Micro in./in.				2256th Cycle Strain in Micro in./in.			
	+50 k	0 k	-50 k	0 k	+50 k	0 k	-50 k	0 k
1	-730	-30	680	20	-750	-40	800	10
2	-640	-20	580	0	-650	-10	670	0
3	-740	-10	700	40	-760	-10	800	20
4	-30	0	20	-10	-30	10	40	0
5	-1060	-30	940	10	-1060	-20	1110	20
6	100	0	-60	0	100	0	-80	0
7	1070	30	-710	20	1060	0	-900	0
8	320	30	-170	10	310	20	-230	10
9	760	50	-770	-10	760	30	-800	0
10	180	20	-150	-10	170	0	-180	-10
11	210	0	-380	0	190	-10	-430	-10
12	190	0	-250	0	190	0	-280	0
13	710	0	-670	0	690	-10	-810	-10
14	150	0	-160	0	160	0	-170	0

TABLE IV STRAINS IN TYPE 1 JOINT-SPECIMEN NO. 6

Gage No.	1st Cycle Strain in Micro in./in.				10th Cycle Strain in Micro in./in.			
	+50 k	0 k	-50 k	0 k	+50 k	0 k	-50 k	0 k
1	-720	-10	690	-10	-710	10	710	0
2	-680	0	670	-10	-680	10	690	10
5	-1130	0	1160	50	-1130	0	1120	0
6	50	-10	-20	50	60	0	-60	10
7	860	-30	-910	-10	850	-20	-910	10
8	230	0	-250	-10	230	0	-240	10
9	620	-10	-1050	-180	660	-10	-830	0
10	140	0	-210	10	150	-10	-210	0
13	860	-40	-650	-40	860	-10	-660	0
14	230	30	-90	30	190	0	-140	0

mental stress results, the gage locations for this specimen were different from those shown in Figure 3 for the other four Type-1 joint specimens (Nos. 2, 3, 4, and 6). Hence, no strain tabulation has been presented for this specimen. However, the principal stresses for the + and - 50 k loads calculated from the strains recorded on the third cycle are plotted in Figures 9 and 10 respectively. As the gages on this specimen were generally located away from the welds, the stress magnitudes are rather small in comparison to the stresses obtained for the Part-1, Type-1 specimen and presented in Figures 7 and 8. Again it was observed for this type of joint that the load-strain relation was basically linear. Figure 11 shows a number of typical load-strain plots.

An observation of the tabulated strain data ϵ_1 and ϵ_2 for gages 1 and 2, located on the diagonal member and presented in Tables I through IV, indicates a concentric loading of the web members. The strain values for those two gages show for each of the specimens tested almost complete identity. Strain variations for these gages are, with the exception of specimen No. 4, less than $\pm$ 4% of the average strain value of $1/2\ (\epsilon_1 + \epsilon_2)$.

The maximum strains recorded and tabulated are about 1100 micro in./in. and occur in the toe of the diagonal member above the weld between the diagonal and the chord member (gage 5). The associated stress values range from about 26 ksi (for specimen No. 3) to about 36 ksi (for specimen No. 6). The strains in the other gages located near the welds are mostly smaller, although not significantly.

A general conclusion can be drawn from the tabulated strain data in comparing the "zero load" strains half way and at the end of a full load cycle. Firstly, the fact that at the end of the cycle the residual strains are virtually zero indicates that progressive yielding does not occur and that the load-strain cycle is stable. However, the fact that the zero-load strains half-way through the load cycle are not zero signifies the presence of a hysteresis loop and a Bauschinger effect. This phenomenon indicates a gradual energy dissipation and will result through accumulated energy losses in fatigue failures.

IV-2-3 Joint Type 3 - Part 2-Specimens

These joint specimens were initially tested under a static load of + and - 50 k with strain gage readings taken at each loading cycle for loads of 0 k, +50 k, 0 k, -50 k, and 0 k. The strain gages were rezeroed after each complete cycle of loading. The strains for each of the six specimens tested are tabulated in Tables V through X. In most cases the strain data are presented for the first and tenth cycle of loading. During the first cycle of loading, very high strains were recorded in the wall of the horizontal and diagonal members near the tip of the gusset plate. The maximum strain was recorded in specimen No. 6 where the strain at gage location 5 reached a magnitude of 5800 micro in./in. (see Table X). The residual strain at that location after completing the first cycle of loading was 4270 micro in./in. The extensive yielding observed during this initial loading cycle would indicate that probably both substantial locked in strains were present due to the welding of the web members to the gusset plates, and that the force transfer between the tube wall and the gusset plate was highly concentrated.

After subjecting each specimen to further load cycles the strains generally stabilized by the tenth cycle as can be concluded from the small residual strains recorded at the end of this cycle (see Tables V

TABLE V STRAINS IN TYPE-3 JOINT SPECIMEN NO. 1 (TAPERED GUSSET PLATE)

Gage No.	1st Cycle Strain in Micro in./in.				10th Cycle Strain in Micro in./in.			
	+50 k	0 k	-50 k	0 k	+50 k	0 k	-50 k	0 k
1	-1210	100	1170	-20	-1270	0	1220	40
2	350	10	-300	50	360	0	-360	-10
3	470	120	-350	40	310	-50	-430	-40
4	-280	120	360	50	-370	0	310	0
5	-3060	-1060	2150	250	-2280	-240	2070	180
6	300	170	-160	-30	180	40	-160	-30
7	170	40	-100	30	130	-10	-140	-10
8	-430	-30	360	-20	-370	20	400	20
9	-730	-80	560	-50	-670	0	630	0
10	150	40	-90	30	130	0	-120	0
11	-360	-40	280	-20	-330	-10	300	-10
12	-660	-80	520	-50	-630	0	590	-10
13	-50	20	60	0	-80	0	50	-10
14	1280	110	-1170	-10	960	-60	-1180	-100
15	-670	-490	-340	-500	-190	-10	150	-10
16	1630	960	420	990	780	30	-580	30
17	150	50	-50	40	120	0	-100	0
18	320	20	-240	40	320	10	-280	0

TABLE VI STRAINS IN TYPE 3 JOINT SPECIMEN NO. 2 (SCALLOPED GUSSET PLATE)

Gage No.	2nd Cycle Strain in Micro in./in.				10th Cycle Strain in Micro in./in.			
	+50 k	0 k	-50 k	0 k	+50 k	0 k	-50 k	0 k
1	-1500	-160	1350	30	-1500	-110	1370	20
2	140	40	-120	10	150	30	-110	-10
3	350	10	-290	0	360	0	-280	0
4	-260	10	300	10	-270	10	300	0
5	-1150	20	1210	40	-1190	0	1190	0
6	-30	-20	50	30	-40	-30	30	0
7	90	-10	-110	0	100	10	-100	0
8	-540	10	270	10	-530	0	290	-10
9	-430	10	670	20	-440	10	660	0
10	90	0	-160	0	100	0	-150	-10
11	-250	20	570	20	-290	0	540	-10
12	-350	20	540	20	-360	10	520	-10
13	-90	10	120	10	-90	10	120	0
14	1200	10	-840	0	1240	0	-860	-10
15	-130	10	190	10	-140	0	190	-10
16	470	-10	-710	-10	510	10	-690	0

TABLE VII STRAINS IN TYPE 3 JOINT SPECIMEN NO. 3 (TAPERED GUSSET PLATE)

Gage No.	1st Cycle Strain in Micro in./in.				10th Cycle Strain in Micro in./in.			
	+50 k	0 k	-50 k	0 k	+50 k	0 k	-50 k	0 k
1	-1310	-160	1560	460	-1130	0	1140	50
2	170	20	-380	-240	140	0	-150	0
3	350	-20	-350	20	310	0	-360	-30
4	-350	-10	330	20	-340	0	300	-10
5	-1690	0	-870	-1770	-770	10	620	0
6	-230	-50	470	310	-120	0	100	20
7	120	0	-100	10	120	0	-110	0
8	-350	0	350	-60	-300	0	420	20
9	-720	-30	460	-110	-640	0	570	20
10	110	0	-110	10	100	0	-130	-10
11	-560	-10	280	-60	-430	0	330	10
12	-670	-20	590	-100	-600	0	690	30
13	-340	-130	50	-140	-190	0	200	20
14	1370	550	-230	550	710	0	-800	-60
15	-700	-580	-470	-580	-120	0	110	0
16	1910	1260	690	1270	680	20	-570	10

TABLE VIII STRAINS IN TYPE 3 JOINT SPECIMEN NO. 4 (TAPERED GUSSET PLATE)

Gage No.	1st Cycle Strain in Micro in./in.				15th Cycle Strain in Micro in./in.			
	+50 k	0 k	-50 k	0 k	+50 k	0 k	-50 k	0 k
1	-1340	-70	1910	620	-1170	-20	1310	30
2	-20	-30	-70	-20	60	-20	-50	0
3	390	10	-300	-30	350	-20	-270	30
4	-390	30	370	-10	-330	-20	400	-10
5	-1730	0	1860	-210	-2160	-480	1770	90
6	-140	-50	30	140	20	0	-20	100
7	100	0	-60	70	130	-20	-50	-20
8	-190	90	580	400	-110	-100	630	-130
9	-460	60	580	70	-540	0	590	-20
10	100	0	-60	70	140	-10	-50	-20
11	-340	40	360	70	-330	0	380	-20
12	-440	50	610	70	-520	-10	-610	-20
13	-700	-610	140	60	-80	-20	90	-20
14	3660	2490	-910	50	920	-10	-900	-30
15	-370	-380	140	60	-110	-30	160	-20
16	1260	800	-630	80	790	0	-620	-10
17	130	0	-	80	150	-20	-110	-20
18	230	10	-	70	290	-20	-200	-20

TABLE IX STRAINS IN TYPE 3 JOINT SPECIMEN NO. 5 (SCALLOPED GUSSET PLATE)

Gage No.	1st Cycle Strain in Micro in./in.				10th Cycle Strain in Micro in./in.			
	+50 k	0 k	-50 k	0 k	+50 k	0 k	-50 k	0 k
1	-1180	-120	1590	560	-1130	-70	1090	10
2	160	20	-740	-610	180	30	-150	0
3	340	30	-280	10	320	10	-280	10
4	-250	50	310	20	-280	0	300	10
5	-1430	-90	2080	710	-1480	-120	1410	30
6	190	-90	-820	-530	400	110	-290	0
7	120	30	-30	30	90	10	-60	10
8	-720	-10	280	-30	-550	-10	450	0
9	-580	-110	430	-100	-460	0	570	10
10	60	20	-10	30	40	0	-20	10
11	-300	-20	650	10	-430	-10	530	10
12	-680	-120	380	-140	-520	-10	600	0
13	20	110	250	110	-100	0	150	0
14	1570	670	-150	600	940	30	-710	0
15	-300	-150	30	-170	-160	0	210	10
16	1000	510	-270	460	560	30	-710	10

TABLE X STRAINS IN TYPE 3 JOINT SPECIMEN NO. 6 (TAPERED GUSSET PLATE)

Gage No.	1st Cycle Strain in Micro in./in.				10th Cycle Strain in Micro in./in.			
	+50 k	0 k	-50 k	0 k	+50 k	0 k	-50 k	0 k
1	-1380	-90	4190	2890	-1560	-210	1370	40
2	210	10	1650	-1450	310	90	-240	-20
3	350	10	-260	0	340	10	-250	0
4	-330	30	430	60	-370	-10	280	10
5	-1450	0	5800	4270	-1940	-420	1630	40
6	90	-60	-1730	-1550	330	150	-200	-10
7	100	-10	-110	0	100	0	-120	0
8	-310	30	440	20	-350	-20	410	0
9	-520	30	650	10	-580	-20	670	0
10	80	10	-70	10	80	10	-80	10
11	-300	30	350	20	-340	-10	340	0
12	-380	30	540	10	-430	-20	540	10
13	-390	-400	-340	-390	10	0	60	0
14	1900	750	-120	730	1140	30	-800	10
15	-440	-240	50	-230	-240	-20	280	-10
16	1000	480	-270	470	600	50	-730	20

through X). In general, the strains recorded in the tenth cycle of loading under maximum load are still rather high.

The scalloped gusset plate arrangement shows basically lower strain values in the area of the intersections than the tapered gusset-plate joints. This tends to indicate that at least for the specimens tested a more uniform load transfer occurred in the scalloped gusset plate joint than in the joints with the tapered gusset plates. However, the strains for the scalloped gusset plate specimens are still rather high, the maximum being in the range of 1400 to 1500 micro in./in. In general it can be observed that for both types of joints the load transfer is concentrated in the walls of the web members near the center portion of the gusset plate between the two web members (gages 5 and 14 as shown in Figure 4).

Considering the often relatively large residual strain values at the half-way point of the load cycle one could expect larger energy losses per cycle than for the Type 1 joints and, therefore, earlier fatigue failures. Furthermore, in some locations (particularly for gages 5 and 14) the residual strain values after completion of the load cycle are large and indicate a continuous yielding. The instability of the load-strain loop and the continuing degrading effect of the material stiffness in those vicinities must result in a drastic reduction of the fatigue resistance of these joints.

V. RESULTS OF ALTERNATING LOADS

V-1 General

The alternating lateral forces acting on off-shore structures produce reversing web member forces. In these studies, as in the earlier ones, the member forces are developed by alternating loads applied to the horizontal web member. These loads were introduced similarly as in Phase I and Phase II, Part 1, by a double acting hydraulic load cylinder with a maximum capacity of ± 80 k. For the alternating load tests, the horizontal branch members were subjected to cylinder loads between ± 25 k to ± 50 k. The load in the diagonal under these conditions ranged from ± 43.6 k to ± 87.3 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 - Thickwall (Part-1 Specimen)

This thick-walled Type 1 joint with 0.188 in. wall thicknesses for the web members was tested under an alternating load of ± 25 k, resulting in an alternating nominal stress in the diagonal of ± 14 ksi, or 50% of the design stress.

The first crack, at the location shown in Figure 12, was noted at 67,000 cycles and occurred in the wall of the horizontal member immediately above the weld between the horizontal and column members at a point nearest to the diagonal. This crack had propagated around the horizontal member approximately 2 inches when the test was stopped at 85,600 cycles. The reason for terminating the test was the development of a crack in the wall of the diagonal along the load transition plate on the upper part of the diagonal member. This crack started after 75,000 cycles but propagated rapidly. Hence, after 85,600 cycles it was necessary to terminate the test.

V-2-2 Joint Type 1 - (Part-2 Specimens)

V-2-2-1 Specimen No. 1

Specimen No. 1 of the Type-1 Part-2 specimens was tested under an alternating load of ± 50 k, or an alternating nominal stress of ± 28 ksi in the wall of the basic diagonal member. Because of the 0.258 in. thick-walled portion of the diagonal near the joint the nominal stress in that vicinity was near ± 20.3 ksi.

After 6400 cycles, the first hair line crack was noted in the horizontal branch member immediately above the weld between this member and the column member nearest to the diagonal member (see Figure 13). This crack propagated around the horizontal member about 2 1/2 inches. At about 18,000 cycles a number of hair line cracks were observed in the wall of the chord member along the toe of the weld connecting the horizontal member to the column member. These cracks propagated to lengths of 3 1/4 and 4 1/2 inches respectively before the test was stopped after 22,600 cycles. At 12,300 cycles a crack also developed in the wall of the chord member along the toe of the weld between the diagonal and the chord member. This crack had propagated only about 1 inch when the test was stopped. All cracks were very fine hair line cracks that only could be detected with the aid of a magnifying glass.

The test was terminated because of excessive crack development in the wall of the diagonal near the connection plates.

V-2-2-2 Specimen No. 2

Specimen No. 2 was tested under the same alternating load condition of ± 50 k as specimen No. 1. In this case the first crack was noted, as shown in Figure 14, after 14,500 cycles and occurred in the horizontal member just above the weld between this member and the column member nearest to the diagonal member. This crack had propagated around the horizontal member about 3 inches when the test was stopped at 34,600 cycles. At 20,300 cycles a second crack was noted in the diagonal member adjacent to the column. This crack had also propagated about 3 inches around the diagonal member when the test was stopped. The test was terminated because the weld between the thick and thin-walled sections of the diagonal member cracked and propagated rapidly around the section. Figure 15 shows the crack propagation for this joint specimen after 31,000 cycles of loading.

V-2-2-3 Specimen No. 3

Specimen No. 3 was tested under a reduced alternating load of ± 40 k, or an alternating nominal stress of 22.4 ksi in the 0.188 in. wall of the basic diagonal member. This stress level corresponded with a stress of ± 16.2 ksi in the thickened portion of the diagonal near the joint ($t = 0.258$ in.).

The first crack, noted at 35,600 cycles, was in the wall of the column member immediately along the toe of the weld between this member and the diagonal member at a point near the horizontal member. This crack, as shown in Figure 16, reached after 103,700 cycles a length of 2 inches.

A second crack was noted after 48,700 cycles in the wall of the horizontal member immediately above the weld between the horizontal and the chord member nearest to the diagonal member. This crack propagated over a length of approximately 1 5/8 in. after a total number of 103,700 cycles had been applied.

After about 93,000 cycles, two other cracks were observed in the wall of the column member, on either side of the horizontal branch member along the toe of the weld between the two members. The length of those cracks were 4 1/4 in. and 6 3/4 in. long respectively. The subsequent crack propagation is shown in Figure 16. Without showing any significant propagation beyond about 104,000 cycles the test was terminated after 106,500 cycles because of the extensive crack propagation along the weld between the horizontal and column member, and the crack development along the load transition plates.

Close-ups of the crack propagation along the welds between the web and column members are shown in Figures 17 and 18.

V-2-2-4 Specimen No. 4

Specimen No. 4 was tested like specimens No. 1 and 2 under an alternating load of ± 50 k.

The first crack was noted at 7500 cycles immediately above the weld between the horizontal and column members directly adjacent to the diagonal member. As shown in Figure 19, the crack had propagated 6 1/2 inches when testing was terminated after 19,000 cycles of loading. By that time two additional cracks were observed in the wall of the column member along the toe of the weld between the horizontal and column sections. Figure 20 shows a close-up of the crack propagation in the horizontal web member wall.

V-2-2-5 Specimen No. 5

Specimen No. 5 was tested under the same alternating load of ± 40 k as specimen No. 3. The corresponding stresses in the 0.188 in. wall portion of the diagonal and the 0.258 in. section were ± 22.4 ksi and ± 16.2 ksi respectively.

In this case the first crack was noted at 49,000 cycles in the wall of the horizontal member immediately above the weld between this member and the column section as shown in Figure 21. The crack propagated in one direction only and reached a length of slightly more than 2 inches after 79,900 cycles.

After 66,000 cycles a 1 5/8 in. long crack developed in the column wall immediately along the toe of the above mentioned weld. This crack propagated over a total length of 8 1/4 in. after 90,000 cycles.

A third crack developed in the wall of the diagonal member immediately above the weld between the diagonal and column members. This weld had propagated to a length of 3/4 in. when the test was terminated after 94,900 cycles. The two other cracks showed no noticeable increase in length after about 80,000 and 90,000 cycles respectively.

The test was terminated because of a second crack development in the diagonal along the weld connecting the thick and thin-walled tube sections.

V-2-2-6 Specimen No. 6

Specimen No. 6 was tested under an alternating load of ± 30 k, or an alternating nominal stress of 12.2 ksi, in the thick-walled portion of the diagonal member. The stress in the basic thin-walled section (0.188 in.) was 16.8 ksi.

The first crack was noted in the column wall after 150,000 cycles immediately along the toe of the weld between the diagonal member and the column member at a point adjacent to the horizontal member. After 190,000 cycles of loading this crack had propagated, as shown in Figure 22, about 1 1/2 inches. After 160,000 cycles a second crack was noted in the horizontal member immediately above the weld between that member and the column section.

After 187,000 and 188,000 cycles two additional cracks were observed in the wall of the diagonal member immediately above the weld between the diagonal and column member. These cracks were about 3/4 in. and 1/4 in. long when observed first and did not propagate noticeably.

The test had to be terminated after 217,900 cycles due to failure of the weld in the diagonal between the thin and thick-walled sections. Very little crack propagation took place in any of the above noted cracks between the points marked for the associated number of cycles and the number of cycles at failure. Figure 23 shows in detail the crack propagation.

V-2-3 Joint Type 3

V-2-3-1 Specimen No. 1 (Tapered Gusset Plate)

Specimen No. 1, with a tapered gusset-plate, was tested under an alternating load of $\pm$ 50 k, or an alternating nominal stress of approximately $\pm$ 28 ksi in the diagonal member. The first crack was noted at 1450 cycles immediately above the weld at the intersection of gusset-plate and the diagonal member, directly opposite to the horizontal member, as shown in Figures 24 and 25. This crack propagated in both directions a total of approximately 6 inches when the test was stopped after 2897 cycles.

V-2-3-2 Specimen No. 2 (Scalloped Gusset Plate)

Specimen No. 2, with a scalloped gusset-plate, was tested under an alternating load of ± 50 k. In this case the first crack was noted after 200 cycles and was located, as in Specimen No. 1, in the wall of the diagonal member immediately above the gusset plate. This crack propagated, as shown in Figures 26 and 27, in both directions and had reached a total length of approximately 9 1/2 inches when the test was terminated after 2700 cycles.

V-2-3-3 Specimen No. 3 (Tapered Gusset Plate)

Specimen No. 3, with a tapered gusset-plate, was tested under an alternating load of ± 50 k or an alternating nominal stress in the diagonal member of ± 28 ksi. The first crack at 50 cycles was noted again in the same location as in Specimens Nos. 1 and 2, namely in the wall of the diagonal immediately above the tip of the gusset plate opposite the horizontal web member. This crack propagated, as shown in Figures 28, 29, and 30, in both directions and reached a total length of about 8 inches before terminating the test after 3000 cycles of load reversal. Like the previous Type 3 joints the test was terminated because of excessive tearing of the wall of the diagonal member.

V-2-3-4 Specimen No. 4 (Tapered Gusset Plate)

Specimen No. 4, with a tapered gusset-plate, was tested under an alternating load of ± 40 k, or an alternating nominal stress in the diagonal member of approximately 22.4 ksi or 80% of the design stress.

The first crack was noted at 800 cycles, immediately above the weld at the intersection of the gusset-plate and the diagonal member, directly opposite to the horizontal member, as shown in Figure 31. This crack had propagated about 1 1/2 inches after 8500 cycles. At this point in the test, a second crack of about 1 7/8 inches in length was noted on the opposite side of the diagonal member. Prior to observing any noticeable increase in crack propagations, the diagonal member failed after 10,602 cycles. The failure occurred abruptly through a circumferential crack in the wall of this member. Figures 32 and 33 show the initial crack propagation and ultimate failure mode.

V-2-3-5 Specimen No. 5 (Scalloped Gusset Plate)

Specimen No. 5, with a scalloped gusset-plate, was tested under an alternating load of $\pm$ 50 k, or an alternating nominal stress in the diagonal of 28 ksi.

The first crack was noted after 980 cycles in the wall of the diagonal immediately above the weld at the intersection of the gusset-plate and the diagonal member adjacent to the horizontal member, as shown in Figure 34. A second crack was observed after 2100 cycles and occurred in the wall of the diagonal member at a point diametrically opposite from the location of the first crack and above the weld at the intersection of the diagonal member and the gusset plate. The first crack propagated in both directions around the member and reached a length of about 6 1/2 inches when the test was terminated after 2970 cycles (see Figure 35). The second crack reached a total length of about 4 inches, as shown in Figure 36.

V-2-3-6 Specimen No. 6 (Tapered Gusset Plate)

Specimen No. 6, with a tapered gusset-plate, was tested under an alternating load of ± 30 k, or an alternating nominal stress of 16.8 ksi in the diagonal member. This stress amounts to 60% of the design stress of 28 ksi. Under this load condition the first crack was observed after 14,000 cycles immediately above the weld at the intersection of the gusset-plate and the diagonal member adjacent to the horizontal member. This crack propagated, as shown in Figure 37, in both directions a total of about 10 inches when testing was terminated after 29,200 cycles. Details of the crack propagation are shown in Figures 38 and 39.

VI. CONCLUSIONS AND RECOMMENDATIONS

The results of the static load studies on the Type-1 joints indicate that for the load range of + 50 k to - 50 k in the horizontal web member the load-strain relation is basically elastic. The extreme nominal web member stresses for a basic web member (t = 0.188 in.) are ± 28 ksi in the diagonal and ± 16 ksi in the horizontal branch member. However, because of the increased wall thickness of the web members near the joint-intersection (t = 0.258 in.) the nominal stresses in the thick-walled portions are ± 20.3 ksi and ± 11.6 ksi for the diagonal and horizontal members respectively.

The maximum strains observed in the wall of the diagonal occurred in the toe region immediately above the weld between column member and diagonal at a point directly opposite of the horizontal branch member. These strains represented stresses of 26 ksi to 35 ksi in tension, with an average of 32 ksi, and -29 ksi to -35.5 ksi in compression with an average of -32 ksi. The associated stress concentration factor for the average stress values is (32/20.3) or about 1.6. The stresses in this location are basically unaffected by the thicker chord wall (0.625 in. versus 0.562 in.). Hence the same stress concentration applies. It should be noted that the two chord wall thicknesses represent t/D ratios of 4.5% and 5% respectively and identify the joints as thick-wall joints.

For the horizontal web member the maximum strains and the associated stresses occur immediately above the weld between chord and web member nearest to the diagonal, and are as an average only slightly less than those observed for the diagonal member, namely + 29 ksi and - 28 ksi. Because of the associated lower nominal stress of 11.6 ksi in the horizontal member, the average stresses of 29 and 28 ksi indicate significantly larger stress concentrations than observed for the diagonal member, namely 2.5 and 2.4 respectively. The effect of the thickened chord wall (from 0.562 in. to 0.625 in.) seems to be beneficial for the member stresses although the results are not sufficiently conclusive.

The above discussion is based on the strain data observed after completion of the first cycle of loading. Strain data taken in subsequent cycles were elastic, virtually linear and very consistent.

The strain data for the 0.188 in. thick web member walls of the Type-3 gusset plate joints show invariably higher strains in the diagonal member than in the horizontal member.

For the tapered gusset plate the strains in the wall of the diagonal near the intersection with the gusset plate adjacent to the horizontal web member are large and surpass the yield strain by 10% to 25% (the yield strain being 1690 micro in./in. for a yield stress of $F_y = 48$ ksi). In that vicinity the strain concentration reaches a value of about 2.2. The wall strains in the diagonal web member near the gusset plate intersection, opposite the region discussed above, show significantly lower values. Considering the average local stress value of about 38 ksi as computed from the strain data, the stress concentration factor in this vicinity is 38/28 or about 1.35.

The scalloped gusset plate joint, having an off-set of the two points of intersection between the diagonal member and gusset plate, shows in comparison with the tapered gusset plate joint a more balanced state of stress in the wall of the diagonal at those two points. The strain concentration averages for both points about 1.4. This indicates that these strains, as an average, are only 82% of the yield strain.

The stress conditions in the wall of the horizontal branch member near the points of intersection between the gusset plate and the web member are practically identical for both types of gusset plates. The stress concentration factors are about 1.7 for the area directly opposite the diagonal member and 1.2 for the diametrically opposite point away from the diagonal. With nominal stress values of 16 ksi, the actual member stresses are well within acceptable yield stress limits.

The results of the alternating load studies in this phase of the program are summarized in Table XI. The results of these tests are presented along with the previous test results, in Figures 40 and 41. The plots indicate the relation between the alternating load in the horizontal web member and the number of cycles at which the first crack was observed.

The results, for the Type 1 joints, shown in Figure 40 indicate that increasing the web member wall thickness from 0.188 in. to 0.256 in. results only partially in an improved fatigue performance. For nominal stresses of 28 ksi in the basic diagonal (t = 0.188 in.) there seems to be no improvement (6400 and 7500 cycles of load versus 9900 cycles). This is surprising because the nominal stress in the thickened wall portion is only 20.3 ksi. Only for basic nominal stresses of not more than 22.4 ksi, or 80% of the design stress of 28 ksi, will the fatigue behavior improve.

It can further be noted that increasing the column member wall (0.625 in. or t/D = 5% versus 0.562 in. or t/D = 4.5%) seems to improve

TABLE XI SUMMARY OF TEST RESULTS UNDER ALTERNATING LOAD

SPECIMEN TYPE	SPECIMEN NO.	WEB MEMBER THICKNESS (IN.)	COLUMN MEMBER THICKNESS (IN.)	CYCLIC INPUT LOAD KIPS	NOMINAL DIAGONAL STRESS KSI	NO. OF CYCLES AT OBSERVED FIRST CRACK	TOTAL NUMBER OF CYCLES	REMARKS
1	Old	0.188	0.562	± 25	± 14	67,000	86,800	
1	1	0.258	0.562	± 50	± 20	6,400	22,600	
	2	"	0.625	± 50	± 20	14,500	34,600	
	3	"	0.562	± 40	± 16	35,600	103,700	
	4	"	0.562	± 50	± 20	7,500	19,000	
	5	"	0.625	± 40	± 16	49,000	94,900	
	6	"	0.562	± 30	± 12	150,000	217,863	
3	1	0.188	0.330	± 50	± 28	1,450	2,897	Tapered
	2	"	"	± 50	± 28	200	2,706	Scalloped
	3	"	"	± 50	± 28	50	3,000	Tapered
	4	"	"	± 40	± 22	800	10,602	Tapered
	5	"	"	± 50	± 28	980	2,970	Scalloped
	6	"	"	± 30	± 17	14,000	29,200	Tapered

the fatigue life in general.

An observation of the fatigue data for the Type 3 joints, presented in Figure 41, shows the serious inadequacy of both tapered and scalloped gusset plates at nominal stress levels between 60% and 100% of the design stress (17 ksi and 28 ksi respectively). Actually, for these stress levels, the straight gusset plate design shows a better resistance against fatigue failure. The inadequate performance of both the scalloped and tapered gusset plates is due to high strain concentrations which in case of the tapered gusset plate joint reaches yield strain levels near the points of intersection between the diagonal member wall and the gusset plate. The extended gusset plate draws a concentrated load transfer which causes after crack initiation a rapid crack propagation in the wall of the diagonal member. It is of interest to note that despite the variation in the number of cycles at which the cracks initiated, under a cyclic nominal stress of 28 ksi in the diagonal, the number of cycles at which the test had to be terminated because of dangerous crack growth was almost invariably 3000.

The results seem to indicate further that the tapered gusset plate will basically exhibit an improved performance in comparison with the straight gusset plate under alternating loads provided that the nominal stresses in the wall of the diagonal are not more than 60% of the design stress, or 17 ksi.

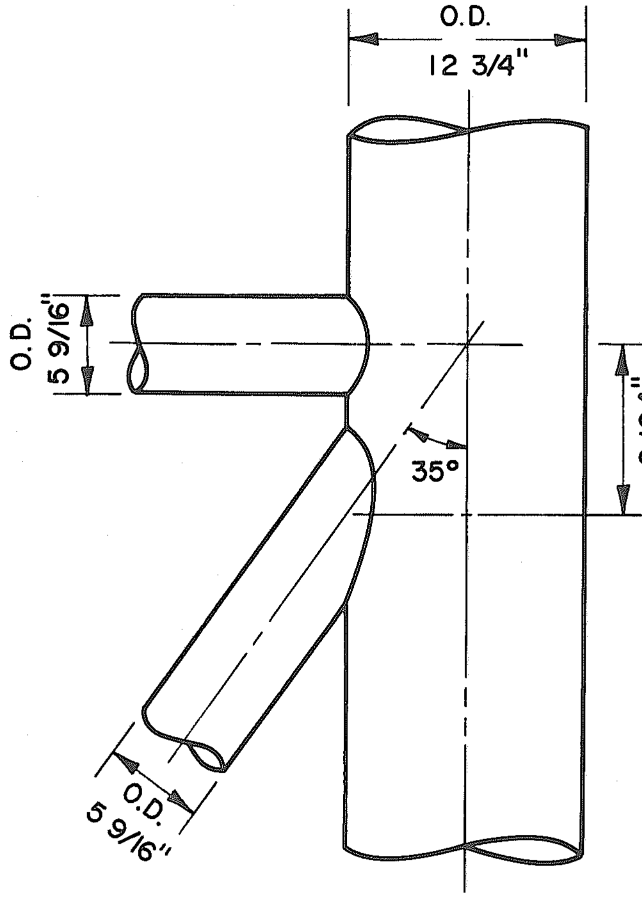
Considering the fatigue performance of the tapered gusset plate joints and the number of cycles at which crack initiation was observed for the scalloped gusset plate joints, it can be expected that in general the fatigue life of the latter joints will be somewhat better than the tapered joints. On that basis it seems safe to predict that for nominal stress levels in the diagonal of 17 ksi or 60% of the design stress, the scalloped gusset plate will have an improved fatigue life as compared to both the straight and tapered gusset plate joints.

Based on the results of the overall studies it seems that increasing the web and chord member sections, under the same conditions of loading, improves the fatigue life of Type-1 joints significantly.

Since the results do not indicate an improvement of the fatigue life of the tubular joints tested at the higher nominal stress loads, further study to clarify the response under such stress intensities seem to be in order for both Type-1 and Type-3 joints. The need for further search in the Type-3 joints seems to be dictated by the use of such joints in large-size tubular truss arrangements.

To evaluate the load transfer and improve the design of gusset-plate joints combined analytical and experimental studies are essential.

Finally, to prove the validity of the results of small-scale joint studies, a study of a limited number of selected full-scale joints under alternating loads is recommended.



SPECIMEN NO.	WEB MEMBER THICKNESS	CHORD MEMBER THICKNESS
1	0.258	0.562
2	0.258	0.625
3	0.258	0.562
4	0.258	0.562
5	0.258	0.625
6	0.258	0.562

THICKNESS IN INCHES

FIG. I JOINT TYPE I - ZERO ECCENTRICITY

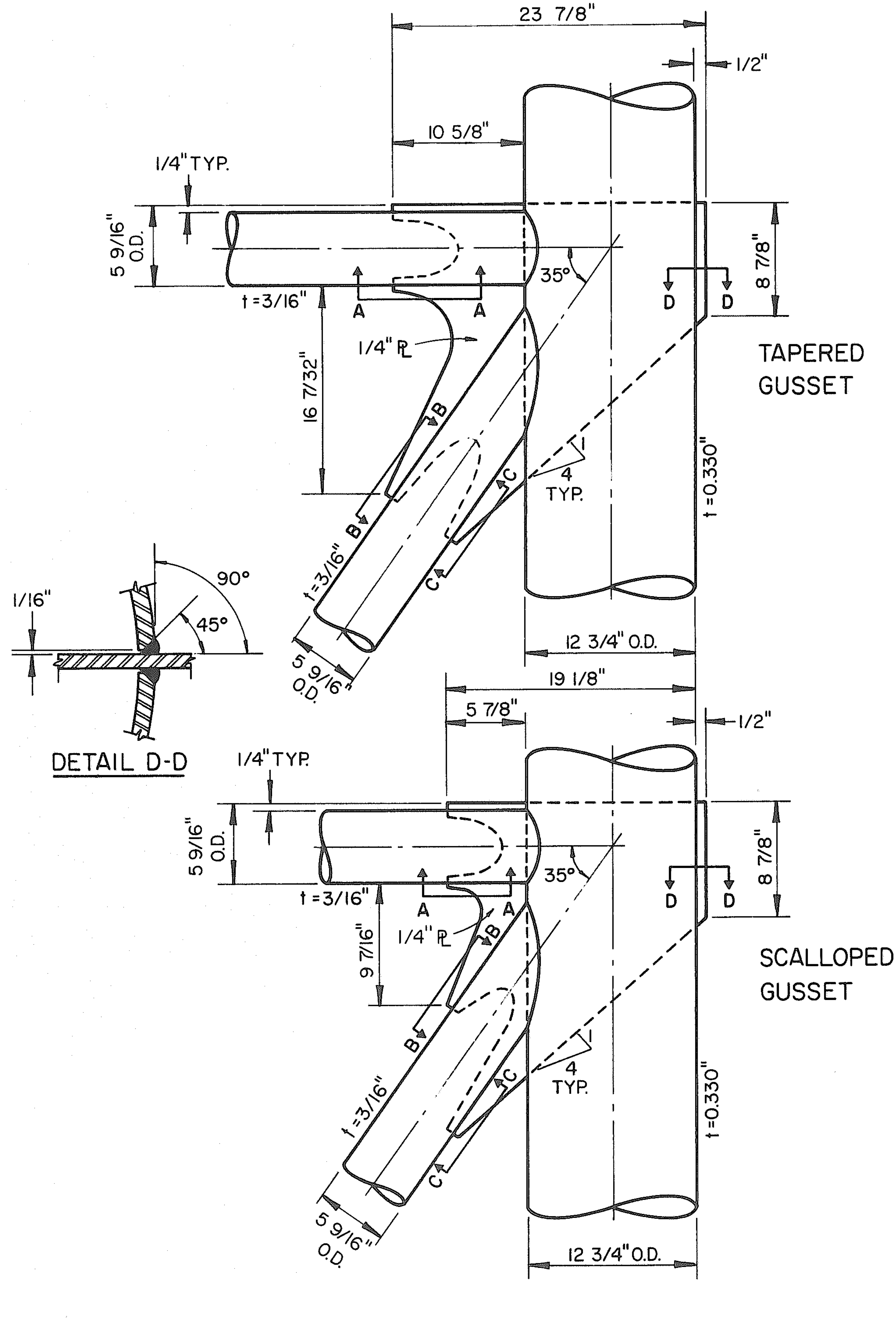
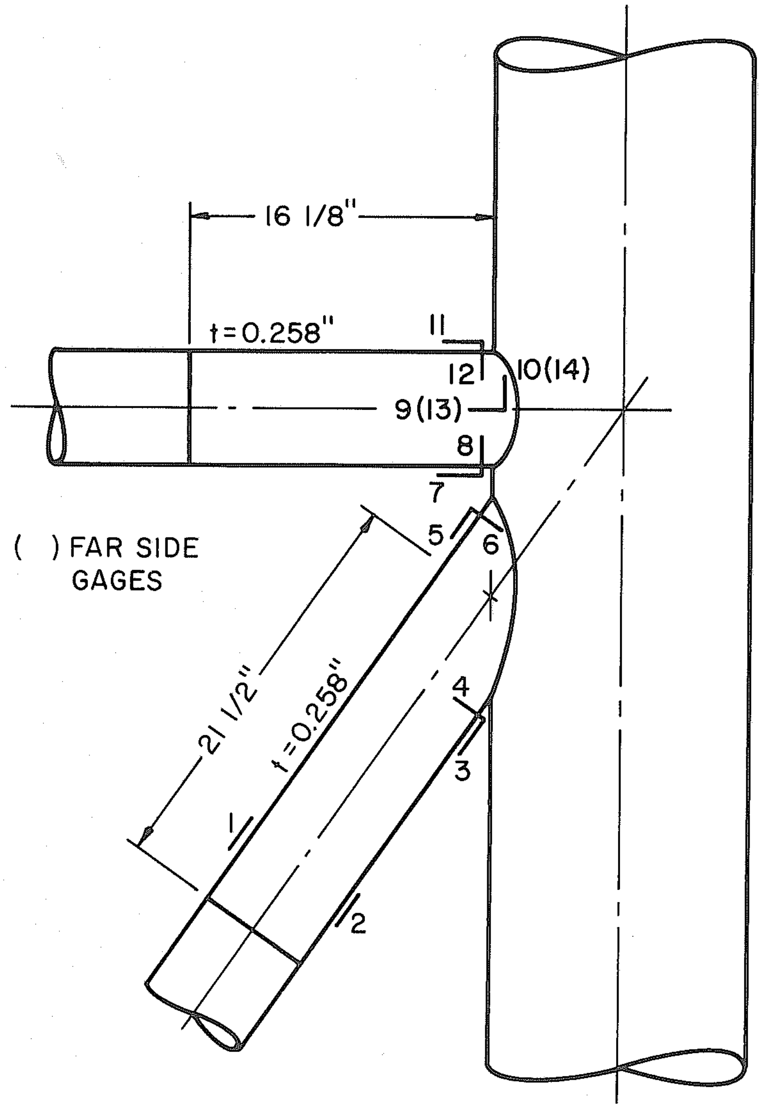
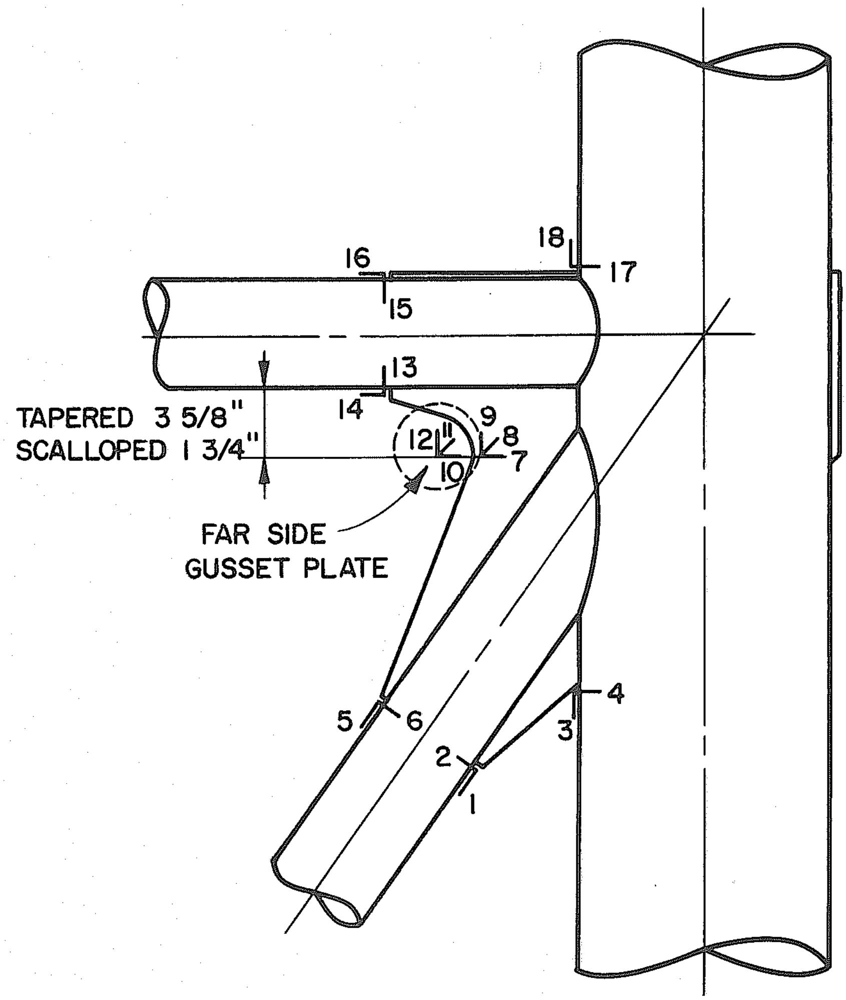


FIG. 2 JOINT TYPE 3



SPECIMEN NO.	STRAIN GAGES
1	NONE
2	1,2,5,6,7,8
3	1,2,5,6,7,8
4	1,2,3,4,5,6,7,8,9,10,11,12,13,14
5	See Figure 6
6	1,2,5,6,7,8,9,10,13,14

FIG. 3 STRAIN GAGE LOCATIONS ON TYPE I JOINT



SPECIMEN NO.	STRAIN GAGES	TYPE GUSSET PLATE
1	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18	TAPERED
2	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16	SCALLOPED
3	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16	TAPERED
4	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18	TAPERED
5	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16	SCALLOPED
6	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16	TAPERED

FIG. 4 STRAIN GAGE LOCATIONS ON TYPE 3 JOINT

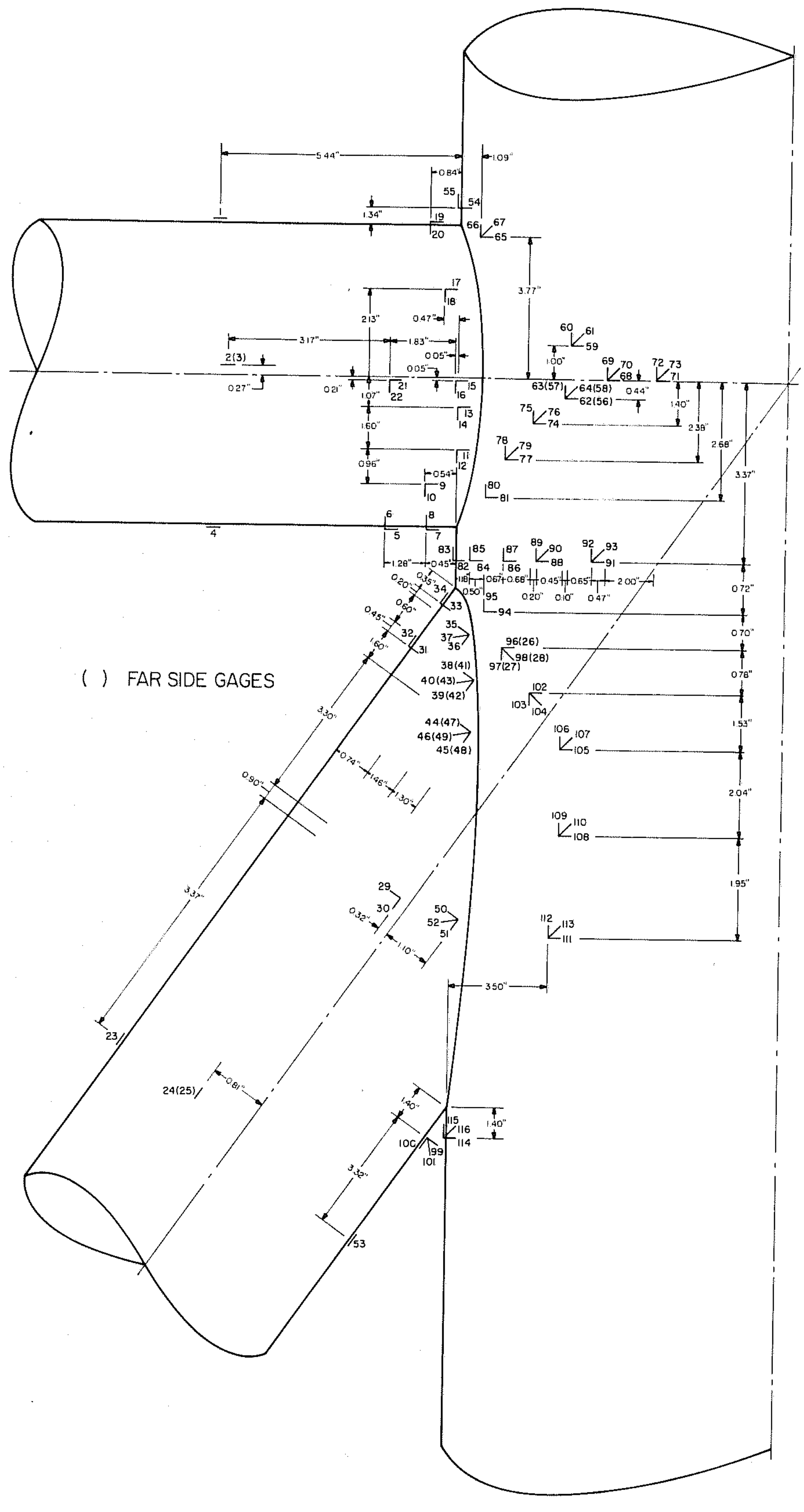


FIG. 5 STRAIN GAGE LOCATIONS ON TYPE I JOINT, PHASE II PART I SPECIMEN

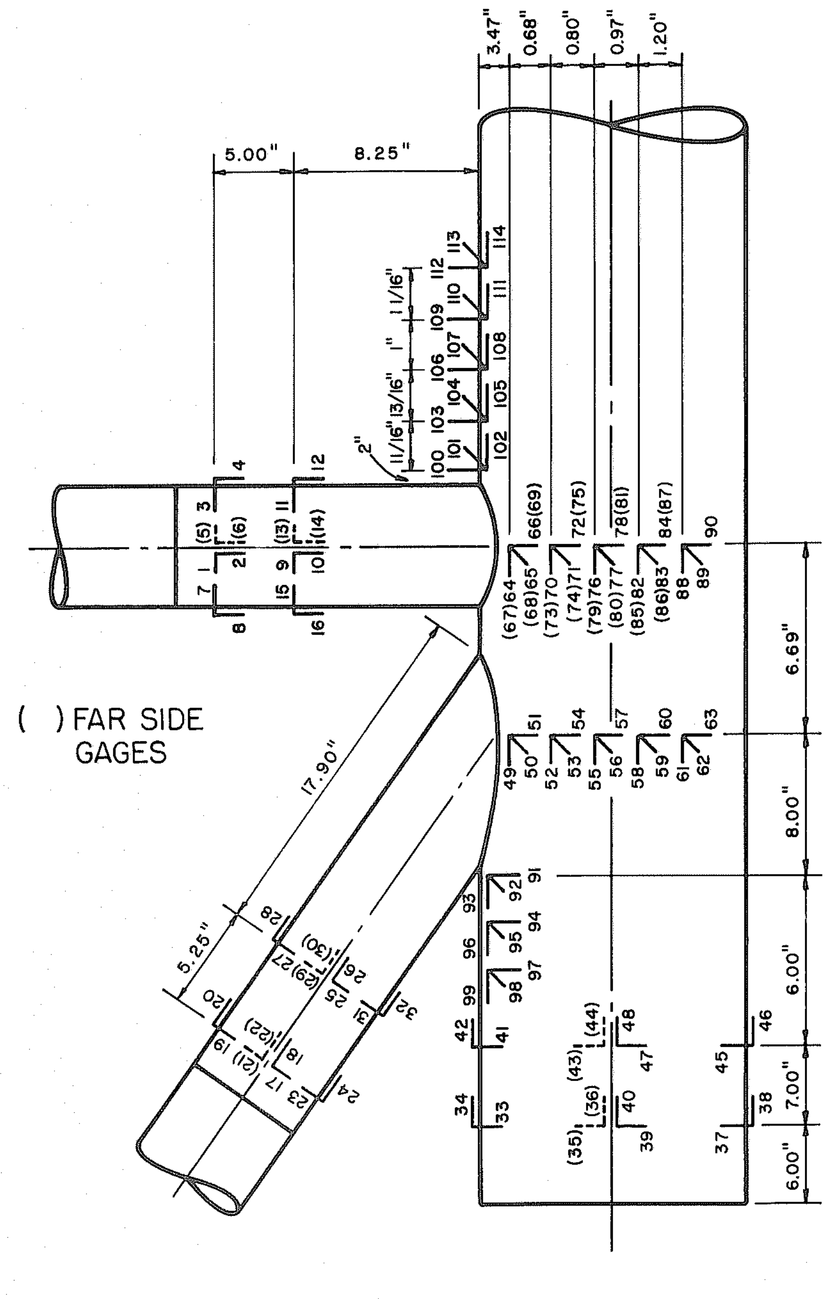


FIG. 6 STRAIN GAGE LOCATION TYPE I JOINT

SPECIMEN 5

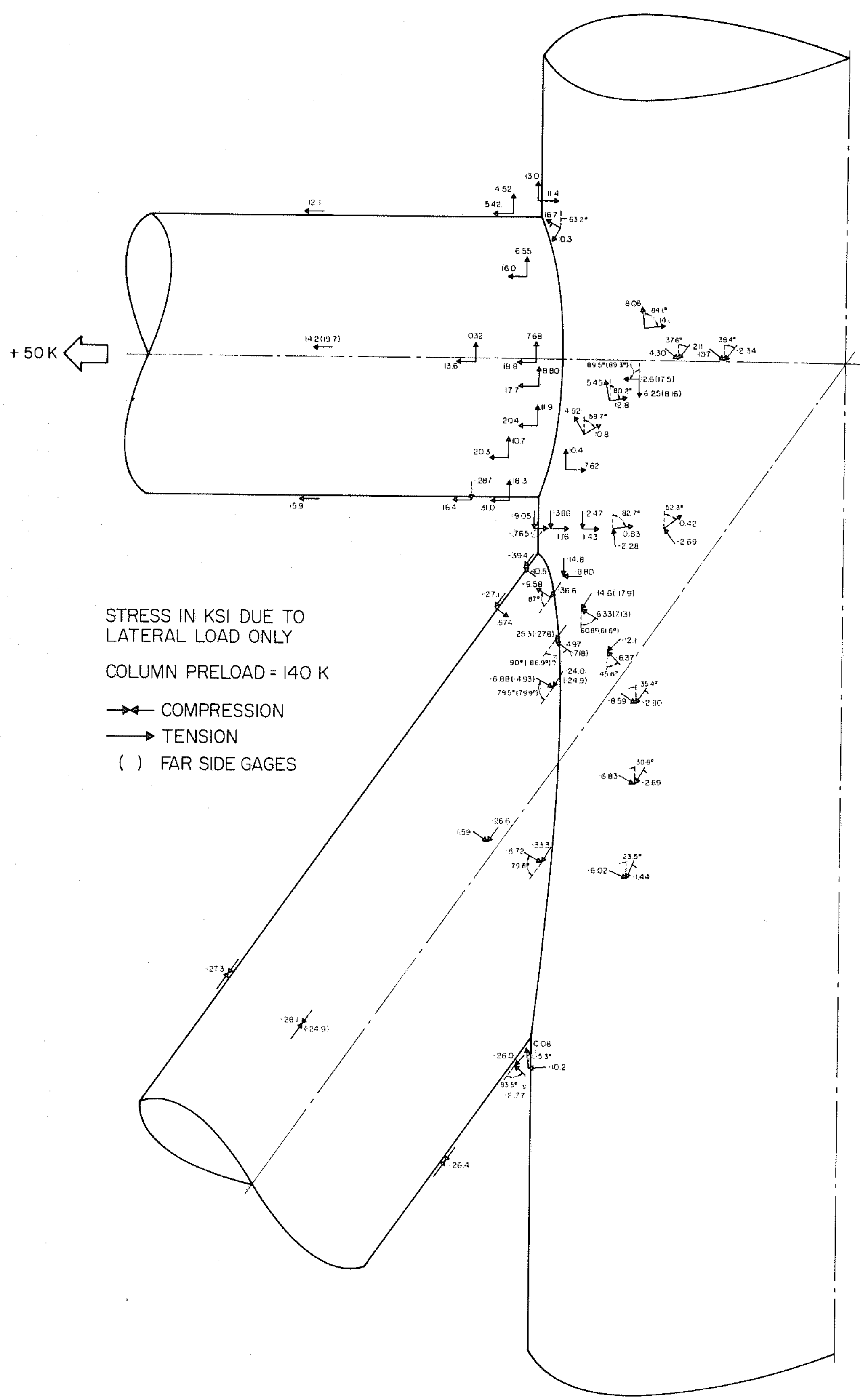


FIG. 7 PRINCIPAL STRESSES - TENSION LOAD IN HORIZONTAL MEMBER (50th CYCLE OF LOADING) PHASE II PART I SPECIMEN

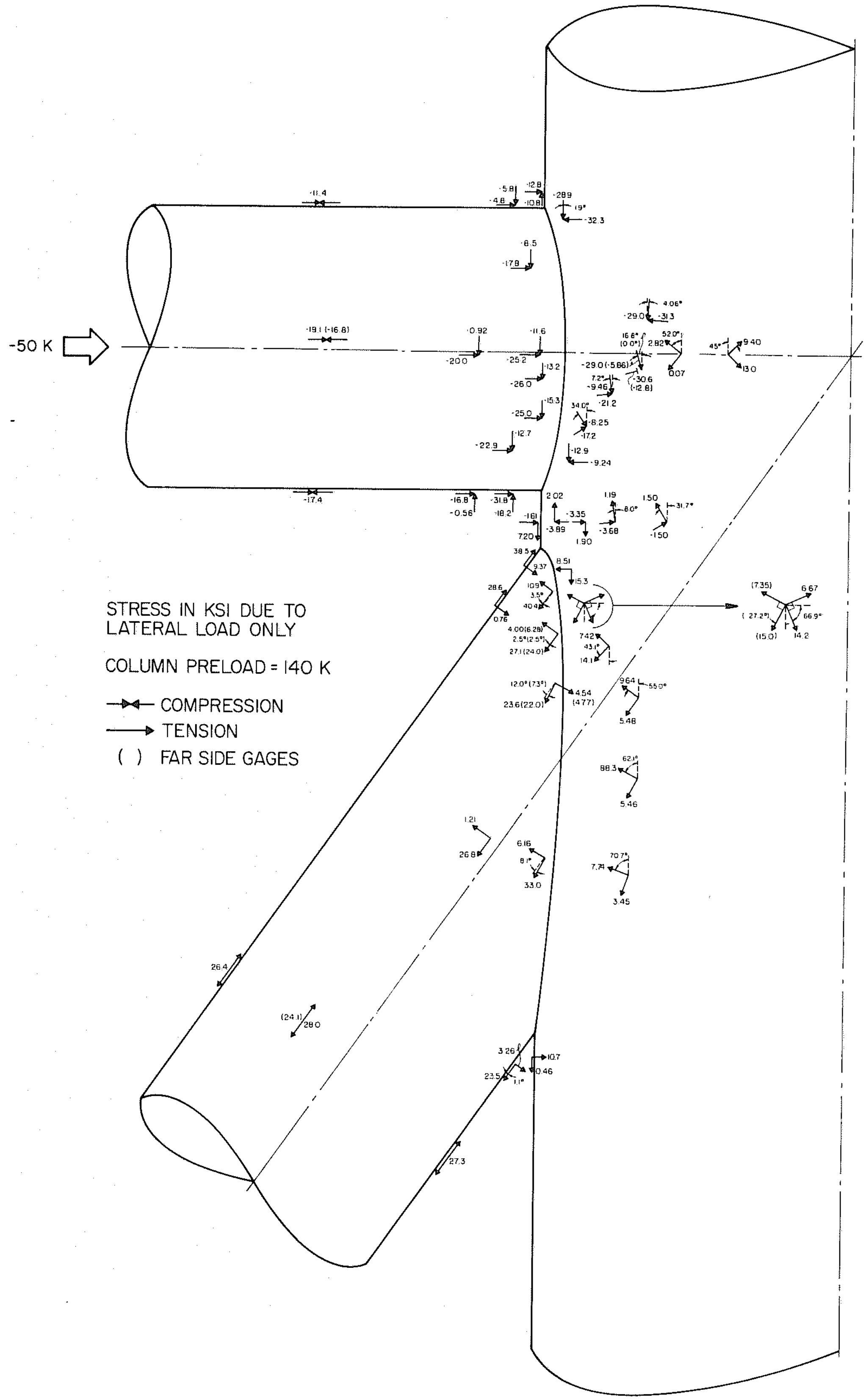


FIG. 8 PRINCIPAL STRESSES - COMPRESSIVE LOAD IN HORIZONTAL MEMBER (50 th CYCLE OF LOADING)
PHASE II PART I SPECIMEN

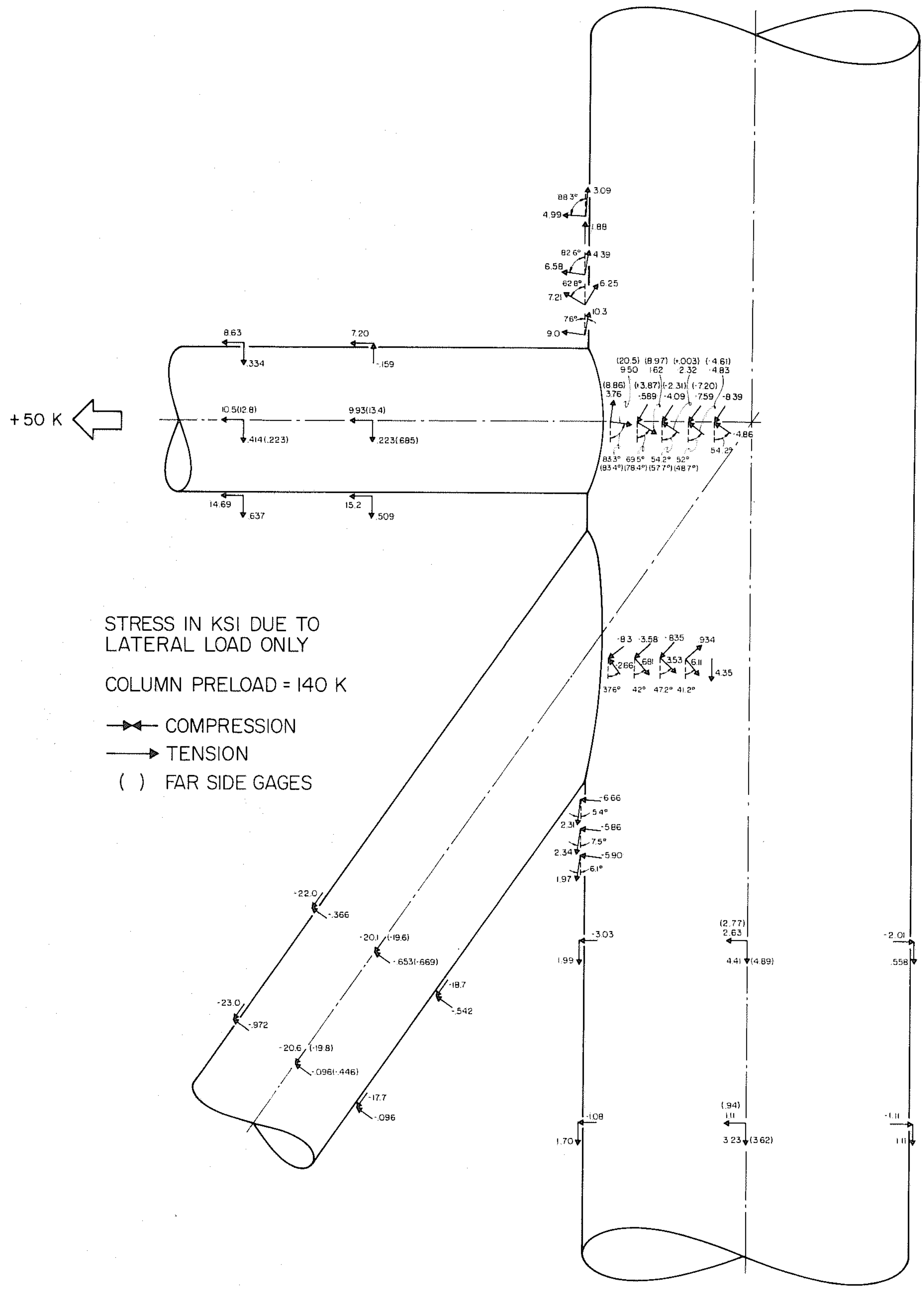


FIG. 9 PRINCIPAL STRESSES - TENSION LOAD IN HORIZONTAL MEMBER - SPECIMEN No. 5 (3rd CYCLE OF LOADING)

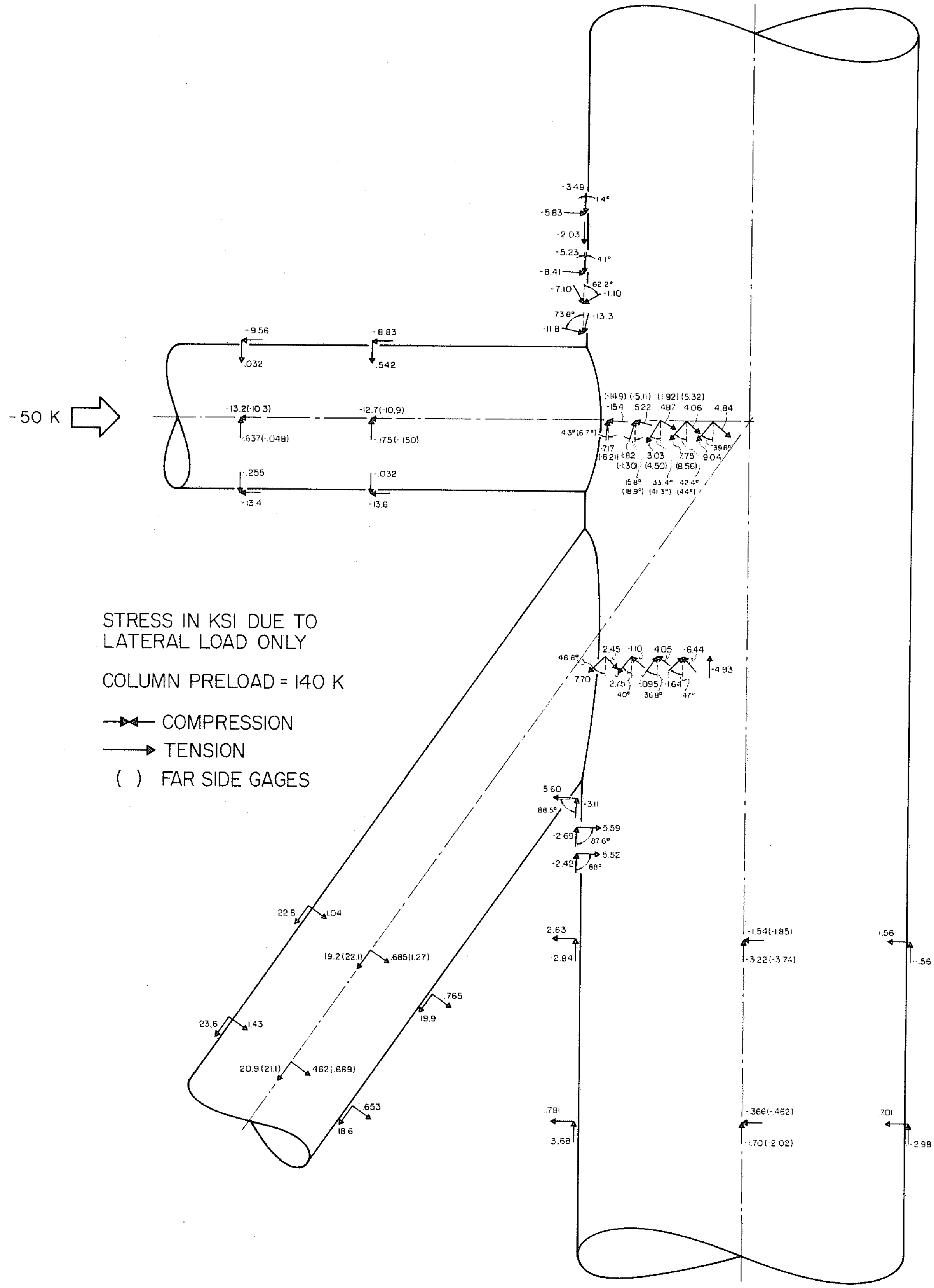
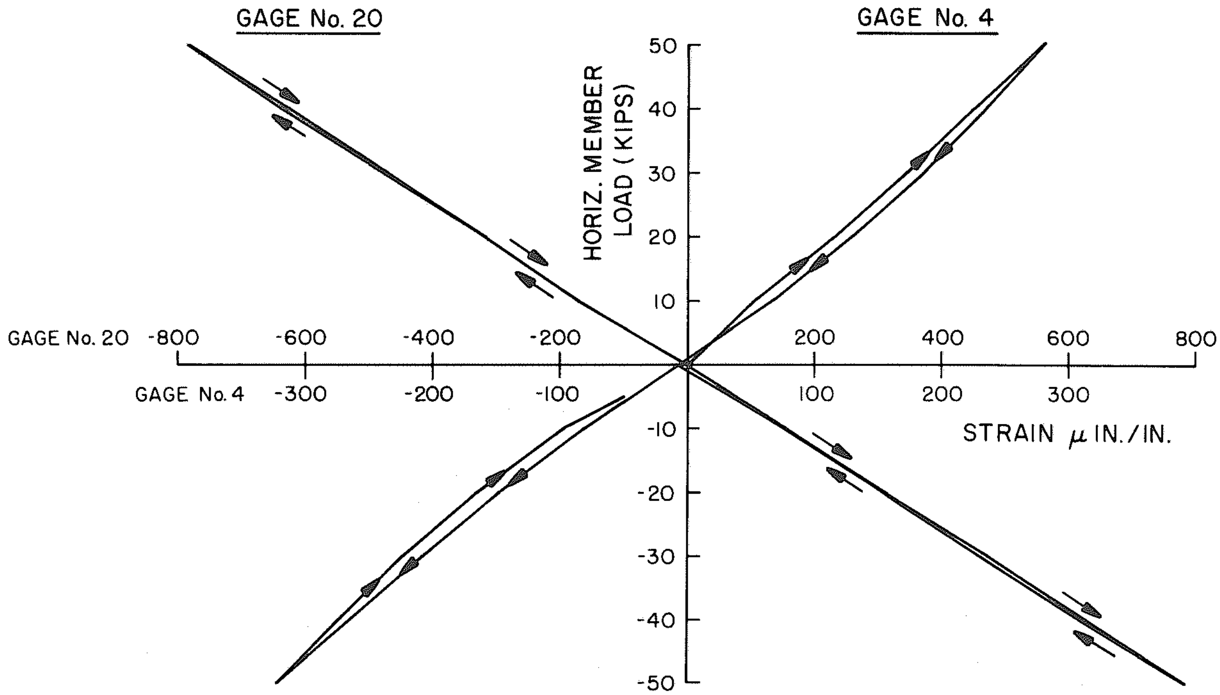


FIG.10 PRINCIPAL STRESSES - COMPRESSIVE LOAD IN HORIZONTAL MEMBER - SPECIMEN No.5 (3rd CYCLE OF LOADING)



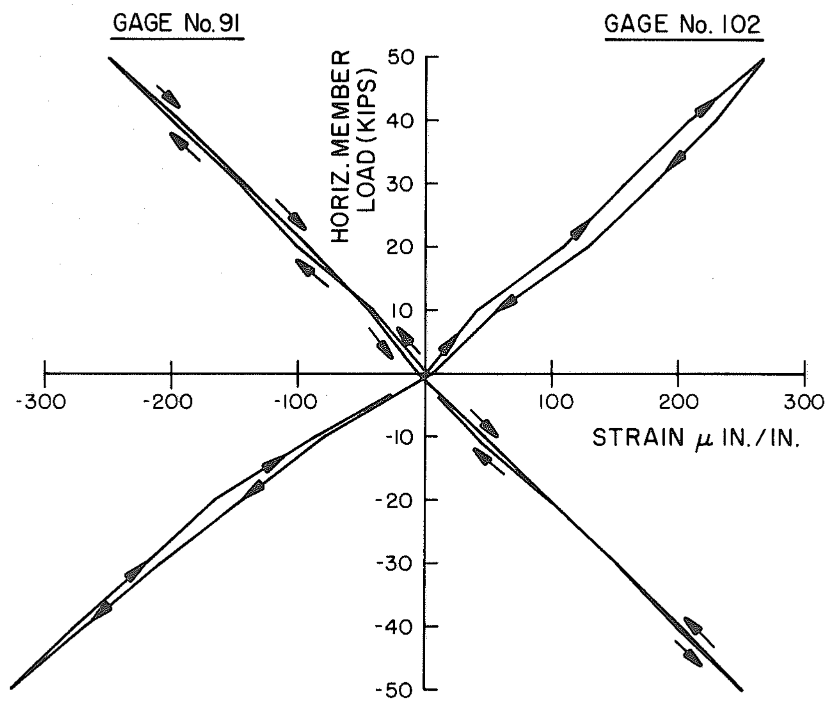
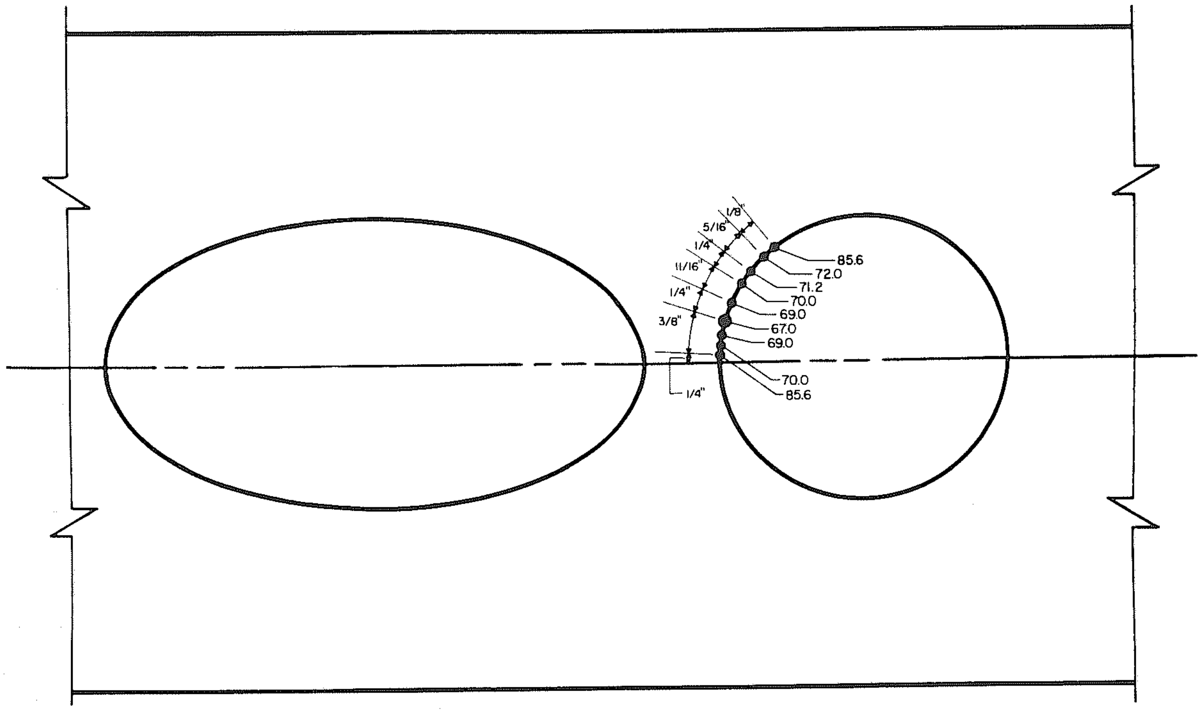


FIG. 11 LOAD-STRAIN RELATIONSHIP, SPECIMEN No. 5 - GAGES No.S 4, 20, 91 AND 102

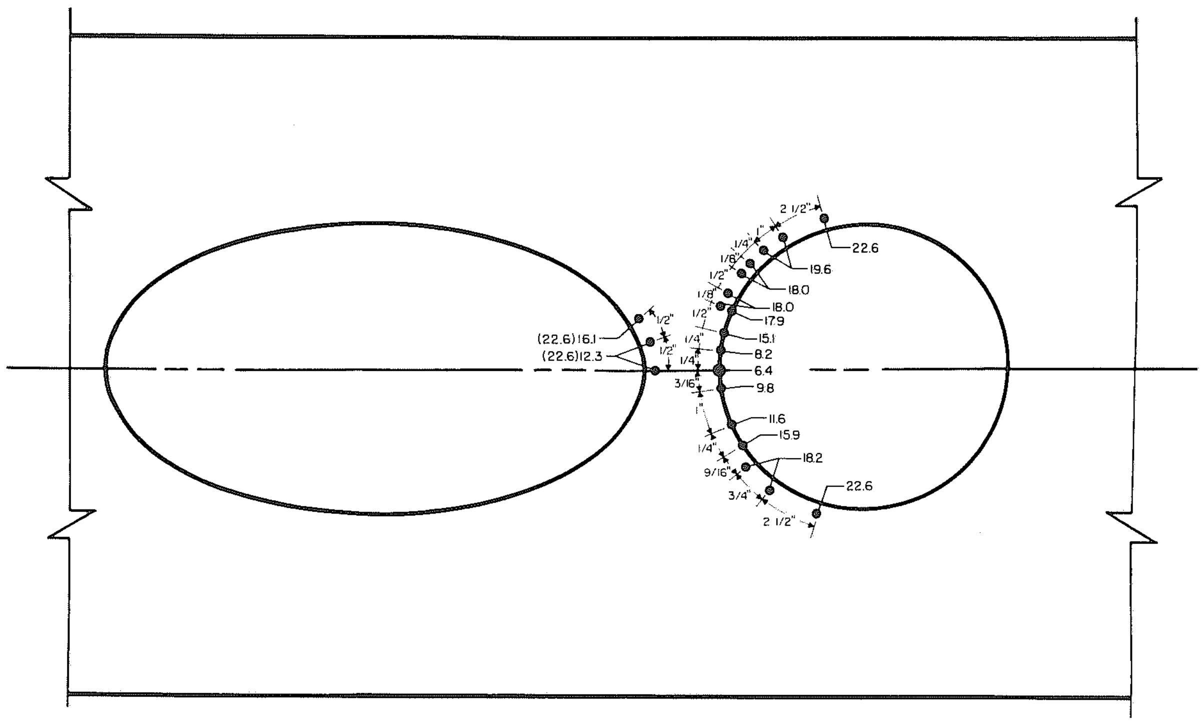


● INDICATES POINT OF CRACK PROGRESSION IN 1000 CYCLES

DIAGONAL : $f_{nominal} = \pm 14.0$ KSI

HORIZONTAL : $f_{nominal} = \mp 8.0$ KSI

FIG. 12 CRACK PROPAGATION IN TYPE I JOINT LOADED AT ± 25K IN HORIZONTAL MEMBER - PHASE II PART I

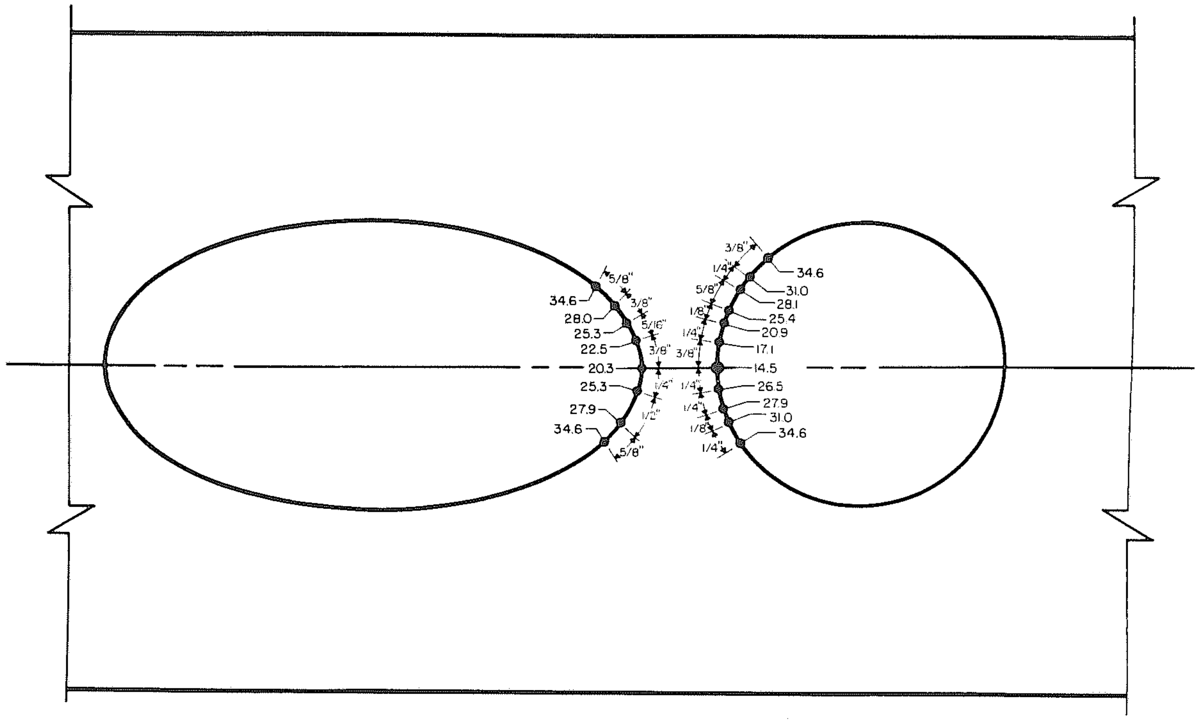


● INDICATES POINT OF CRACK PROGRESSION IN 1000 CYCLES

DIAGONAL : $f_{nominal}$ = ± 28.0 KSI (t = 0.188 IN.)
= ± 20.3 KSI (t = 0.258 IN.)

HORIZONTAL : $f_{nominal}$ = ∓ 16.0 KSI (t = 0.188 IN.)
= ∓ 11.6 KSI (t = 0.258 IN.)

FIG. 13 CRACK PROPAGATION IN TYPE I JOINT SPECIMEN N° 1 LOADED AT ± 50 K IN HORIZONTAL MEMBER



● INDICATES POINT OF CRACK PROGRESSION IN 1000 CYCLES

DIAGONAL : $f_{nominal}$ = ± 28.0 KSI (t = 0.188 IN.)
= ± 20.3 KSI (t = 0.258 IN.)

HORIZONTAL : $f_{nominal}$ = ∓ 16.0 KSI (t = 0.188 IN.)
= ∓ 11.6 KSI (t = 0.258 IN.)

FIG. 14 CRACK PROPAGATION IN TYPE I JOINT SPECIMEN Nº 2 LOADED AT ± 50 K IN HORIZONTAL MEMBER

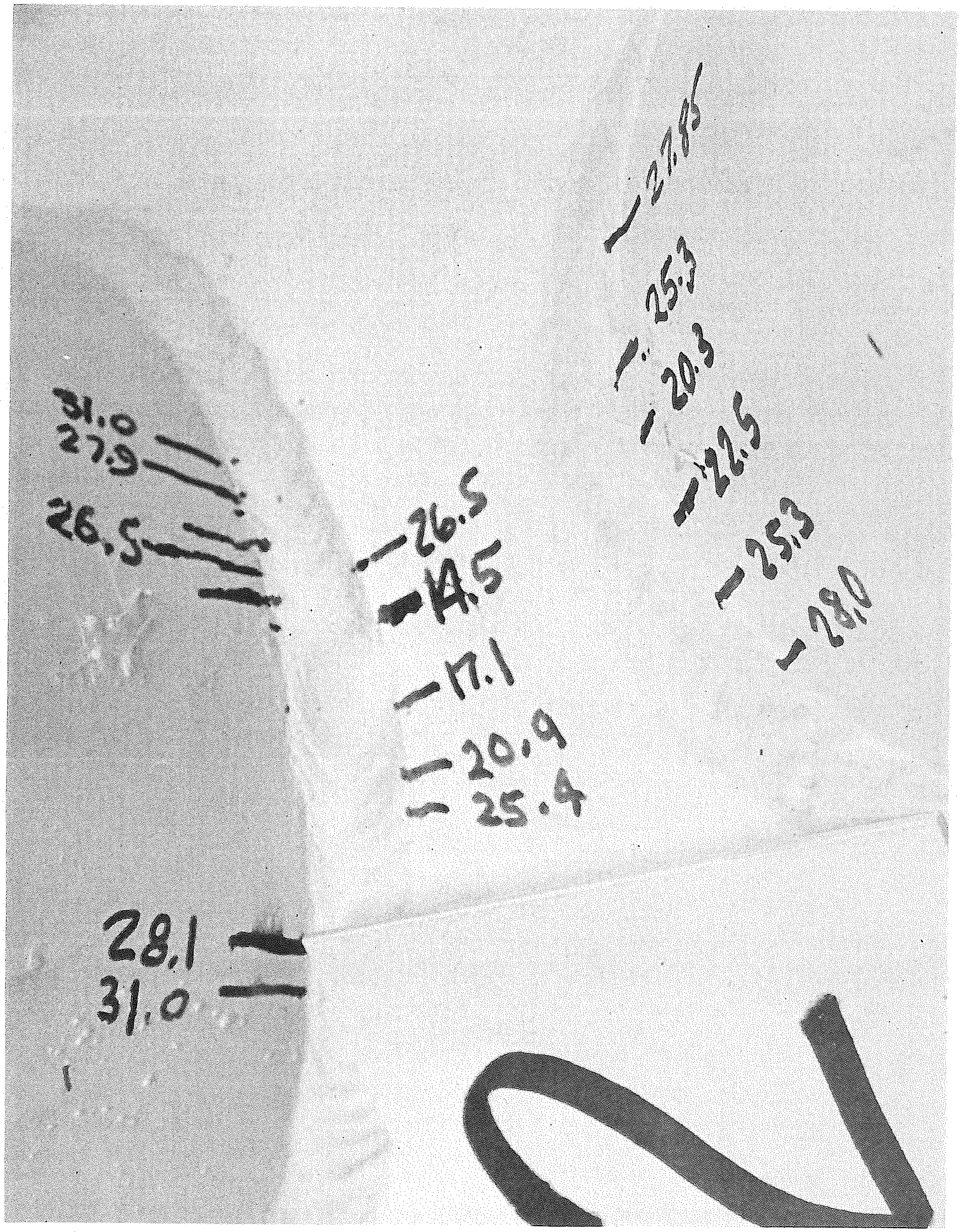
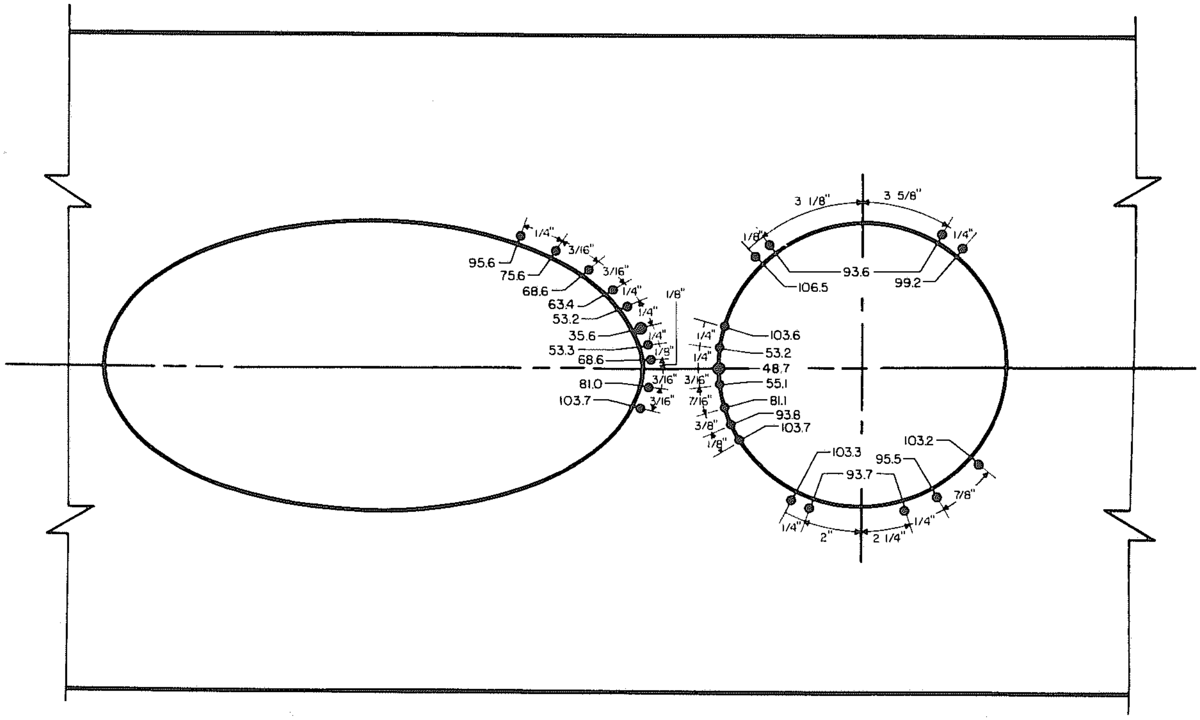


FIG. 15 JOINT TYPE I - SPECIMEN No. 2, DETAILED CRACK PROPAGATION



● INDICATES POINT OF CRACK PROGRESSION IN 1000 CYCLES

DIAGONAL : $f_{nominal}$ = ± 22.4 KSI (t = 0.188 IN.)
= ± 16.2 KSI (t = 0.258 IN.)

HORIZONTAL : $f_{nominal}$ = ∓ 12.8 KSI (t = 0.188 IN.)
= ∓ 9.3 KSI (t = 0.258 IN.)

FIG. 16 CRACK PROPAGATION IN TYPE I JOINT SPECIMEN Nº 3 LOADED AT ± 40 K IN HORIZONTAL MEMBER

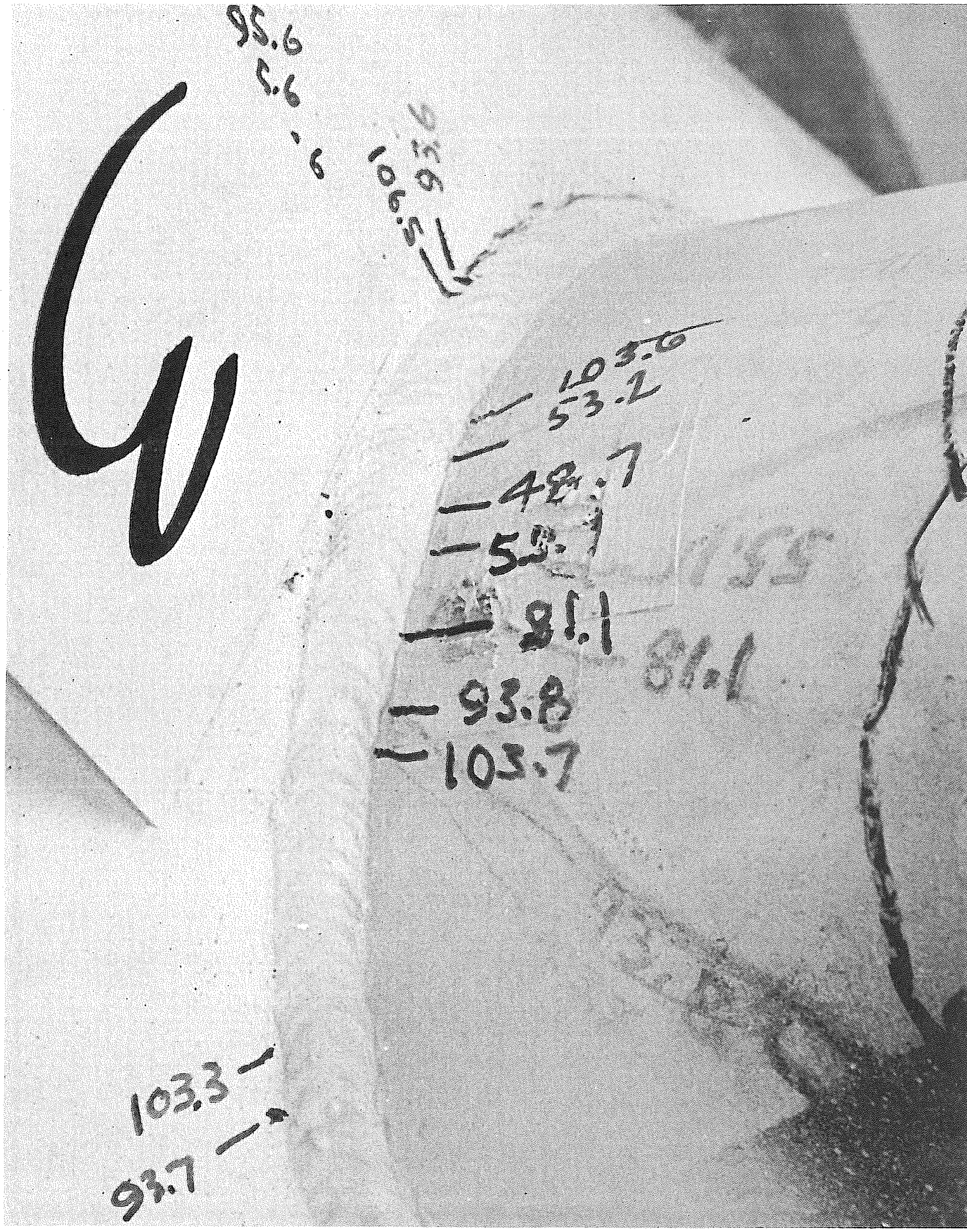
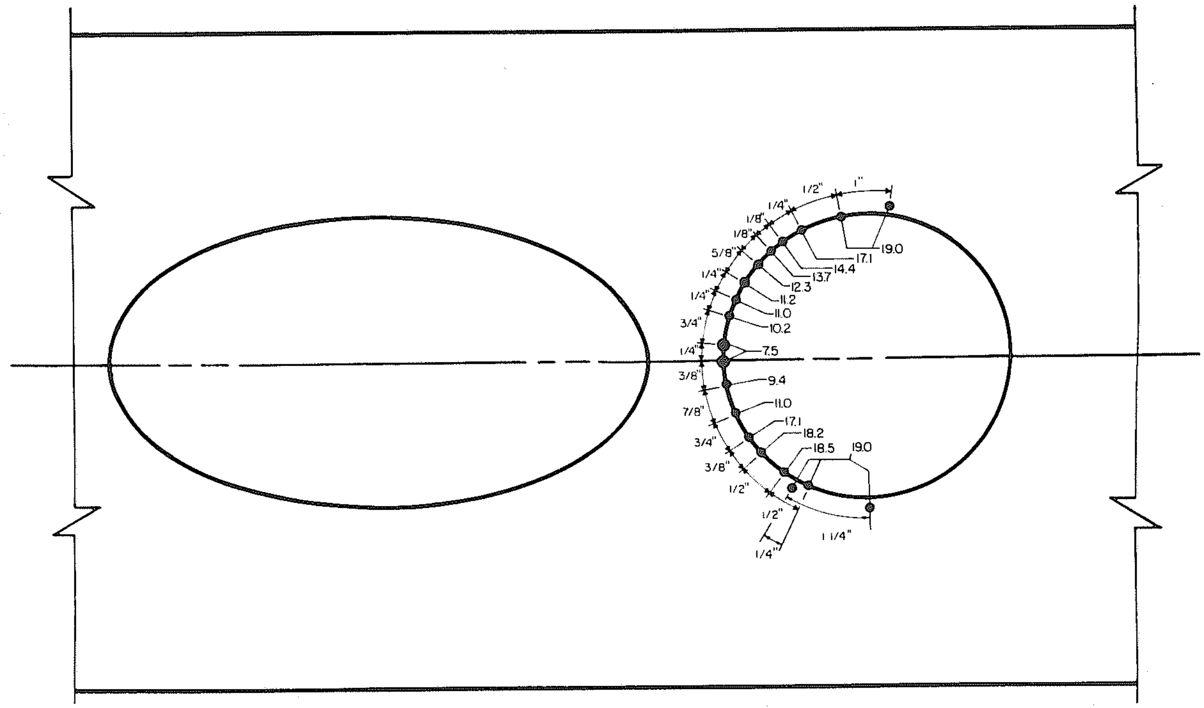


FIG. 17 JOINT TYPE I - SPECIMEN No. 3 DETAILED CRACK PROPAGATION IN HORIZONTAL AND COLUMN MEMBER WALLS

FIG 18 JOINT TYPE I - SPECIMEN No. 3 DETAILED CRACK PROPAGATION IN COLUMN MEMBER WALL



● INDICATES POINT OF CRACK PROGRESSION IN 1000 CYCLES

DIAGONAL : $f_{nominal}$ = ± 28.0 KSI (t = 0.188 IN.)
= ± 20.3 KSI (t = 0.258 IN.)

HORIZONTAL : $f_{nominal}$ = ∓ 16.0 KSI (t = 0.188 IN.)
= ∓ 11.6 KSI (t = 0.258 IN.)

FIG. 19 CRACK PROPAGATION IN TYPE I JOINT SPECIMEN Nº 4 LOADED AT ± 50 K IN HORIZONTAL MEMBER

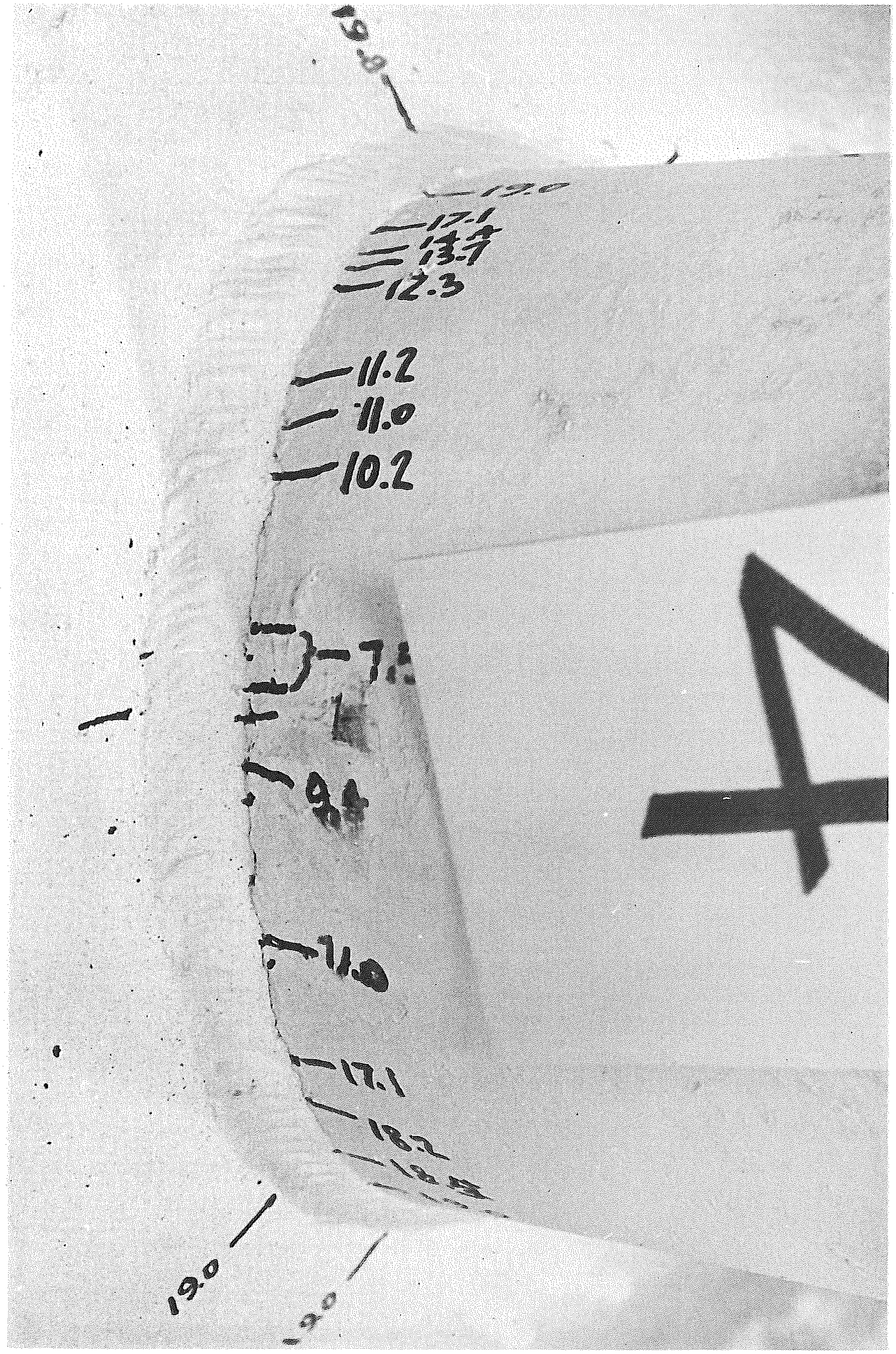
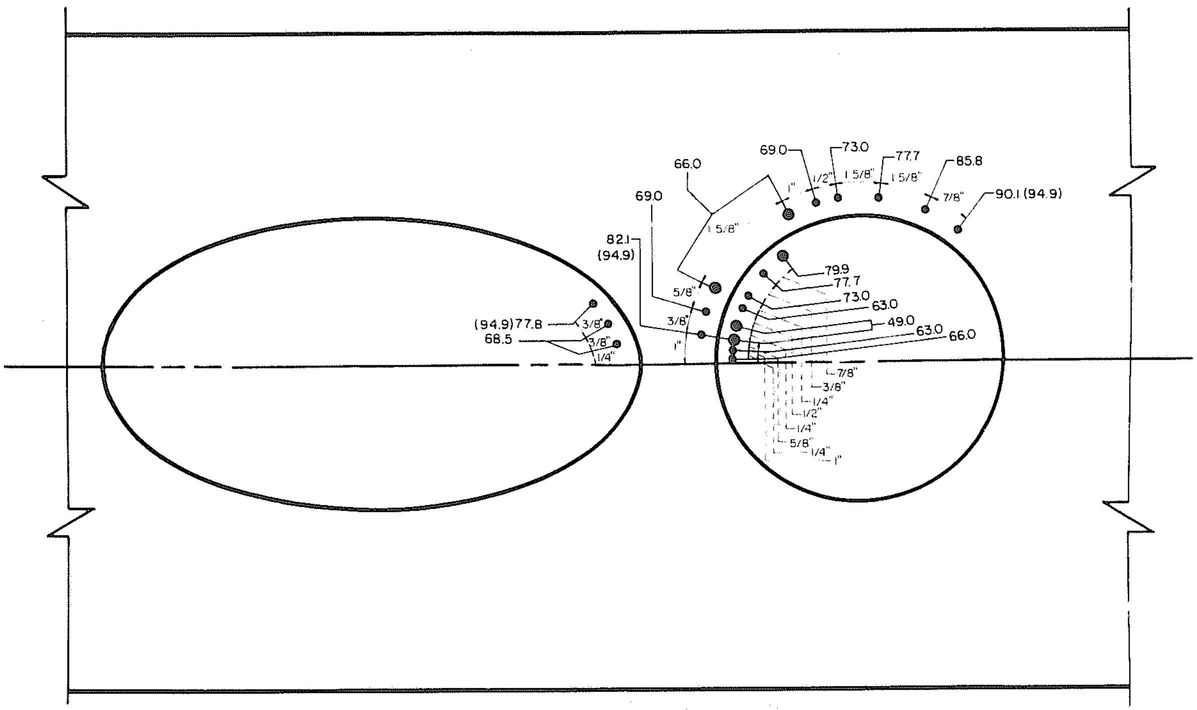


FIG. 20 JOINT TYPE I - SPECIMEN No. 4, DETAILED CRACK PROPAGATION IN HORIZONTAL MEMBER WALL

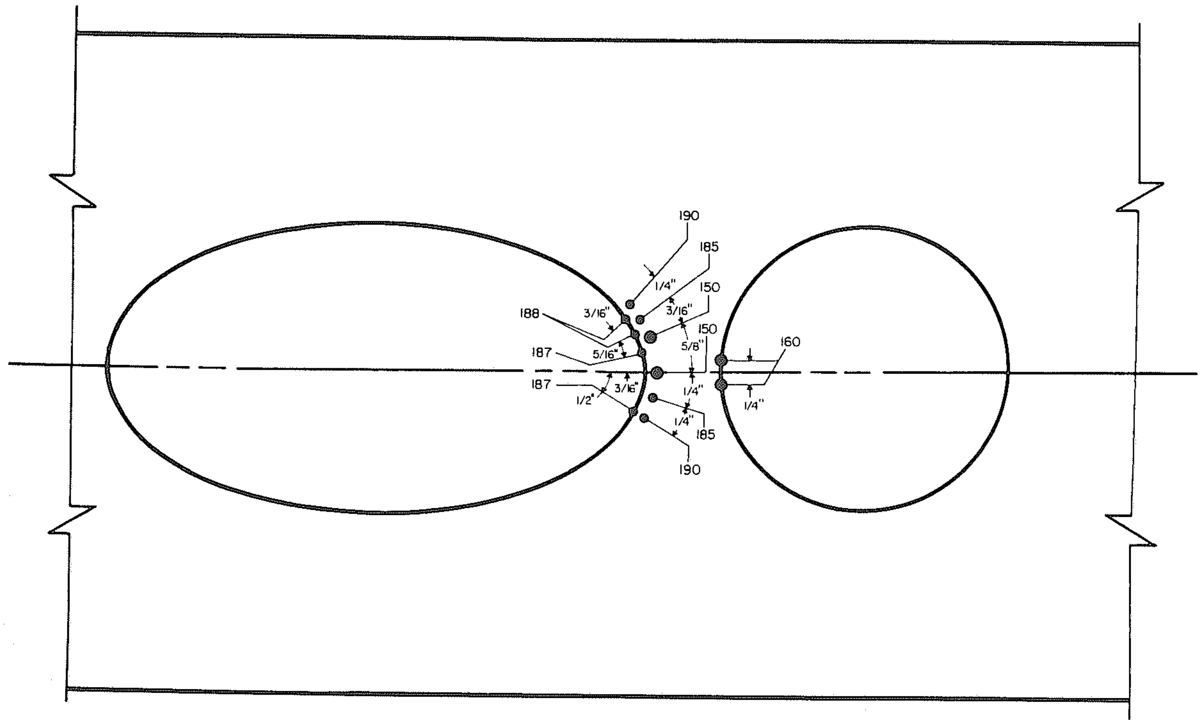


● INDICATES POINT OF CRACK PROGRESSION IN 1000 CYCLES

DIAGONAL : $f_{nominal}$ = ± 22.4 KSI (t = 0.188 IN.)
= ± 16.2 KSI (t = 0.258 IN.)

HORIZONTAL : $f_{nominal}$ = ∓ 12.8 KSI (t = 0.188 IN.)
= ∓ 9.3 KSI (t = 0.258 IN.)

FIG. 21 CRACK PROPAGATION IN TYPE I JOINT
SPECIMEN Nº 5 LOADED AT ± 40 K IN HORIZONTAL MEMBER



● INDICATES POINT OF CRACK PROGRESSION IN 1000 CYCLES

DIAGONAL : $f_{nominal}$ = ± 16.8 KSI (t = 0.188 IN.)
= ± 12.2 KSI (t = 0.258 IN.)

HORIZONTAL : $f_{nominal}$ = ∓ 9.6 KSI (t = 0.188 IN.)
= ∓ 7.0 KSI (t = 0.258 IN.)

FIG. 22 CRACK PROPAGATION IN TYPE I JOINT
SPECIMEN Nº 6 LOADED AT ± 30 K IN HORIZONTAL MEMBER

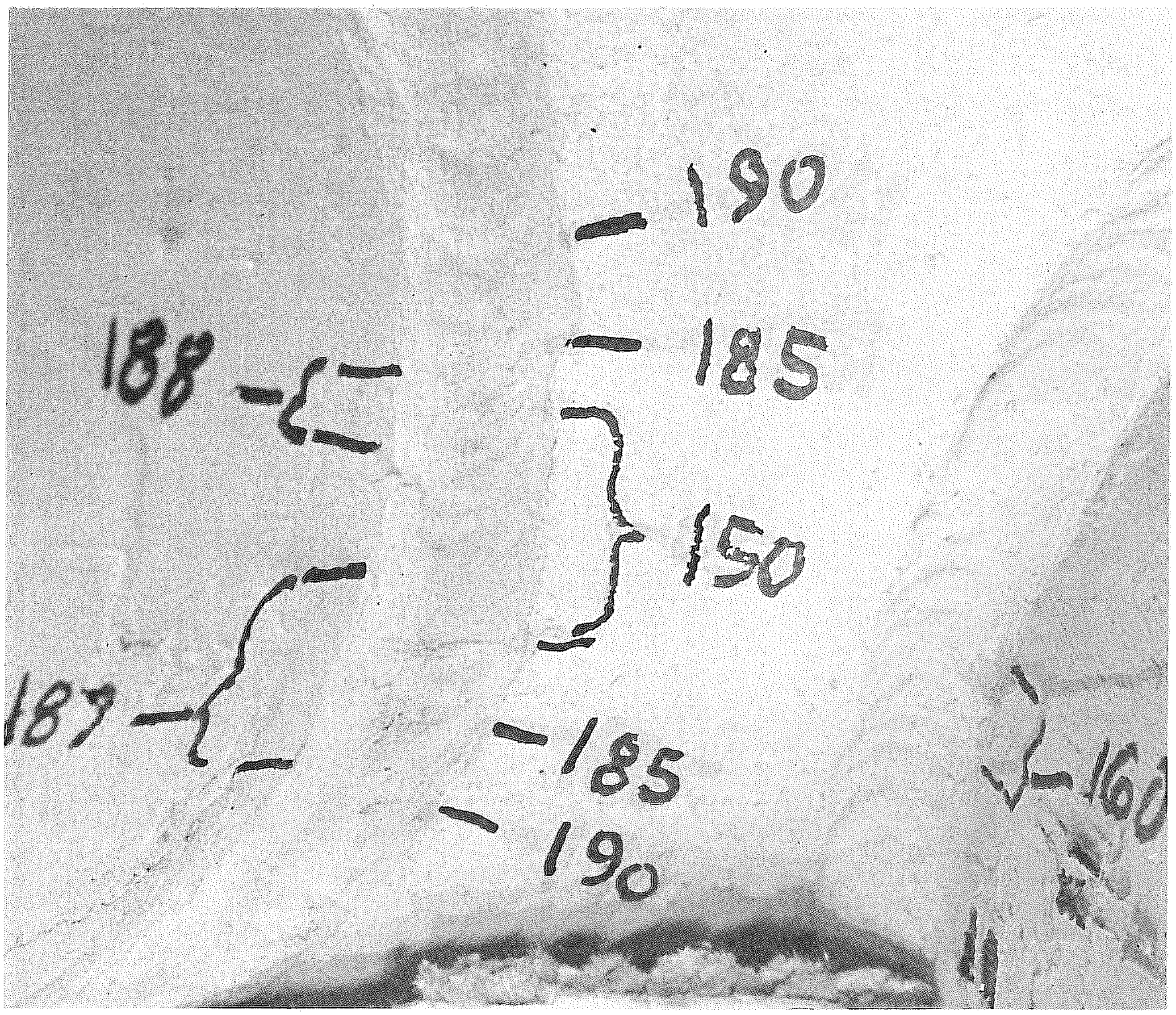


FIG. 23 JOINT TYPE I - SPECIMEN No. 6 DETAILED CRACK PROPAGATION IN COLUMN AND WEB MEMBER WALLS

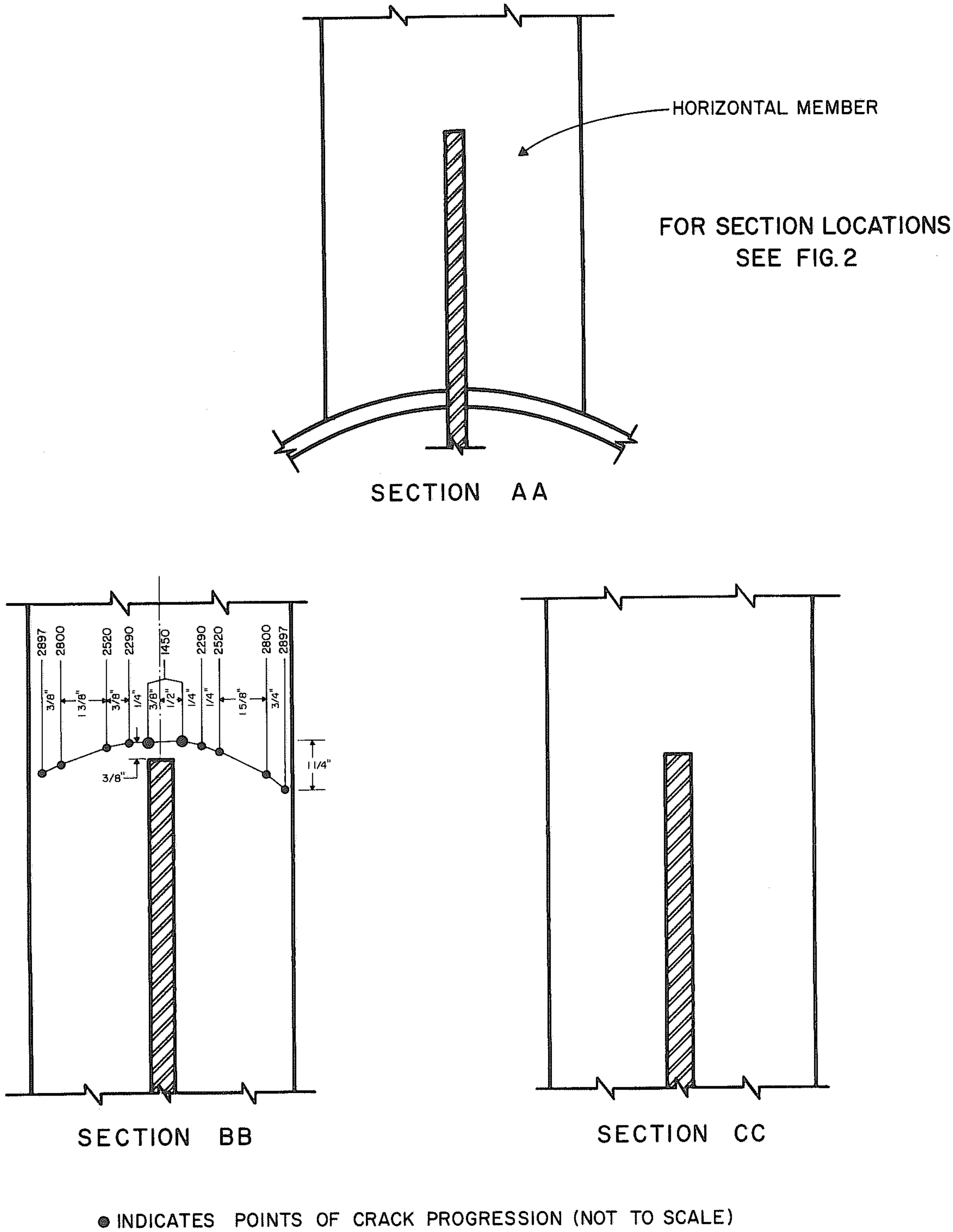


FIG.24 CRACK PROPAGATION IN TYPE 3 JOINT
SPECIMEN Nº 1 LOADED AT ± 50 K IN HORIZONTAL MEMBER
(TAPERED GUSSET PLATE)

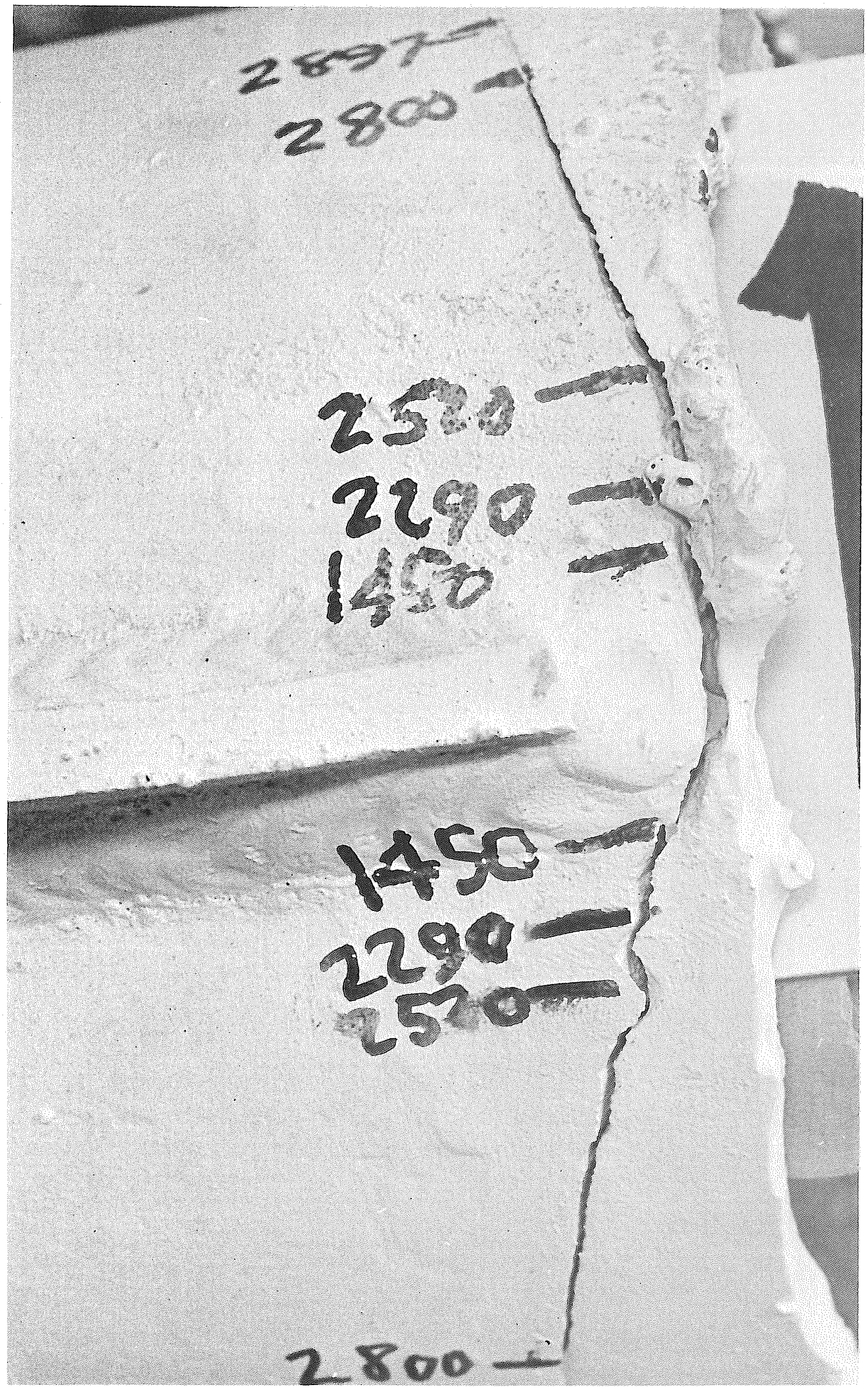
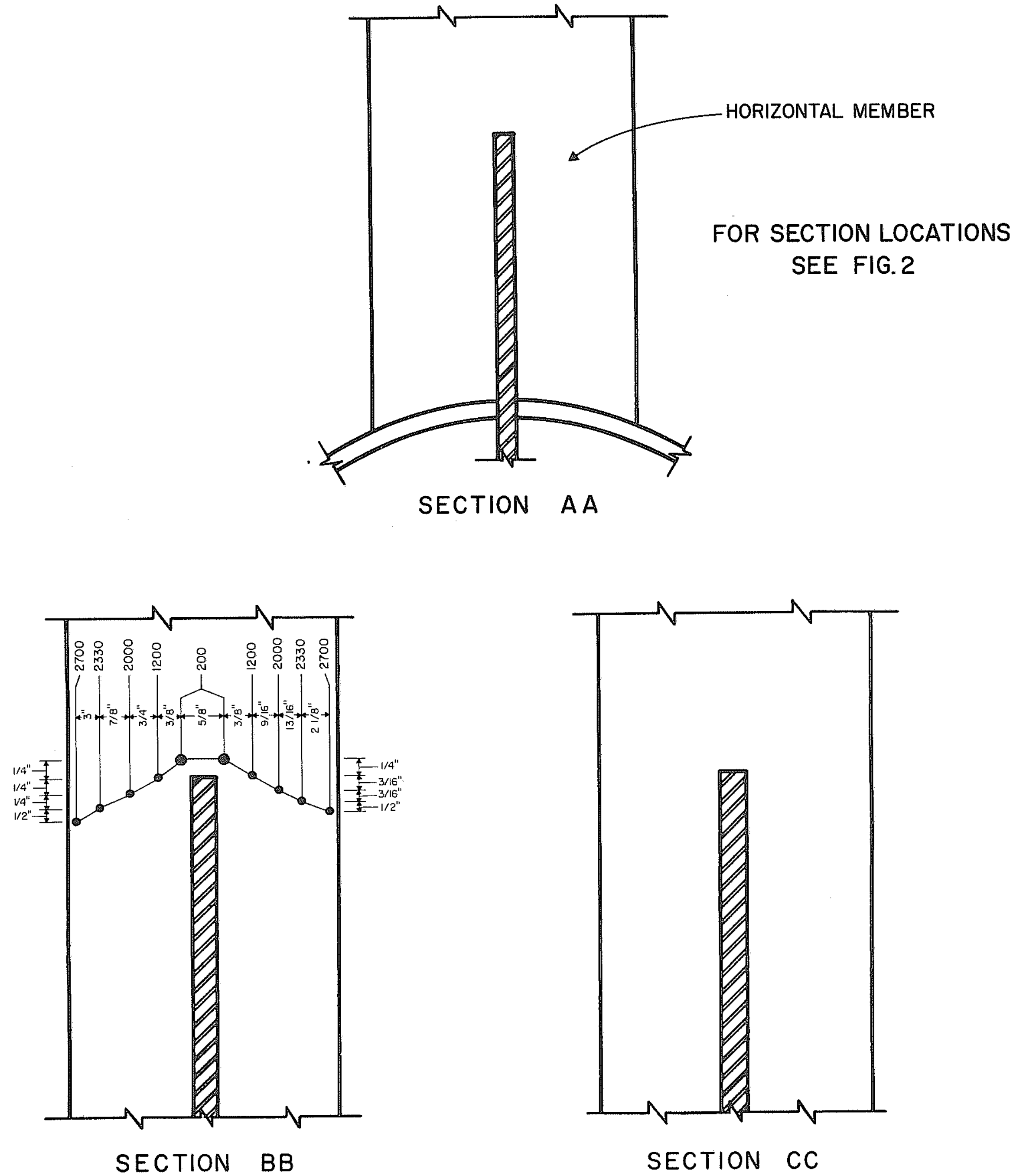


FIG. 25 JOINT TYPE 3 - SPECIMEN No. I (TAPERED GUSSET PLATE)
DETAILED CRACK PROPAGATION IN DIAGONAL MEMBER



● INDICATES POINTS OF CRACK PROGRESSION (NOT TO SCALE)

FIG.26 CRACK PROPAGATION IN TYPE 3 JOINT
SPECIMEN Nº 2 LOADED AT ± 50 K IN HORIZONTAL MEMBER
(SCALLOPED GUSSET PLATE)

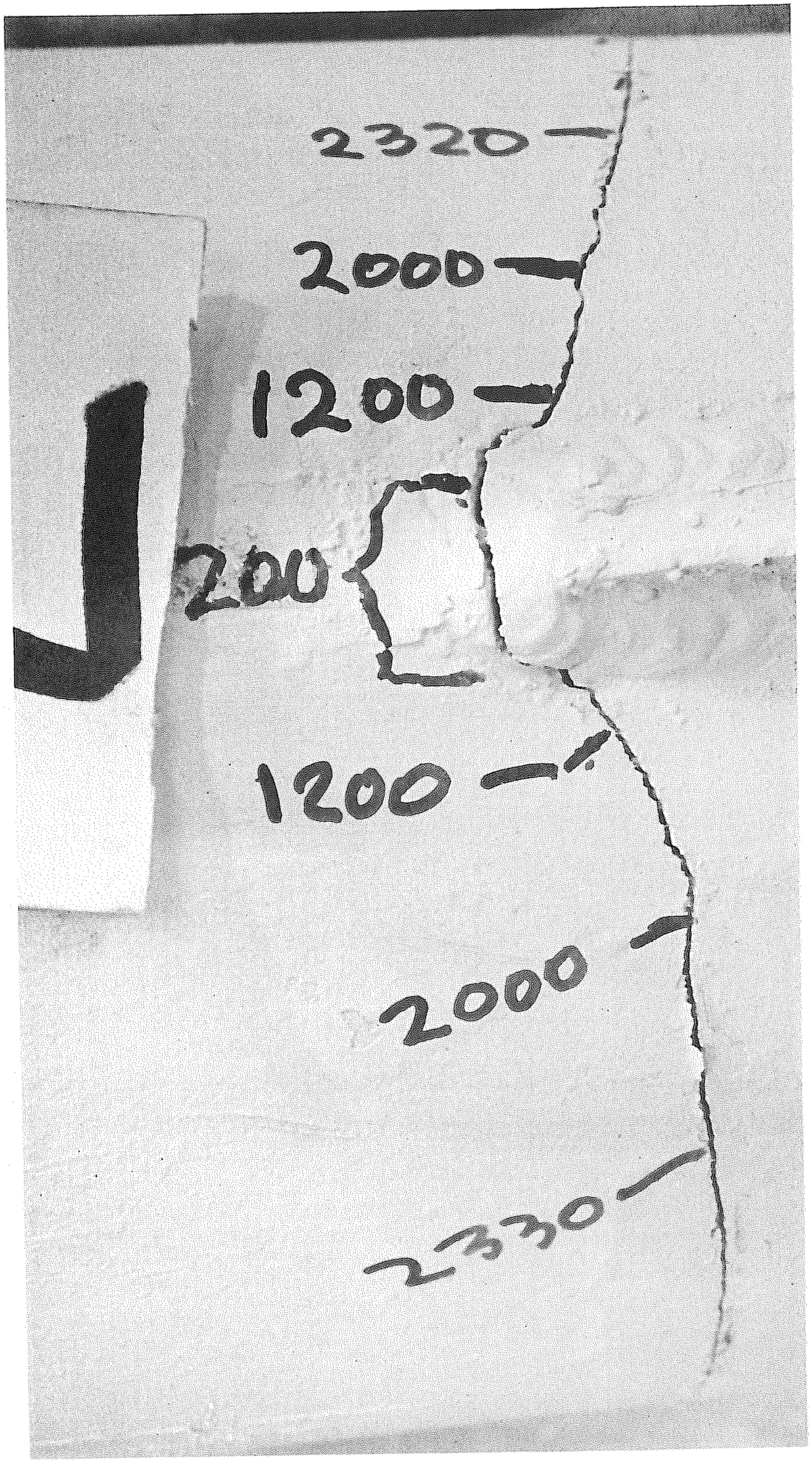
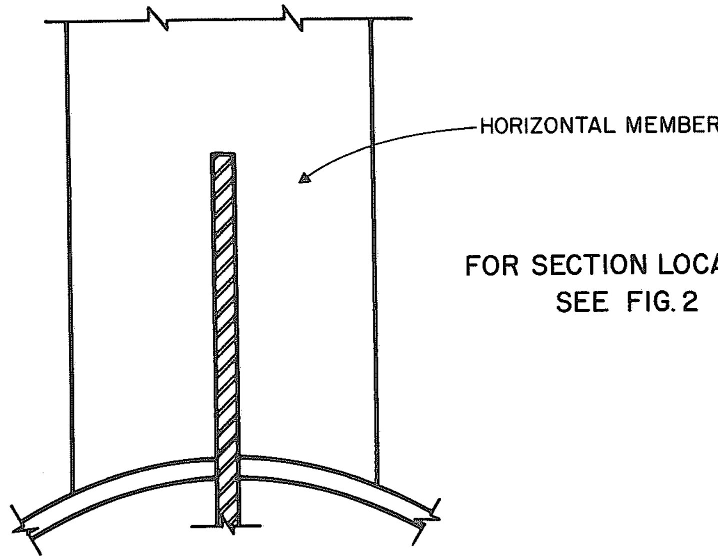
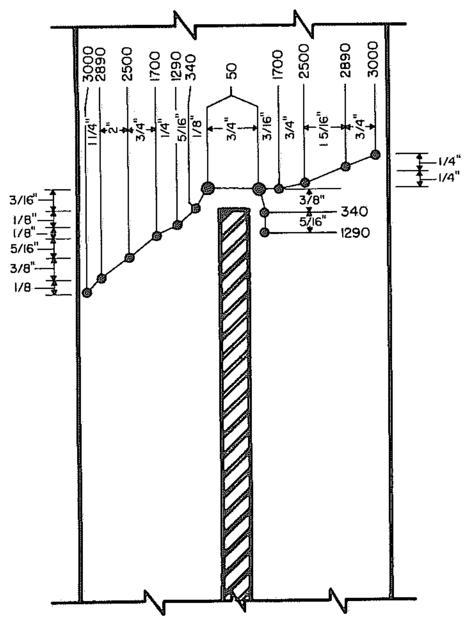


FIG. 27 JOINT TYPE 3 - SPECIMEN No. 2 (SCALLOPED GUSSET PLATE) DETAILED CRACK PROPAGATION IN DIAGONAL MEMBER

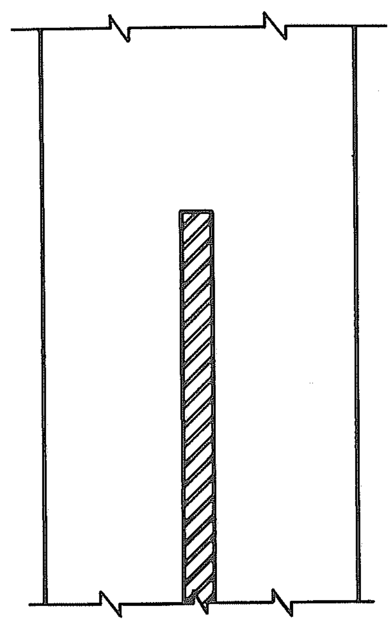


FOR SECTION LOCATIONS SEE FIG. 2

SECTION AA



SECTION BB



SECTION CC

● INDICATES POINTS OF CRACK PROGRESSION (NOT TO SCALE)

FIG. 28 CRACK PROPAGATION IN TYPE 3 JOINT SPECIMEN No. 3 LOADED AT ± 50 K IN HORIZONTAL MEMBER (TAPERED GUSSET PLATE)

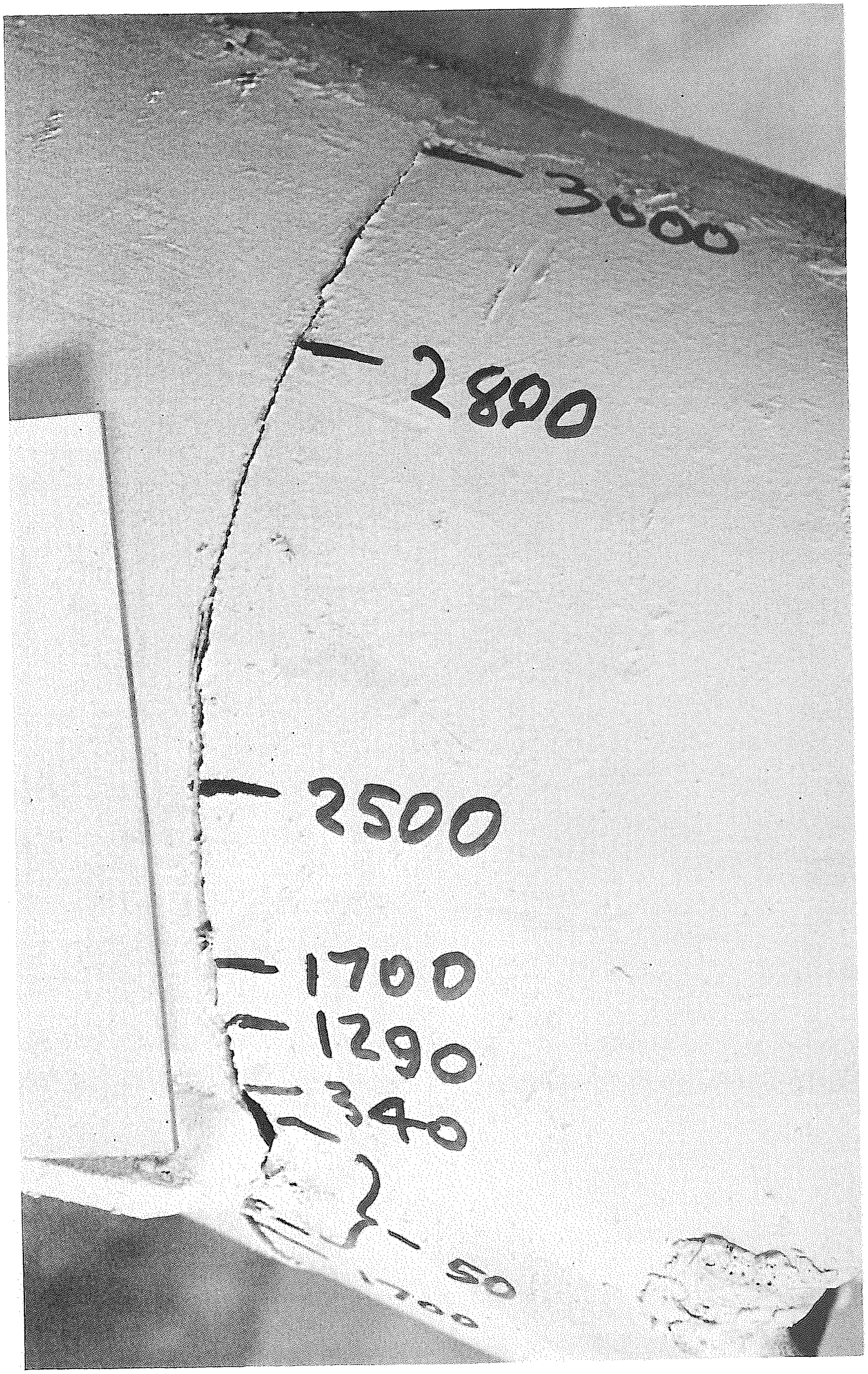


FIG. 29 JOINT TYPE 3 - SPECIMEN No. 3 (TAPERED GUSSET PLATE) DETAILED CRACK PROPAGATION IN DIAGONAL MEMBER

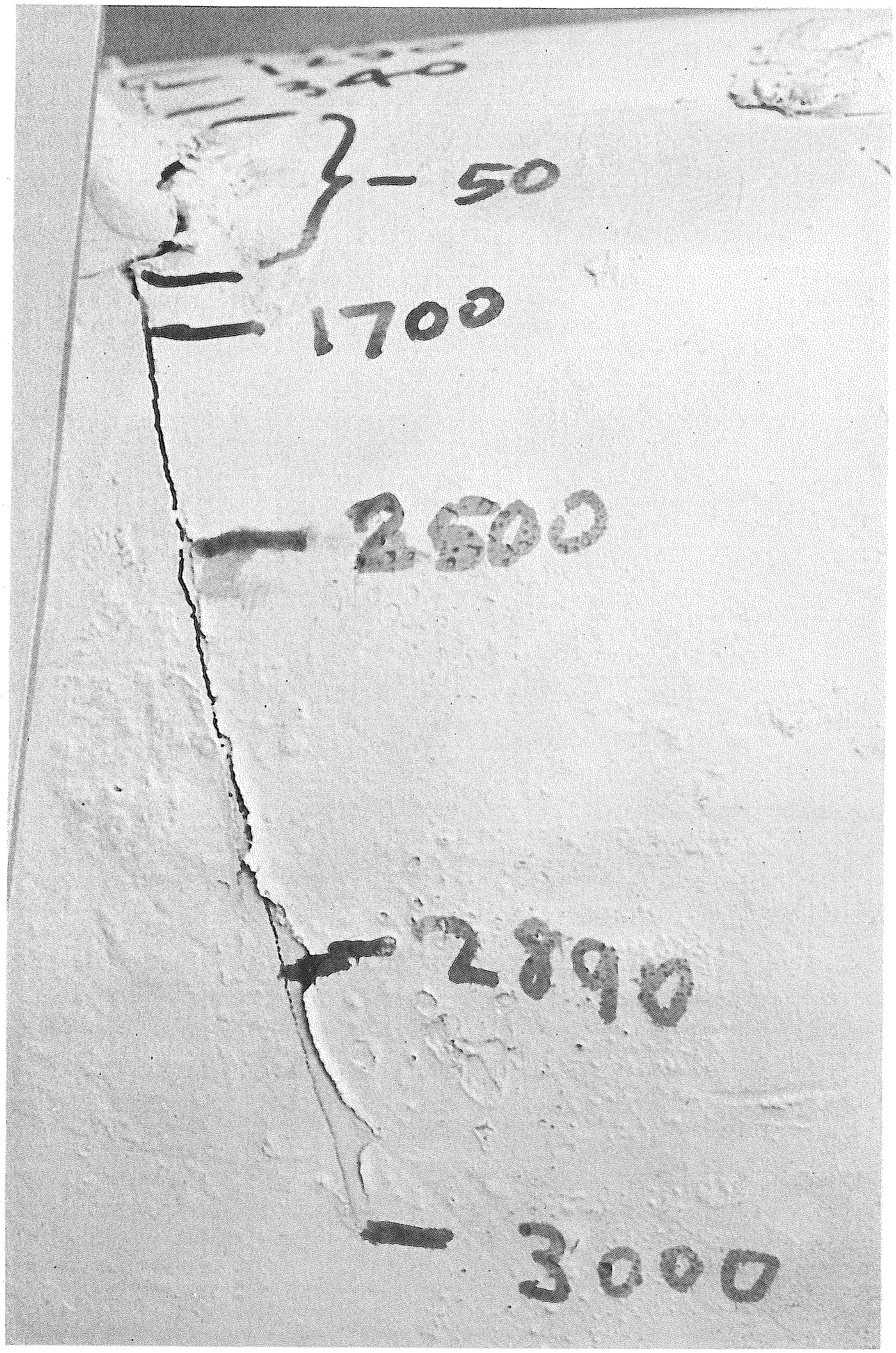
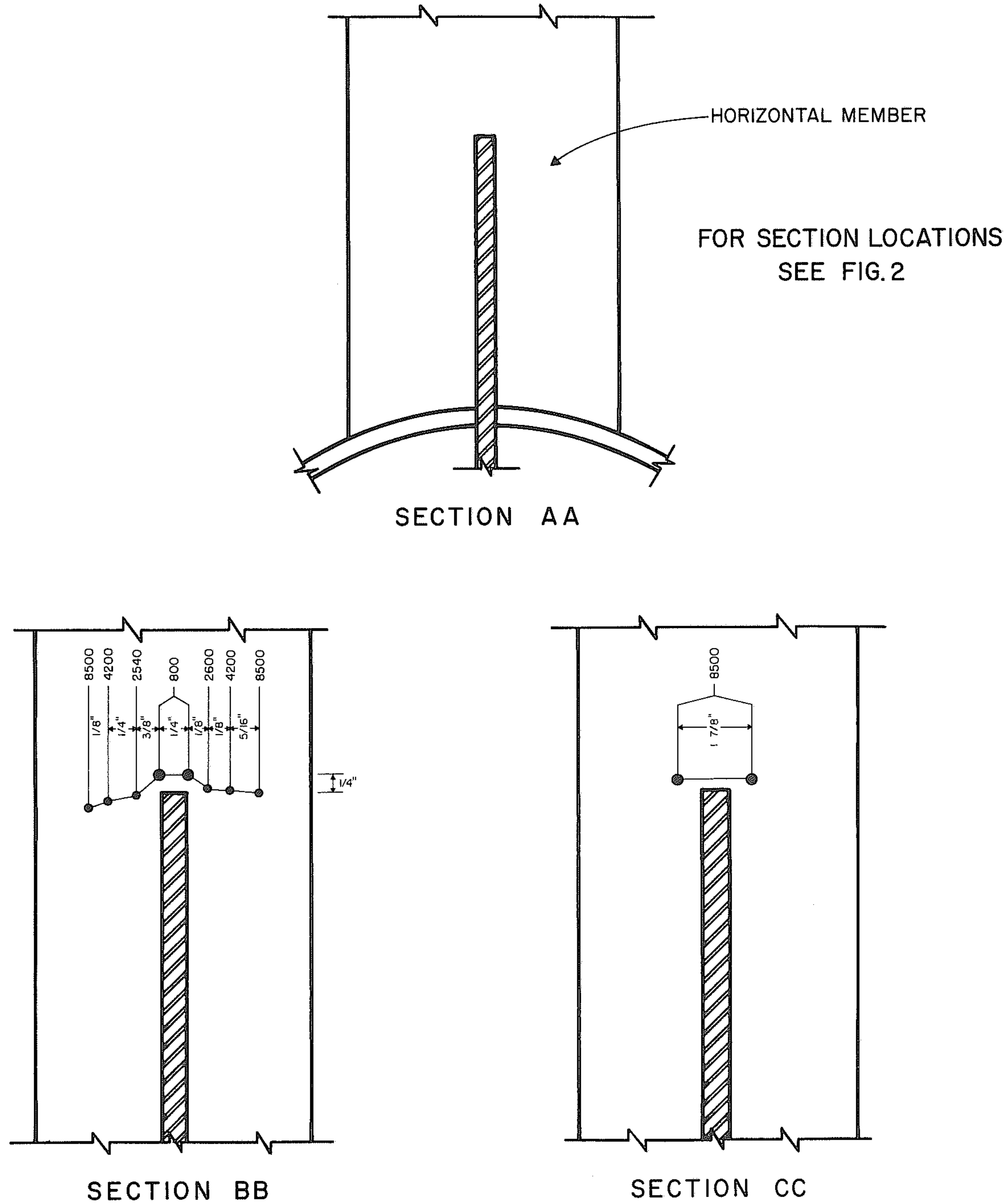


FIG. 30 JOINT TYPE 3 - SPECIMEN No. 3 (TAPERED GUSSET PLATE) DETAILED CRACK PROPAGATION IN DIAGONAL MEMBER



● INDICATES POINTS OF CRACK PROGRESSION (NOT TO SCALE)

FIG. 31 CRACK PROPAGATION IN TYPE 3 JOINT
SPECIMEN Nº 4 LOADED AT ± 40 K IN HORIZONTAL MEMBER
(TAPERED GUSSET PLATE)

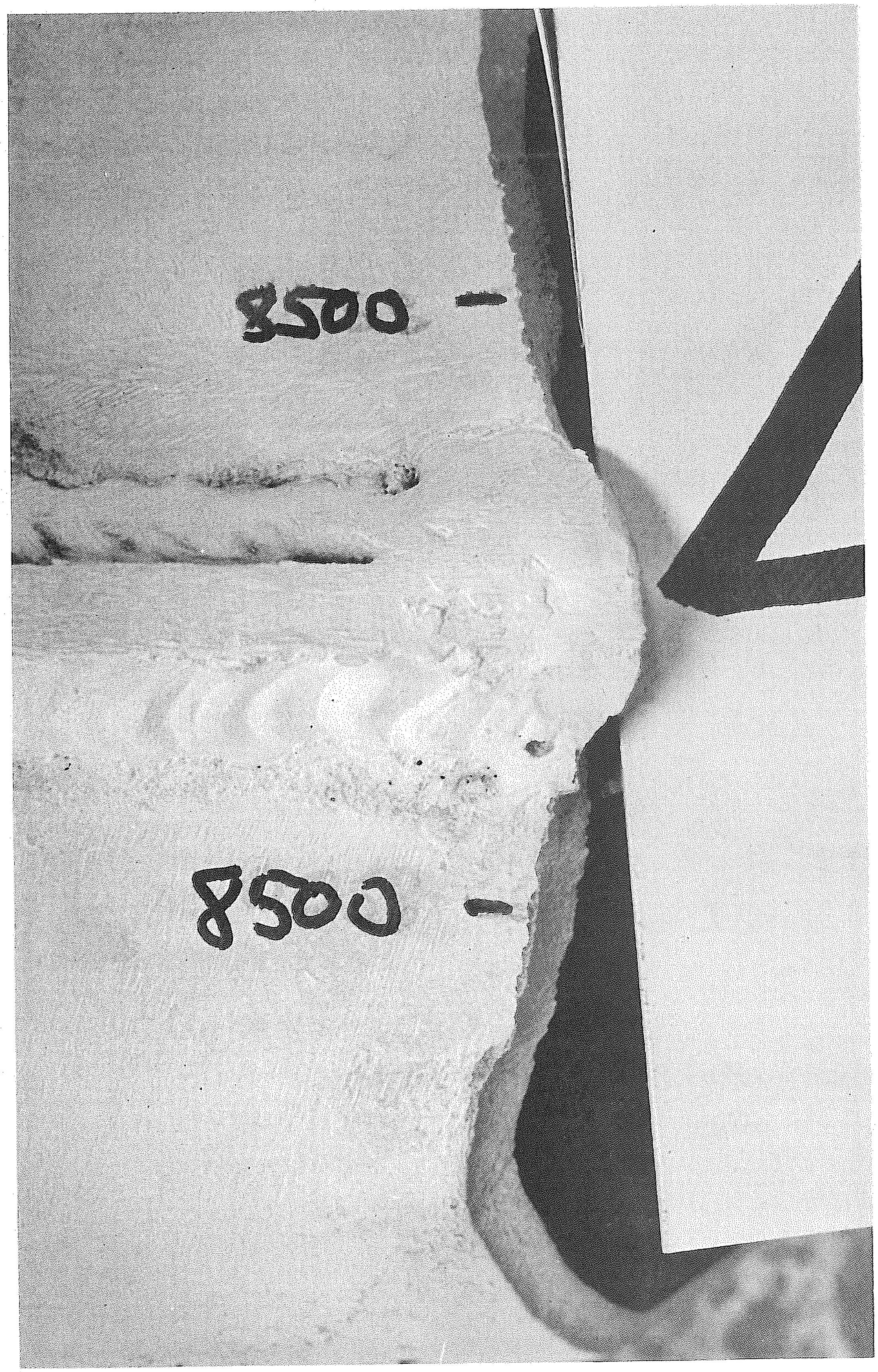


FIG. 32 JOINT TYPE 3 - SPECIMEN No. 4 (TAPERED GUSSET PLATE)
DETAILED CRACK PROPAGATION AND FAILURE MODE
OF DIAGONAL MEMBER

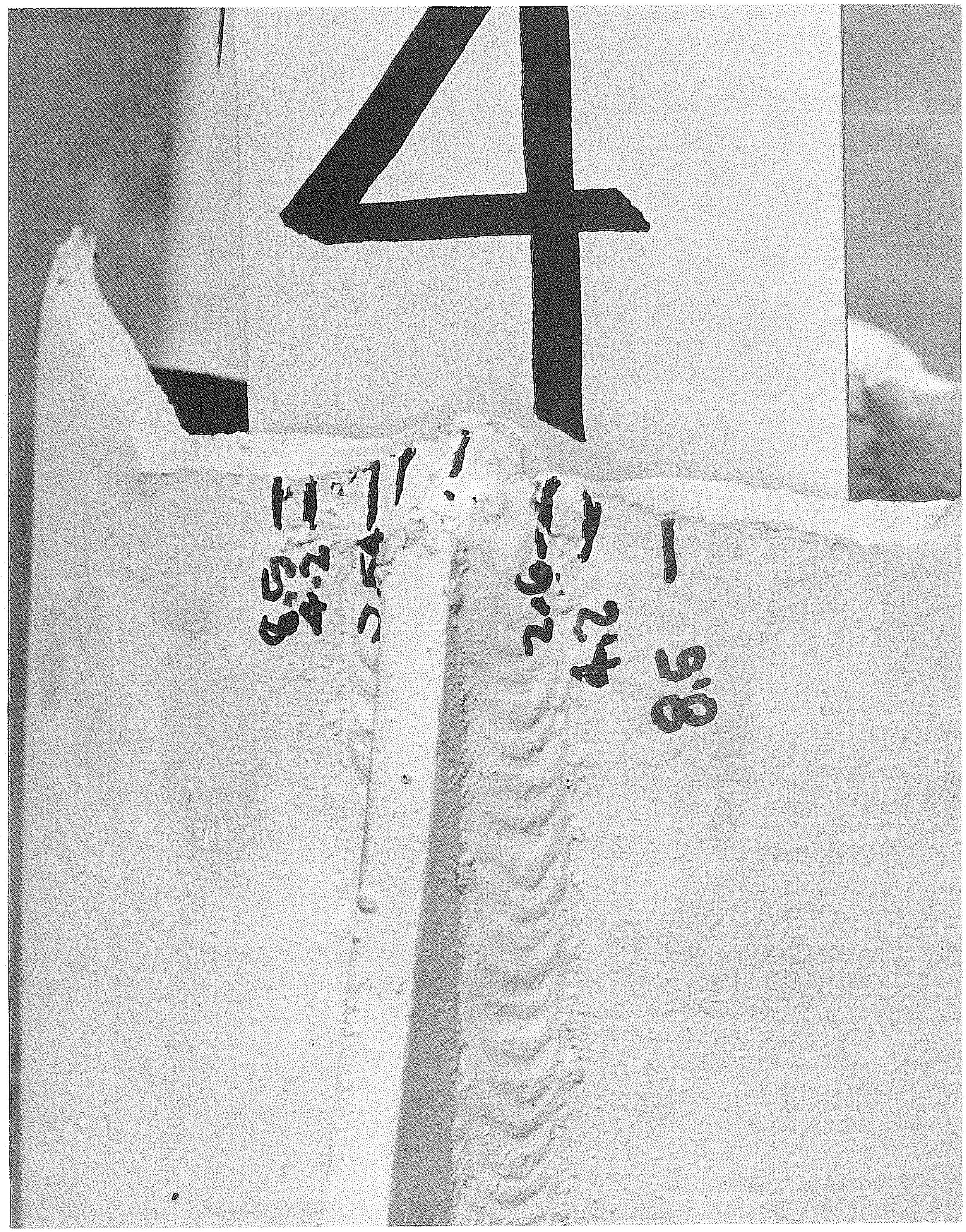
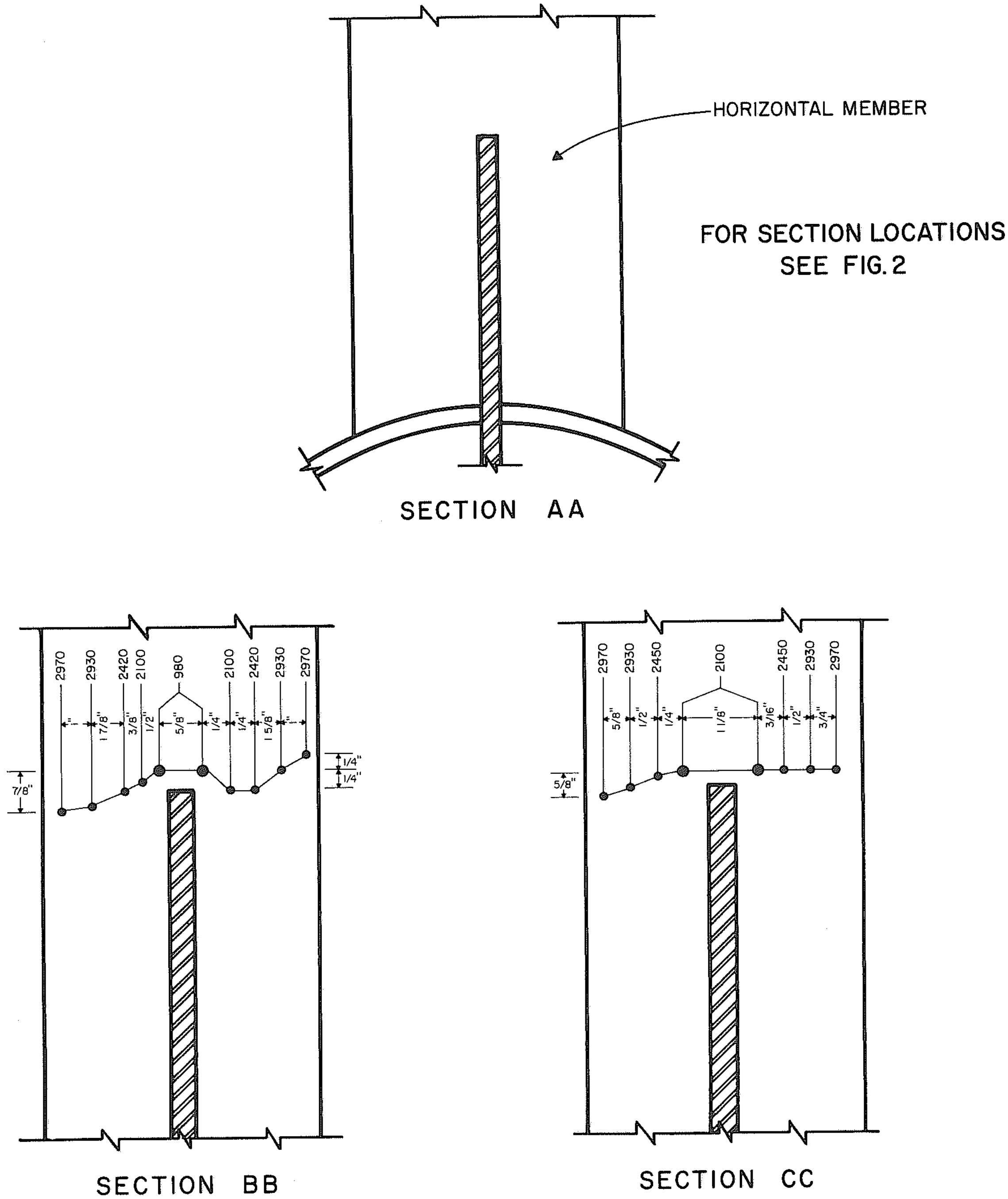


FIG. 33 JOINT TYPE 3 - SPECIMEN No. 4 (TAPERED GUSSET PLATE) DETAILED CRACK PROPAGATION AND FAILURE MODE OF DIAGONAL MEMBER



● INDICATES POINTS OF CRACK PROGRESSION (NOT TO SCALE)

FIG. 34 CRACK PROPAGATION IN TYPE 3 JOINT
SPECIMEN Nº 5 LOADED AT ± 50 K IN HORIZONTAL MEMBER
(SCALLOPED GUSSET PLATE)

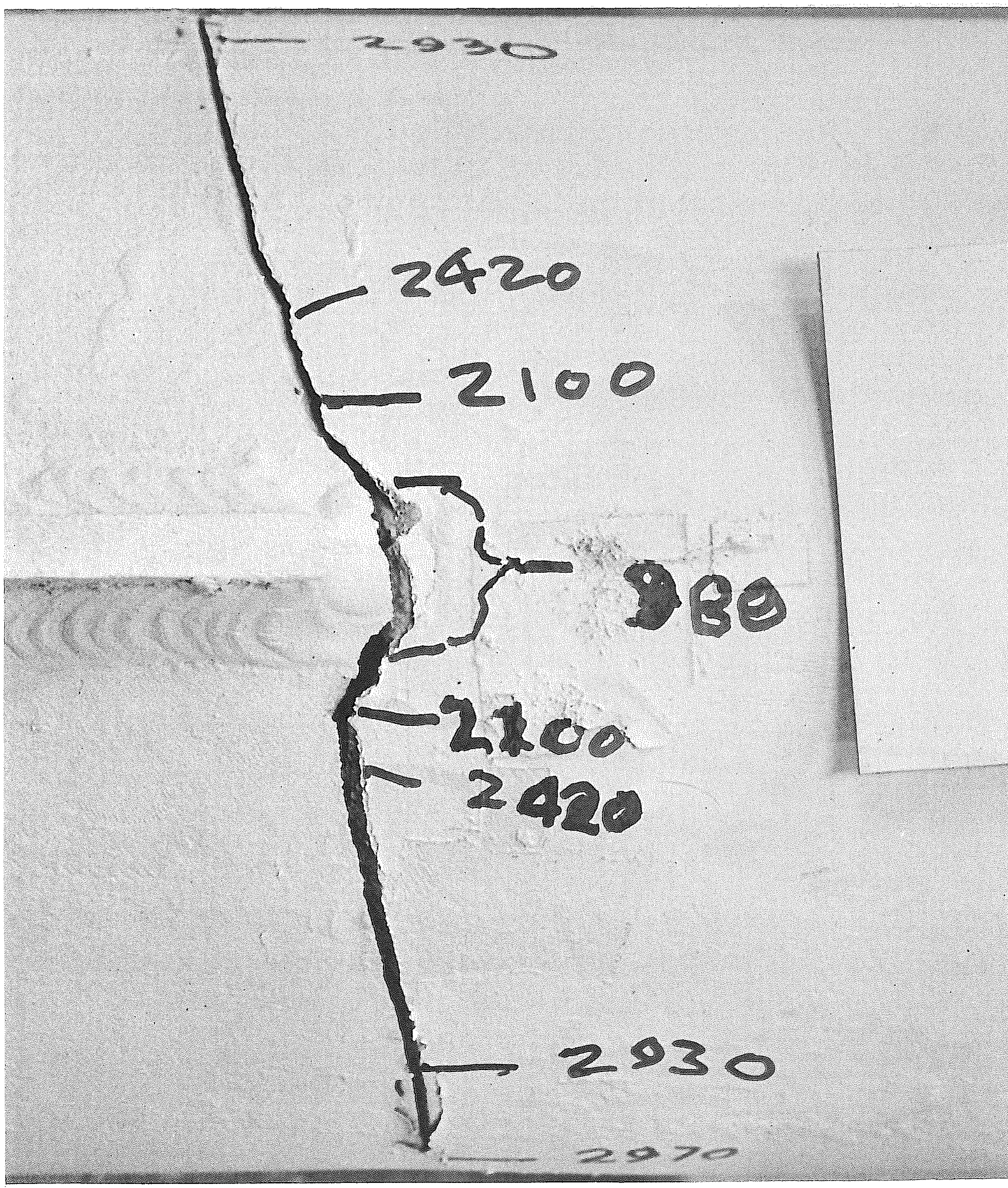


FIG. 35 JOINT TYPE 3 - SPECIMEN No. 5 (SCALLOPED GUSSET PLATE) DETAILED CRACK PROPAGATION IN DIAGONAL MEMBER

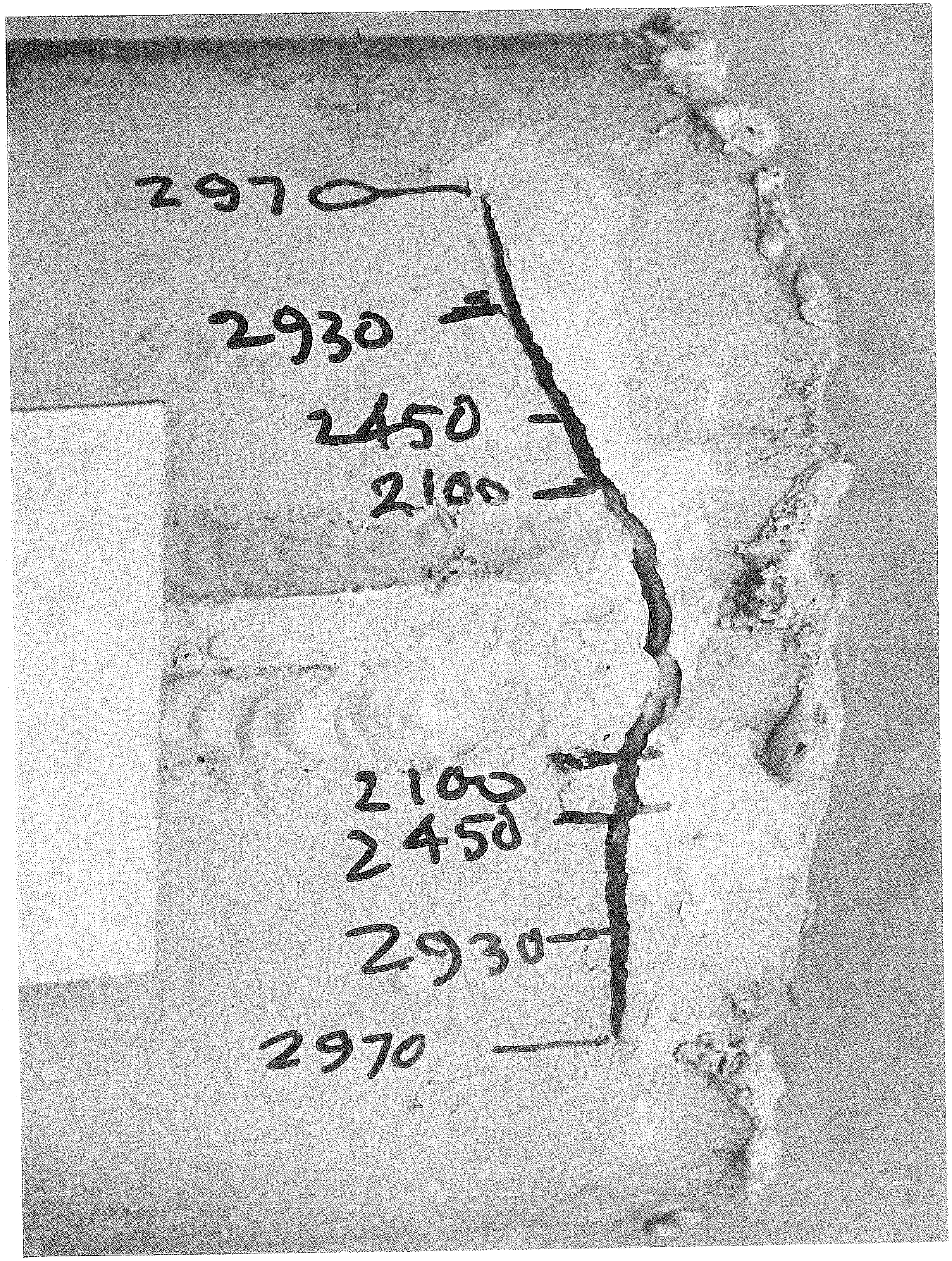
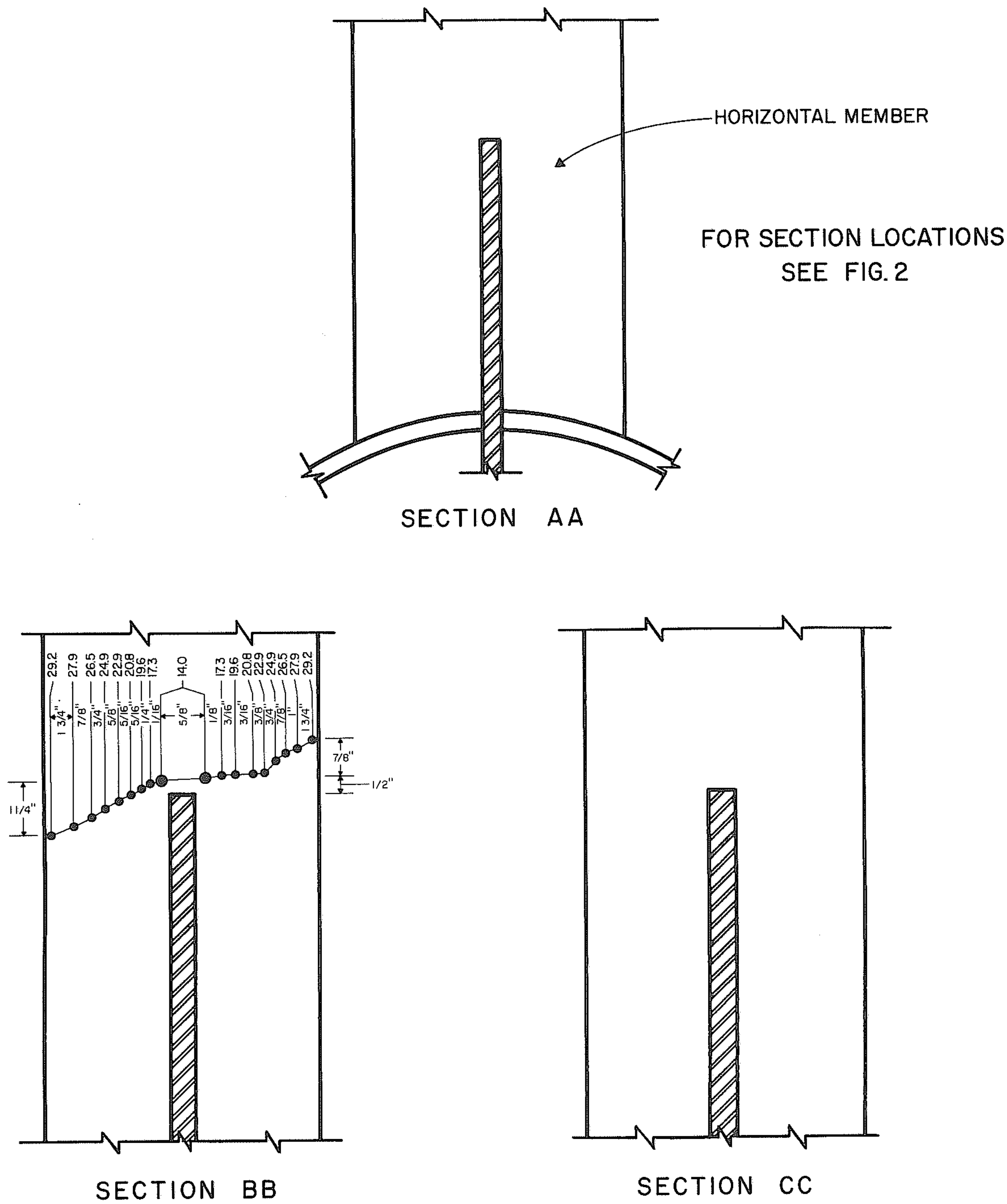


FIG. 36 JOINT TYPE 3 – SPECIMEN No. 5 (SCALLOPED GUSSET PLATE) DETAILED CRACK PROPAGATION IN DIAGONAL MEMBER



● INDICATES POINTS OF CRACK PROGRESSION IN 1000 CYCLES

(NOT TO SCALE)

FIG. 37 CRACK PROPAGATION IN TYPE 3 JOINT
SPECIMEN N° 6 LOADED AT ± 30 K IN HORIZONTAL MEMBER
(TAPERED GUSSET PLATE)

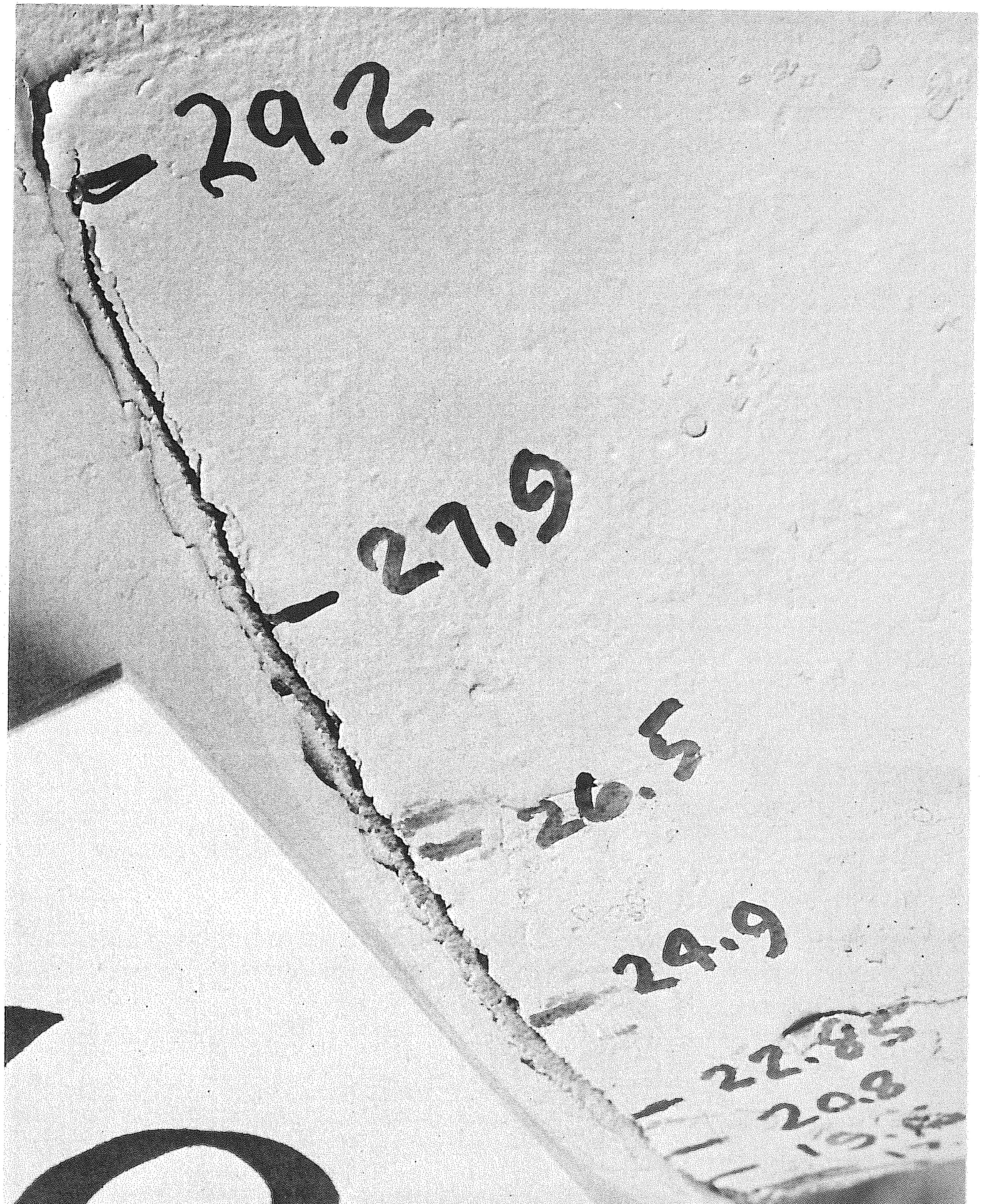


FIG. 38 JOINT TYPE 3 - SPECIMEN No. 6 (TAPERED GUSSET PLATE) DETAILED CRACK PROPAGATION IN DIAGONAL MEMBER

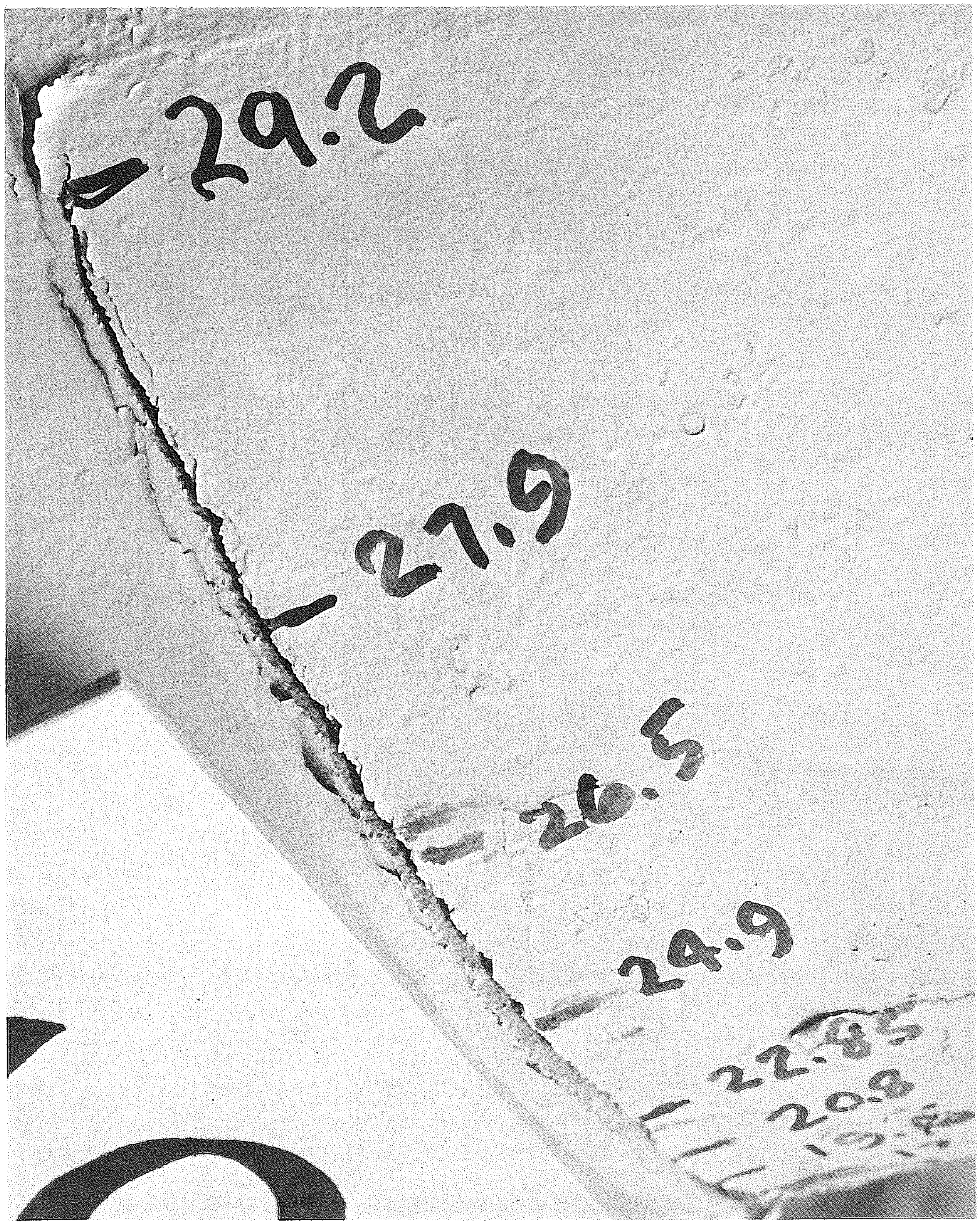


FIG. 38 JOINT TYPE 3 - SPECIMEN No. 6 (TAPERED GUSSET PLATE) DETAILED CRACK PROPAGATION IN DIAGONAL MEMBER

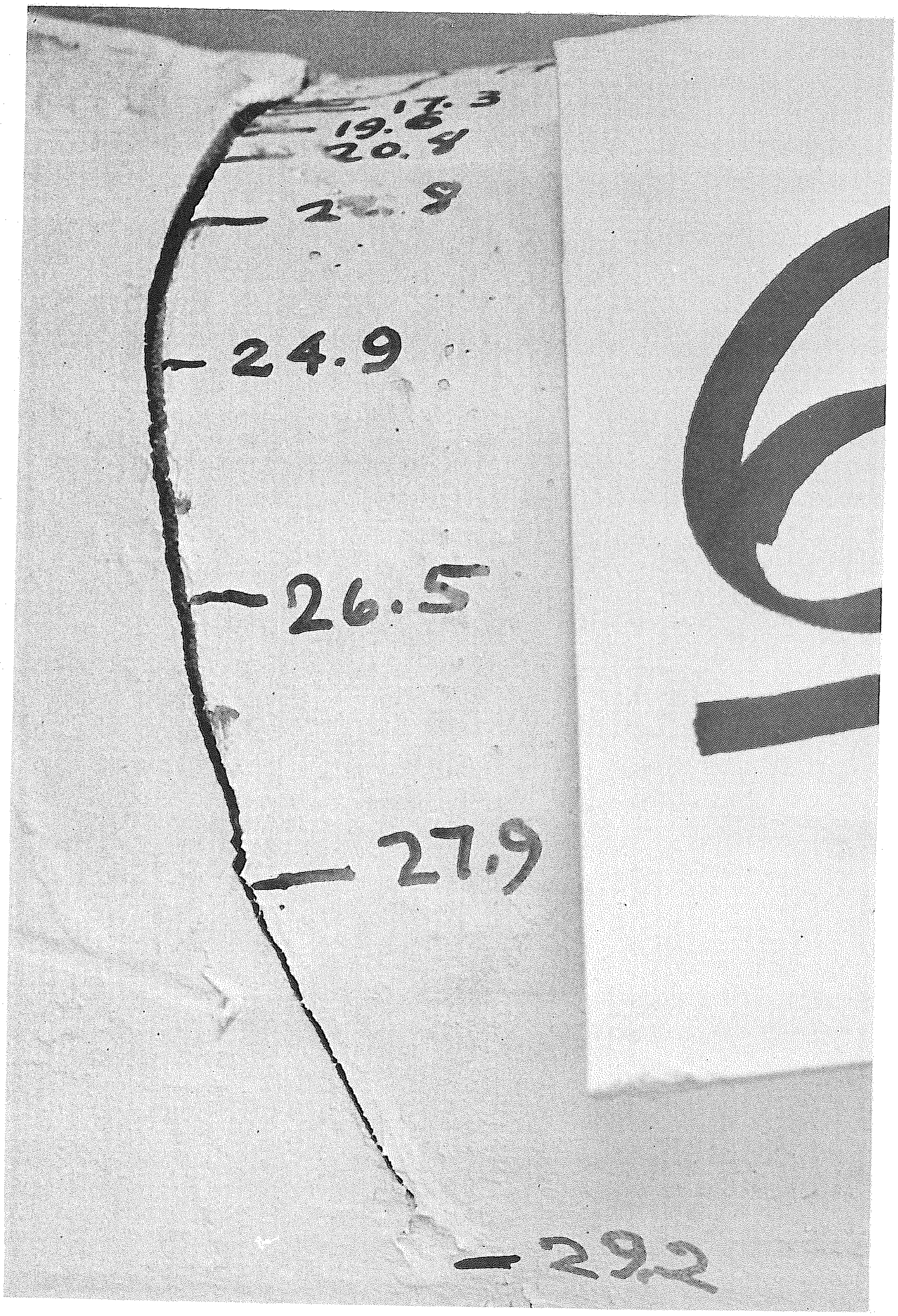


FIG. 39 JOINT TYPE 3 - SPECIMEN No. 6 (TAPERED GUSSET PLATE) DETAILED CRACK PROPAGATION IN DIAGONAL MEMBER

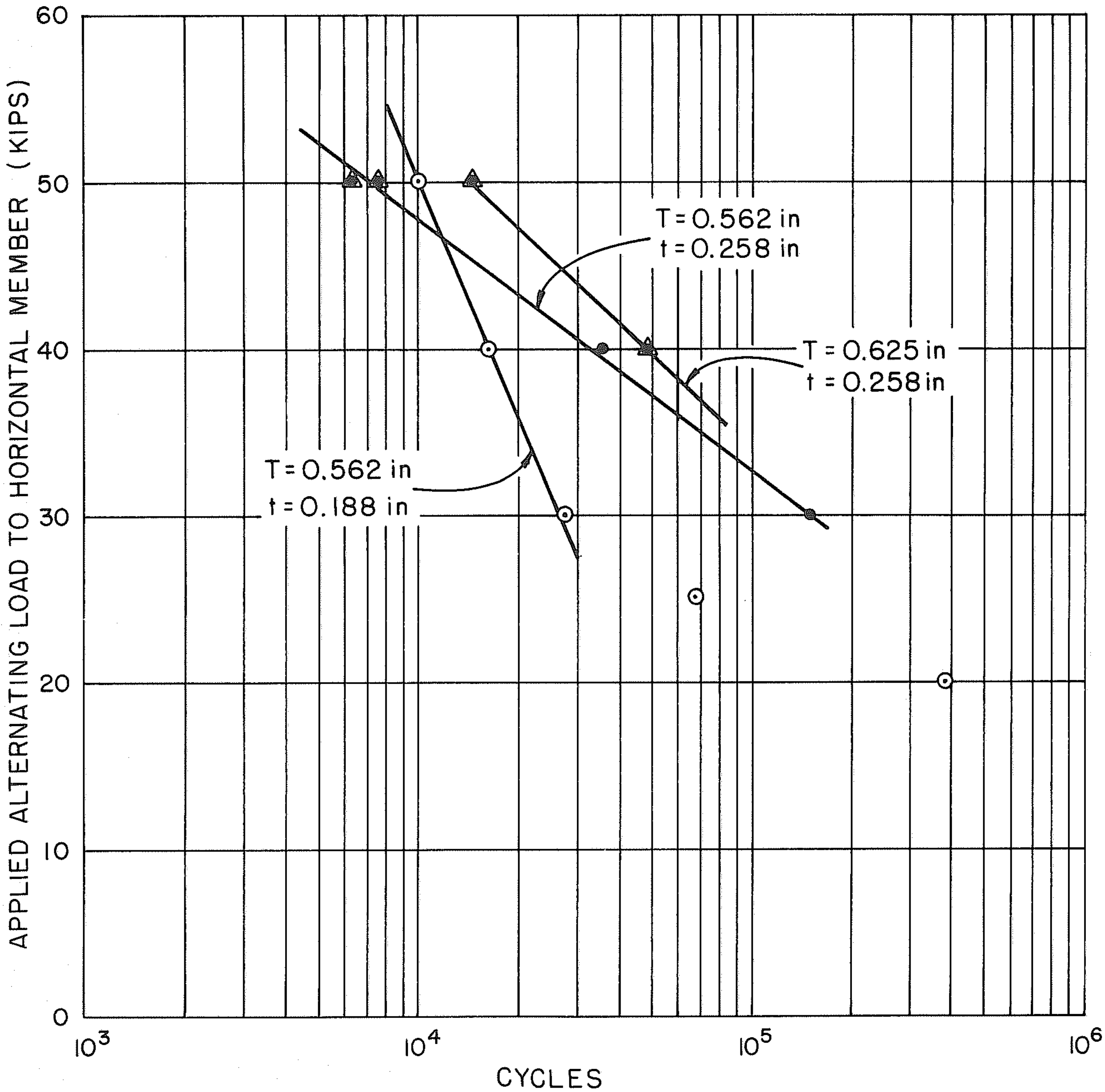
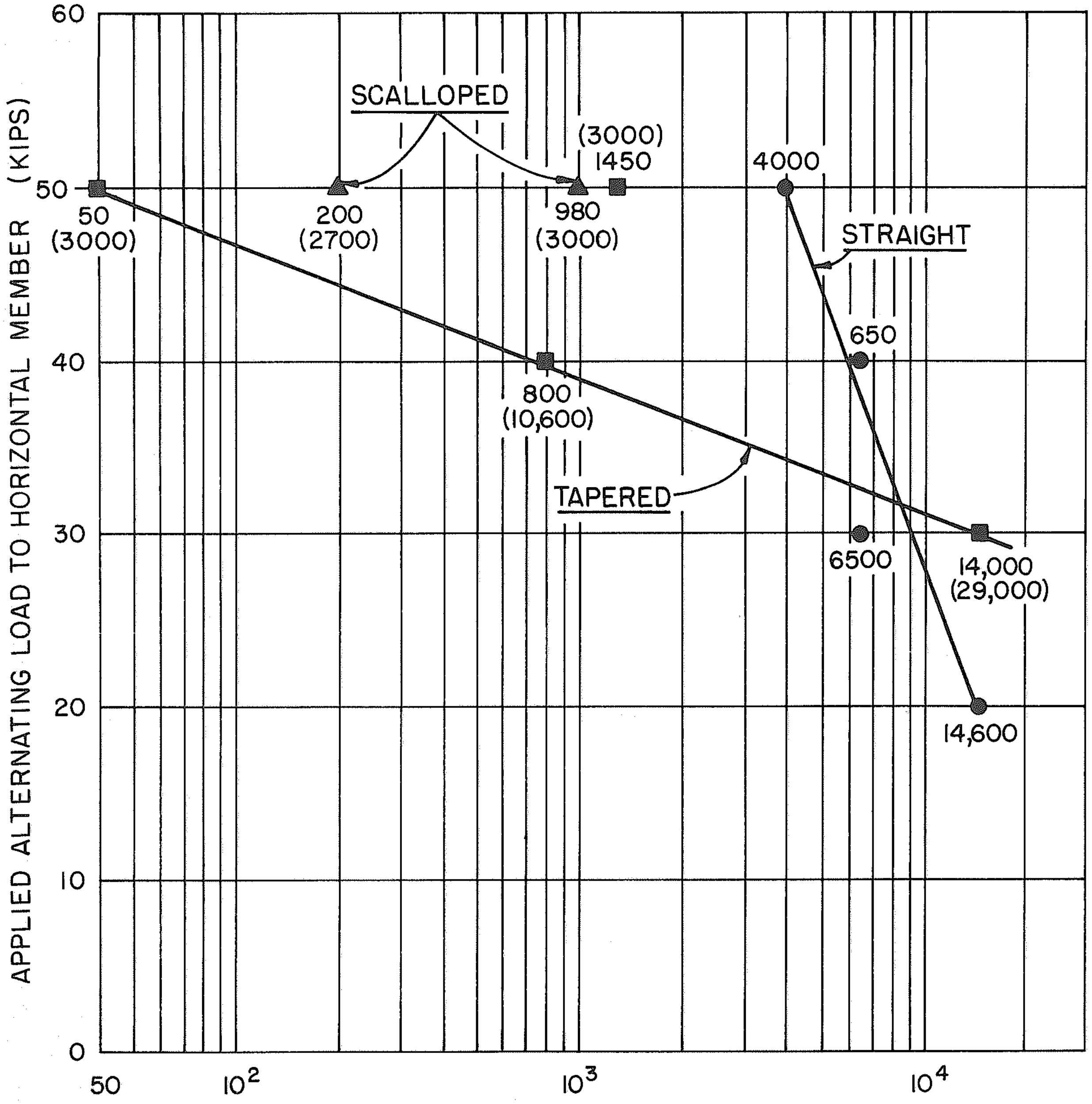


FIG. 40 ALTERNATING LOAD LIFE OF TYPE I TUBULAR CONNECTIONS



( ) INDICATE VALUES AT TERMINATION OF TEST

FIG. 41 ALTERNATING LOAD LIFE OF TYPE 3 TUBULAR CONNECTIONS