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Author

Bouwkamp, Jack

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BEHAVIOR OF TUBULAR TRUSS JOINTS UNDER STATIC LOADS

BY
J. G. BOUWKAMP

Report to the Sponsors: American Iron and Steel Institute,
New York.

JULY, 1965

COLLEGE OF ENGINEERING
OFFICE OF RESEARCH SERVICES
UNIVERSITY OF CALIFORNIA
BERKELEY CALIFORNIA

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

BEHAVIOR OF TUBULAR TRUSS JOINTS
UNDER STATIC LOADS

A Report of an Investigation

by

J. G. Bouwkamp
Associate Professor of Civil Engineering

to

American Iron and Steel Institute
New York, N.Y.

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

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I. INTRODUCTION

I-1. General

The circular tube has long been recognized as an ideal structural element to carry concentric compressive loads. Therefore, the use of tubular members for columns developed rapidly when circular structural sections became available. However, the application of tubes for truss-construction developed only after welding became an accepted method of joining structural elements.

The first applications showed a welding of the tube members to a gusset plate, thus imitating the practices used with standard rolled sections. Gradually, however, new fabrication methods allowed the design of directly inter-welded tubular sections. The major contribution was undoubtedly the development of a fully automatic oxyacetylene tube-cutting machine for cutting circular tubes to fit flat as well as cylindrical surfaces (tubes). The great potential of these machines is first of all the reduction of the preparation cost of the joints. A simple three-lever operating system controls the three variables describing the cut, namely: the inner diameter of the branch tube to be cut, the outer diameter of the tube to which the branch tube is to be welded, and the angle between the axes of these tubes. This operating system governs the mathematically exact cutting curve as well as the required bevel at any point along this cut. A simultaneous rotation of the concentrically clamped tube and a combined longitudinal and angular movement of the cutting torch result in a perfectly clean cut, which does not need any further manual adjustment.

It is obvious that the better fit between the fully automatically cut tubes leads to further savings in fabrication cost as compared with the

cost of joining tubes cut manually. Operational studies have shown that the welding of the sections cut automatically resulted in a 30% reduction of welding time and electrodes.

The considerations necessary for an effective design of a joint build up from tubular sections are quite different from those governing the design of a connection of standard rolled sections. The major difference between the tubular section, as compared with a standard rolled section, is the radial flexibility of the tube. This flexibility will greatly influence the response of the joint as effected by the member forces and the introduced restraining effects due to the inter-welding of the members.

In order to achieve an effective load distribution and, consequently, the lowest weld stresses, the first design objective is to obtain the longest possible weld between the connecting members. The second objective is to design for the best local stress distribution in the welds. These objectives can be achieved by laying out the welds radially over the greatest possible wall surface. The effect of the load transfer between directly connected tubular members depends largely on the relative dimensions of the members. Therefore, the ratio d/D , between the outside diameters d of the web member and D of the chord member, and the ratio t/D , between the wall thickness t and outside diameter D of the chord tube, are extremely important. The ultimate response is further effected by the relative arrangement of the two web members in the joint, and the subsequent interwelding of these branch members.

I-2. Objectives and Scope

The general objective of the reported program of research was to provide preliminary information for an effective design of directly inter-welded two-dimensional truss joints built of circular tubes. Therefore a number of specially designed joints were tested under static loads in order to determine the elastic and ultimate load response of those connections and to investigate the effect of the in-plane eccentricity and resulting inter-welding of the tubular web members. Also the effect of the outside diameter ratio, d/D , of the web and chord members on the ultimate load capacity of a tubular joint and the effect of the wall thickness to diameter ratio, t/D , of the chord member tube were studied. In order to investigate the influence of these effects on the yield and ultimate load of fully welded tubular connections, a total of thirteen joint specimens were included in this program.

For the evaluation of the effects of the joint eccentricity, resulting in an over lapping of the branch member tubes, and the ratio d/D of the O.D. diameters of web and chord tubes, a total of nine specimens were tested. These joints had a chord tube with an O.D. of 6.625 in. and web member tubes of approximately 2 inches, 3 inches and 4 inches respectively, thus resulting in " d/D ratios" of approximately 0.33, 0.50 and 0.67 respectively. The joint-eccentricity was investigated in three steps, e.g., $e = + 0.25D$, 0, and $-0.25D$. The selection of the specific "diameter ratios" was based on the common practice in tubular design. A ratio of 0.33 can be considered a minimum. The value of 0.67 is a reasonable upper limit, since in practice

very few trusses do have branch members with a diameter d larger than $0.67 D$. (D = diameter of chord number).

While the nine specimens of the main group all had a medium t/D ratio for the chord member, two additional series of two specimens each, were tested to evaluate the effect of the wall thickness to outer-diameter ratio of the chord member tubes. Therefore, an extreme t/D value was chosen for each group. The other dimensions were kept unchanged in order to make a direct comparison with the specific results of the first series of nine specimens. In order to evaluate this t/D effect in this initial phase only joint specimens with a zero joint eccentricity were tested. All specimens were observed under a static load only, with an additional, step-wise increasing, compressive load in the chord tube.

I-3. Acknowledgement

The work reported herein was conducted in the Structural Engineering Materials Laboratory, Division of Structural Engineering and Structural Mechanics, Department of Civil Engineering, University of California, Berkeley. The program was sponsored by the American Iron and Steel Institute, New York, through a research grant administered by the Office of Research Services, College of Engineering, University of California.

The Engineering Project Subcommittee of the American Iron and Steel Institute Committee on Building Research and Technology, chaired by Mr. F. E. Falhy, gave valuable advise and approved the final program of research. Mr. John V. Schwafel, Resident Engineer of the AISI Engineering

Division in San Francisco acted as local liaison between the American Iron and Steel Institute and the investigator.

The pre-cut pipes for the fabrication of the joint specimens were donated by the United States Steel Corporation, Pittsburgh, Pennsylvania.

A number of persons made significant contributions to the work described in this report, and the author wishes to thank them all. Particularly the contributions by Messrs. C. K. Sun, and J. Okita, Graduate Students, and Messrs. J. R. Chisholm, R. P. Engelhard and P. F. Pfaelzer, undergraduate students, is gratefully acknowledged.

II. PROGRAM OBJECTIVES

The investigation was directed towards the evaluation of the influence of the three major structural variables in the design of joints built from circular tubes or pipes. These variables are:

- a. The ratio between the outer diameter $\underline{d}$ of the web members and the outer diameter $\underline{D}$ of the chord members.
- b. The ratio between the wall thickness t and outer diameter $\underline{D}$ of the chord member
- c. The length of weld between the branch members at the joint. This quantity is often expressed in relative terms as the joint-eccentricity, being the distance between the point of intersection of the web-member system lines and the centerline of the chord tube.

Figure 1 shows the basic parameters and the type of joints investigated in this program.

From an observation of the different joints as presented in Figure 1 it becomes obvious that for the same arrangement of the joint system lines the joint strength will reduce when the d/D ratio diminishes. In such an instance the load application on the chord tube wall will be more severe due to the tension in the diagonal and the compression in the vertical web member. This will become particularly critical when the web members are not interwelded. In that instance the entire transfer of the web member forces will take place through the chord member wall. In case of a joint with substantially interwelded web members - see joint (c) in Figure 1 - the major

portion of the web member forces are transferred directly through the weld between the two branch or web members. It is therefore quite obvious that a lack of intersection (and subsequent interwelding) between the web members will reduce in general the ultimate strength of a tubular joint.

Finally it can be noted that a reduction of the wall thickness of the chord will reduce the joint strength. This will be particularly evident when the web member forces are acting on the chord member without any interwelding between the web member tubes.

To develop an initial program to determine the relative effect of these parameters a limited number of specimens were to be designed and tested. Because a study of the influence of these three parameters, when tested in at least three steps would have lead to an excessive number of twenty seven specimens a reduced program was developed and resulted in a total of thirteen specimens.

III. PROGRAM - DESIGN

Due to the availability of a previously designed special loading frame the joints in this program were designed with a 45 degree diagonal and a 90 degree vertical branch member. Since it was decided originally to use in this study a self-contained loading unit using a hydraulic load cylinder with a capacity of 200 kip the variation of the tube sizes for the joint specimens was limited. Figure 2 shows the basic loading scheme for a specimen mounted, in the test frame.

In order to investigate the influence of the three parameters (d/D , t/D , and the "joint eccentricity") on the ultimate static strength of the joint a series of $3 \times 3 \times 3 = 27$ specimens should have been desirable. However, this was considered impractical and unnecessary both from an economical as well as an engineering point of view. Therefore two series were designed. Series I consisted of nine specimens and was designed to investigate the influence of the diameter ratio d/D and the joint eccentricity. Series II consisted of six specimens and was developed to investigate the influence of the chord-member geometry (t/D -ratio). Figure 3 and 4 show the specimens for both series. The specimens joint-type 4 and 6 with a medium chord-wall thickness were tested only once. Hence the total number of specimens tested was thirteen.

Both Figures 3 and 4 also give the selected member sizes. Critical in the selection of these web-member sizes was the anticipated maximum failure load of 222k for the diagonal member with an O.D. of 4-1/2 in. and a wall

thickness of 0.237 in. (seamless pipe, ASTM Specification A53, Grade B). This failure load would correspond with a load of 157k applied to the vertical web member: Although it was realized that a joint with a heavier web member (O.D. = 4-1/2 in., $t = 0.337$ in.) could be failed in this frame, the member with a wall thickness $t = 0.237$ in. was nevertheless selected. The reason for this selection was based on the opinion that, in a design, an engineer should rather select a larger size member with a relatively thin wall than a smaller size member with a heavy wall. The selection of a member with a larger diameter d , resulting in an increased d/D value, would always result in an improved load distribution in the joint. Hence the web member with a wall thickness of 0.237 in. was selected as the largest section which, considering the O.D. value of 4-1/2 in., was structurally still practical.

The reason for selecting a heavier wall for the vertical web members as compared to the diagonal members was based on the requirement that buckling of the vertical branch member should be prevented. Hence the 4-1/2 in. O.D. vertical web members for joint-types 3, 6 and 9 were selected as 0.438 in. In that case, at the maximum anticipated failure load, which was based on an ultimate stress of 70 ksi, the stress in the vertical members would only be 28 ksi.

The required maximum practical value for the d/D ratio is approximately 0.67 and dictated an O.D. for the chord tube of 6-5/8 in. Considering the intended smaller d/D ratios of approximately 0.33 and 0.50

a selection of the diameters of 2-1/2 in. and 3-1/2 in. respectively for the web members became automatic.

The selection of the minimum, medium and maximum wall thicknesses for the chord members and the associated t/D values, was effected by the limited availability of tube sizes and the fact that a thick-walled, small-diameter member is structurally less appropriate as a compression member than a tube with a larger diameter and a smaller wall thickness. Hence the minimum available wall thickness of 0.280 in. for a 6-5/8 in. O.D. member was selected as the lower limit. The next two larger thicknesses of 0.432 in. and 0.562 in. were subsequently selected for the medium and maximum wall thicknesses.

Since it was considered practically feasible to incorporate joint-eccentricities of + and - 0.25 D in the design of tubular connections, these specific values were selected for the test specimens. The positive-eccentricity joint would be selected if the designer, in order to reduce the fabrication cost decided to omit any inter-welding between incoming web members. For a joint with a negative eccentricity of - 0.25 D the fabrication cost will be higher. However at the same time the resulting inter-welding of the web members will in general raise the joint strength most effectively.

Figure 5 shows the detailed design of a typical joint specimen. All test specimens were designed to fit the special loading frame. Commercial seamless pipe, ASTM Specification A53, Grade B, a readily available product, was used for all joints.

The following specifications were issued to the fabricator:

- 1) Pipe shall be electric weld or seamless, manufactured in accordance with ASTM-A53, Grade B or API 5-L Grade B for basic OH Steel. Sworn mill test reports are required.
- 2) Steel plate and structural shape material shall be in accordance with ASTM Specification A-36 for plate and structural shapes, except as indicated. For pin-hole plate of diagonal member material shall be ASTM A441.
- 3) Cutting shall be accurate and smooth--if possible on automatic tube cutting and beveling machine. For details of beveling see sketch attached (Figure 6). Bevels may be machine cut or torch cut. Slag and cutting dross shall be removed before fitting.
- 4) Every weld shall have full thickness penetration throughout. Excessive accumulation of slag and welding dross on the inside surface of weld shall be removed.
- 5) Small tack welds, penetrating to the bottom of the groove, shall be used in fitting up. If free from cracks, they may become a part of the finished weld. Finished welds shall be free from cracks.
- 6) Workmanship and procedure to be in accordance with AWS Specification D2.0-63 for Welded Highway and Railway Bridges. Welding electrodes shall be manufactured in accordance with the requirements of the most recent edition of ASTM Specification A-233. The electrodes used and the welding voltage -- shall be recorded and the information submitted along with the finished specimens.

- 7) Qualification of welding procedures and operators is required according to the AWS Specification cited above. All connections between the tubes of the joint specimens as well as the test specimens shall be made by the same operator.
- 8) Sequence of welding for supports:
 - a) Weld tube to plate
 - b) Weld angle stiffeners to tube
 - c) Weld plate to stiffeners
- 9) Specimens shall be cleaned by fabricator after fabrication, but are not to be painted. The area near the joint shall be sandblasted over a distance along each connected member equal to two times the diameter of each member measured from the joint welds.

When delivery of the specimens took place it was noticed that the specimens were severely over-welded, with weld sizes of 2 to 4 times those specified. Since the originally specified weld sizes, as was learned from earlier tests, could be regarded as adequate it was felt that the over-welding would not increase the strength of these connections severely under static loading. However, the stiffness of the joints was severely influenced by the excessive welding and would undoubtedly effect the test results. It was felt that removal of the excess material would adjust this deficiency without effecting the ultimate static strength of these joints. Following a consultation with Messrs. T. V. Schwafel, AISI, San Francisco, and R. R. Graham, Jr., U.S.S., Pittsburgh, the fabricator was informed that these specimens were unacceptable and that the welds were to be gouged and finished to size by grinding. After this work was performed successfully the specimens were accepted.

IV. INSTRUMENTATION

The instrumentation for all thirteen specimens was designed in order to provide information about the critical stress in the joint under the influence of the static loads. A large number of electric resistance wire strain gages were placed in critical locations as close as possible to the welds. The gage length of all gages was 5/16 in. To determine the state of stress only cross and rosette gages were used.

Figure 7 shows the gaging scheme for all types of specimens. In general it can be noted that for joints without web-member intersections the gages were placed along the length of the diagonal member to investigate the relative load transfer through the weld between the diagonal and chord members. Also the chord member wall itself was instrumental substantially in that instance. For joints where the web members have a common intersection a large number of the instrumentation was placed in the critical area near the weld between the two web members. The instrumentation on the chord members wall in this case was substantially similar as compared to a joint with non-intersecting web members.

It should be noted from Figure 7 that some gages were placed in symmetrical positions on the near side and far side of the web members. These gages would provide comparative information regarding the load-symmetry.

In addition to the electric strain gage instrumentation, which was predominantly located on the near side of the joints, stress-coat was applied to the far side of each joint in order to obtain immediate information

about the stress-trajectory pattern. The latter results should provide particular information about the relative influence of the radial stiffness of the chord members on the ultimate response of the joint.

V. TEST PROCEDURE

V-1. Loading

As discussed in Chapter III the specimens were designed to fail under the action of a maximum load of 200 k applied to the vertical web member (see Figure 2). Such a load however is inadequate to represent the actual loading in a truss joint, where the chord member force would be subjected to an additional "overall" load. It was felt that such a loading should be included to assure a sufficiently representative test arrangement. The possibility of performing one or two pilot tests to establish the most severe load procedure for the chord tube was studied thoroughly. The load-selection, based on the results of those tests, would then be adopted for all specimens in this program.

Several different test procedures were considered, namely:

1. Investigation with no "overall" load in the chord tube.
2. Investigation with a constant compressive pre-load in the chord member.
3. Investigation with a constant tensile pre-load in the chord member.
4. Investigation with a step-wise increased compressive load in the chord member.
5. Investigation with a step-wise increased tensile load in the chord member.

After evaluating the anticipated influences of the several load possibilities, it was decided that all specimens could be tested with a step-wise increasing compressive load in the chord tube (case 4), thus eliminating the previously mentioned pilot tests. This decision was based on the following considerations:

- sub 1: The no-load condition in the chord tube is unrealistic and is therefore unacceptable.
- sub 2: The compressive pre-load, to be introduced by means of long H.S. steel bolts, passing through the heavy square plates at the bottom and at the free end of the chord member (see Figure 8) was considered unrealistic, since under increased truss-loading both the overall chord member stresses and the web member stresses should increase proportionally. Furthermore, the overall chord tube stress would not remain constant if only bolts were used, since the applied web member loads would be reacted by the total chord section, including the bolts, thus changing the bolt force and the pre-stressing load. This meant that the stress distribution in the wall of the chord tube of the test joint would differ from the state of stress in the prototype truss. Although this difference would be reduced by incorporating high-capacity, flexible box car springs (see Figure 8), it was felt that this loading was also technically undesirable.
- sub 3: For the same reasons as discussed under sub. 2, it was felt that the pre-tension load procedure should also be rejected.

Thus the remaining possibilities were a step-wise applied increasing compressive or tensile loading of the chord tube simultaneously with the application of an additional load to the web-members. The final selection of a step-wise compressive loading was based on the following considerations. First, it is obvious, that in the case of non-intersecting web members, the often thin wall of the chord tube between the web-members will be bent considerably (both longitudinally and radially). Since failure can be expected to develop in that area the stress conditions under compressive loads will be more critical than under tensile loads. These compressive loads will tend to increase the deformations in the chord wall. A tensile load however would reduce these deformations. Hence, for joints with non-intersecting web members, a compressive load is more critical than a tensile load. Furthermore, in the case of intersecting web members, the joint failure, in all probability, will not occur in the chord tube wall, but rather in the wall of the diagonal web member. In that instance it is again the compressive force which seemed to be more critical than the tensile load. The compressive load would in all probability introduce due to the radial restraint of the joint a compressive lateral strain in the web members in the direct vicinity of the joint area. This development, combined with the longitudinal tensile strains in the diagonal web member, as caused by the diagonal tension loading, would create a critical yield condition. However it should be noted that for joints with small web-member intersections, (joint types 3 and 5, and to a lesser degree joint type 7, see Figure 3) this yield condition, could be less severe than the

development of additional tensile stresses at the root of the inside corner of the intersecting web members when the chord member would be subjected to a tensile load.

Considering however the overall program it seemed that the step-wise compressive load would cause in general the most severe stress condition. It was therefore decided to use this loading for all specimens in order to maintain a general basis for comparison. The step wise increased load was applied by means of a 100 ton hydraulic jack acting against the free end of the column member. For practical reasons of mounting and testing the specimens, the joints were loaded with the chord member in a vertical position. Figure 9 shows the complete test scheme.

The loads in the two load cylinders were increased simultaneously. The magnitude of the step-wise increased loads was determined on the basis that, as a result of both cylinders, the nominal stresses in the vertical web member and the chord member should be identical.

Figure 10 lists for each specimen the maximum possible cylinder loads P_1 and P_2 , as well as the associated stresses. The load P_1 , applied against the vertical web member, introduces in each specimen a failure load in the 45 degree diagonal at an assumed nominal ultimate stress of 70 ksi. The stress in the chord members due to load P_1 is further increased by load P_2 , applied to the chord member, in order to create a combined stress in that member equal to the stress in the vertical due to load P_1 . In the tests the loads in both cylinders were increased step-wise

in proportion to the respective assumed maximum loads P_1 and P_2 .

In relation to the loading system it should be noted that, when under increasing loads the yield stress in the diagonal member would be reached, the joint would tend to deform due to the elongation of the diagonal member (see Figure 11a). The critical feature in this case would be the bending of the low-stressed 90-degree web member. These bending stresses would increase very rapidly under progressive yielding of the diagonal. Also the consequently introduced additional lateral force acting on the cylinder would be undesirable. It was therefore decided to introduce a correcting movement of the base of the chord member, as shown in Figure 11b. This movement was introduced by an auxiliary jack acting against the base plate of the chord member. By maintaining the vertical position of this member the joint deformation was restricted to a slight rotation of the diagonal. This additional rotation, occurring at the time that yielding in the member would be in full progress, was considered acceptable.

V-2. Recording

The strain gages were recorded at each load step. The magnitude of the load steps introduced by cylinder 1 were determined depending on the optimum loads as shown in Figure 10. The load introduced simultaneously by cylinder 2 was pro-rated on the basis of the optimum loads P_1 and P_2 for both cylinders. The strains were recorded on a Gilmore multi-channel strain gage recorder, which simultaneously printed and plotted these values

for each load step. The 96-channel recorder scanned step-wise the strains of all gages and plotted these values on separate charts. The 96 charts were printed on a graph-paper loop. The strain values in each diagram were identified by a specific channel number and were plotted against the appropriate load. Figures 12 shows the test set-up. The strain-recording equipment is shown on the left side of the same figure. It should be noted that the figure shows the first specimen to be tested. The test however was halted immediately, when joint deformations as shown in Figure 11a started to develop. To control these deformations, according to the scheme shown in Fig. 11b, the support condition for the chord member was changed to the system shown in Figure 9.

The stress-coat cracks developed during loading were observed and retraced to provide a general pattern of cracks to indicate the compression stress trajectories. The tensile stresses of course are acting normal to those cracks. The stress-coat was not used with the intent to provide quantitative information about the strain values. This information together with the stresses were obtained from the strain gage data.

VI. TEST RESULTS

VI-1. General

To discuss the results of these tests, the ultimate load and associated failure mode as well as the elastic stress distribution for a specific reference load will be presented for each joint.

The recorded load-strain plots were studied to determine the strain-load ratio in the elastic range. To obtain accurate information about this elastic behavior the specimens were unloaded and reloaded a couple of times during the testing process. To compare the elastic behavior of similar joints, the stresses in those joints were evaluated for the same reference load. This load was in terms of the force P_1 applied to the vertical web member. For specimens type 1, 2, 3 and 4, 5, 6 these reference loads were 30 k. and 50 k. respectively. The elastic stress distribution for specimens type 7, 8 and 9 was evaluated for a reference load of 70 k. applied to the vertical branch member. Simultaneously with this load P_1 a load P_2 was applied to the chord member. The loads in both cylinders were increased step-wise in a constant rate such that, for an expected nominal failure stress of 70 ksi in the tension diagonal, the maximum compressive stresses in chord and vertical members would practically be the same (28 ksi).

VI-2. Detailed Test Results

VI-2.1 JOINT TYPE 1. (see Figure 3)

This specimen had a positive eccentricity, with web members of 2-3/8 O.D. and a chord tube wall of 0.432 in. (O.D. of 6-5/8 in.). Failure

occurred as a crack in the wall of the tension tube above the weld in the 45° crotch between the chord-member and the diagonal as shown in Figure 13.

The failure load, applied to the vertical web member, was 71 k. in compression, which corresponds with a tension of 100 k. in the diagonal. The load applied to the chord tube by means of the 2nd load cylinder, was 154 k. at failure. The maximum load in the chord tube due to the two compressive cylinder forces was $154 + 71 = 225$ k., which corresponds with a nominal compressive stress of $225/8.4 = 26.8$ ksi. At failure, the nominal compressive stress in the vertical web member was $71/2.66 = 26.7$ ksi, and the nominal tensile stress in the diagonal was $100/1.48 = 67.6$ ksi.

The above results are tabulated in Table I.

Local yielding of the diagonal member started at a load of approximately -25 k. in the vertical branch member or approximately + 35 k. in the diagonal. Gage 33, located on the wall of the diagonal in the corner where later failure occurred - See Figure 14a - showed the earliest sign of yielding. Pronounced yielding in this gage occurred under a cylinder-load of -35 k., or a load of + 50 k. in the diagonal. Gages 41 and 45 located on the wall of the tension diagonal close near the weld showed also considerable strains. Overall yielding of the diagonal occurred under a load of + 64.5 k. in the diagonal. (cylinder load - 45 k.). This yield load was in excellent agreement with the yield load of 62.5 k. ($F_y = 42.2$ ksi) recorded in a pure tension test of a 2-3/8 in. O.D. pipe (wall thickness 0.218 in., length 4 ft). The failure load of this pipe was 96.2 k. ($F_{ult} =$

TABLE I. FAILURE LOADS AND STRESSES FOR SPECIMENS OF SERIES I

Joint-Type	1	2	3	4	5	6	7	8	9
Joint-eccentricity	Positive	Zero	Negative	Positive	Zero	Negative	Positive	Zero	Negative
O.D. web-member	2-3/8 in.	2-3/8 in.	2-3/8 in.	3-1/2 in.	3-1/2 in.	3-1/2 in.	4-1/2 in.	4-1/2 in.	4-1/2 in.
t diagonal member	0.218 in.	0.218 in.	0.218 in.	0.216 in.	0.216 in.	0.216 in.	0.237 in.	0.237 in.	0.237 in.
t chord-member*	0.432 in.	0.432 in.	0.432 in.	0.432 in.	0.432 in.	0.432 in.	0.432 in.	0.432 in.	0.432 in.
P ₁ - load in vertical at failure	-71 k.	-73 k.	-70 k.	-105 k.	-110 k.	-110 k.	-150 k.	-150 k.	-160 k.
P ₂ - load in chord at failure	-154 k.	-160 k.	-152 k.	-105 k.	-110 k.	-110 k.	-71 k.	-75 k.	-76 k.
P - failure load in diagonal	+100 k.	+103 k.	+99 k.	+148 k.	+155 k.	+155 k.	+212 k.	+212 k.	+226 k.
F - nominal failure stress in diagonal	67.6 ksi	69.7 ksi	66.9 ksi	+66.6 ksi	+69.8 ksi	+69.8 ksi	66.9 ksi	+67.0 ksi	71.4 ksi
Joint-efficiency	100%	100%	100%	95%	100%	100%	100%	100%	100%

*O.D. chord member 6-5/8 in.

65.0 ksi).

Comparing the ultimate load of 96.2 k. with the failure load of 100 k. in the diagonal it can be concluded that the joint strength is equivalent to the member strength. (Joint-efficiency = 100% - see Table I).

The principal stresses and directions due to both cylinder forces and based on the elastic strains are shown in Figure 15. The cylinder loads P_1 and P_2 are 30 k. and 65 k. respectively. It should be noted from Figure 14a that at this load level only gage 33 had reached a true yield strain.

VI-2-2. JOINT TYPE 2 (Figures 3 and 4)

a. Joint Type 2 - Thin Wall

The zero-eccentricity joint with 2-3/8 in. O.D. web members and a chord-wall thickness of 0.280 in. failed under a compressive load of 60 k. applied to the vertical web member. The chord load at that instance was -67 k. The latter load was applied step-wise with the other load, in order to maintain identical compressive stresses in chord and vertical members. The early failure of the joint prevented the full development of the ultimate strength of the diagonal member, which now reached a nominal tensile stress at failure of only $60\sqrt{2}/1.48 = 57.4$ ksi. The compressive stresses in the vertical and chord members were $60/2.66 = 22.6$ ksi and $(67 + 60)/5.58 = 22.8$ ksi respectively. Table II presents the complete results.

Comparing the joint failure load with the member failure load of 96.2 k., we can conclude that the joint-efficiency was only 88%, $(60\sqrt{2}/96.2 \times$

TABLE II. FAILURE LOADS AND STRESSES FOR SPECIMENS OF SERIES II
All Joints have a Zero-Eccentricity

Joint Type	2 (thin wall)	2 (medium wall)	2 (thick wall)	8 (thin wall)	8 (medium wall)	8 (thick wall)
Joint-eccentricity						
O.D. web-member	2-3/8 in.	2-3/8 in.	2-3/8 in.	4-1/2 in.	4-1/2 in.	4-1/2 in.
t diagonal member	0.218 in.	0.218 in.	0.218 in.	0.237 in.	0.237 in.	0.237 in.
t chord-member*	0.280 in.	0.432 in.	0.562 in.	0.280 in.	0.432 in.	0.562 in.
P_1 - load in vertical at failure	-60 k.	-73 k.	-75 k.	-132 k.	-150 k.	-150 k.
P_2 - load in chord at failure	-67 k.	-160 k.	-225 k.	0 k.	-75 k.	-130 k.
P - failure load in diagonal	+85 k.	+103 k.	+106 k.	+187 k.	+212 k.	+212 k.
F - nominal failure stress in diagonal	+57.4 ksi	69.7 ksi	71.6 ksi	+59.0 ksi	+67.0 ksi	+67.0 ksi
Joint-efficiency	88%	100%	100%	91%	100%	100%

* O.D. chord members 6-5/8 in.

100%). The failure developed as a local buckling of the chord tube wall under the predominant influence of the compressive load in the vertical web member. At the same time a small crack was noticed in the wall of the diagonal, (on the side of the vertical member) about 1 in. above the weld connecting the diagonal to the chord tube. (see Figure 16).

This thin-wall joint had a very limited elastic range. Figure 17a shows the location of the critical gages and the associated load-strain diagrams. At a load of 14 k. in the diagonal (cylinder load $P_1 = 10$ k.) local yield strains were reached in gage 20. Under a load of 25 k. in the diagonal, yielding was also registered in gage 29. Although the other gages presented in Figure 17a showed substantial strains, progressive local yielding only occurred after a cylinder load of 30 k. had been reached. Actually it was only after the applied load was increased to 45 k. that substantial yielding in the diagonal and chord member did develop.

Figure 18 shows the state of stress due to the combined effect of a 30 k. and a 33.5 k. cylinder load. Many areas can be noted where high stresses, approaching yielding, were developed under this load. The thin-wall tube near the weld is generally highly stressed. This trend resulted ultimately in excessive deformations of the joint. (see Figure 16). It should be noted that for these pipes, based on tests, according to ASTM specifications, a yield stress of $F_y = 42$ ksi, was determined.

b. Joint Type 2 - Medium Wall

This joint failed due to a crack in the wall of the tension tube above the weld in the 45° corner between the chord member and the diagonal. The compressive loads applied to the vertical web member and chord tube were 73 k. and 160 k. respectively. Tables I and II give the complete results of this test. Figure 19 shows the failure in a far progressed state. It should be noted that this failure is similar to that observed in joint type 1.

Overall yielding of the diagonal started at a load P_1 of 45 k. Based on the ultimate load of 73 k., which corresponds with a tension load in the diagonal of 103 k., it can be noted that the joint-efficiency was 100%. (tensile strength of diagonal test tube was 96.2 k.).

Figure 14b presents the load strain curves for the gages on the diagonal tension member. The same information is also presented in Figure 17b. The latter figure allows a direct comparison of the strains in the Type 2 joints with different wall thicknesses for the chord member.

It can be noted from gage 20 in Figure 14b that local yield strains were developed after a load P_1 of approximately 25 k. had been applied. Subsequent yielding developed in gages 29 and 25 respectively. The maximum strains recorded for gages located on the chord wall near the welds indicated a relatively low stress level as compared to the stresses recorded for the diagonal member. The same conclusion can be drawn from an observation of the stresses presented in Figure 20.

c. Joint Type 2 - Thick Wall

This zero-eccentricity joint had a chord member with an O.D. of 6-5/8 in. and a wall thickness of 0.562 in. The failure occurred in the diagonal when the load applied to the vertical reached a value of 75 k. This corresponded with a joint-efficiency of 100%. The load P_2 in the chord member at failure was 225 k. The nominal failure stress in the diagonal (O.D. 2-3/8 in., $t = 0.218$ in.) was $(75 \sqrt{2}) / 1.48 = 71.6$ ksi. Table II gives the complete test results.

Failure was due to a crack in the tube-wall of the diagonal 5/8 in. above the weld in the 45° corner between the diagonal and chord member. See Figure 21. Excessive yielding in the diagonal started at a load of 50 k.

Figure 17c presents the load-strain relation for the gages on the diagonal member located in the critically stressed areas. The strains recorded for gage 20 were again the largest and indicated an early yielding at approximately 30 k. This load is higher than the load recorded for the medium thick chord wall. A similar increase of yield load was noticed for the recorded strain in gage 29. The maximum strain values recorded in the chord tube were again small as compared with the strains recorded for the diagonal. The same conclusion can be drawn from observing the general stress distribution for this joint as determined from the elastic strains and presented in Figure 22.

VI-2-3. JOINT TYPE 3 (Figure 3)

The negative-eccentricity joint, with web members of 2-3/8 in. O.D. and a chord tube with a wall thickness of 0.432 in. and an O.D. of 6-5/8 in., failed under a compressive load of 70 k. in the vertical web member. Failure was caused by a progressive necking of the diagonal member at a distance of about 12 in. from the actual joint. (See Figure 23). The chord member at failure was subjected to a compressive load of 152 k. This load was increased in step-wise intervals in order to maintain, due to the two load cylinders the same compressive stress in both the vertical member and the chord tube. Table I indicates a failure load in the diagonal of 99 k. and a corresponding nominal failure stress of 66.9 ksi. Considering the ultimate strength of 96.2 k. for this type of pipe section as determined in a separate test, the failure load of 99 k. indicated a joint-efficiency of 100%.

Figure 14c shows the critical strains as recorded in the diagonal member. Although the strain in gage 29 had the largest strain rate for a load greater than $P_1 = 20$ k., strains in general were more uniform in the diagonal than previously had been observed for the medium-wall joints type 1 and 2. Also the load-strain ratio for gage 29 showed a smaller value than previously noted, thus indicating a more uniform load transfer. The stress distribution, as presented in Figure 24, proved to be more uniform than for the joints with similar web members. Also, as a result of the larger overlap of the web members the stress values for the chord members were in general lower.

VI-2-4. JOINT TYPE 4 (Figure 3)

This positive-eccentricity joint had 3-1/2 in. O.D. web members. The chord member had an O.D. of 6-5/8 in. and a wall thickness $t = 0.432$ in. Yielding of the diagonal member was apparent at a load of 70 k. applied to the vertical member. Failure occurred under a load of 105 k. and was characterized by a necking of the diagonal and the development of a small crack in the wall of the diagonal about 5/8 in. above the weld between the diagonal and the chord member in the 45° corner between these two members. (See Figure 25). The nominal tensile stress in the diagonal at failure was $(105\sqrt{2}) / 2.23 = 66.6$ ksi. The nominal compressive stresses in the chord and vertical members at the instant of failure were $(105 + 105) / 8.4 = 25$ ksi. and $105/4.21 = 24.9$ ksi. respectively. Table I presents the results of this test.

To determine the joint-efficiency, a 3-1/2 in. O.D. pipe was subjected to a tensile load. The 6 ft. long section was cut from the same pipe as the diagonal. Yielding occurred at a load of 97 k. and failure at a load of 155.5 k. The corresponding stresses were respectively $F_y = 43.5$ ksi and $F_{ult} = 69.8$ ksi. A comparison of the ultimate load with the failure load of 148 k. in the diagonal indicates a joint-efficiency of 95%.

From the critical strain plots, as shown in Figure 26a, it is obvious that a very large strain in gage 39 was developed at a relatively low load. Also gage 28 recorded a considerable strain. Furthermore, the large strains in gages 10 and 14 clearly indicate, that an arrangement of

non-intersecting web members causes considerable stresses in the chord tube. Although gage 10 recorded initially a low strain rate, a severe yielding developed rapidly after load P_1 was raised to 60 k.

Figure 27 presents the state of stress in the joint for the indicated loading as based on the elastic strains. The general state of stress indicates high stresses in both the diagonal and chord member.

VI-2-5. JOINT TYPE 5 (Figure 3)

This zero-eccentricity joint with the same members as Joint Type 4 failed under a load of 110 k. applied to the vertical. This failure was caused by a small crack in the wall of the diagonal about 5/8 in. above the weld between the chord member and the diagonal in the 45° corner between these two members (see Figure 28). The ultimate load of 155.5 k. in the diagonal was identical to the one recorded in the tensile test. Consequently the joint-efficiency is 100%. The nominal tensile stress in the diagonal at failure was $(110\sqrt{2}) / 2.23 = 69.8$ ksi. The nominal compressive stresses in the chord and vertical members at that instant were $(110 + 110) / 8.4 = 26.2$ ksi and $110 / 4.21 = 26.2$ ksi respectively. Table I presents the complete results.

The critical strain plots as shown in Figure 26b indicate a marked improvement over the strains recorded for Joint Type 4. The strains in the diagonal as well as in the chord member were reduced considerably. This is particularly evident for the chord member strains. Also the reduction in strain in the diagonal in the 45° corner between this member and

the chord tube is quite obvious. This general improvement is undoubtedly a result of the overlapping of the two web members.

Figure 29 shows a similarly improved stress distribution as compared with the results of Joint Type 4. (Figure 27).

VI-2-6. JOINT TYPE 6 (Figure 3)

The negative eccentricity joint with 3-1/2 in. O.D. web members failed at a load of 110 k. applied to the vertical member. The additional chord load was approximately 110 k. Failure was due to cracking of the wall of the diagonal member above the weld in the 45° corner connecting the diagonal and chord members (see Figure 30). The stresses at failure were: $110\sqrt{2}/2.22 = 70.5$ ksi (tension) in the diagonal; and $110/4.21 = 26$ ksi (compression) and $(110 + 110)/8.4 = 26.2$ ksi (compression) in the vertical and chord members respectively. The complete results are presented in Table I. The joint-efficiency for this joint can be set at 100%.

The critical strain plots are presented in Figure 26c. The strain recorded in gage 44 is substantially the same as the strain at that location in Joint Type 5. However the other strain values presented, show a further reduction as compared with the two previously studied joints. In general it can be noted, that the increased overlap of the web members improved the overall response of this joint. A similar conclusion can be drawn from the stress distribution presented in Figure 31.

VI-2-7. JOINT TYPE 7 (Figure 3)

This positive-eccentricity joint failed under a load of 150 k. applied to the vertical web member. Failure was due to a pronounced necking of the diagonal tension member however without the development of a crack near the weld. (See Figure 32). The nominal tensile stress in the diagonal as failure was $(150 \sqrt{2}) / 3.17 = 66.9$ ksi. The nominal compressive stresses at failure in the vertical and chord members were $150/5.59 = 26.9$ ksi and $(150 + 71) / 8.4 = 27.4$ ksi respectively. Table I presents the general results of this test.

To determine the ultimate strength of the pipe used for the diagonal, a 6 ft. long pipe section was tested under tension. Yielding started at a stress of 39.8 ksi. The ultimate load was 204.5 k. which corresponds with an ultimate stress of $204.5/3.17 = 64.5$ ksi. Comparing this result with the failure load in the diagonal of $150 \sqrt{2} = 212$ k., the joint-efficiency proved to be 100%. The joint reached in all probability a higher load as a result of the radial restraint of the diagonal caused by the presence of the weld between the web members.

The critical strains under increasing loads are presented in Figure 33a. The high strain in the wall of the diagonal near the weld between this member and the chord tube is most evident (gage 50). The other strains in the diagonal, as presented in the same figure, are considerably lower than the strain in gage 50. It is further of interest to note that these strains are all quite similar in magnitude. The strains measured in

the chord member wall near the vertical member are low. This tendency has been observed previously in most other joints.

The stress distribution in this joint for a load combination of $P_1 = 70$ k. and $P_2 = 33$ k. has been presented in Figure 34. These stresses, as in all cases presented, are based on the linear elastic strains under the given reference loading.

VI-2-8. JOINT TYPE 8 (Figures 3 and 4)

a. Joint Type 8 - Thin Wall

The zero-eccentricity joint failed under a compressive load of 132 k. applied to the vertical member. During this test the chord was not loaded separately since the stresses in vertical and chord were already identical under the applied load P_1 . (Area of both members is practically the same). At 125 k. a general necking of the diagonal was observed. At failure a small crack in the wall of the diagonal above the weld in the 45° corner between the chord-member and diagonal was observed, see Fig. 35a. Figure 35b shows the complete joint after failure.* The nominal failure stress in the diagonal was $132 \sqrt{2}/3.17 = 59$ ksi in tension and the nominal stress in both the vertical and chord members was $132/5.59 = 23.6$ ksi in compression. The results of this test are presented in Table II.

A comparison of the load of 187 k. in the diagonal, at failure, with the ultimate tensile load of 204.5 k. for this pipe, indicates a joint-efficiency of only 91%.

* (Gage leads cut).

The critical strains in this joint are presented in Figure 36a. It is of interest to note, that the thin and more flexible chord wall indeed seems to reduce the restraining effect of this tube on the diagonal. As a result the strains in gage 18 for instance were considerably smaller than the values recorded for similar gages in other joints. All together a more uniform stress transfer seems to be a result of this geometric arrangement.

The strains recorded for gages 5 and 8 however, are relatively large as a result of the low flexibility of the chord wall. The stress distribution in the joint under a reference load of 70 k. is shown in Figure 37. The stresses are based on the linear elastic strains at this reference load.

b. Joint Type 8 - Medium Wall

The zero-eccentricity joint with 4-1/2 in. O.D. web members and a chord tube with a wall thickness of 0.432 in. (O.D. 6-5/8 in.) exhibited a necking of the diagonal member when the load applied to the vertical member reached 128 k. At 150 k. the specimen failed with the development of a crack in the wall of the tension tube above the weld in the 45° corner between the chord-tube and diagonal (see Figure 38). The load applied to the chord tube by means of the 2nd load cylinder was 75 k. The total load in the chord tube at failure due to both cylinders was $150 + 75 = 225$ k., which corresponds with a nominal compressive stress of $225/8.4 = 26.8$ ksi. The nominal compressive stress in the vertical web member at failure was $150/5.59 = 26.9$ ksi, and the nominal tensile stress in the diagonal was

$150 \sqrt{2}/3.17 = + 67$ ksi. The loads in both cylinders was increased step-wise in order to maintain identical stress levels in the chord and vertical members. The joint-efficiency of this connection was 100% as compared with the failure load of the same pipe section in tension (204.5 k.). The complete results are presented in Tables I and II.

The critical strains for this joint are presented in Figures 33b and 36b. Figure 33 permits a evaluation of the influence of the joint-eccentricity on the strain distribution in the joint. Figure 36, on the other hand, permits an evaluation of the influence of the chord-wall thickness on the major strains.

A study of the strain-diagrams shows again a high strain rate in the vicinity of gage 18. This rate however is smaller than observed in Joint Type 7 (gage 50 - Figure 33a). This improvement is undoubtedly due to the larger amount of overlapping of the two web members. At the same time the heavier chord wall in this case seems indeed to restrain the diagonal more than in case of a joint with a thin walled chord section. This is obvious from the increased strain rate for gage 18 in the medium-wall joint as compared with the same gage in the thin-walled connection (see Figures 36a and 36b).

The strains recorded in the gages located on the chord-tube wall clearly indicate the favorable influence of the overlap of the two web members. A comparison of the strains for the gages 5 and 8 in Joint Type 8 (Figure 33b) with those located at similar locations in Type 7 (gages 12 and

15 in Figure 33a), clearly show the strain reduction due to the larger inter-welding. A similar reduction can be noted from comparing the strain values for the gages 5 and 8 in the thin-wall and medium-wall joints (Figures 36a and 36b, respectively).

The state of stress based on the static strains for a reference load P_1 of 70 k. is presented in Figure 39. These stress-values clearly show an improved state of stress for the chord wall when compared with those recorded in the medium-wall specimen.

c. Joint Type 8 - Thick Wall

The zero-eccentricity joint with 4-1/2 O.D. web members and a 6-5/8 O.D. chord member with a wall thickness of 0.562 in. failed under a load of 150 k. applied to the vertical member. The additional force in the chord member at failure was -130 k. Failure was caused by the development of a small crack in the diagonal tube wall about 3/4 in. above the weld joining the chord and diagonal members in the 45° corner (see Figure 40). The magnitude of the failure load indicated a joint-efficiency of 100%. The nominal tensile stress in the diagonal at failure was $(150 \sqrt{2}) / 3.17 = 67.0$ ksi. The nominal compressive stresses in the chord and vertical members were $(150 + 130) / 10.7 = 26.2$ ksi and $150 / 5.59 = 26.9$ ksi respectively. Table II contains the tabulated test results for this joint.

The critical strains for this thick-wall joint are presented in Figure 36c. It is obvious from the strain record that the stresses in the wall near the gages 18 and 28 seem to be of the same order of magnitude.

This would indicate a relatively uniform stress distribution. Considering however the structural arrangement of the joint it seems that such a conclusion might be erroneous, since the heavier chord wall would cause the development of a larger stress in the wall of the diagonal near the chord as compared to the stress in the wall next to the vertical member .

Based on this anticipated development one would also expect in the wall of the diagonal for the same load a larger stress near the chord for the thick-wall joint than for the medium-wall joint. However this is contrary to the experimental results (Figures 36b and 36c).

The general elastic stress distribution for a reference load P_1 of 70 k. is presented in Figure 41. An observation of the stresses indicate that load P_1 might have been applied in an eccentric position, located towards the outside of the joint. (towards the left of the center-line of the vertical member as presented in Figure 41). In that instance the difference in the compressive stresses of 34.1 ksi on the left side of the vertical and 8.7 ksi on the right side seem to be logical. The presence of such an eccentric moment would also explain the high stress of 33.4 ksi in the chord wall for the rosette 3.4.5. This moment would also cause an increase of the strain in gage 28 and reduction of the strain in gage 18. This would clarify the otherwise questionable strain curves for those two gages (see Figure 36c). Also the initial compressive strain recorded for gage 18 can thus be explained.

The above considerations probably invalidate the presented detailed response of this joint for comparative studies. The ultimate responses however was not effected by this presumably erroneous loading which was discovered after the test was completed.

VI-2-9. JOINT TYPE 9 (Figure 3)

This specimen had a negative-eccentricity and web members with a 4-1/2 in. O.D. The chord member had an O.D. of 6-5/8 in. and a wall thickness of 0.432 in. The loads in the vertical member and the chord member were increased step-wise to obtain equal nominal stresses in both members. At a load of 140 k., applied to the vertical web member, yielding in the diagonal member became apparent, followed by a necking of the section. The ultimate load (P_1) was 160 k. A small crack in the diagonal tube wall just along the weld in the 45° corner between the chord and diagonal tubes occurred under the ultimate load. The additional chord load at failure was -76 k. Figure 42 shows the specimen after failure. The nominal stress in the diagonal at failure was $(160\sqrt{2}) / 3.17 = 71.4$ ksi. The nominal stresses in the vertical and the chord members were $160/5.59 = 28.6$ ksi and $(160 + 76) / 8.4 = 28.8$ ksi respectively. The results of this test indicated a joint-efficiency of 100%. (See Table I)

Figure 33c shows the critical strains in Joint Type 9. An observation of the recorded strains for gages located on the diagonal clearly show a fairly uniform strain distribution as compared with the

results of similar joints with positive and zero eccentricities. As a result of the negative eccentricity and the resulting larger weld length between the diagonal and other joint members the load transfer was greatly improved. Also the strains in the chord wall were considerably less than those recorded previously. The same general result can be noted from the stress distribution presented in Figure 43 for a reference load P_1 of 70 k.

VI-3. Stress Coat Results

The strain gage instrumentation as can be noted from Figure 7 was predominantly located on the near side of the joint. The far side was treated with stress coat. The results of the stress coat crack pattern under increasing loads were merely intended for a qualitative analysis of the joint behavior.

The crack patterns shown in Figures 44 and 45, present the results for the joints type 2 and 8. These patterns are rather typical and need a closer observation. Figure 44 indicates some important developments in the chord tube as effected by the wall thickness of the chord member. The thin-wall joint, Figure 44a, clearly shows the location of the isotropic stress point relatively close to the vertical member. This point is identified by the sharp return of the traced crack pattern. The location of this point close to the joint indicates the presence of high stresses in the chord wall near the welds below and to the left of the vertical member. Also a large yielding zone, where the stress coat gradually chipped off, is clearly noticeable in

the chord wall under the diagonal. An observation of Figure 44b indicates an improved state of stress. Due to the larger radial stiffness of the chord tube the isotropic point has been "pushed" away from the joint-area. Correspondingly the strains and stresses were found to be less than for the thin-section. In the thick-wall joint the increased thickness of the chord wall did not even permit the development of a crack pattern.

The traced stress-coat crack patterns for joint type 8 - Figure 45 - show a tendency similar to the ones discussed for joint type 2. Again we notice a distinct difference in the crack pattern. For the highly stressed thin-wall joint the stress-coat cracks turn sharply towards the web members as shown in Figure 45a. This is contrary to the pattern for the lower stressed medium-wall joint, as shown in Figure 45b, where the lines have a tendency to pass by the joining area.

In general it was noted that the crack patterns showed a very consistent tendency. In the case of high stresses in the chord wall the crack lines normally sharply bend towards the vertical member. In case of lower stresses, due to either a larger wall thickness of the chord member or a larger overlap of the branch members - see Figure 46 - the crack lines diverged. This development coincided with the isotropic point moving away from the actual connection. It is thus obvious that the shape of the crack pattern becomes a clear visual and qualitative representation of the state of stress.

VI-4. General Observations

To complete the discussions of the test results some additional observations are in order:

- a. The strains and stresses for corresponding gages on the near and far sides of the diagonal and vertical members show in general a good agreement. This indicates that the fabrication of the specimens and the loading indeed have been symmetrical with respect to the plane of the joint.
- b. The auxiliary jack moved the bottom support of the chord member in order to maintain a vertical orientation of this member in the loading frame. This corrective movement was only introduced when overall yielding in the diagonal developed after the load P_1 had reached a value of about 60% of the ultimate failure load. Therefore, the strain and stress records, presented previously, are correct and have not been effected by this additional load. Consequently, the consistently high strains in the 45° crotch between the diagonal and chord member are fully reliable. The mode of failure after the corrective motion had been introduced might have been influenced slightly by this adjustment. However, considering the fact that under pre-yield conditions, the extreme stresses in the joint did occur in the same zone as where future failure would develop, it becomes obvious, that failure indeed did occur in the most critically stresses region. There is no doubt that the adjustment

of the support, at least for the joints in which failure occurred in the wall of the diagonal, did not effect the magnitude of the failure loads. One can assume that this is also true for the joints with lower joint-efficiencies. In general, it should be noted, that the type of joint deformation introduced by this auxiliary jack after yielding of the web member occurred, is identical to the type of panel distortion which would take place in a truss prior to a collapse without lateral instability.

- c. A comparison of the ultimate strength of individual pipe sections and the joint failure loads indicates, in all instances where the joint-efficiency is 100%, that the failure loads are larger than the strength of the pipe itself. This is undoubtedly a result of the radial restraint of the diagonal due to the interwelding of the members in the failure zone. It can be safely assumed that the initial overwelding, which was corrected prior to the tests, did not effect the results.

VII. CONCLUSIONS

The following specific conclusions can be drawn:

- 1) Joint-eccentricity: The joint-eccentricity and resulting overlap of the branch members have a considerable influence on the stresses in the joint, particularly for the chord member. In case the eccentricity does not result in an overlap the chord-wall stresses are very high and an early yielding will occur at several locations. This is clearly illustrated by the results for joints type 1 and 2 (medium wall) as shown in Figures 15 and 20. It was further noticed that the stresses in the branch members were not effected substantially by the overlap between these members. However, the stresses in the chord members wall were in all instances reduced most effectively by this arrangement. This development can be noted from Figures 20 and 24, for joints with a small d/D ratio, and from Figures 27 and 29 for joints with a larger d/D value. In case the overlap between the web members increases, a reduction in the strains and stresses of the chord member will occur. The specific stresses in Figures 34, 39 and 43 show this development and indicate that for a large overlap--see Figure 43--the transfer between web members and chord member becomes predominantly a shear transfer. The above observations are also supported by the specific strains in the corresponding joints.
- 2) Geometric relation between the O. D. of chord and web members (d/D):
It is obvious that the influence of this structural relation is closely

associated with the joint eccentricity. The results indicated that, for joints with non-intersecting web members and the same load in the vertical member, the state of stress in the chord tube does not differ greatly for d/D values between 0.3 and 0.5. However, in all other cases the overall stresses in the chord tube reduced considerably. For instance, the average stress values for joint Type 5, with a d/D value of 0.53 and a zero eccentricity, were only 50% of those recorded for the non-intersecting zero-eccentricity joint Type 2 (Medium) with a d/D ratio of 0.36. For joint Type 8, $d/D = 0.68$, the proportionally adjusted chord member stresses reduced as far as 20% of those recorded for joint Type 2 (Medium).

3) Wall thickness to O. D. ratio of chord member (t/D):

An observation of the strain diagrams in Figure 17 and the stresses in Figure 18, 20 and 22 for joints Type 2 show a considerable influence of the t/D values. A similar conclusion can be drawn from Figure 36 for the strains and Figures 37, 39 and 41 for the stresses in joint Type 8.

Independent of the fact that the web members do not intersect (Type 2 joint, $d/D = 0.36$) or do intersect (Type 8 joint, $d/D = 0.68$) the reduction of the chord stresses is most prominent. In the first instance a general stress reduction of 50% was recorded for the joint with a t/D value of 0.065 as compared with the information from the similar thin-wall joint with a t/D value of 0.042. This reduction was

even as much as 75% for a Type 2 joint with a t/D value of 0.085. In case of the Type 8 joints, with different wall thicknesses, a similar tendency was observed. The reduction in the recorded average stresses was again about 50% for a joint with a t/D value of 0.065 as compared to the one with a t/D value of 0.042. For the joint with a t/D value of 0.085 the reduction was even more. From the above observations it becomes obvious that an increase of the wall thickness of the chord tube is most effective. The percentage reduction of the stresses for increasing wall thicknesses is practically unaffected by the amount of intersection, which however by itself reduces the stresses considerably.

An additional observation should be made regarding the maximum stresses in the diagonal as far as the influence of the wall thickness t of the chord is concerned. It has been noted before⁽¹⁾ that for chord members with a low t/D ratio ($= 0.014$) the maximum stress in the wall of the diagonal will develop in the 45° crotch between the two web members. This is a result of the very low radial flexibility of the chord member which does not restrain the diagonal sufficiently in the part immediately adjacent to the weld in the 45° corner between chord tube and diagonal. This lack of stiffness results in a low stress at that point and causes, due to the larger local stiffness in the 45°

(1) Bouwkamp, J. G. "Research on Tubular Connections in Structural Work," Bulletin No. 71, Welding Research Council, August 1961

crotch between the web members, a very high stress in that vicinity. However as can be observed from the present test results this stress pattern changes when the wall thickness of the chord increases. These results indicated that, as a result of the increased radial stiffness of the chord tube, the maximum strains did appear in the wall of the diagonal near the 45° crotch between the diagonal and chord member rather than in the corner between the two web members.

The results of this study have indicated that, for a d/D value larger than 0.36 and a t/D value larger than approximately 0.060, the strength of a tubular Pratt-truss joint with a zero-eccentricity, is at least equal to the ultimate strength of the tension diagonal, provided that the t_1/d ratio is not larger than 0.10 (t_1 = wall thickness of diagonal). Although the joints tested, had t_1/d values of 0.092 (Type 2), 0.062 (Type 5) and 0.054 (Type 8) it can be expected that the wall thickness t_1 can be increased for large d/D values without reducing the recorded joint efficiencies of 100% for these large d/D joints. A maximum value for t_1/d of 0.10 seems to be realistic. Figure 47 shows a chart with the joint-efficiency values so far obtained as a function of t/D and d/D . The approximate location of the 100%-efficiency line, as based on the presently available results, is shown in the same figure.

For a negative-eccentricity joint the presently available joint-efficiency values as a function of t/D and d/D are presented in Figure 48. It is the author's opinion that the 100% joint-efficiency values are

definitely applicable for joints in which the t_1/d ratio is 0.10 or less. It is quite well possible that even for larger values of t_1/d the same 100%-efficiency will be found. However, such a joint would normally be a poor design, because the load transfer in a joint will be much better with thin-wall, large-diameter web-members than with thick-wall, small-diameter sections. The larger length of weld, covering a larger area of the chord tube wall (larger d/D value), will namely provide a better load transfer than a shorter and heavier weld covering only a small surface of the chord wall (small d/D value).

In both Figures 47 and 48 a proposed 100% joint-efficiency line has been presented. The relative difference of the approximate positions of the 100%-efficiency contour lines for the connections with zero and negative joint-eccentricities could be expected. The results reported herein have clearly established that for joints with a zero-eccentricity and t/D ratios of 0.060 or larger, and d/D ratios equal or larger than 0.30, the joint efficiency under static loads is 100%. For t/D ratios smaller than 0.06 the efficiency reduces rapidly for these joints. This tendency was clearly illustrated by the results of the two thin-wall joints Type 2 and 8 ($t/D = 0.042$). For negative eccentricity joints under static loads minimum t/D ratio for a 100% joint-efficiency and a d/D ratio equal or larger than 0.30 seems to be 0.040 (see Figure 48).

While in general the 100% joint-efficiency values are applicable for t_1/d ratios of 0.10 or less, the recorded efficiency values smaller than

100% are not directly applicable to connections with different t_1/d ratios. If the joint-efficiencies are a result of local failure of the chord wall, the results obtained can be applied to diagonal members with a wall thickness t_1 different from the one tested. Assuming that failure occurred under a load P in the diagonal due to a local buckling of the chord, the joint efficiency can be determined as $(P/P_{ult}) \times 100\%$. (P_{ult} = ultimate load of diagonal pipe). In such an instance the load P will be constant for any joint with the same t/D and d/D values. P_{ult} , however, will be different depending on the wall thickness t_1 of the diagonal. For a thin walled section, P might be larger than P_{ult} . In that instance the joint-efficiency is 100%. Should the diagonal be a thick-wall section, such that P_{ult} is larger than P , the joint efficiency would be less than 100%.

However, in case of a small intersection between the web members the joint efficiency values obtained cannot be applied accurately to a joint in which the wall thickness for the diagonal is different from the one tested. Results of future tests in Phase II of this program have to provide information about the joint-efficiency for these particular joints.

Finally, it should be noted that for joints built from tubes with a $F_y = 36$ ksi and designed according to the specified t/D , d/D and t_1/d values, the wall thickness t_2 of the vertical member should be at least $1.4 t_1$ in order to achieve a 100% joint-efficiency. In that case overall yielding in the vertical member will be prevented prior to reaching the ultimate stress in the diagonal, namely:

$$f_{\text{vert}} = (0.707 P_{\text{diag}}) (1.4 A_{\text{diag}}) = 0.5 f_{\text{diag}} \cong 0.5 f_{\text{ult}} \cong 35 \text{ ksi} < F_y$$

Should the ultimate buckling stress F_e be less than F_y , the wall thickness t_2 for the diagonal should be increased to $t_2 = (F_y/F_e) (1.4 t_1)$.

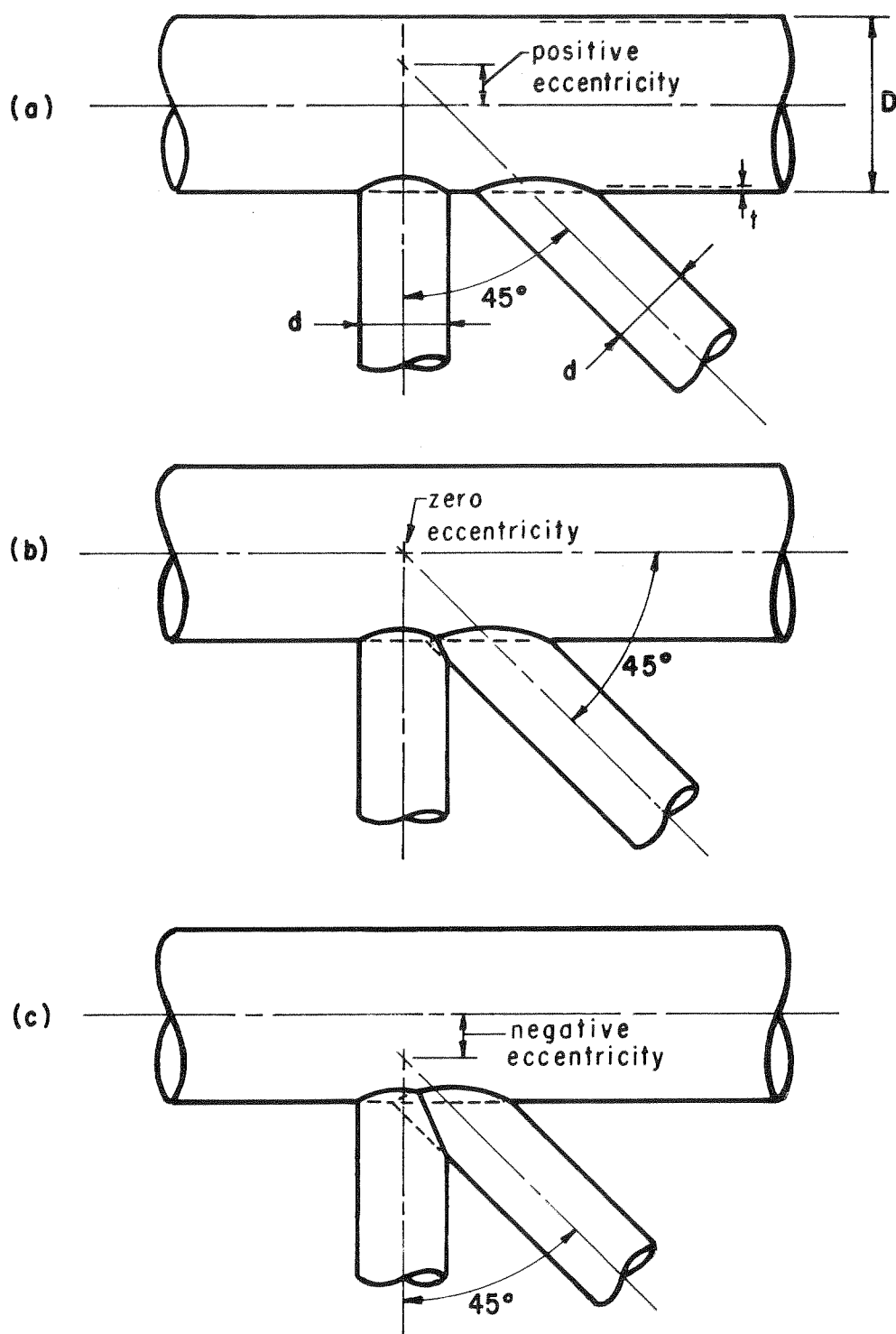


FIG. 1 SCHEME OF TYPICAL JOINTS

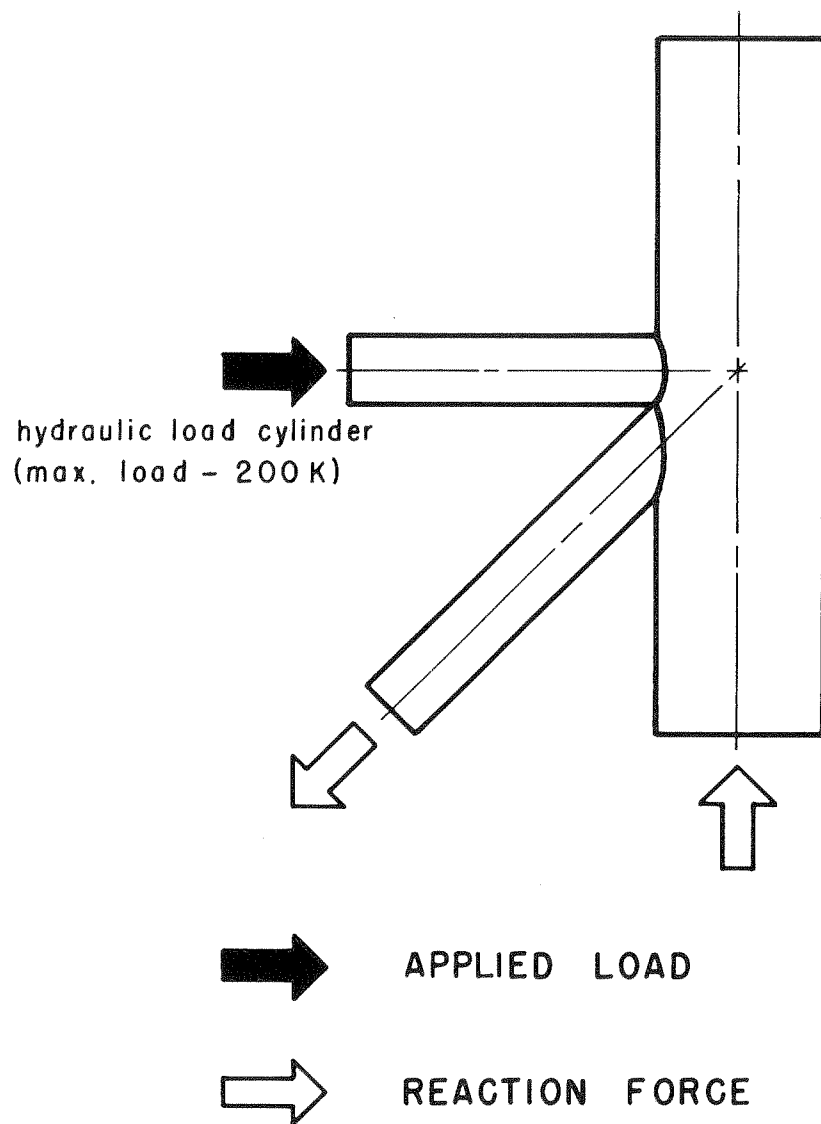


FIG. 2 BASIC LOADING SCHEME

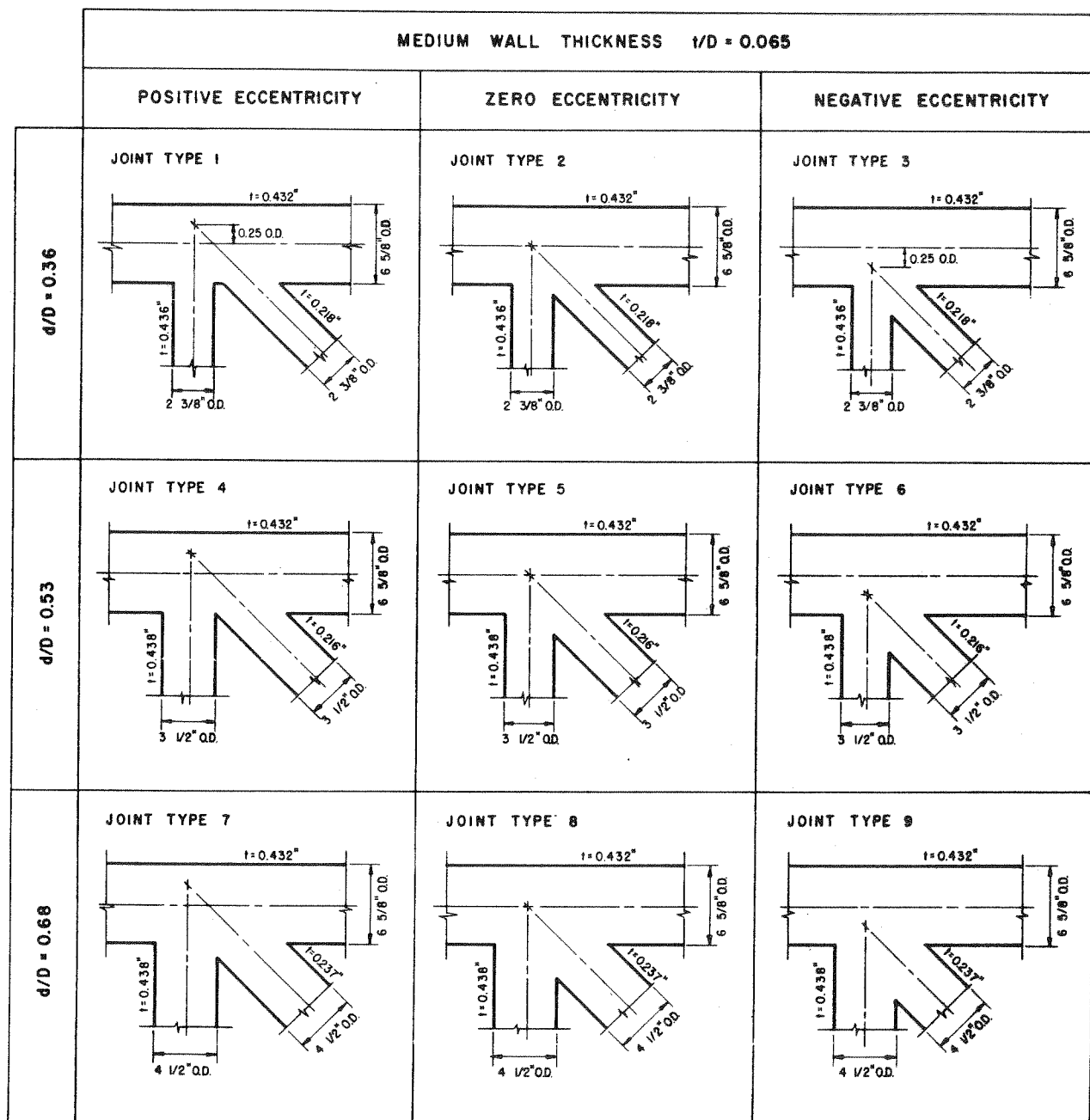


FIG. 3 TEST SPECIMENS SERIES I

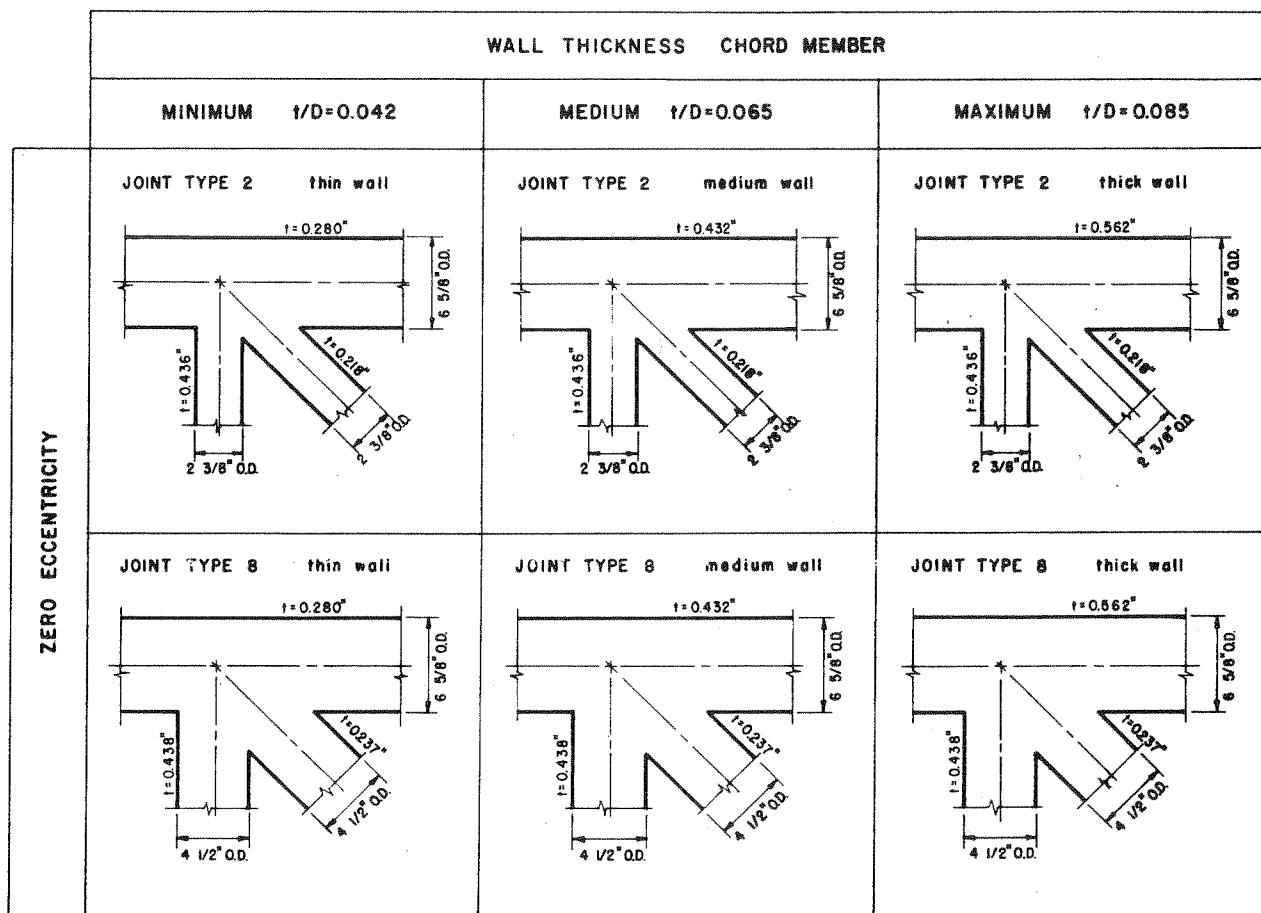


FIG. 4 TEST SPECIMENS SERIES II

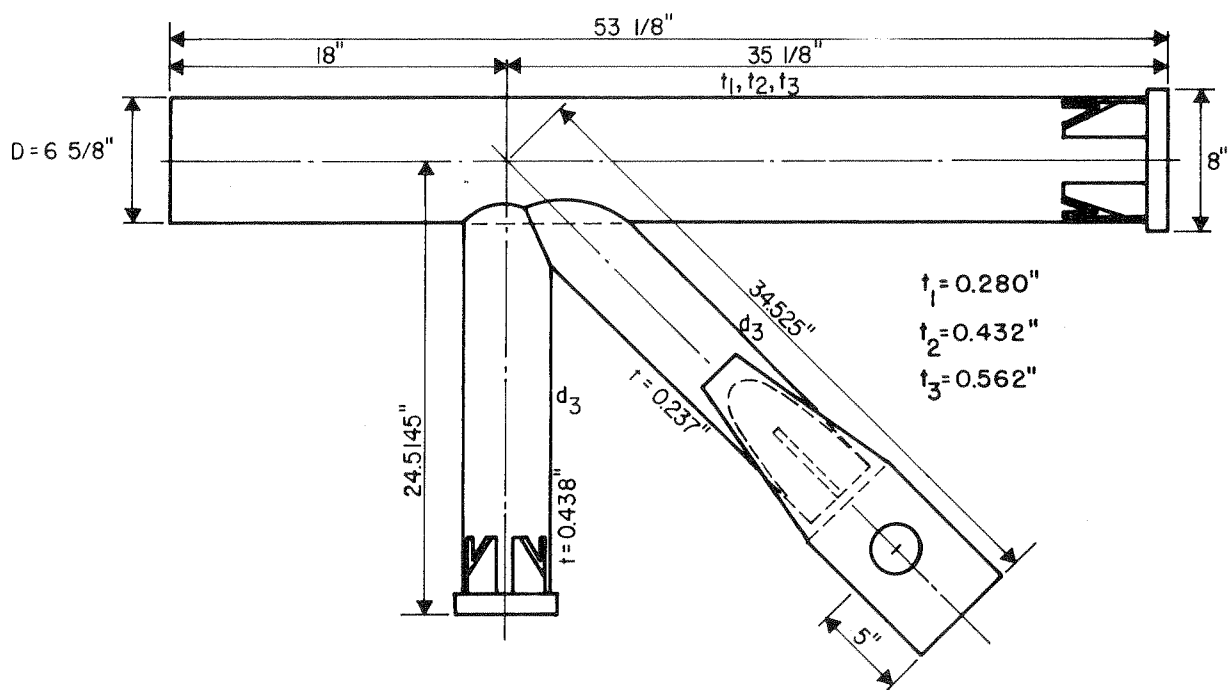
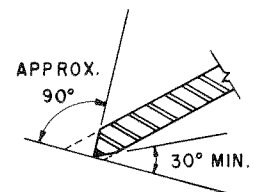
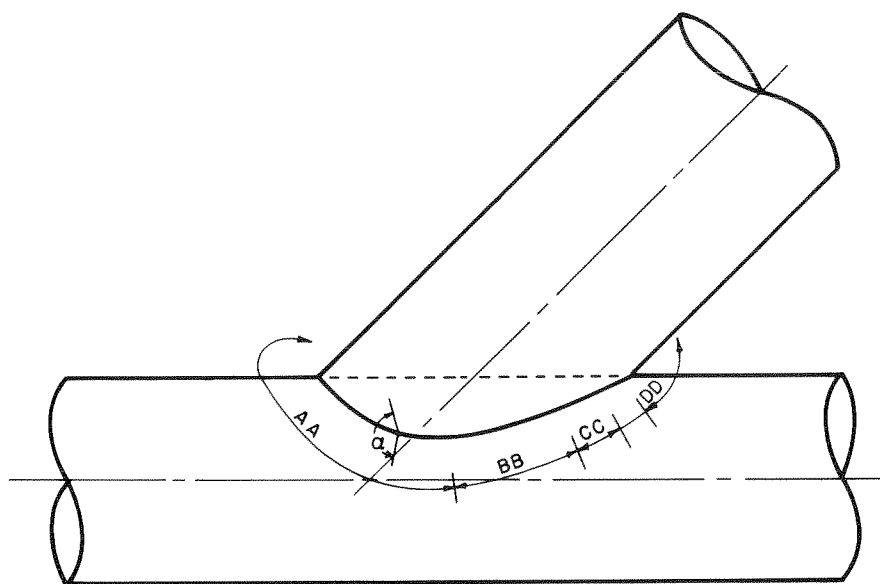


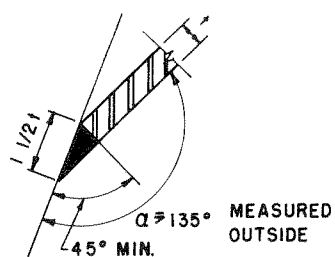
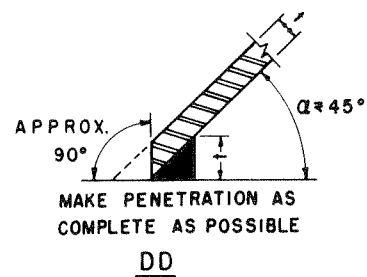
FIG. 5 JOINT TYPE 8



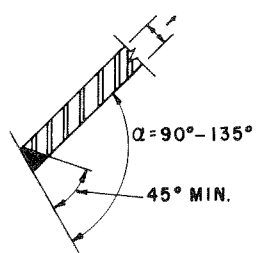
TRANSITION FROM
DETAIL CC TO DD
BY GRADUAL UNIFORM
BEVELING

TYPICAL CONNECTION ELEVATION

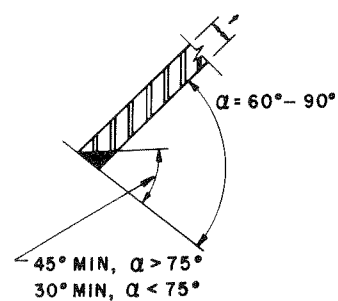
ANGLE α IS MEASURED PERPENDICULAR
TO JOINT LINE AND ON THE OUTSIDE OF PIPE



AA



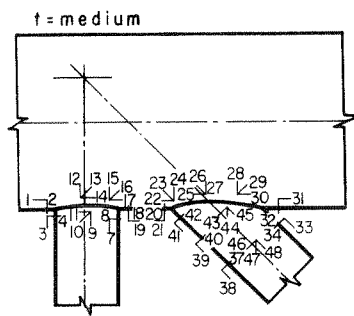
BB



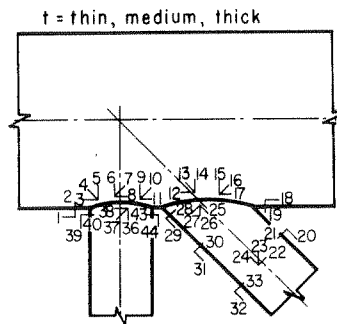
CC

DETAILS OF WELD FROM ONE SIDE ONLY

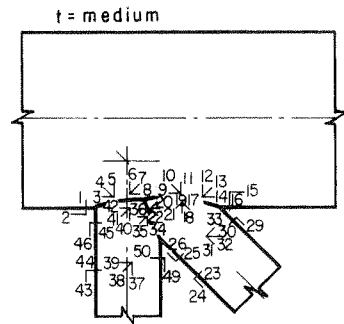
FIG. 6 WELDING DETAILS



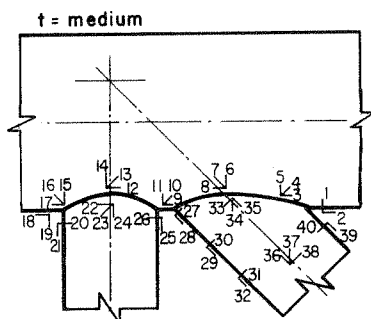
GAGES 9-11 AND 46-48
REPEATED ON FAR SIDE
JOINT TYPE 1



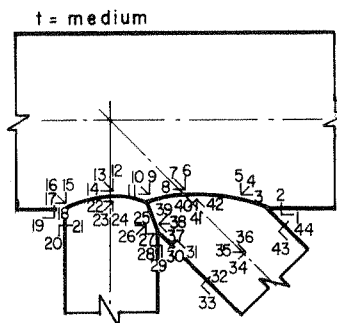
GAGES 22-24 AND 36-38
REPEATED ON FAR SIDE
JOINT TYPE 2



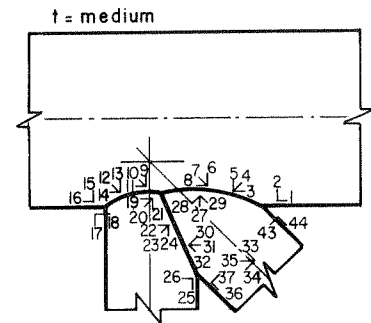
GAGES 31-33 AND 37-39
REPEATED ON FAR SIDE
JOINT TYPE 3



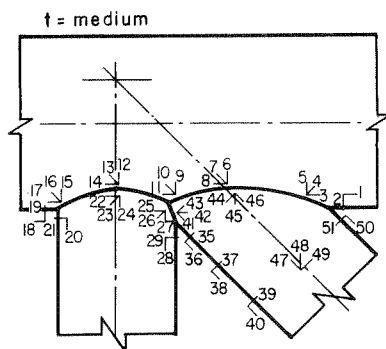
GAGES 22-24 AND 36-38
REPEATED ON FAR SIDE
JOINT TYPE 4



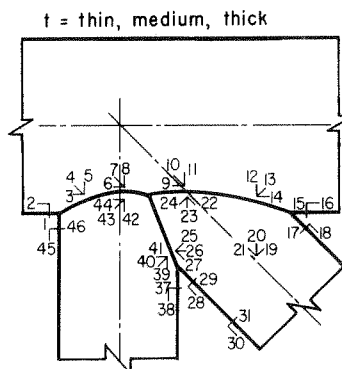
GAGES 22-24 AND 34-36
REPEATED ON FAR SIDE
JOINT TYPE 5



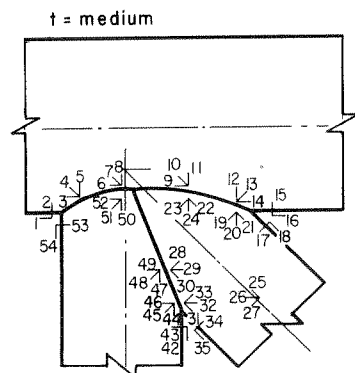
GAGES 19-21 AND 33-35
REPEATED ON FAR SIDE
JOINT TYPE 6



GAGES 22-24 AND 47-49
REPEATED ON FAR SIDE
JOINT TYPE 7



GAGES 19-21 AND 42-44
REPEATED ON FAR SIDE
JOINT TYPE 8



GAGES 25-27 AND 50-52
REPEATED ON FAR SIDE
JOINT TYPE 9

NOTE: ALL GAGES NEAR WELDS ARE LOCATED WITHIN 0.5 INCHES FROM WELD.

FIG. 7 BASIC SCHEME OF STRAIN-GAGE
INSTRUMENTATION

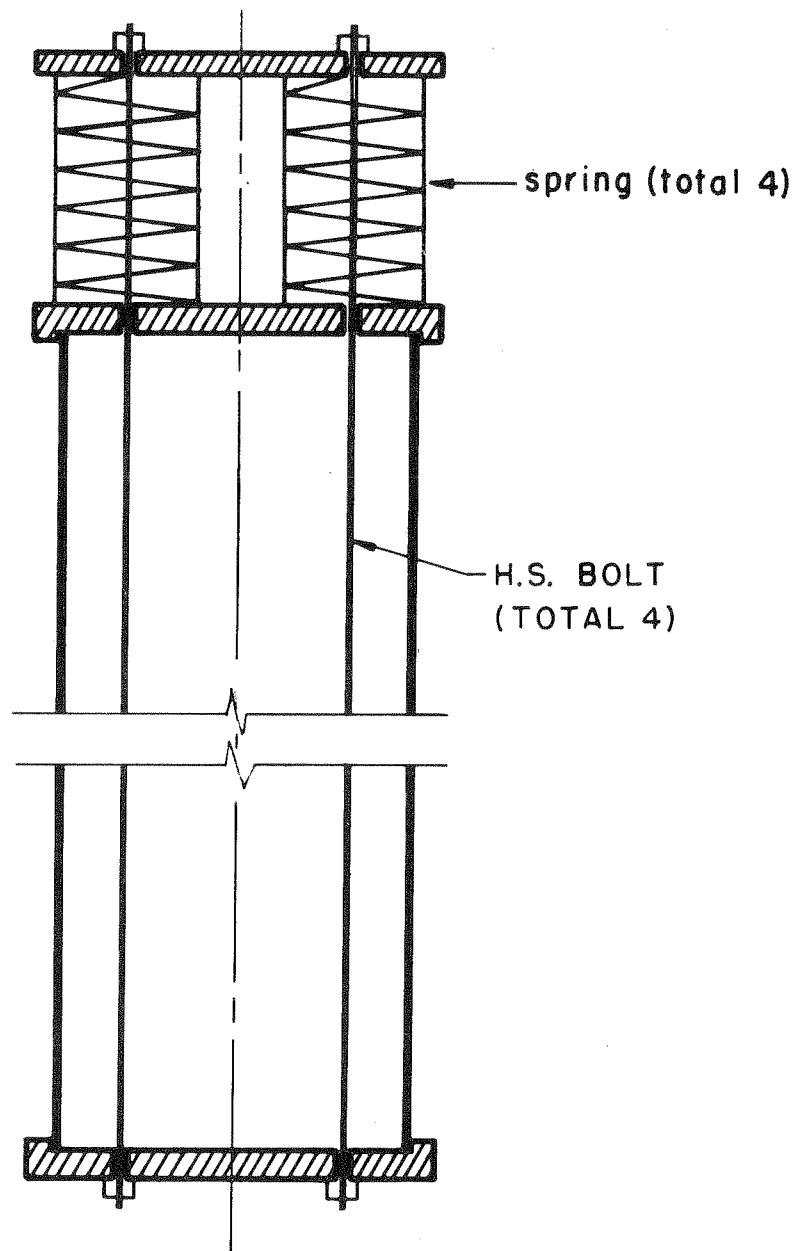


FIG. 8 INTRODUCTION OF COMPRESSIVE
PRE-LOAD IN CHORD TUBE

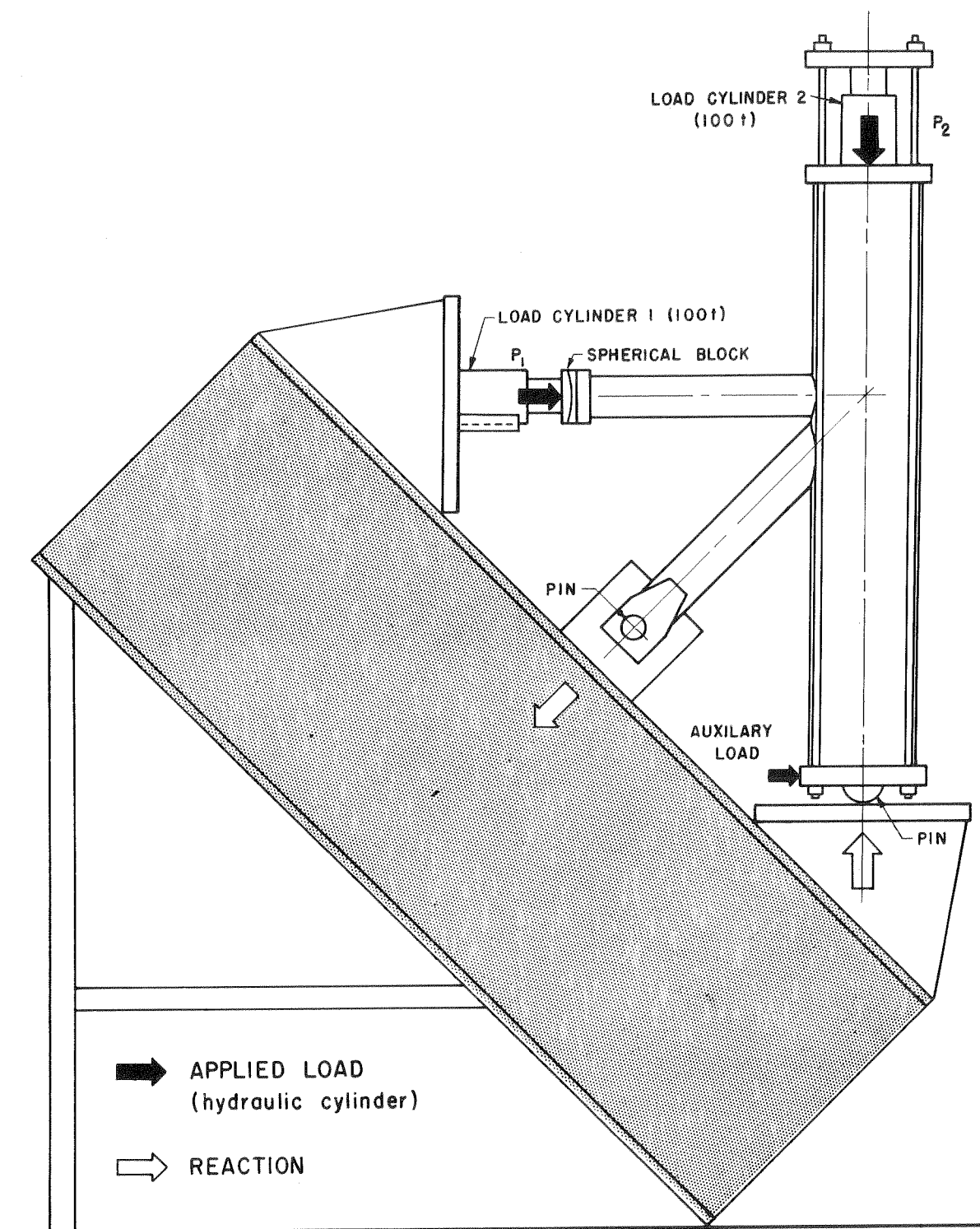
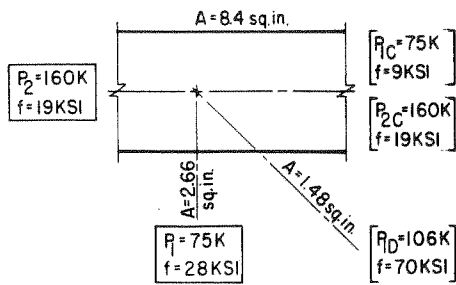
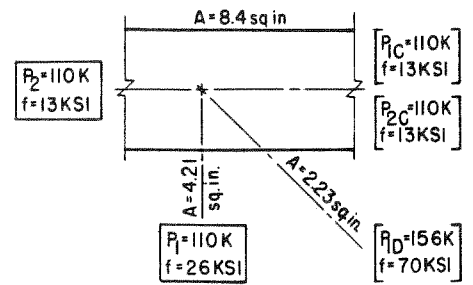


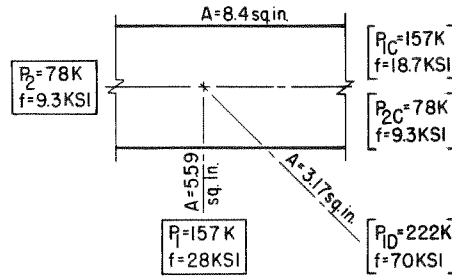
FIG. 9 COMPLETE LOADING SCHEME



TYPES 1,2,3 (medium wall)

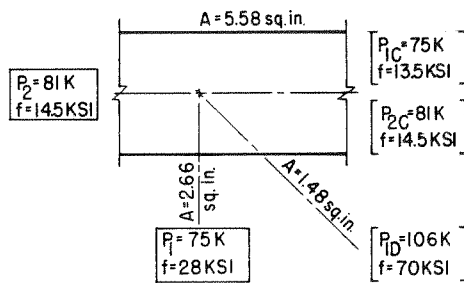


TYPES 4,5,6 (medium wall)

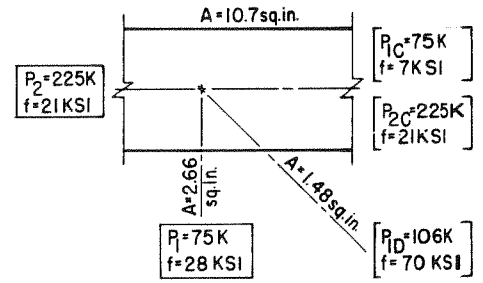


TYPES 7,8,9 (medium wall)

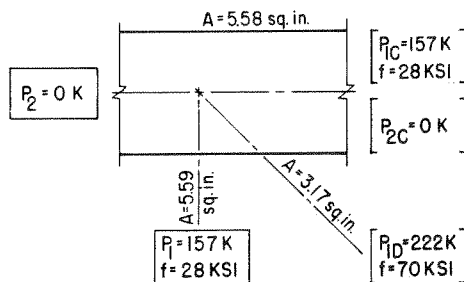
SERIES I



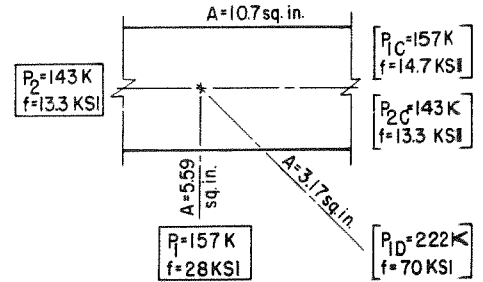
TYPE 2 (thin wall)



TYPE 2 (thick wall)



TYPE 8 (thin wall)

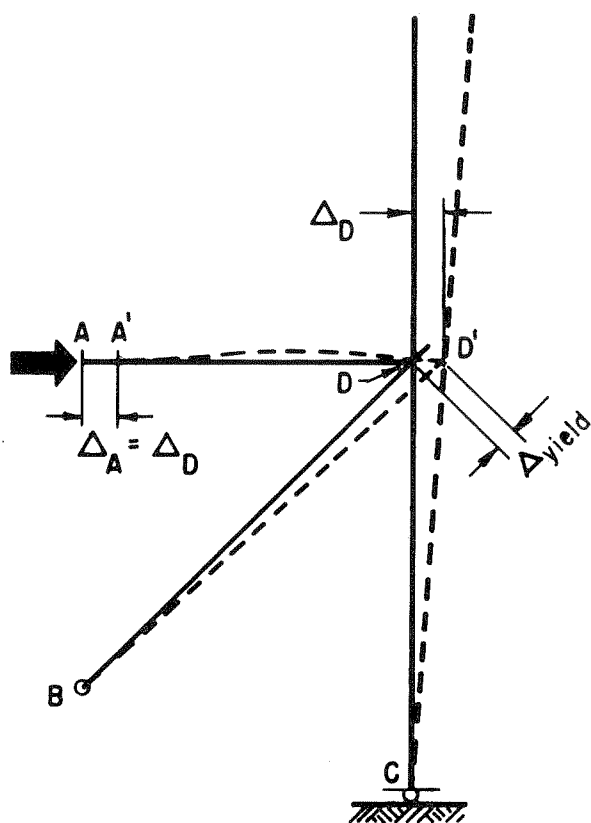


TYPE 8 (thick wall)

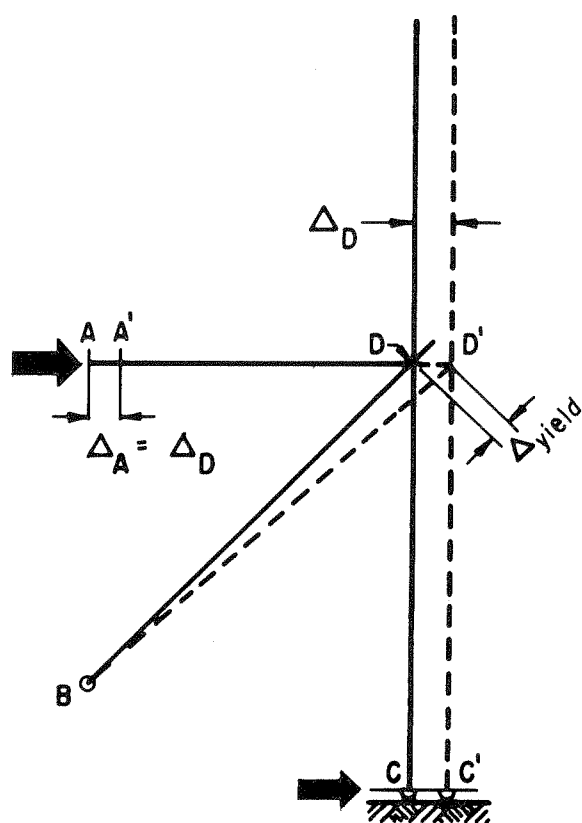
SERIES II

NOTE: SERIES II ALSO INCLUDES JOINTS 3 AND 8 (medium wall)

FIG. 10 BASIC TEST DESIGN LOADS - SERIES I AND II



(a) UNCONTROLLED SECONDARY DEFORMATIONS



CORRECTING MOVEMENT
BY AUXILIARY JACK

(b) CONTROLLED SECONDARY DEFORMATIONS

FIG.11 JOINT DEFORMATIONS IN LOADING FRAME



FIG. 12 LOADING FRAME AND RECORDING EQUIPMENT

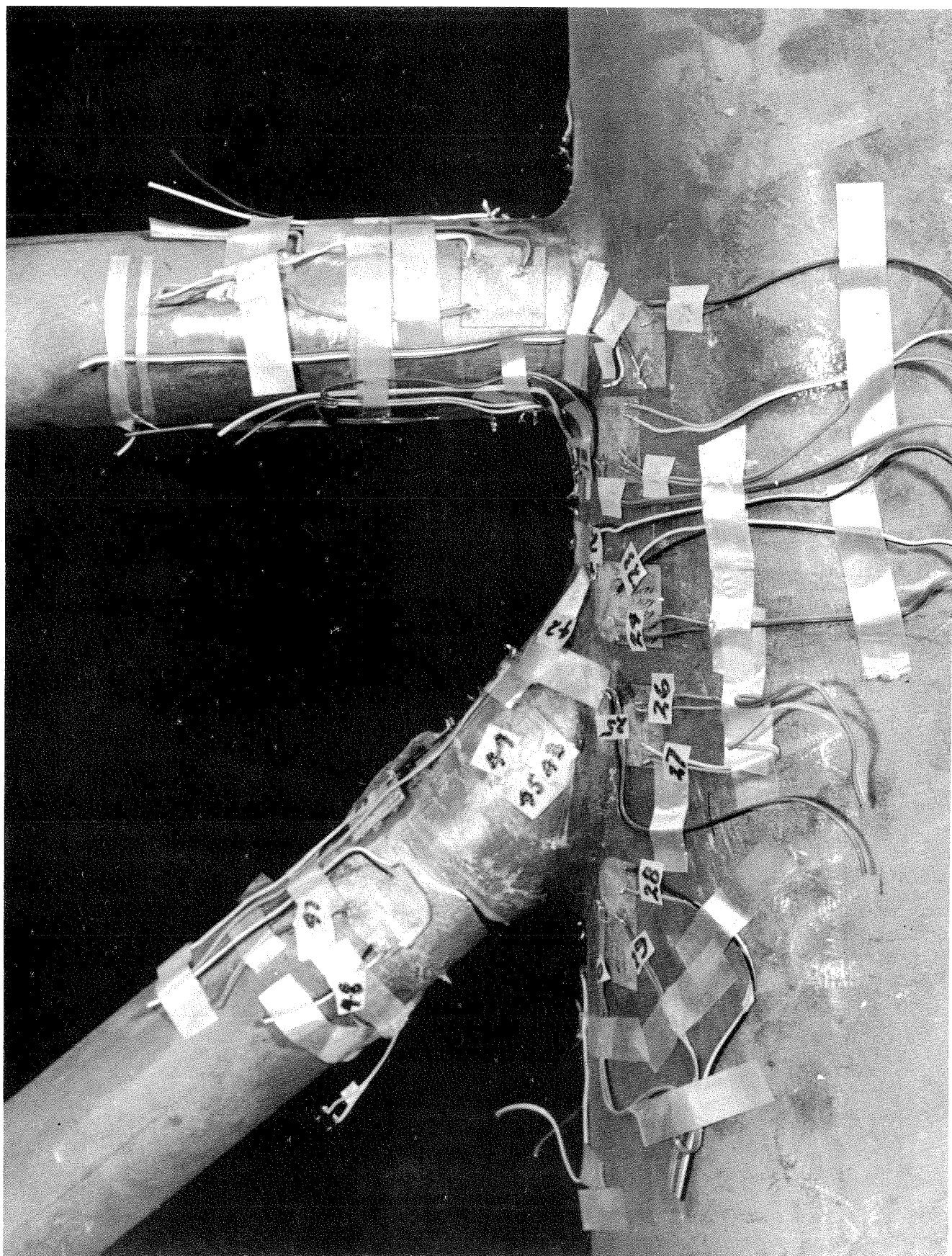


FIG. 13 JOINT TYPE I AFTER FAILURE

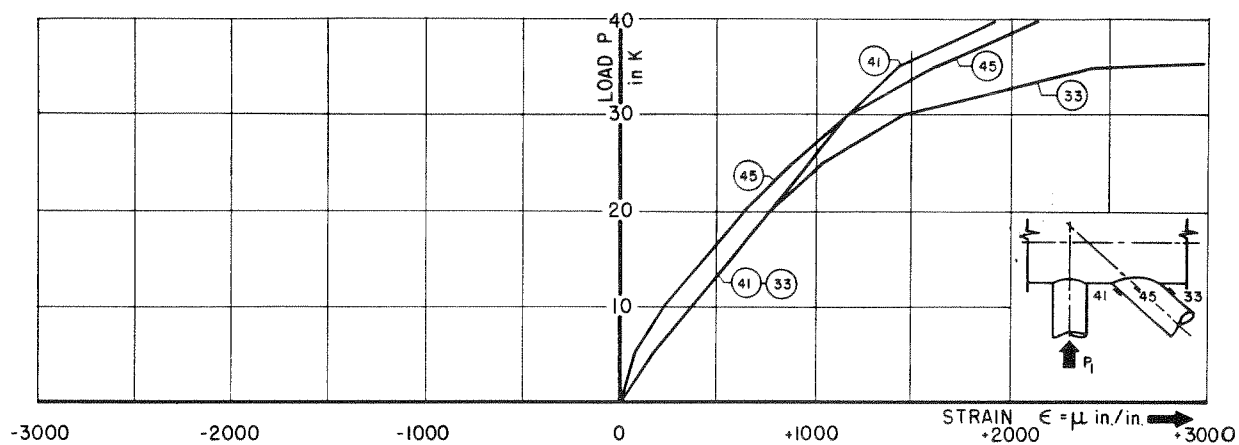


FIG.14a CRITICAL STRAINS IN JOINT TYPE I

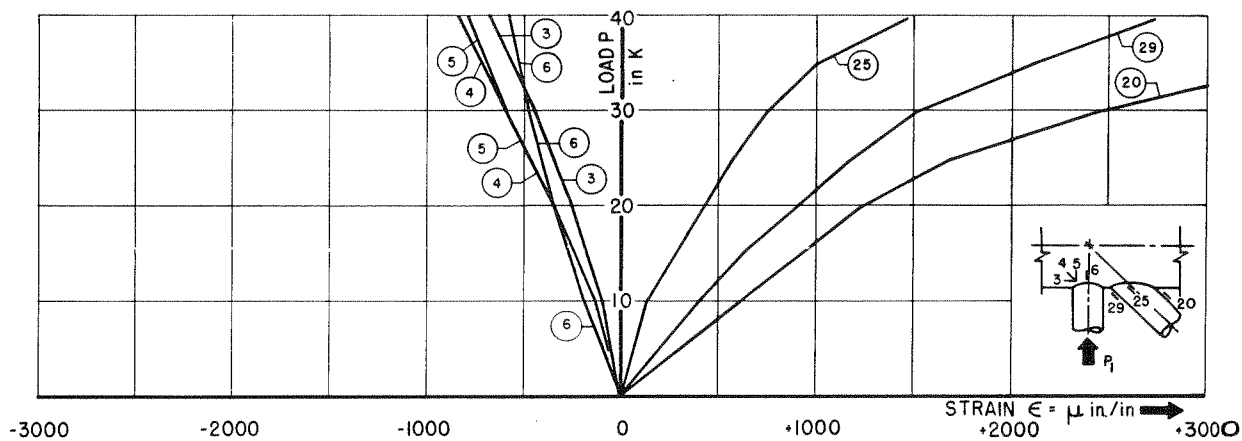


FIG.14 b CRITICAL STRAINS IN JOINT TYPE 2 (medium wall)

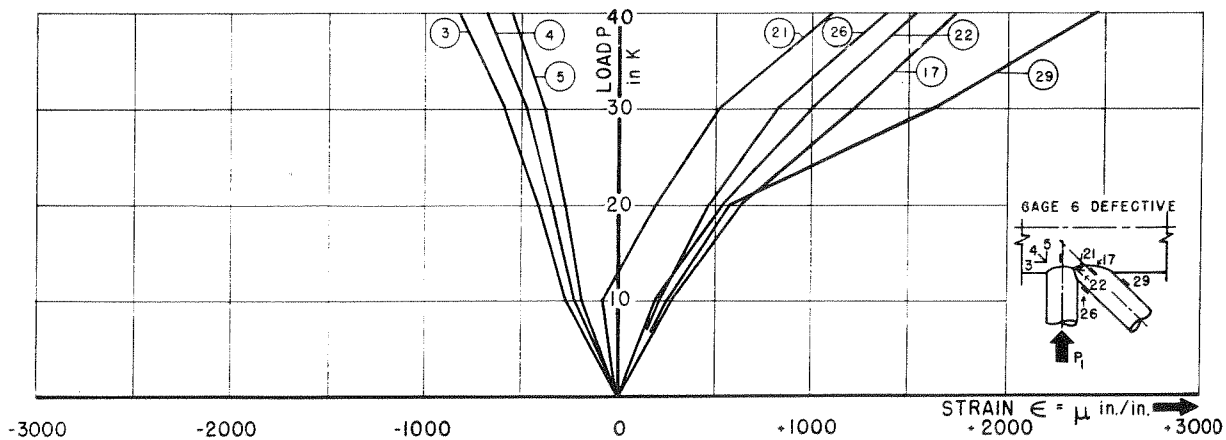
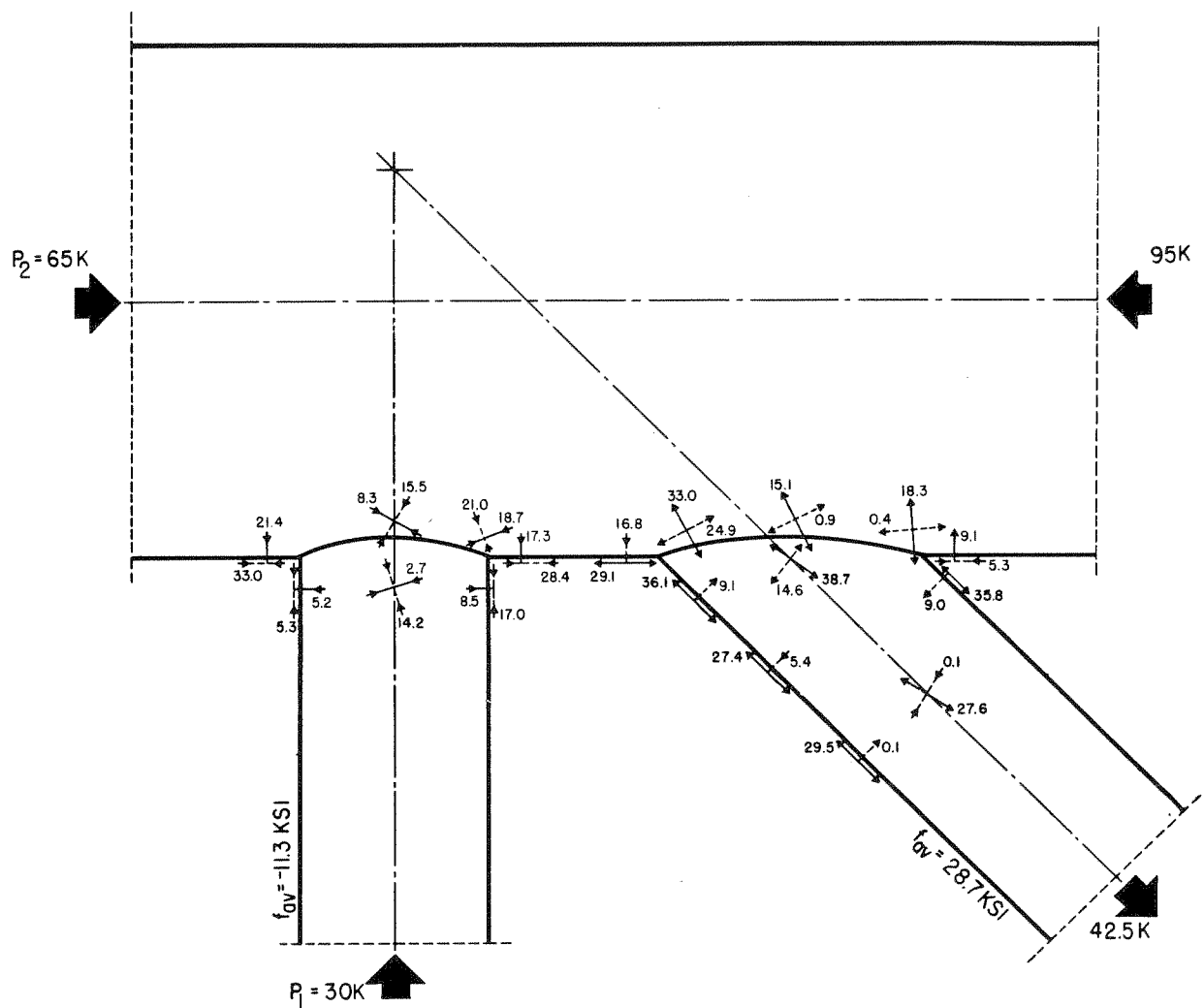


FIG.14c CRITICAL STRAINS IN JOINT TYPE 3



MEMBER DIMENSIONS

CHORD: O.D. = $6\frac{5}{8}"$ $t = 0.432"$ (MEDIUM WALL)
 VERTICAL: O.D. = $2\frac{3}{8}"$ $t = 0.436"$
 DIAGONAL: O.D. = $2\frac{3}{8}"$ $t = 0.218"$

JOINT TYPE I, POSITIVE ECCENTRICITY

STRESS VALUES IN KSI BASED ON ELASTIC STRAINS AT REFERENCE LOAD OF 30 K.

— DIRECTION OF σ_1
 - - - DIRECTION OF σ_2

← TENSION
 → COMPRESSION

FIG. 15 PRINCIPAL STRESSES AND DIRECTIONS
 JOINT TYPE I

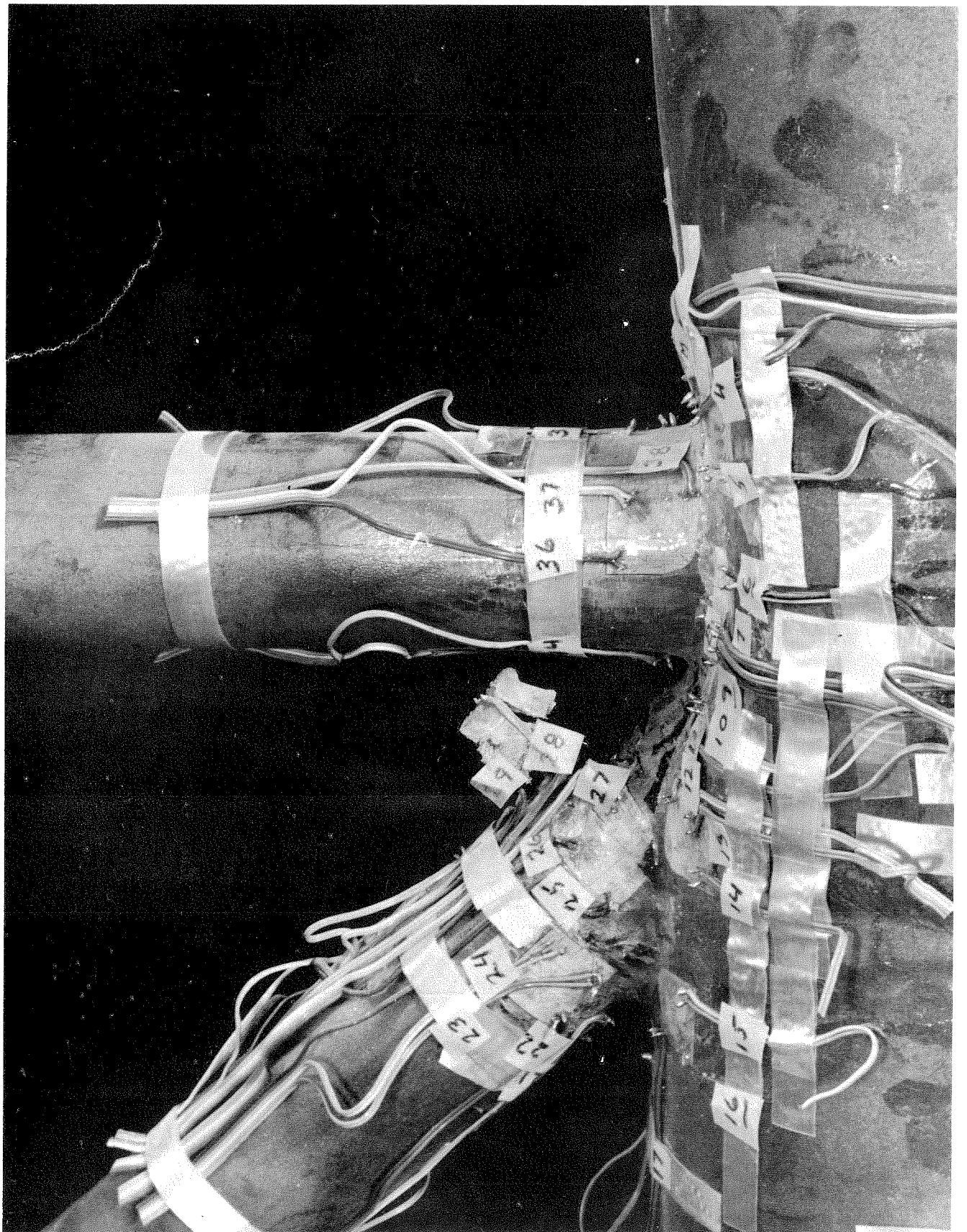


FIG.16 JOINT TYPE 2 (thin wall) AFTER FAILURE

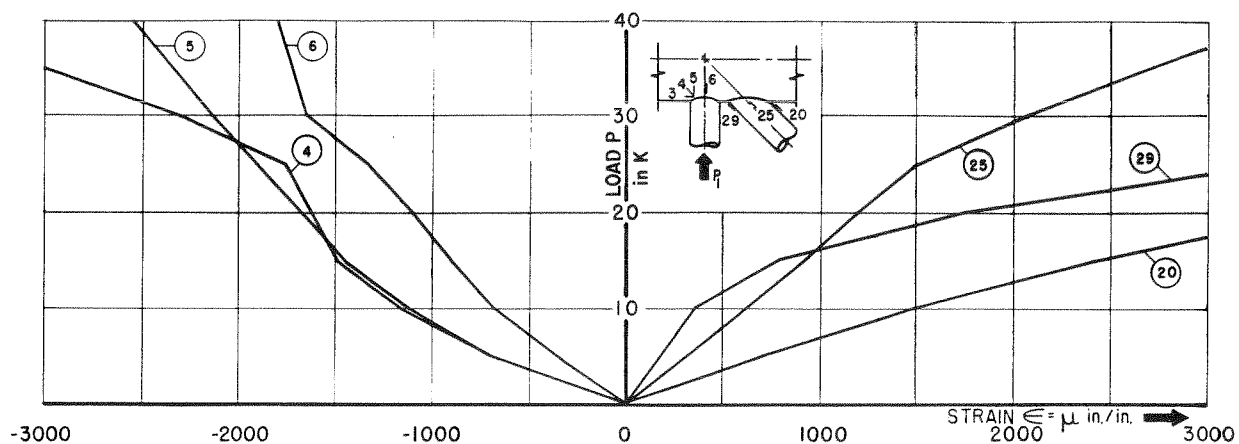


FIG.17a CRITICAL STRAINS IN JOINT TYPE 2 (thin wall)

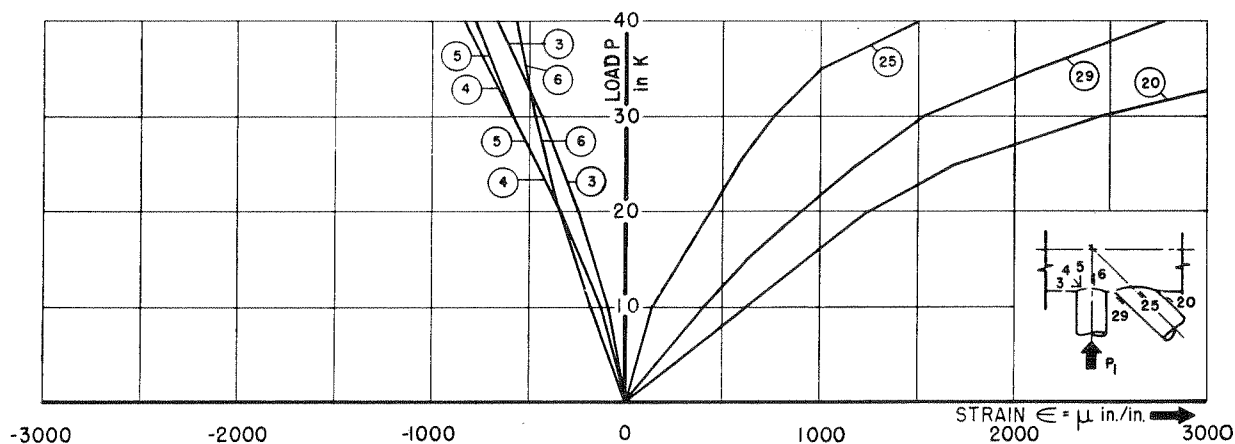


FIG.17b CRITICAL STRAINS IN JOINT TYPE 2 (medium wall)

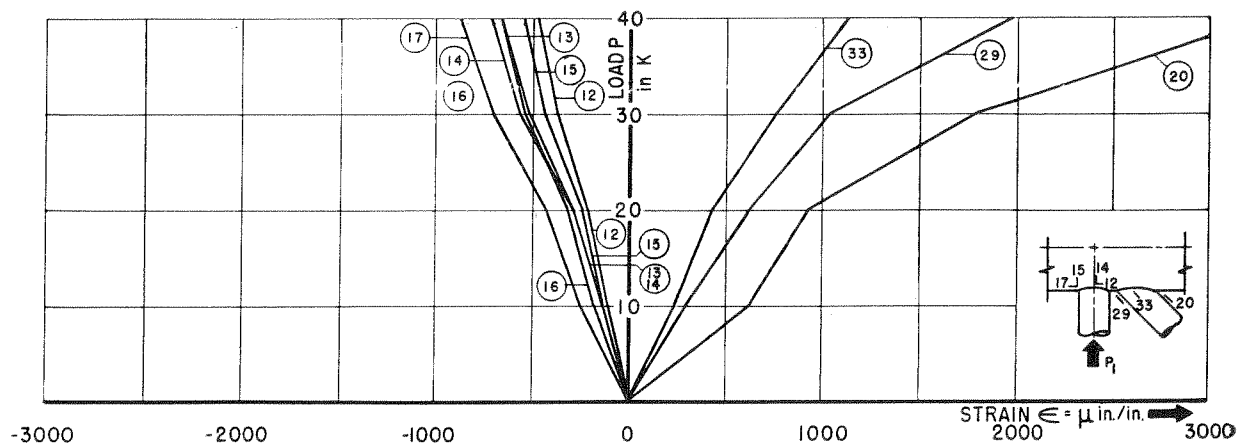
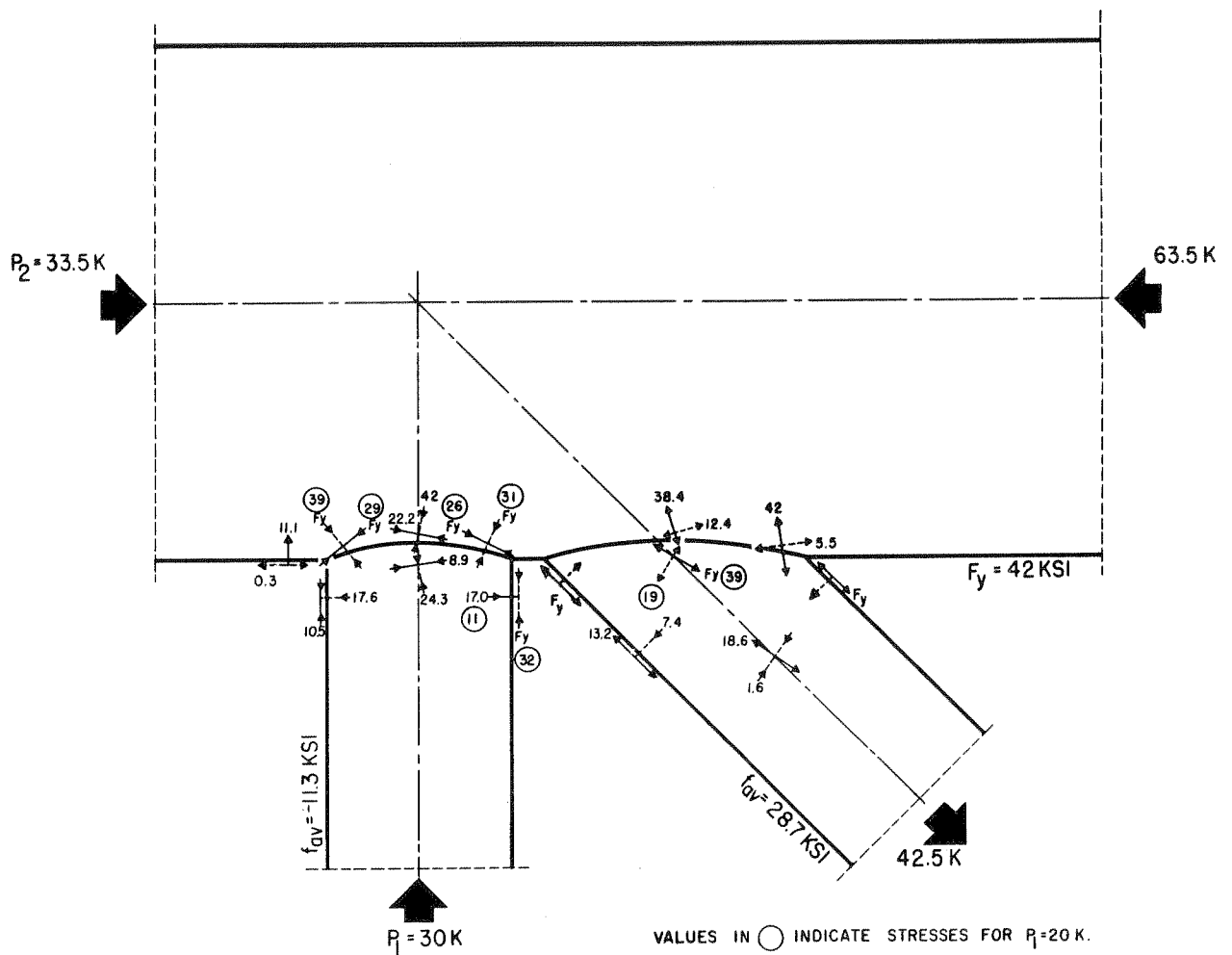


FIG.17c CRITICAL STRAINS IN JOINT TYPE 2 (thick wall)



MEMBER DIMENSION

CHORD: O.D. = $6\frac{5}{8}"$ $t = 0.280"$ (THIN WALL)
 VERTICAL: O.D. = $2\frac{3}{8}"$ $t = 0.436"$
 DIAGONAL: O.D. = $2\frac{3}{8}"$ $t = 0.218"$

JOINT TYPE 2, ZERO ECCENTRICITY

STRESS VALUES IN KSI BASED ON ELASTIC STRAINS AT REFERENCE LOAD OF 30 K.

— DIRECTION OF σ_1
 - - - DIRECTION OF σ_2

↔ TENSION
 → COMPRESSION

FIG. 18 PRINCIPAL STRESSES AND DIRECTIONS
 JOINT TYPE 2 (thin wall)

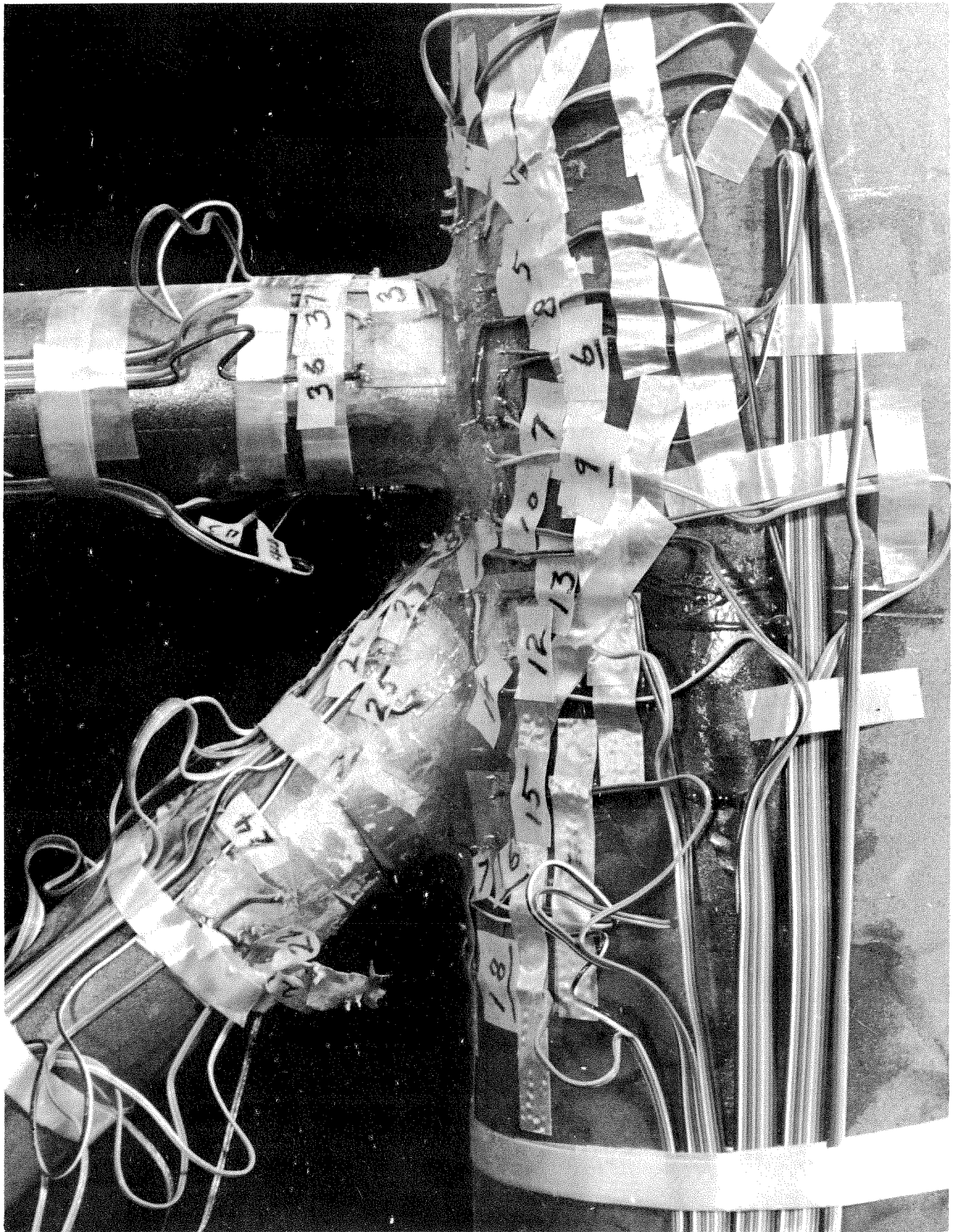
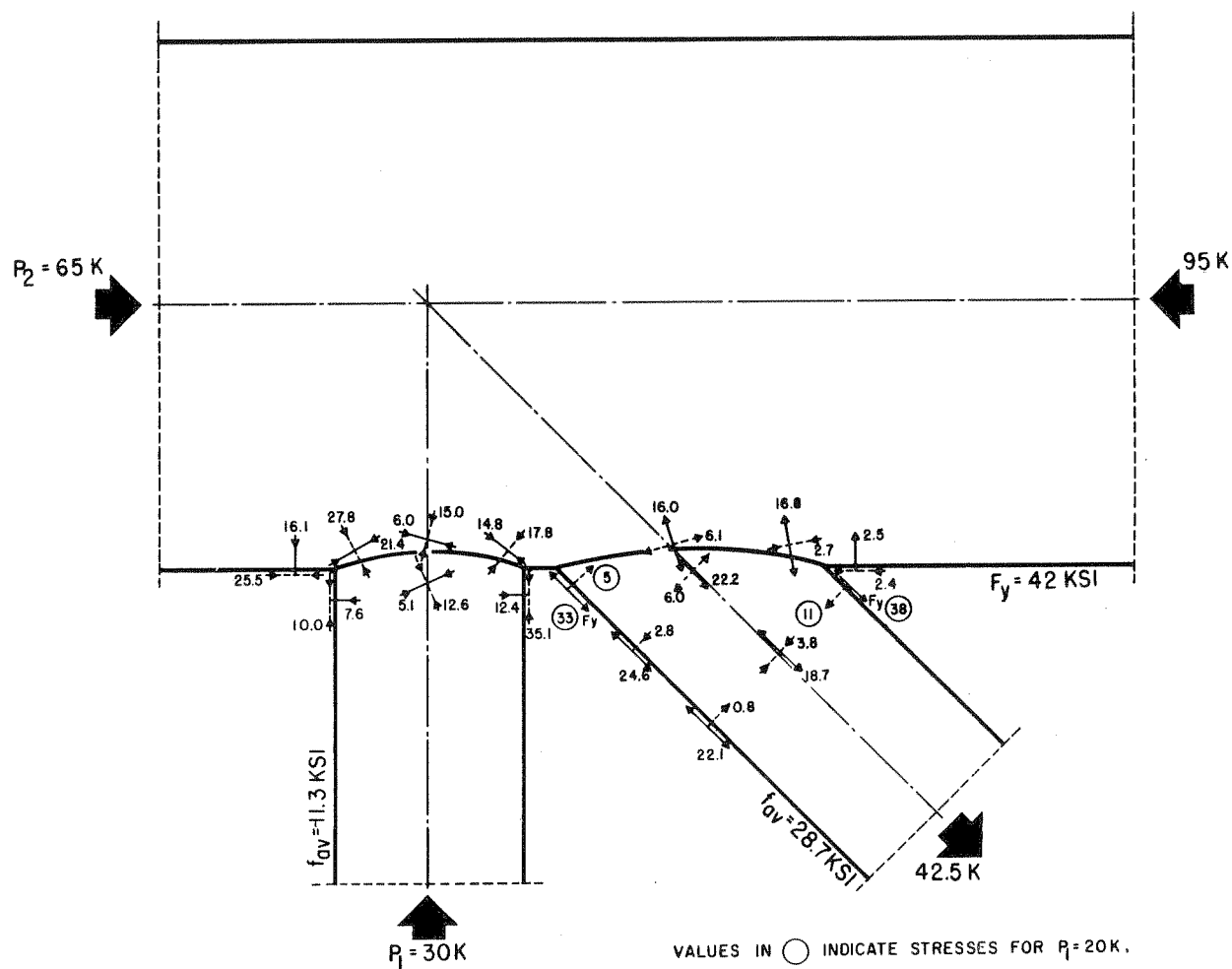


FIG. 19 JOINT TYPE 2 (medium wall) AFTER FAILURE



MEMBER DIMENSIONS

CHORD: O.D. = $6\frac{5}{8}"$ $t = 0.432"$ (MEDIUM WALL)
 VERTICAL: O.D. = $2\frac{3}{8}"$ $t = 0.436"$
 DIAGONAL: O.D. = $2\frac{3}{8}"$ $t = 0.218"$

JOINT TYPE 2, ZERO ECCENTRICITY

STRESS VALUES IN KSI BASED ON ELASTIC STRAINS AT REFERENCE LOAD OF 30K.

— DIRECTION OF σ_1
 - - - DIRECTION OF σ_2

← → TENSION
 → ← COMPRESSION

FIG. 20 PRINCIPAL STRESSES AND DIRECTIONS
 JOINT TYPE 2 (medium wall)

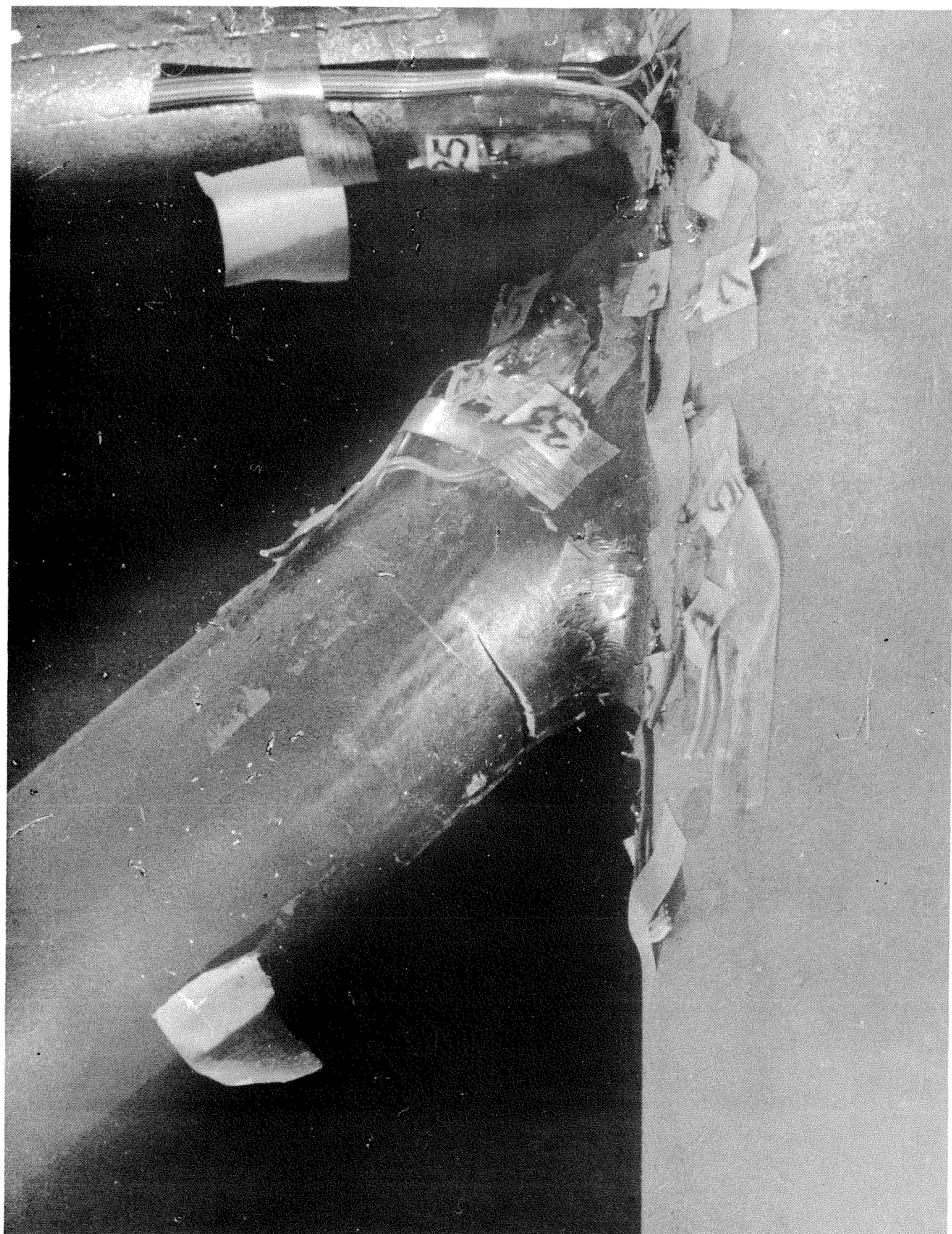
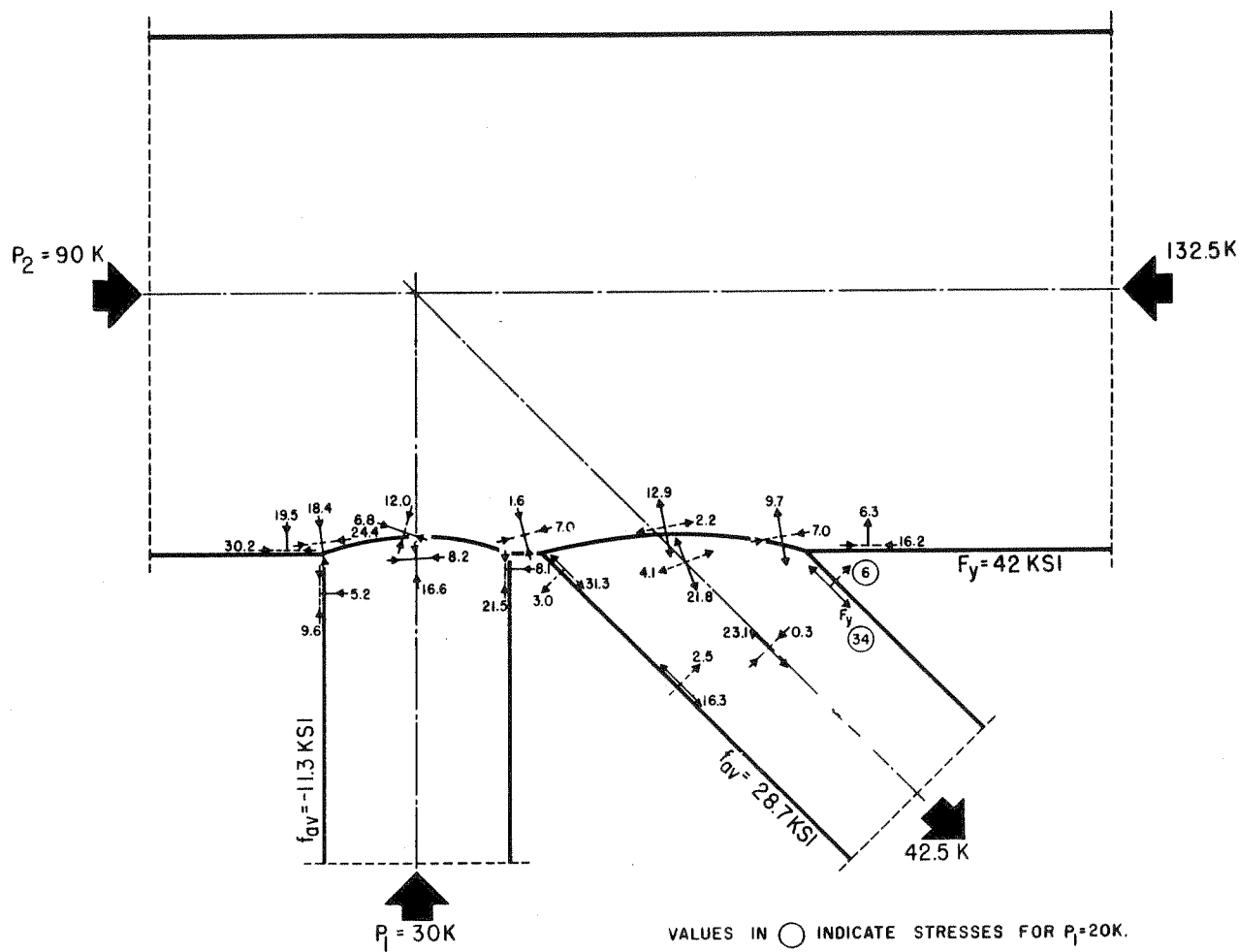


FIG. 21 JOINT TYPE 2 (thick wall) AFTER FAILURE



VALUES IN ○ INDICATE STRESSES FOR $P_1 = 20K$.

MEMBER DIMENSIONS

CHORD: O.D. = $6\frac{5}{8}"$ $t = 0.562"$ (THICK WALL)
 VERTICAL: O.D. = $2\frac{3}{8}"$ $t = 0.436"$
 DIAGONAL: O.D. = $2\frac{3}{8}"$ $t = 0.218"$

JOINT TYPE 2, ZERO ECCENTRICITY

STRESS VALUES IN KSI BASED ON ELASTIC STRAINS AT REFERENCE LOAD OF 30K.

— DIRECTION OF σ_1
 - - - DIRECTION OF σ_2

↔ TENSION
 ⇝ COMPRESSION

FIG. 22 PRINCIPAL STRESSES AND DIRECTIONS
 JOINT TYPE 2 (thick wall)

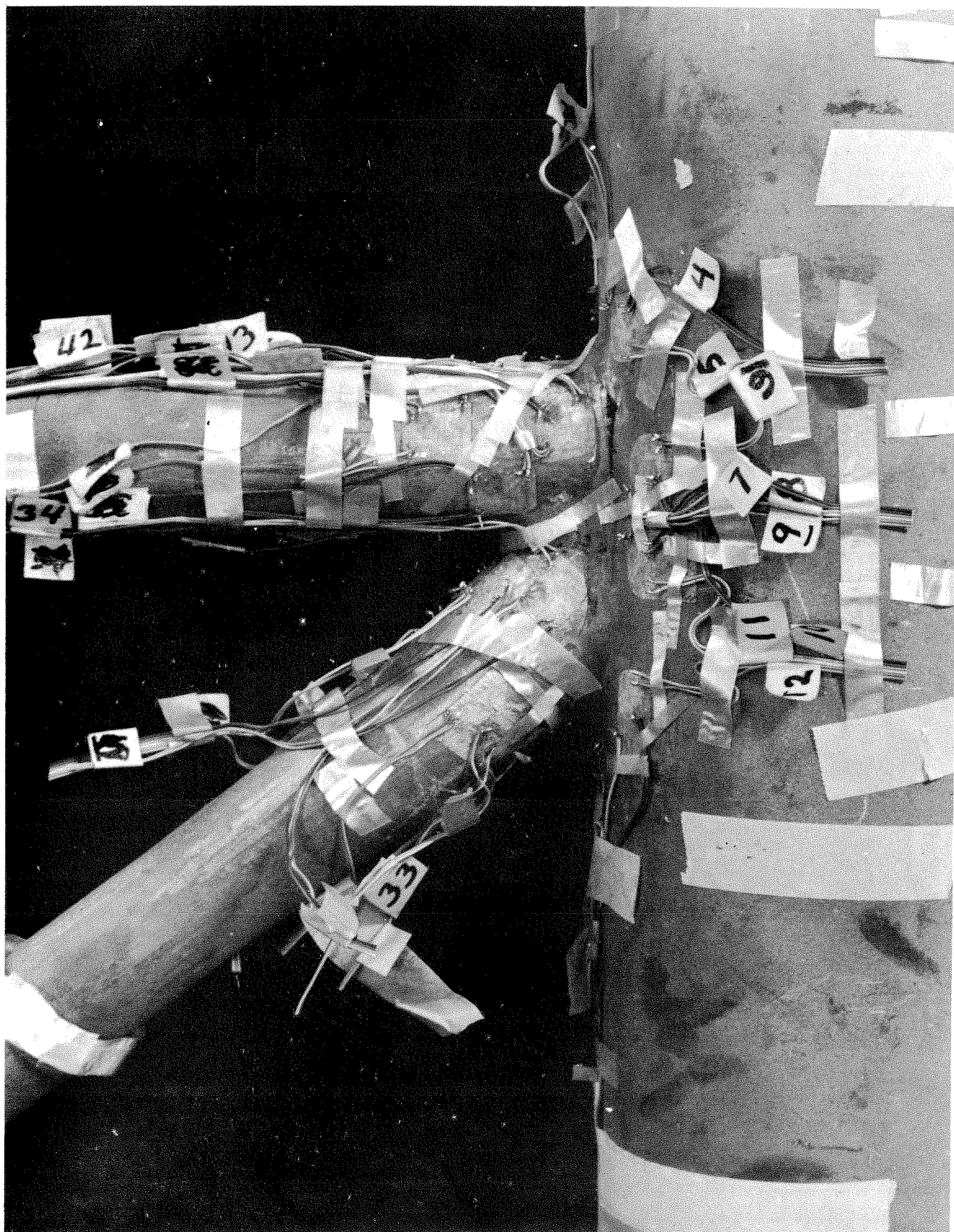
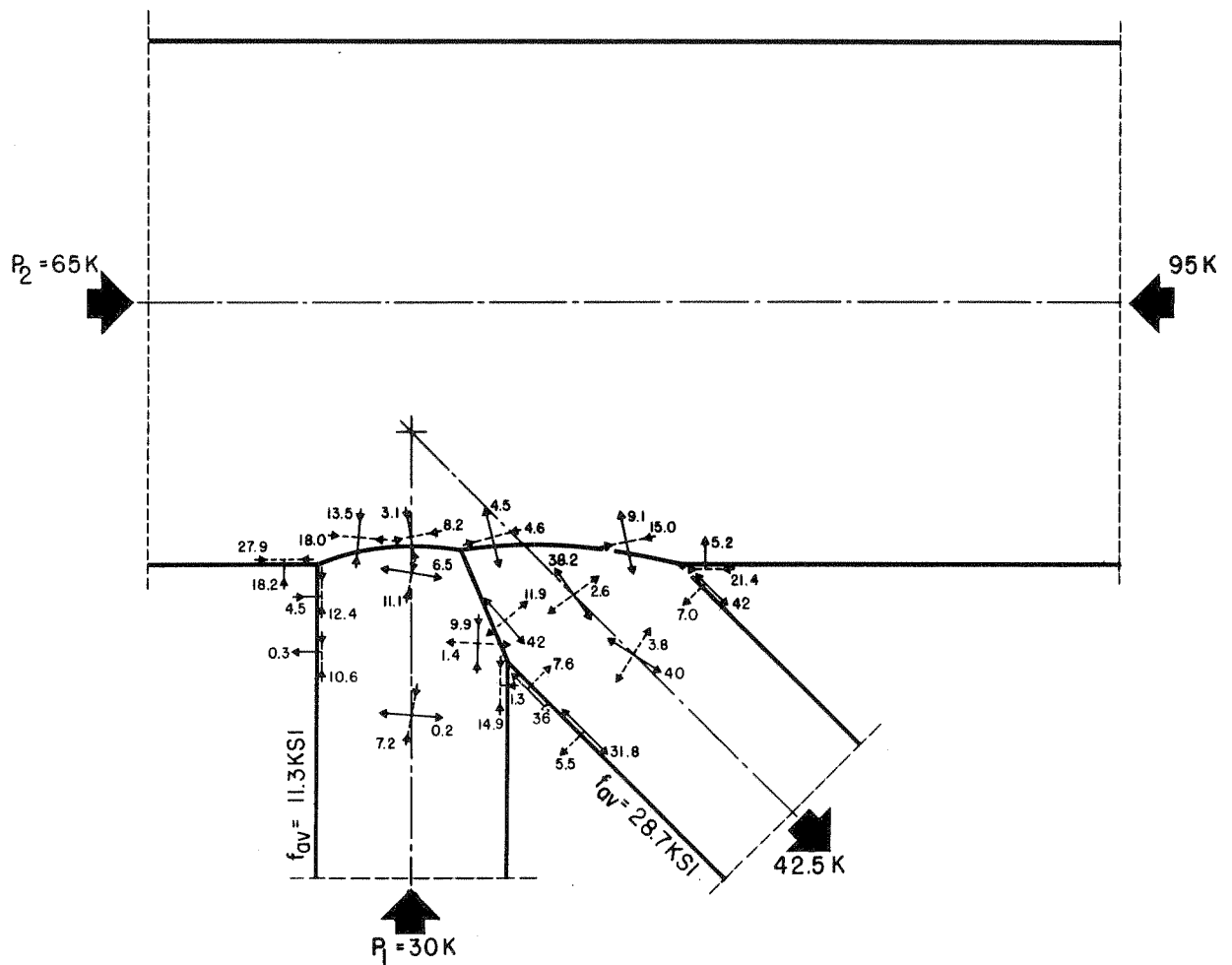


FIG. 23 JOINT TYPE 3 AFTER FAILURE



MEMBER DIMENSIONS

CHORD: O.D. = $6\frac{5}{8}"$ $t = 0.432"$ (MEDIUM WALL)
 VERTICAL: O.D. = $2\frac{3}{8}"$ $t = 0.436"$
 DIAGONAL: O.D. = $2\frac{3}{8}"$ $t = 0.218"$

JOINT TYPE 3, NEGATIVE ECCENTRICITY

STRESS VALUES IN KSI BASED ON ELASTIC STRAINS AT REFERENCE LOAD OF 30K.

——— DIRECTION OF σ_1

----- DIRECTION OF σ_2

←→ TENSION

→← COMPRESSION

FIG. 24 PRINCIPAL STRESSES AND DIRECTIONS
JOINT TYPE 3

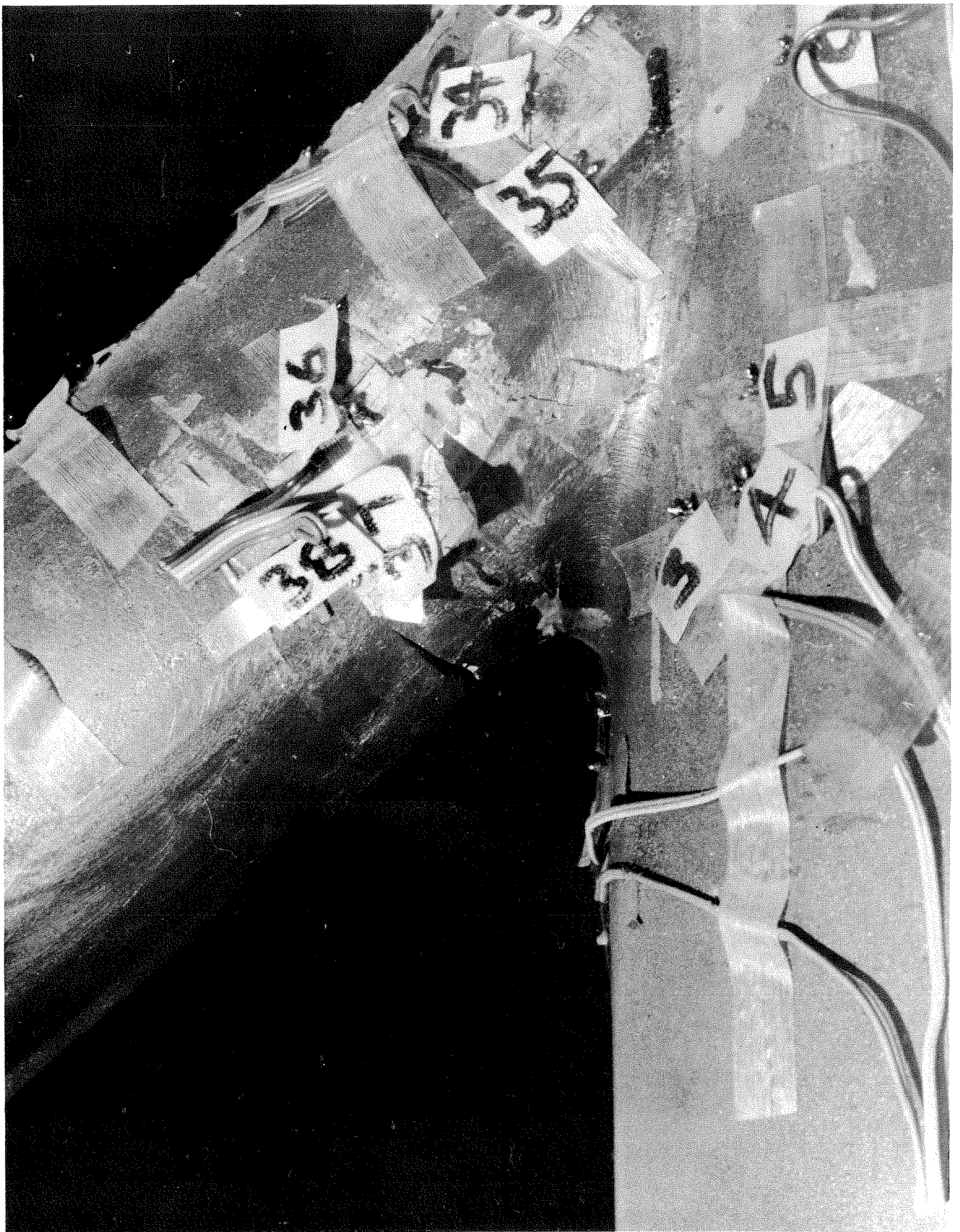


FIG. 25 JOINT TYPE 4 AFTER FAILURE

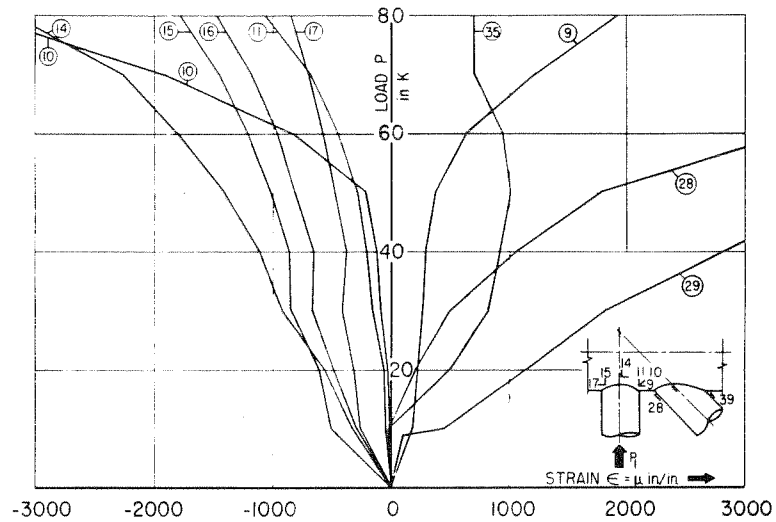


FIG. 26a CRITICAL STRAINS IN JOINT TYPE 4

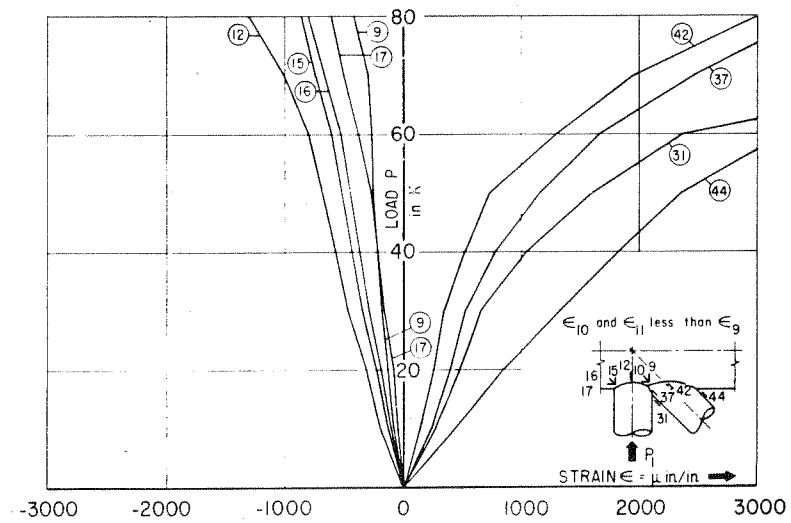


FIG. 26b CRITICAL STRAINS IN JOINT TYPE 5

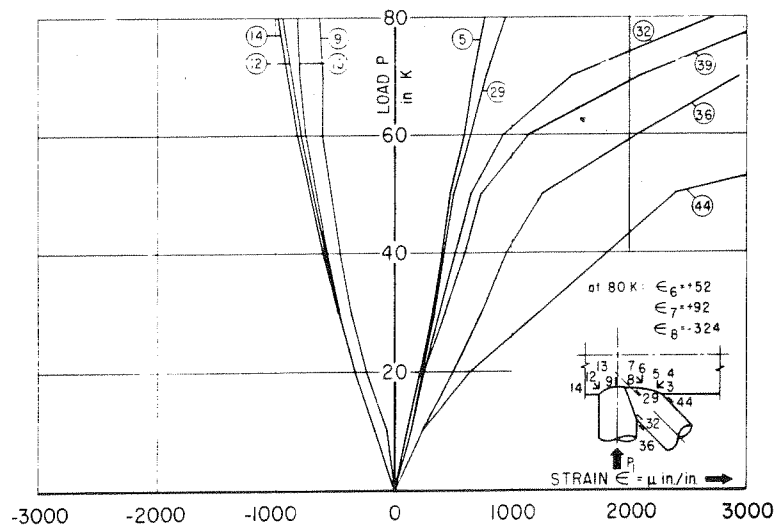
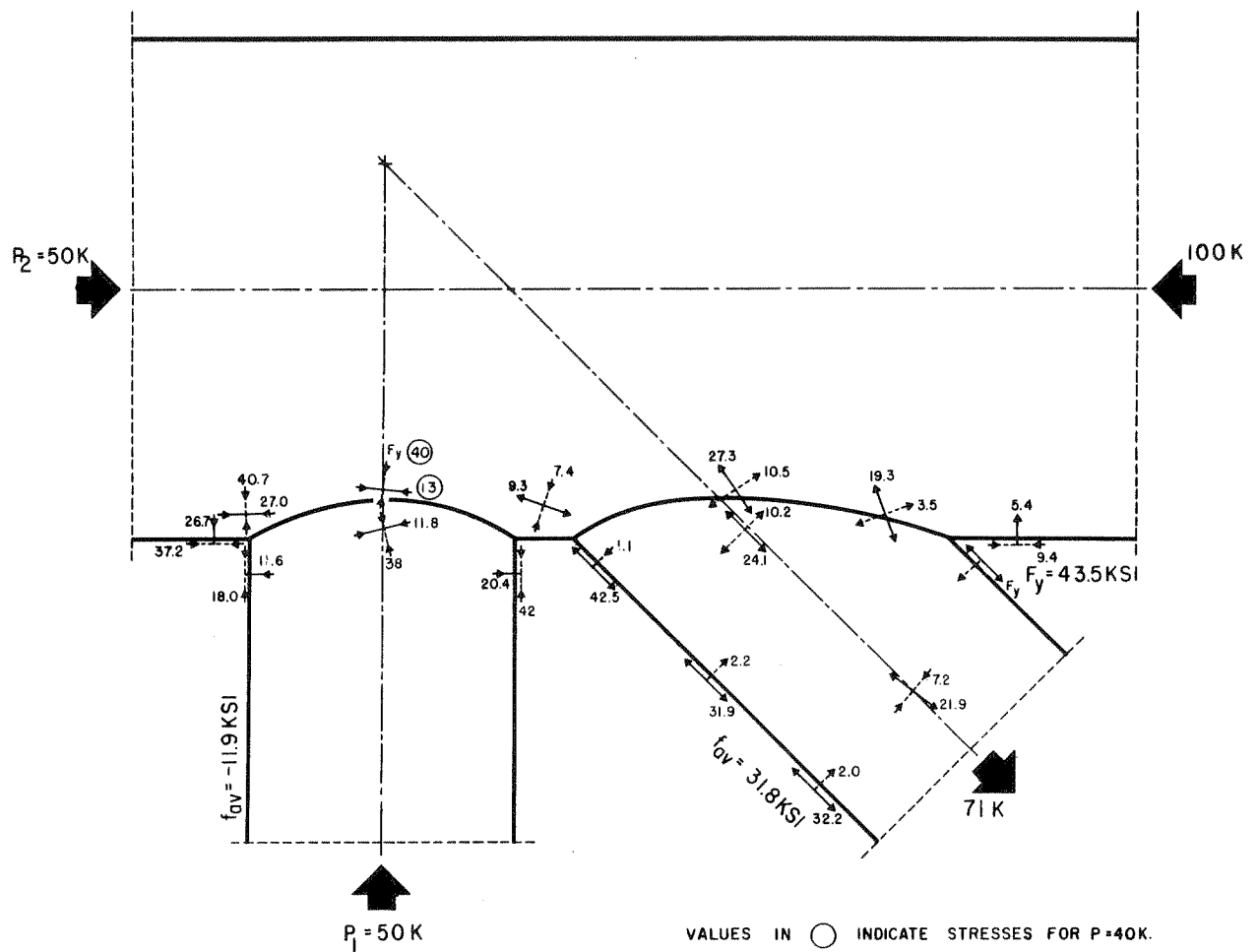


FIG. 26c CRITICAL STRAINS IN JOINT TYPE 4



MEMBER DIMENSIONS

CHORD: O.D. = $6\frac{5}{8}"$ $t = 0.432"$ (MEDIUM WALL)
 VERTICAL: O.D. = $3\frac{1}{2}"$ $t = 0.438"$
 DIAGONAL: O.D. = $3\frac{1}{2}"$ $t = 0.216"$

JOINT TYPE 4, POSITIVE ECCENTRICITY

STRESS VALUES IN KSI BASED ON ELASTIC STRAINS AT REFERENCE LOAD OF 50 K.

— DIRECTION OF σ_1
 - - - DIRECTION OF σ_2

↔ TENSION
 → COMPRESSION

FIG. 27 PRINCIPAL STRESSES AND DIRECTIONS
 JOINT TYPE 4

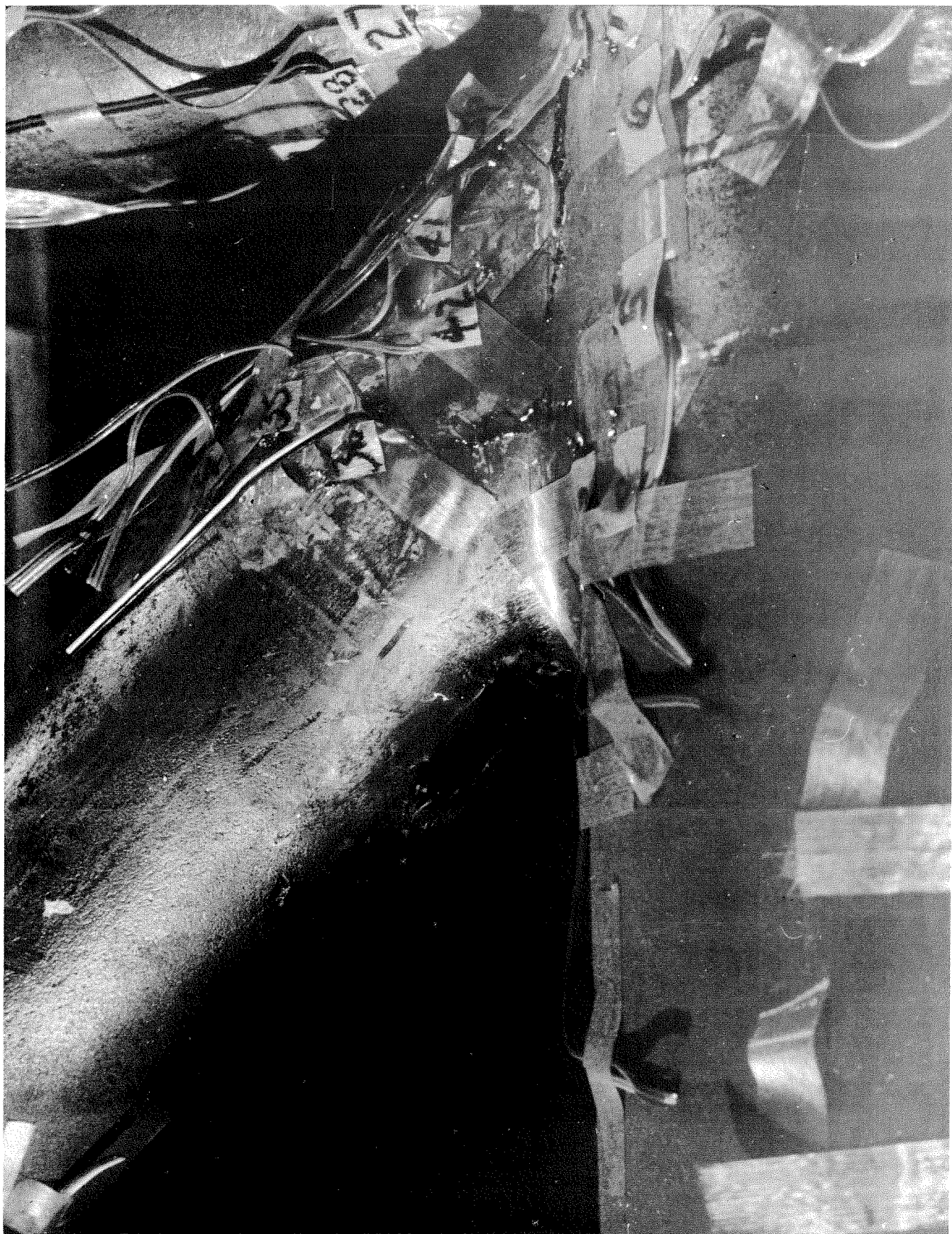
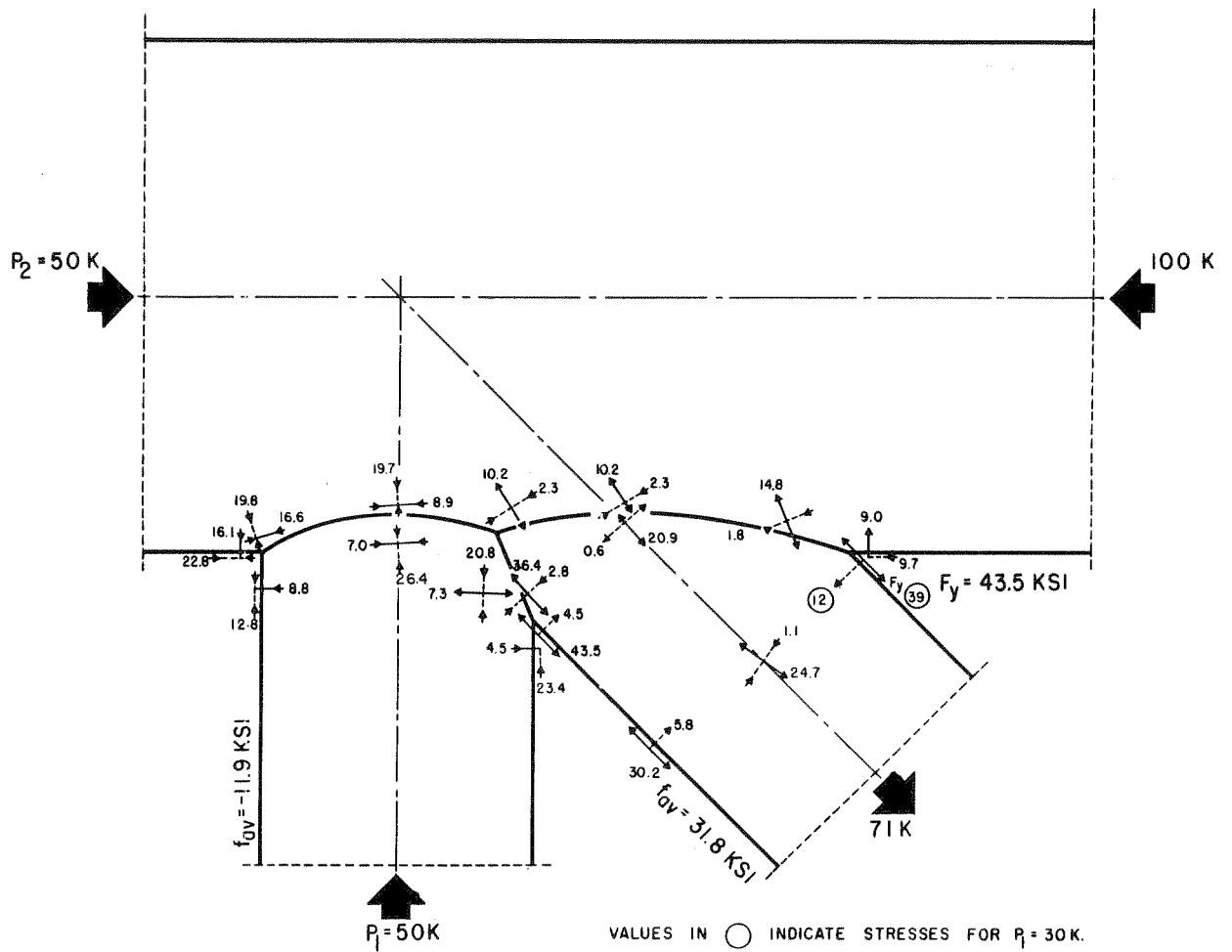


FIG. 28 JOINT TYPE 5 AFTER FAILURE



MEMBER DIMENSIONS

CHORD: O.D. = $6\frac{5}{8}"$ $t = 0.432"$ (MEDIUM WALL)
 VERTICAL: O.D. = $3\frac{1}{2}"$ $t = 0.438"$
 DIAGONAL: O.D. = $3\frac{1}{2}"$ $t = 0.216"$

JOINT TYPE 5, ZERO ECCENTRICITY

STRESS VALUES IN KSI BASED ON ELASTIC STRAINS AT REFERENCE LOAD OF 50 K.

——— DIRECTION OF σ_1
 - - - - DIRECTION OF σ_2

↔ TENSION
 → COMPRESSION

FIG. 29 PRINCIPAL STRESSES AND DIRECTIONS
 JOINT TYPE 5

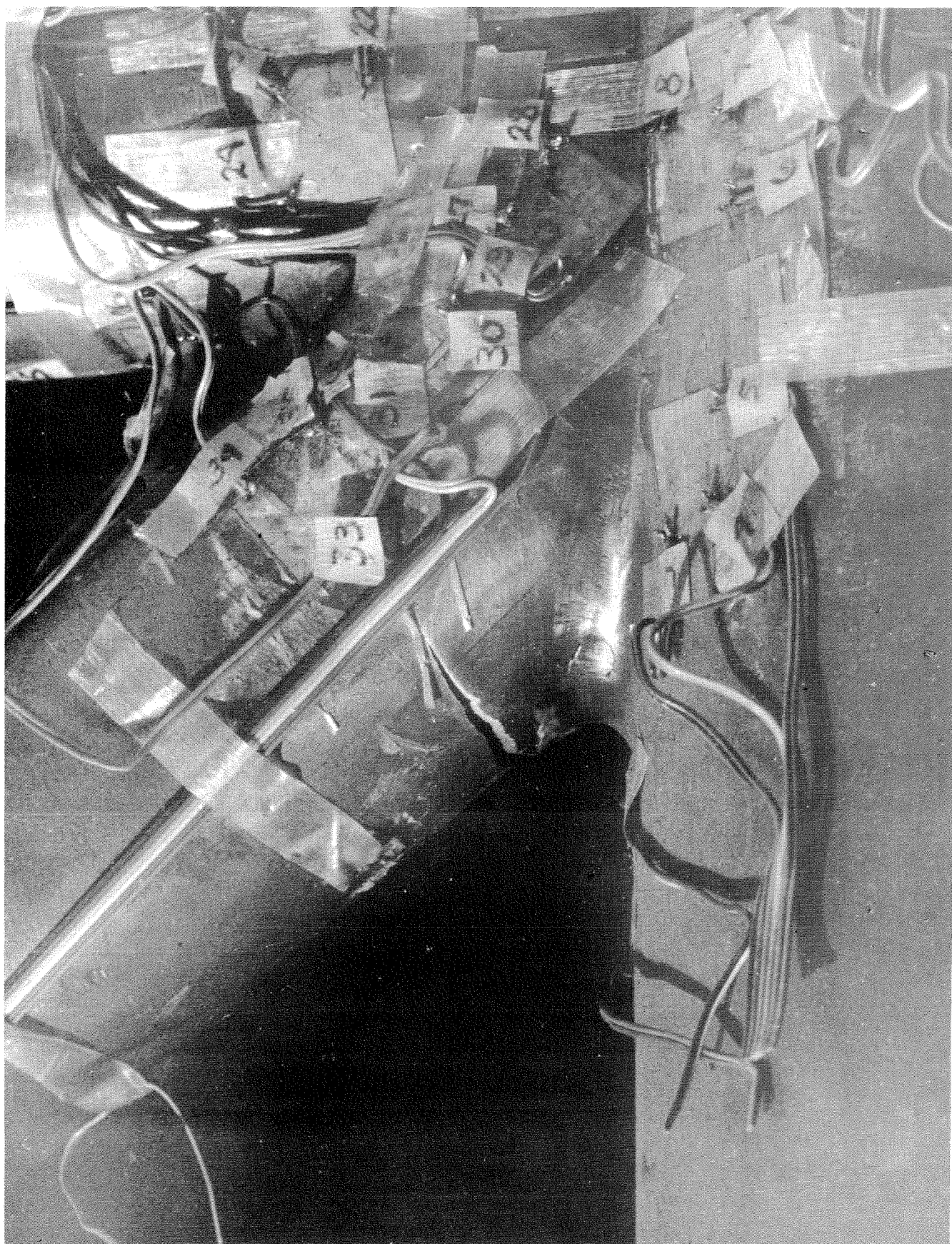
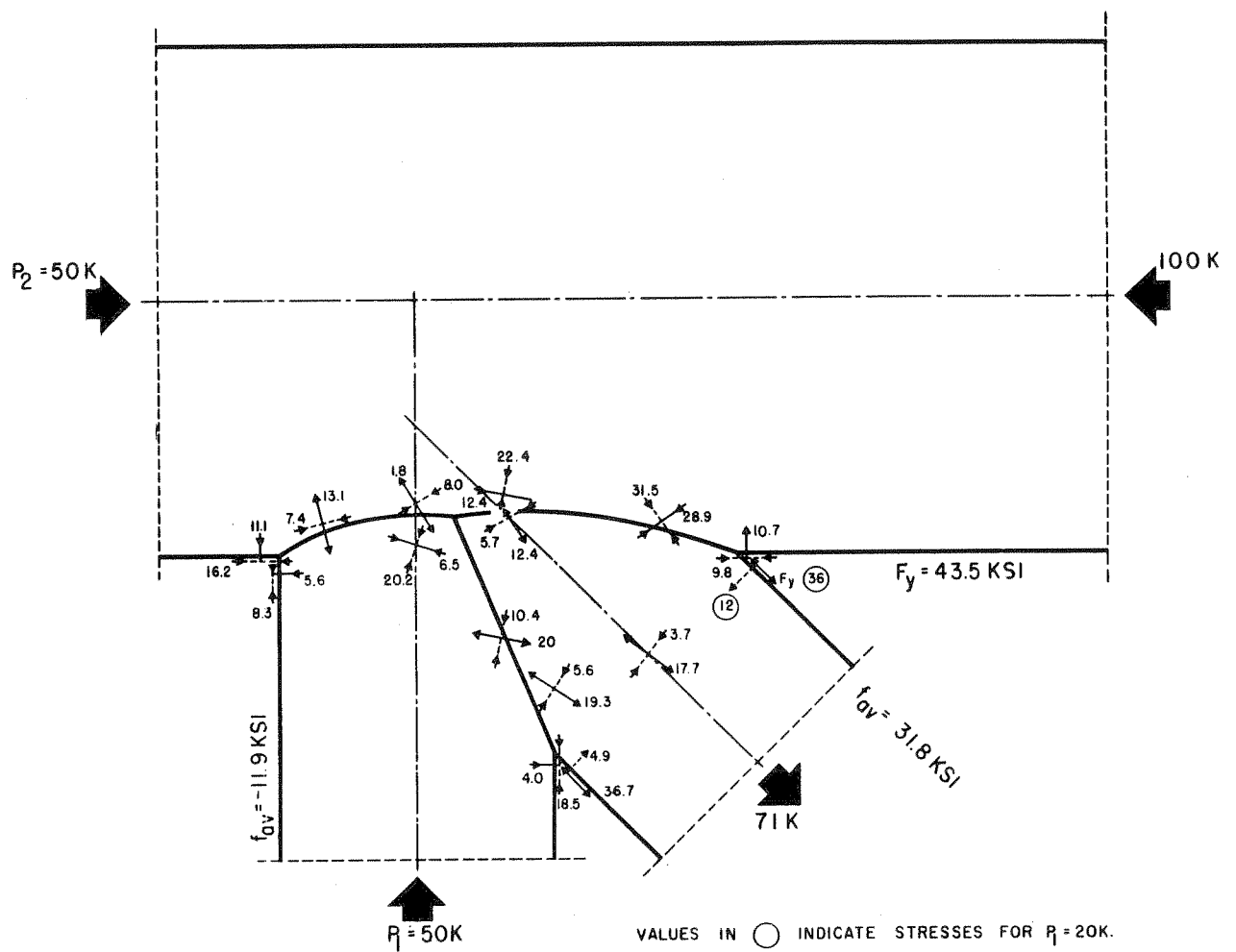


FIG. 30 JOINT TYPE 6 AFTER FAILURE



MEMBER DIMENSIONS

CHORD: O.D. = $6\frac{5}{8}"$ $t = 0.432"$ (MEDIUM WALL)
 VERTICAL: O.D. = $3\frac{1}{2}"$ $t = 0.438"$
 DIAGONAL: O.D. = $3\frac{1}{2}"$ $t = 0.216"$

JOINT TYPE 6, NEGATIVE ECCENTRICITY

STRESS VALUES IN KSI, BASED ON ELASTIC STRAINS AT REFERENCE LOAD OF 50K.

— DIRECTION OF σ_1
 - - - DIRECTION OF σ_2

← TENSION
 → COMPRESSION

FIG. 31 PRINCIPAL STRESSES AND DIRECTIONS
 JOINT TYPE 6

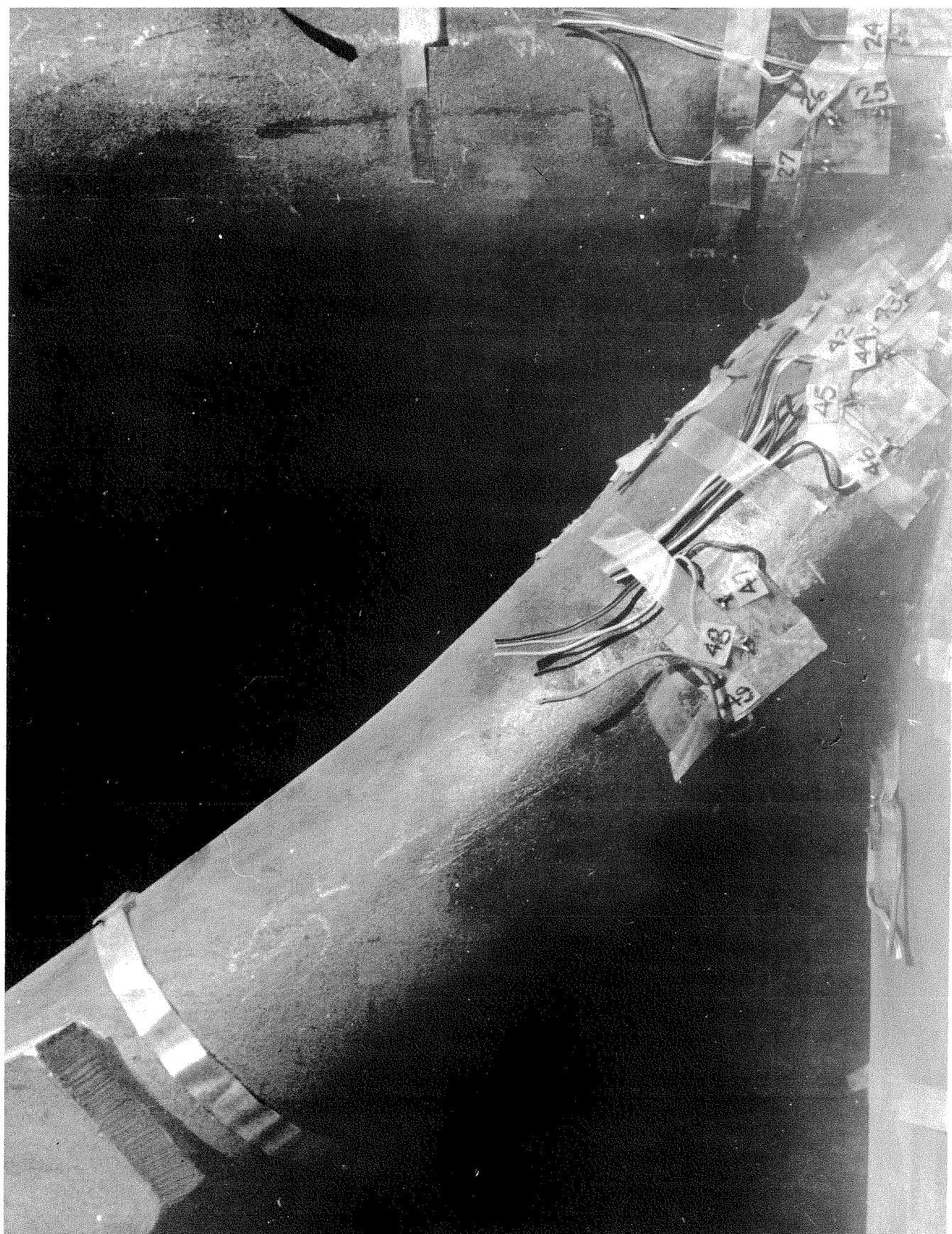


FIG. 32 JOINT TYPE 7 AFTER FAILURE

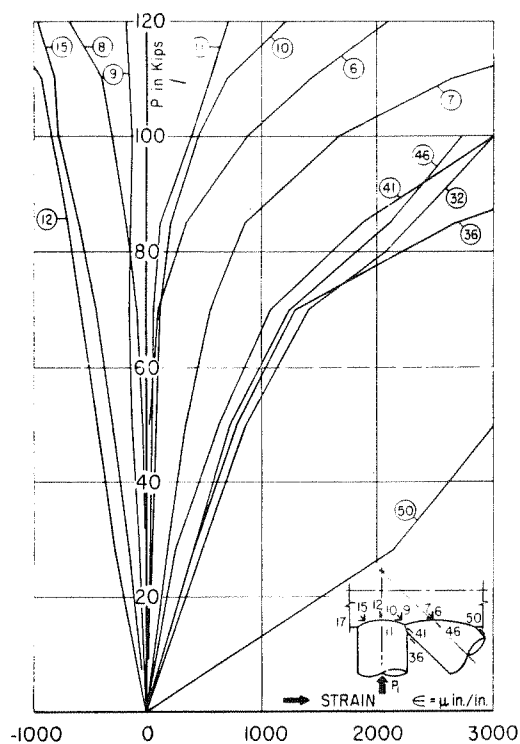


FIG. 33a CRITICAL STRAINS IN JOINT TYPE 7

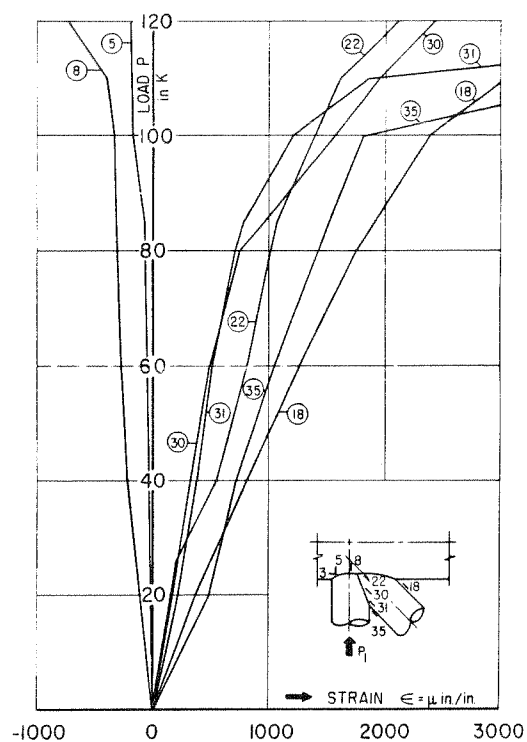


FIG. 33c CRITICAL STRAINS IN JOINT TYPE 9

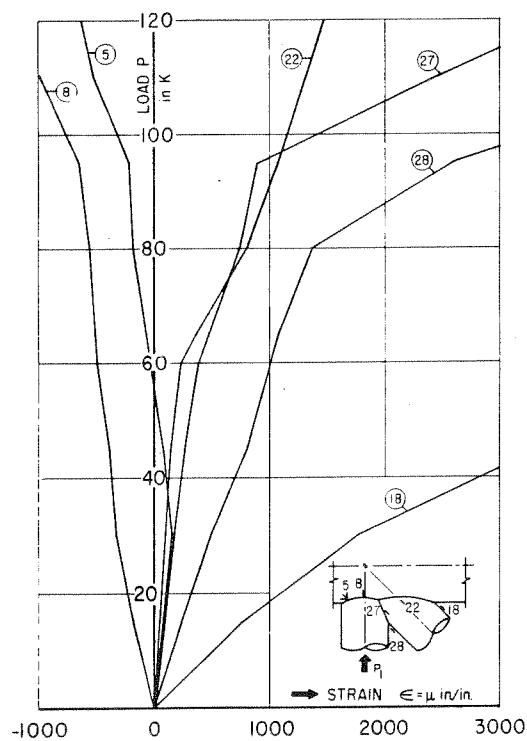
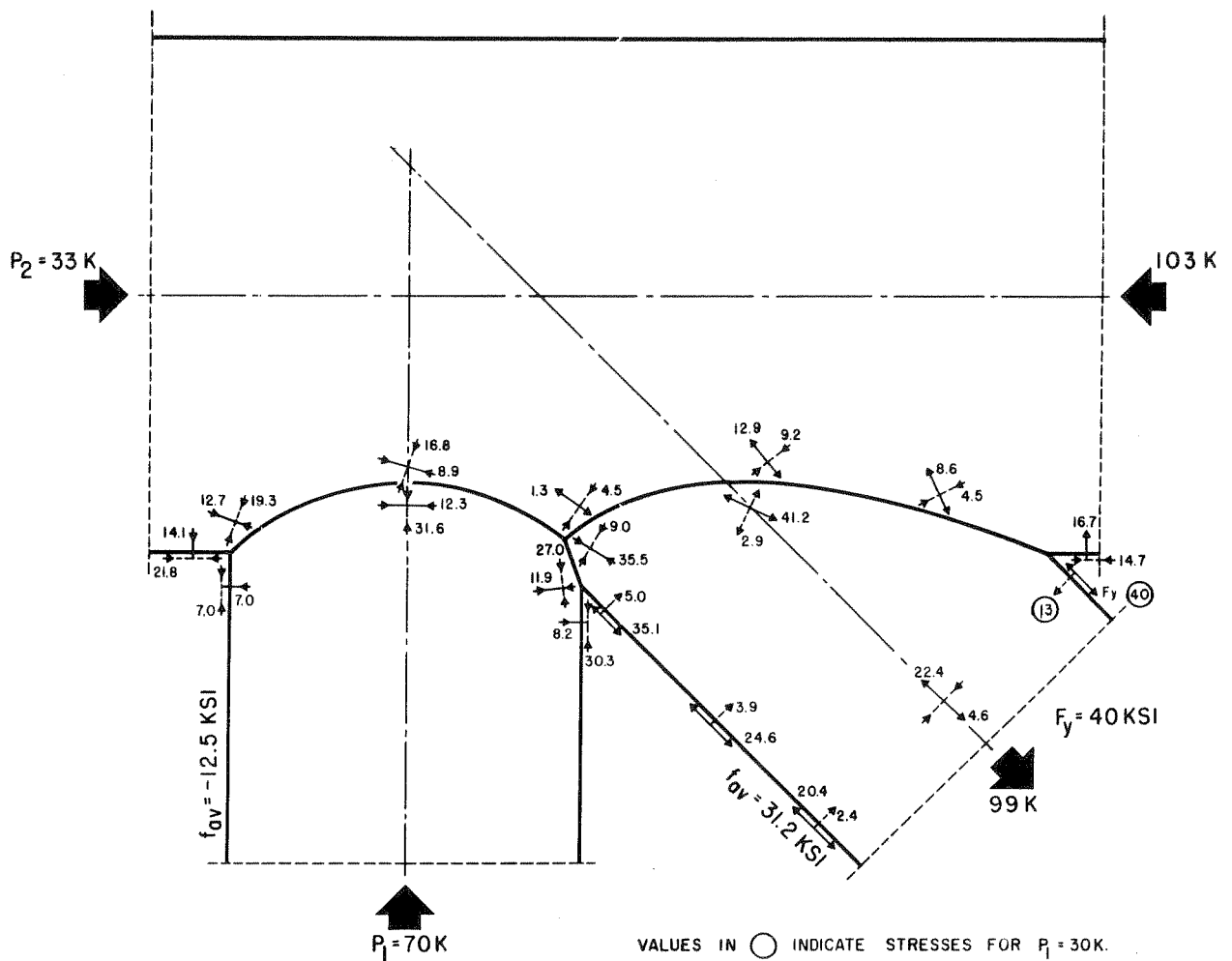


FIG. 33b CRITICAL STRAINS IN JOINT TYPE 8
(medium wall)



MEMBER DIMENSIONS

CHORD: O.D. = $6 \frac{5}{8}''$ $t = 0.432''$ (MEDIUM WALL)
 VERTICAL: O.D. = $4 \frac{1}{2}''$ $t = 0.438''$
 DIAGONAL: O.D. = $4 \frac{1}{2}''$ $t = 0.237''$

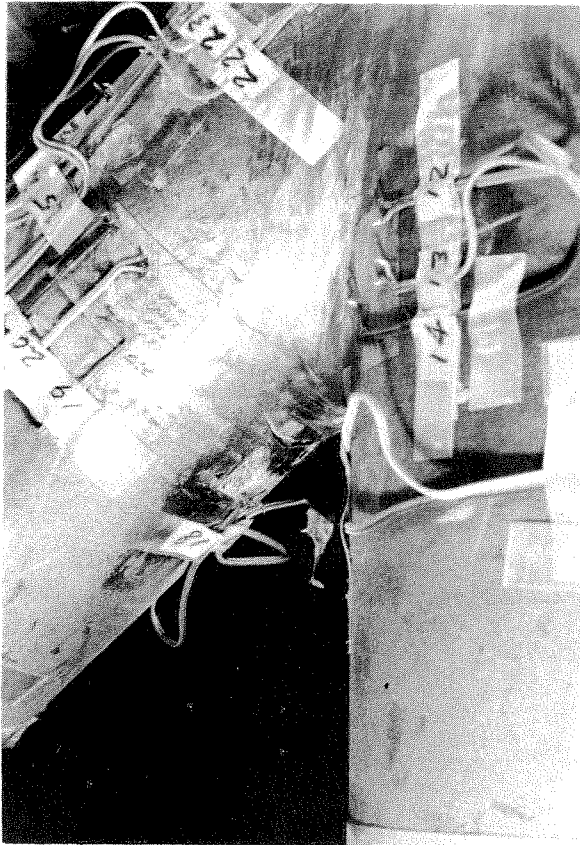
JOINT TYPE 7, POSITIVE ECCENTRICITY

STRESS VALUES IN KSI BASED ON ELASTIC STRAINS AT REFERENCE LOAD OF 70 K .

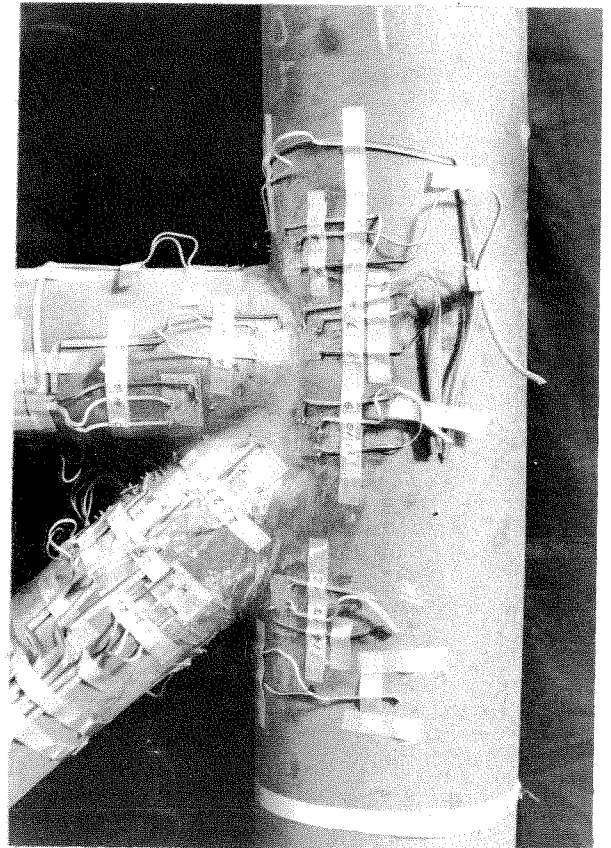
— DIRECTION OF σ_1
 - - - DIRECTION OF σ_2

← TENSION
 → COMPRESSION

FIG. 34 PRINCIPAL STRESSES AND DIRECTIONS
 JOINT TYPE 7



35 a



35 b

FIG. 35 JOINT TYPE 8 (thin wall) AFTER FAILURE

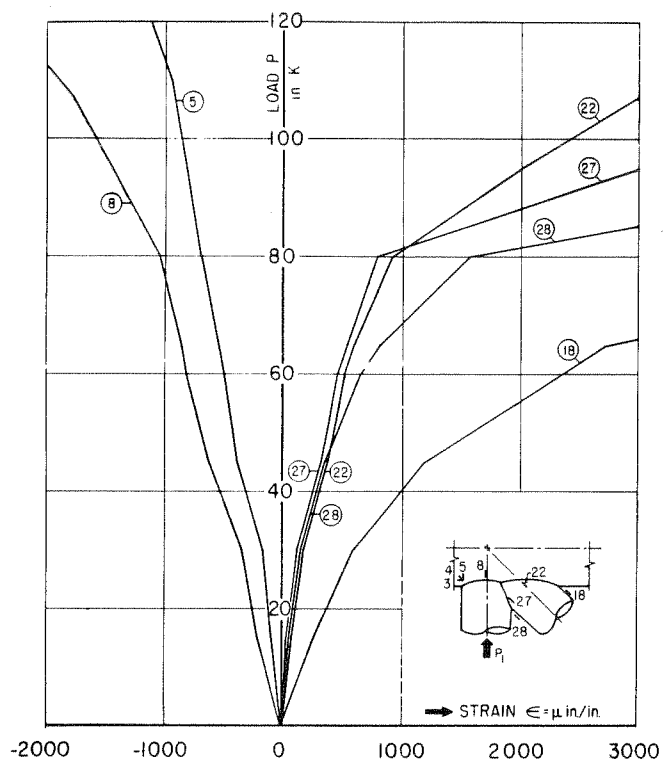


FIG. 36a CRITICAL STRAINS IN JOINT TYPE 8
(thin wall)

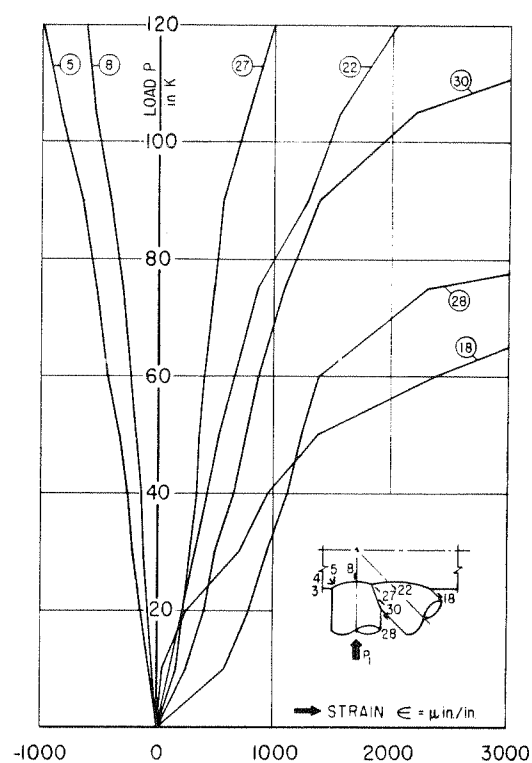


FIG. 36c CRITICAL STRAINS IN JOINT TYPE 8
(thick wall)

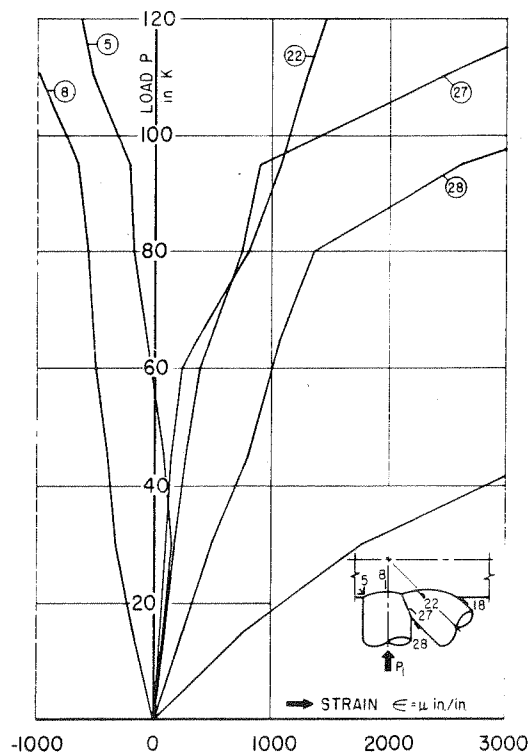


FIG. 36b CRITICAL STRAINS IN JOINT TYPE 8
(medium wall)

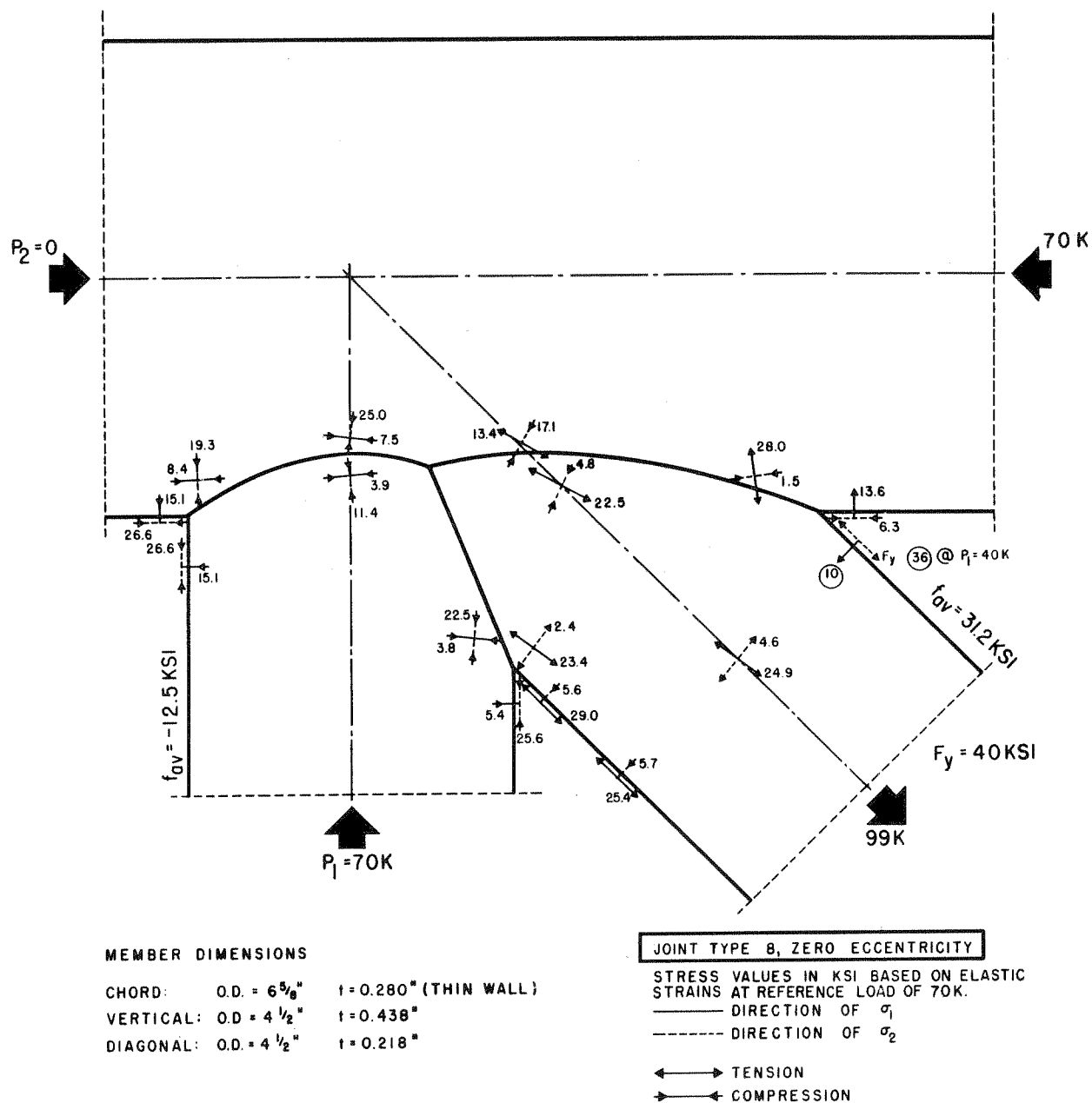


FIG. 37 PRINCIPAL STRESSES AND DIRECTIONS
JOINT TYPE 8 (thin wall)

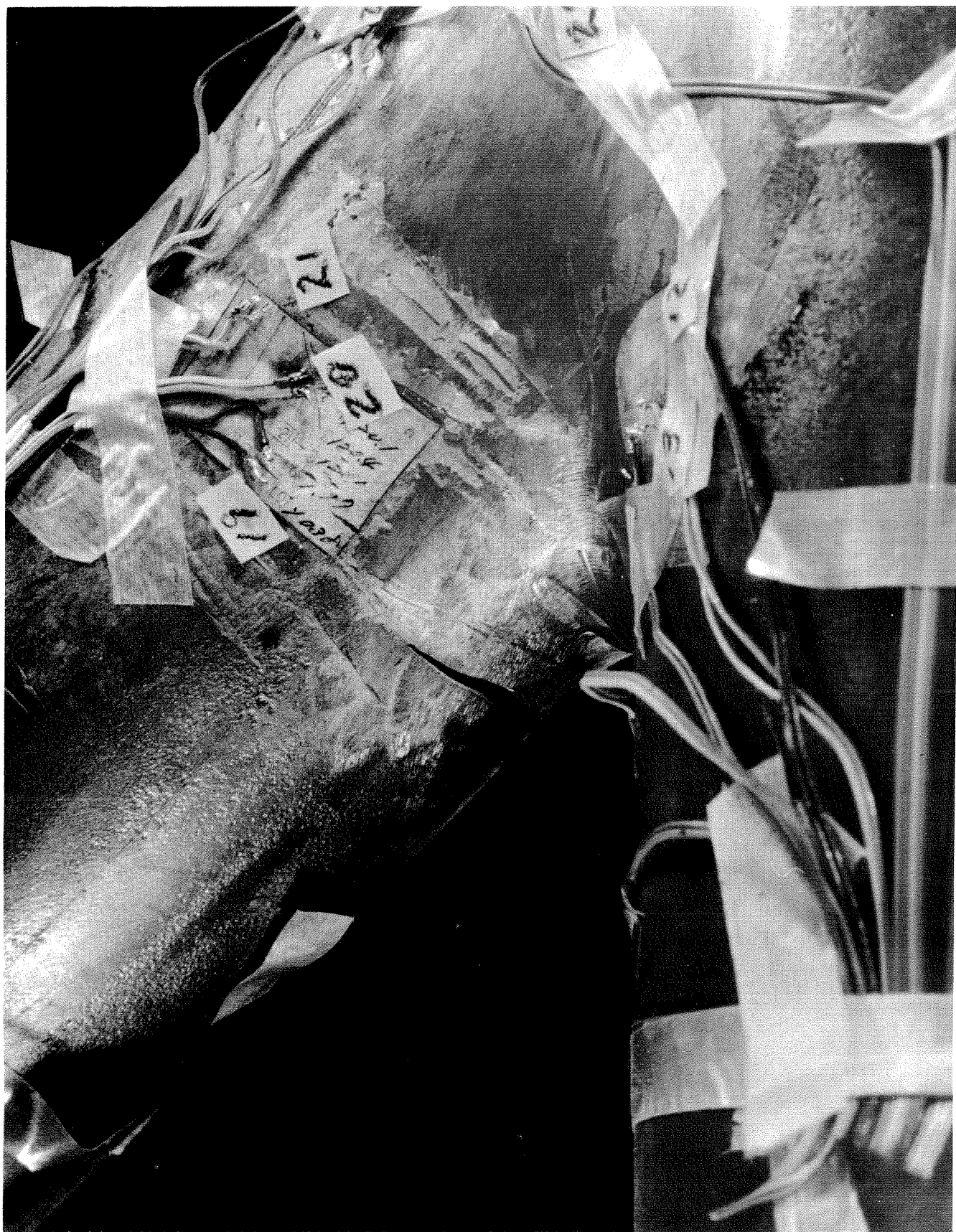
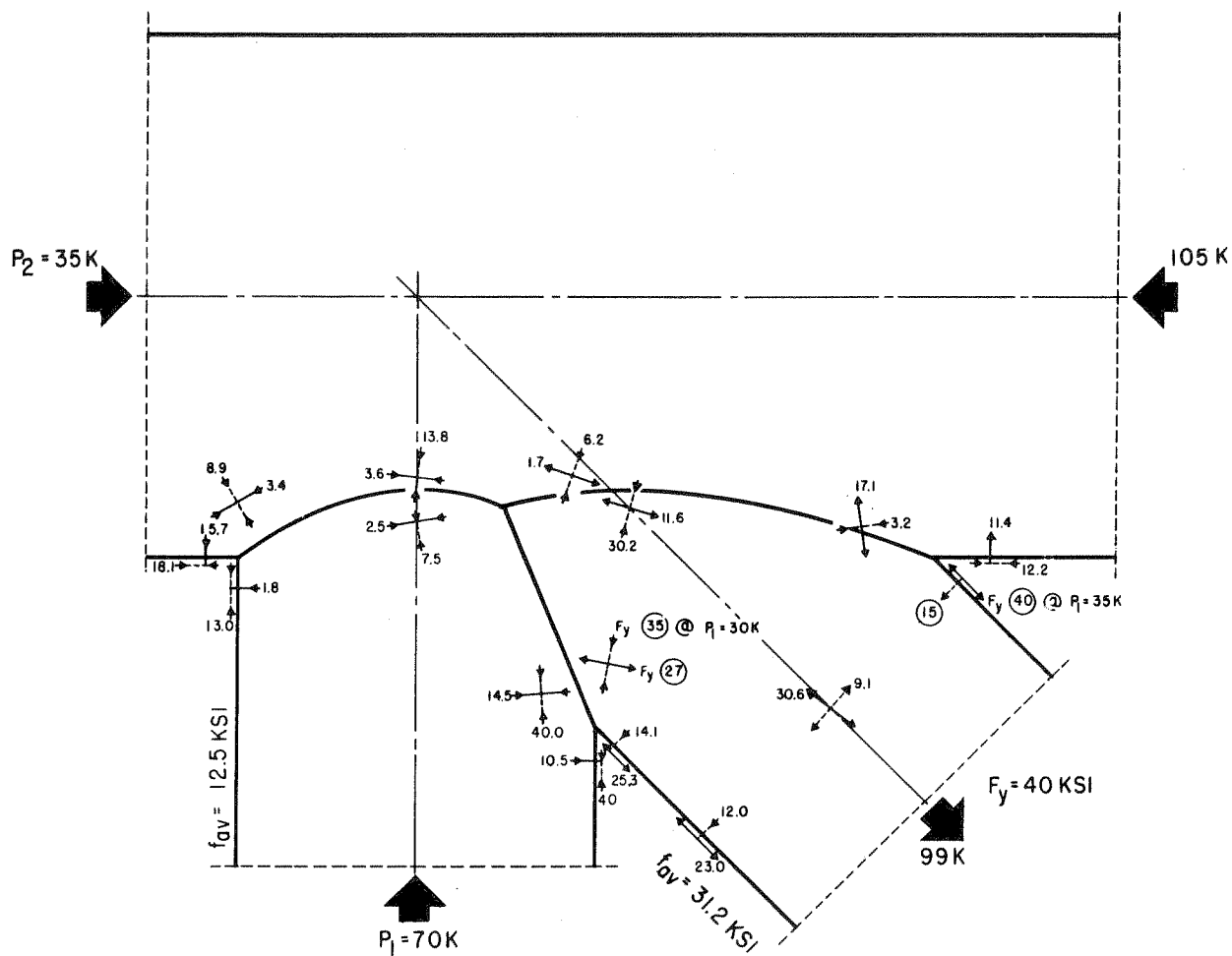


FIG. 38 JOINT TYPE 8 (medium wall) AFTER FAILURE



MEMBER DIMENSIONS

CHORD: O.D. = $6\frac{5}{8}$ " $t = 0.432$ " (MEDIUM WALL)
 VERTICAL: O.D. = $4\frac{1}{2}$ " $t = 0.438$ "
 DIAGONAL: O.D. = $4\frac{1}{2}$ " $t = 0.237$ "

JOINT TYPE 8, ZERO ECCENTRICITY

STRESS VALUES IN KSI BASED ON ELASTIC STRAINS AT REFERENCE LOAD OF 70K.

— DIRECTION OF σ_1
 - - - DIRECTION OF σ_2

← TENSION
 → COMPRESSION

FIG. 39 PRINCIPAL STRESSES AND DIRECTIONS
 JOINT TYPE 8 (medium wall)

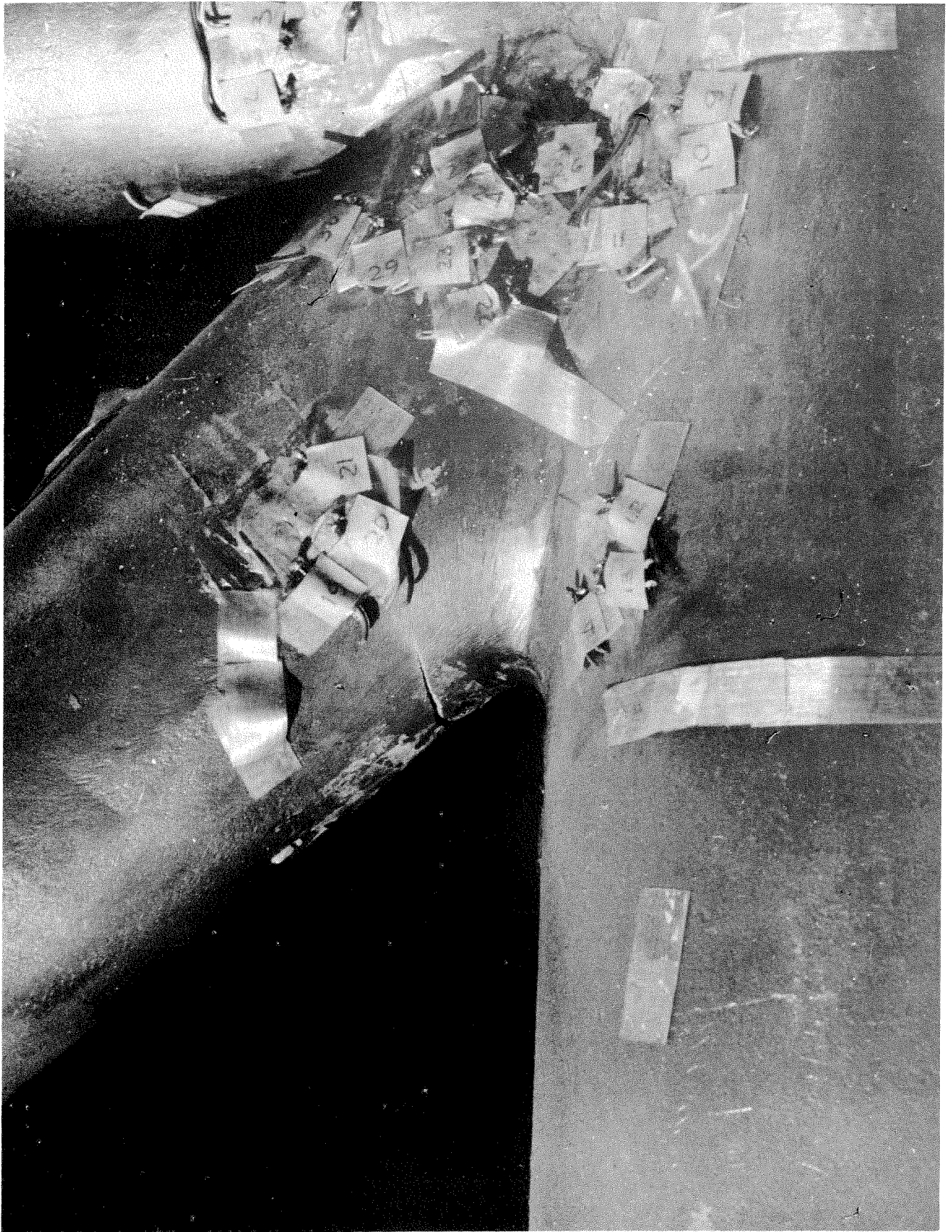
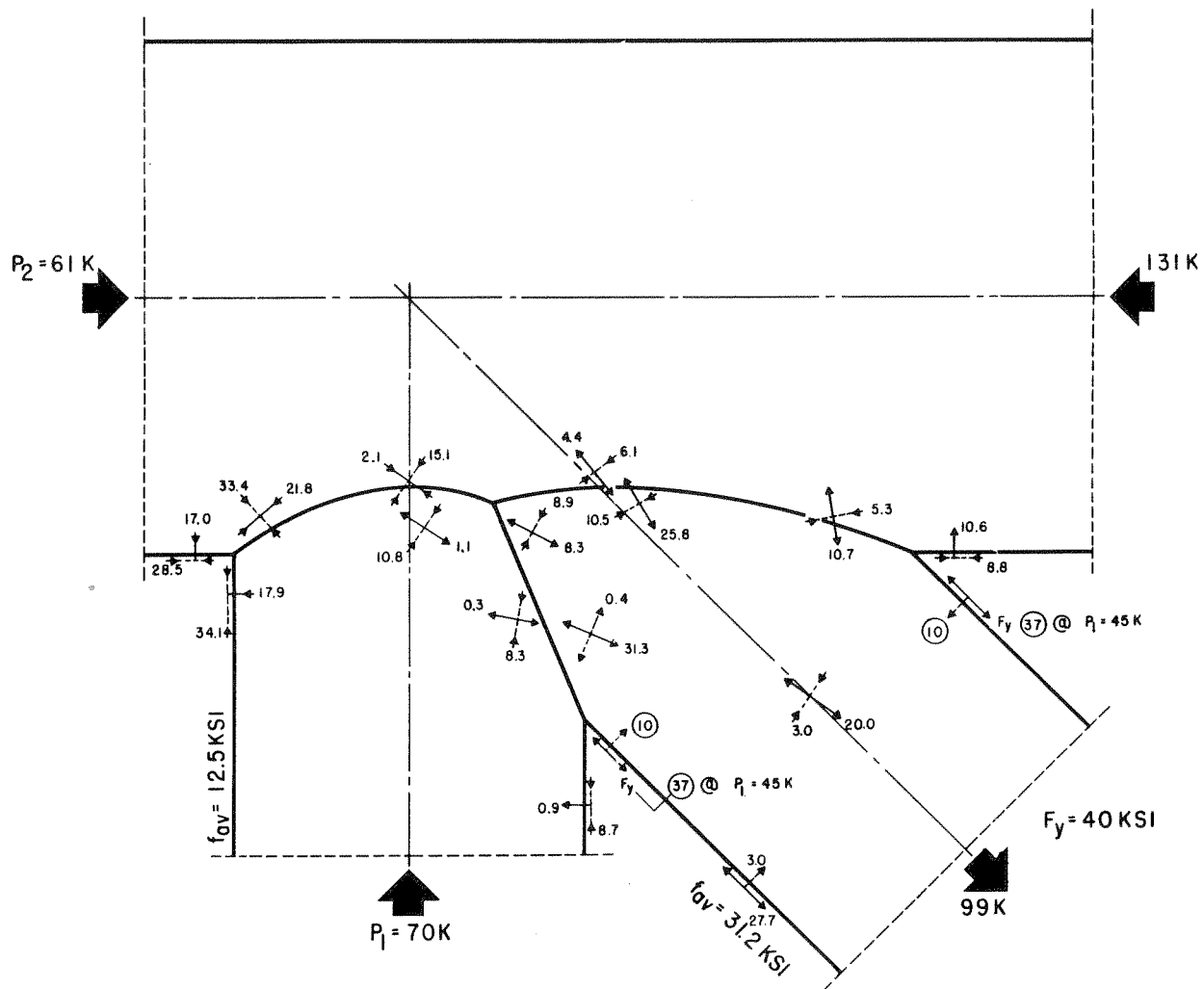


FIG. 40 JOINT TYPE 8 (thick wall) AFTER FAILURE



MEMBER DIMENSIONS

CHORD: O.D. = $6\frac{5}{8}"$ $t = 0.562"$ (THICK WALL)
 VERTICAL: O.D. = $4\frac{1}{2}"$ $t = 0.438"$
 DIAGONAL: O.D. = $4\frac{1}{2}"$ $t = 0.237"$

JOINT TYPE 8, ZERO ECCENTRICITY

STRESS VALUES IN KSI BASED ON ELASTIC STRAINS AT REFERENCE LOAD OF 70K.

——— DIRECTION OF σ_1
 - - - - DIRECTION OF σ_2

← → TENSION
 ← → COMPRESSION

FIG. 41 PRINCIPAL STRESSES AND DIRECTIONS
 JOINT TYPE 8 (thick wall)

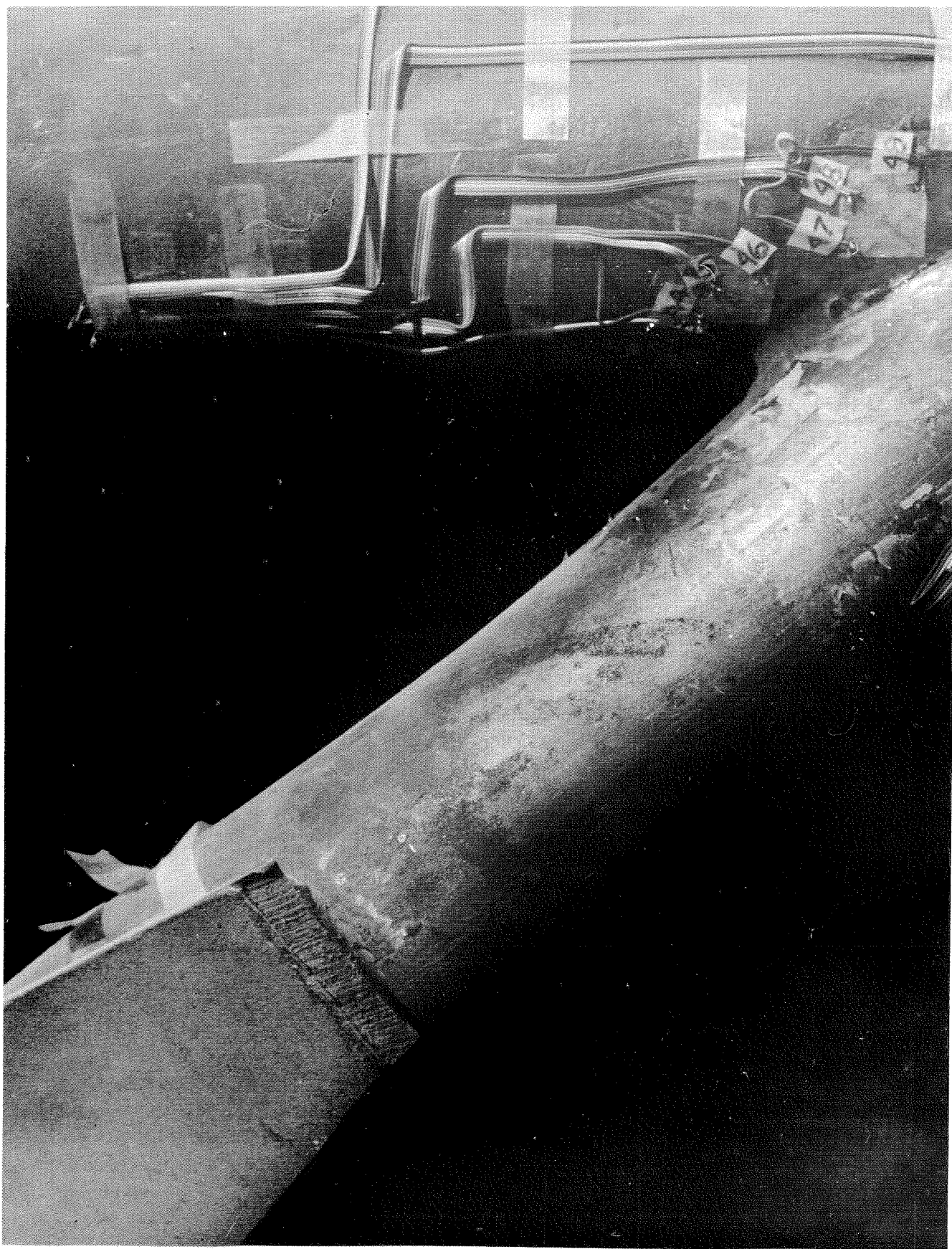
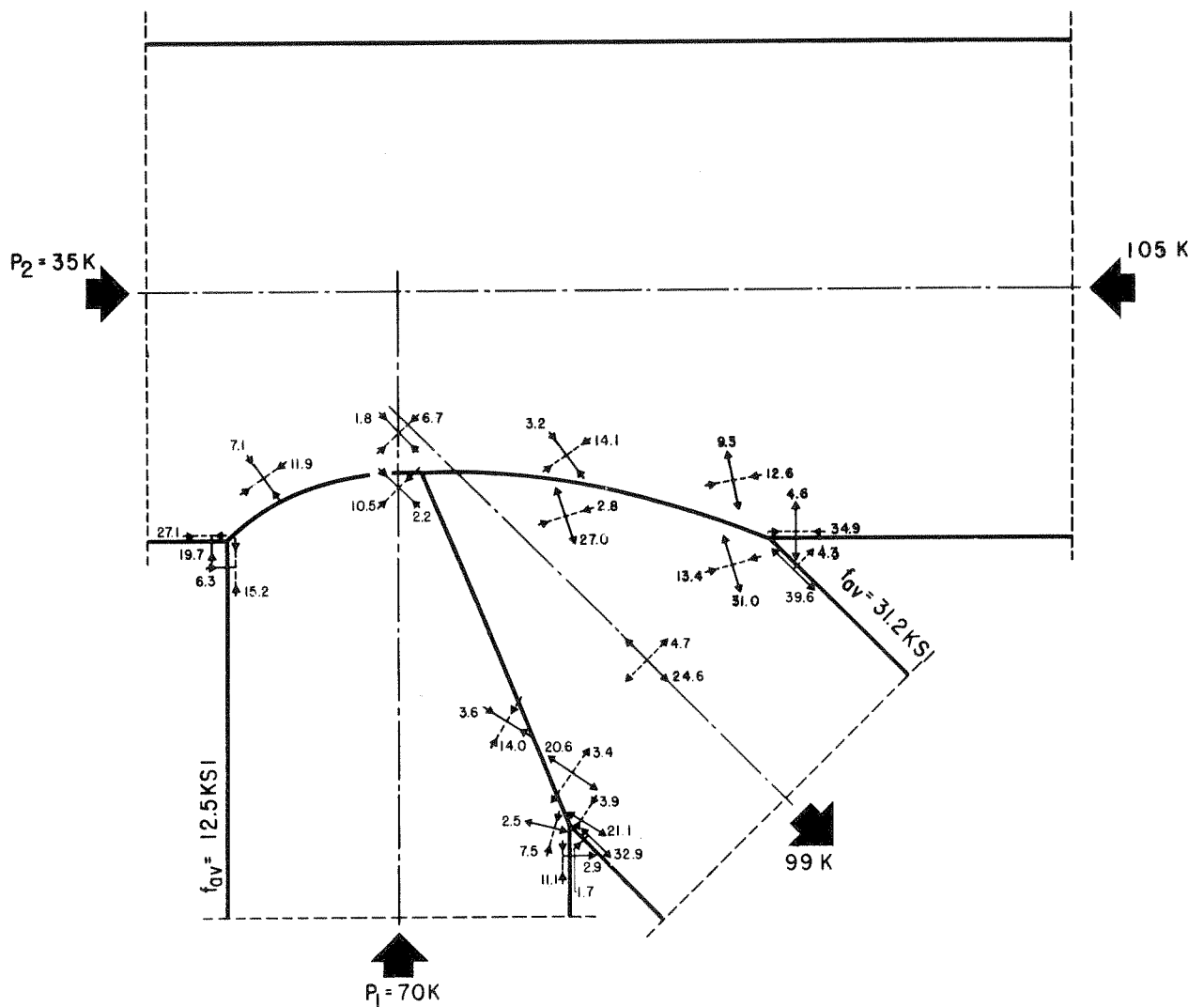


FIG. 42 JOINT TYPE 9 AFTER FAILURE



MEMBER DIMENSIONS

CHORD: O.D. = $6\frac{5}{8}"$ $t = 0.432"$ (MEDIUM WALL)
 VERTICAL: O.D. = $4\frac{1}{2}"$ $t = 0.438"$
 DIAGONAL: O.D. = $4\frac{1}{2}"$ $t = 0.237"$

JOINT TYPE 9, NEGATIVE ECCENTRICITY

STRESS VALUES IN KSI BASED ON ELASTIC STRAINS AT REFERENCE LOAD OF 70 K.

— DIRECTION OF σ_1

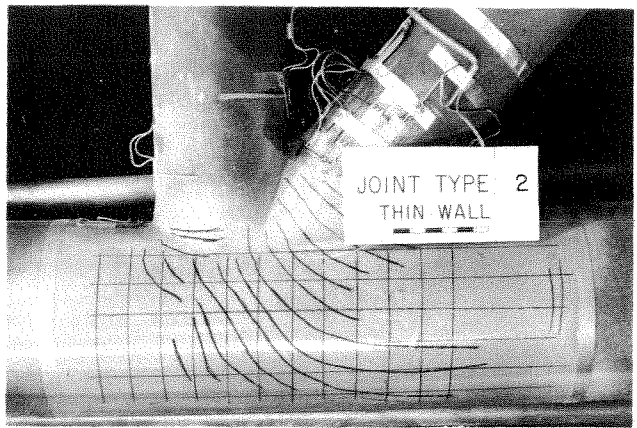
--- DIRECTION OF σ_2

← TENSION

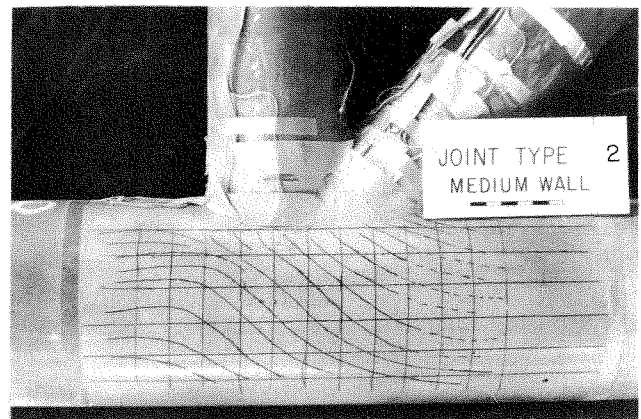
→ COMPRESSION

FIG. 43 PRINCIPAL STRESSES AND DIRECTIONS
JOINT TYPE 9

a. thin wall



b. medium wall



c. thick wall

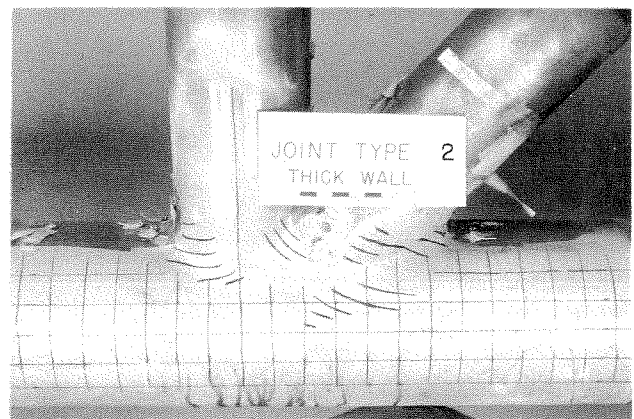
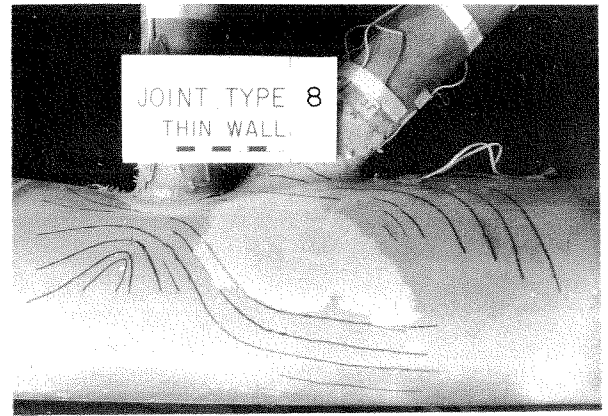
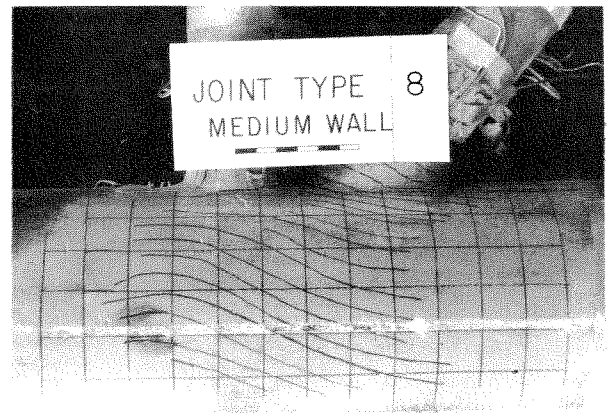


FIG. 44 STRESS-COAT CRACK PATTERN
JOINT TYPE 2

a. thin wall



b. medium wall



c. thick wall

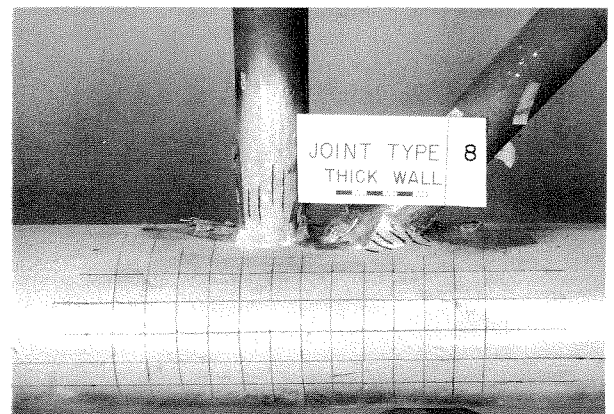


FIG. 45 STRESS-COAT CRACK PATTERN
JOINT TYPE 8

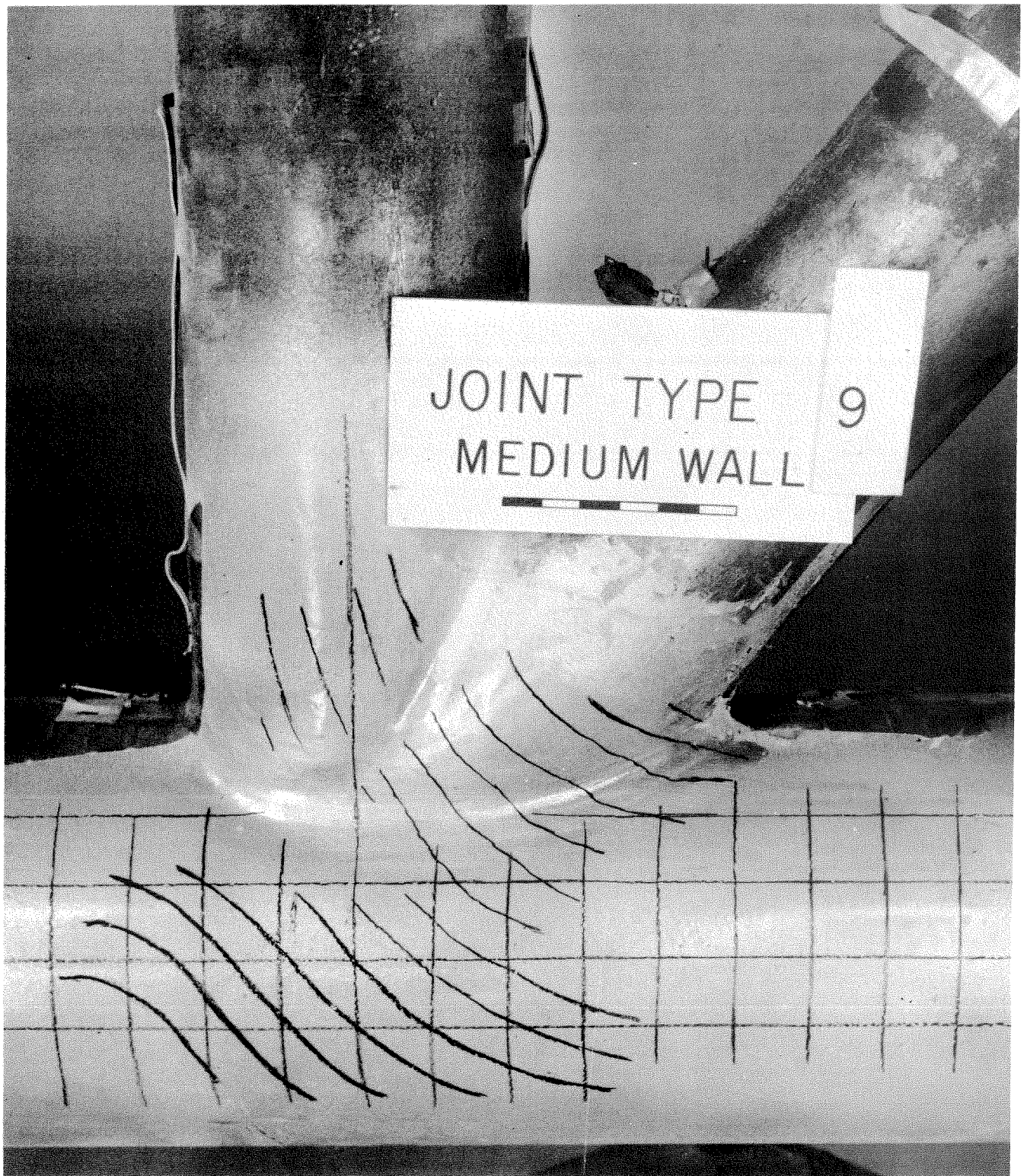
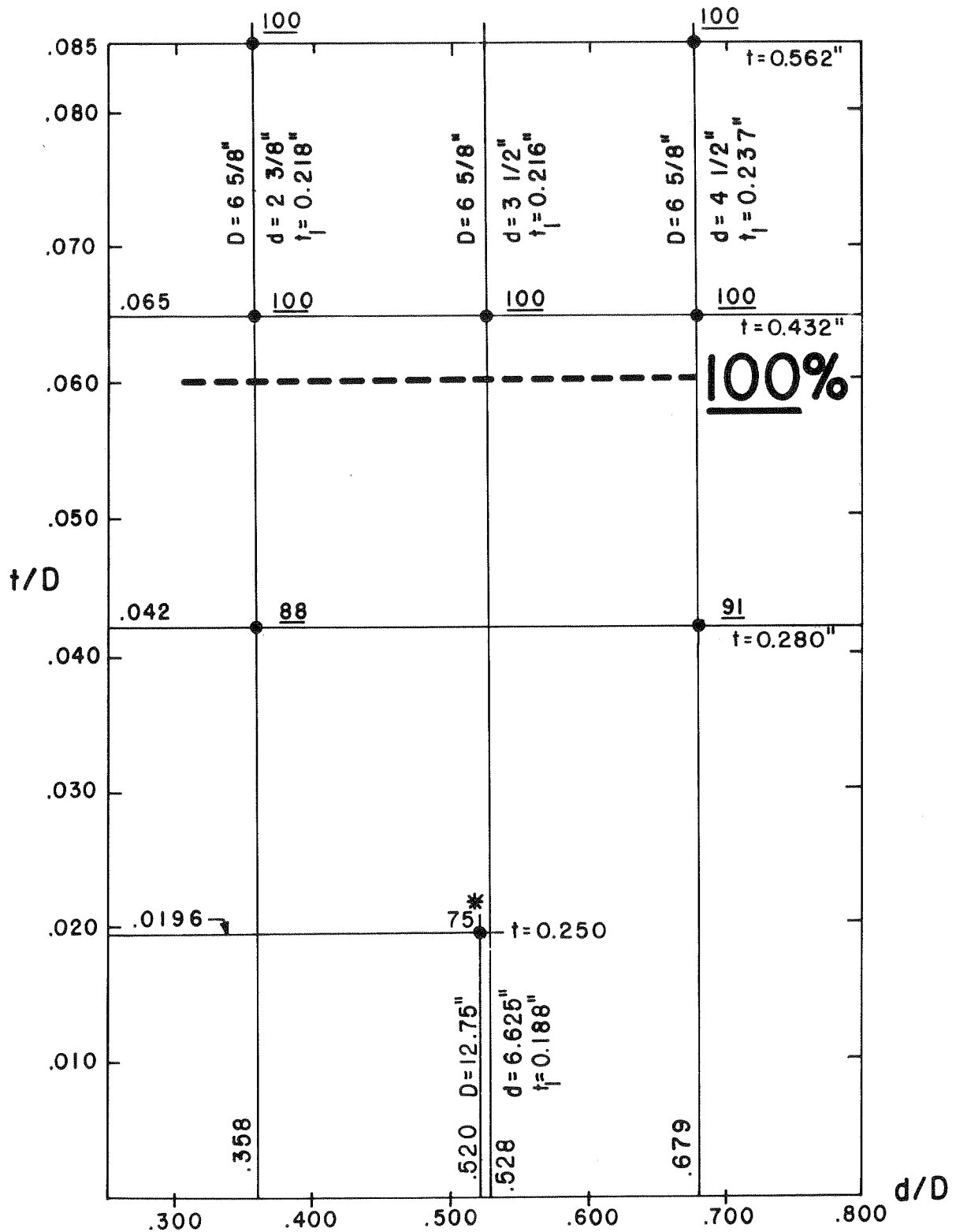
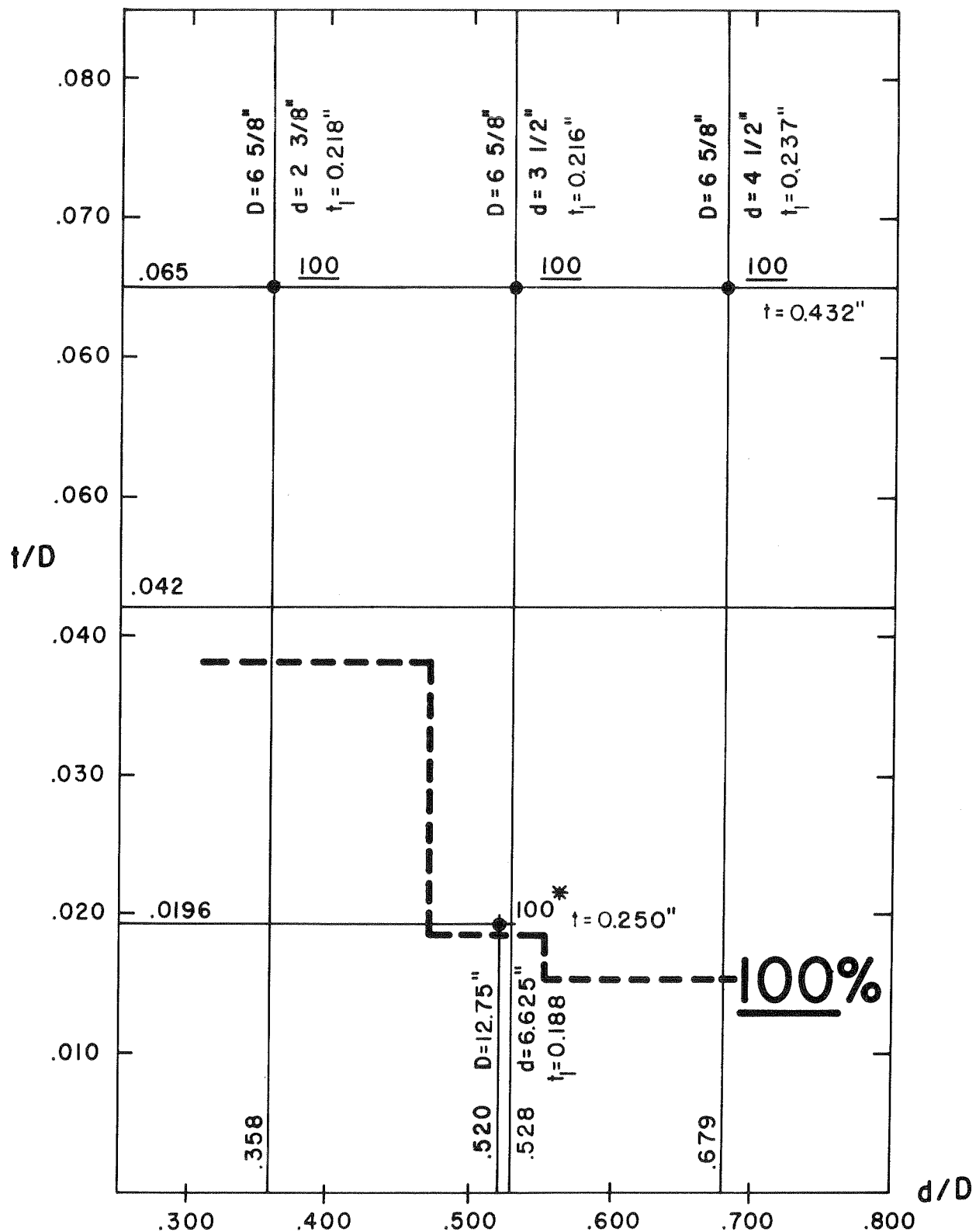


FIG. 46 STRESS-COAT CRACK PATTERN
JOINT TYPE 9



* JOINT EFFICIENCY IN % FOR JOINT TESTED AT U.C. IN 1959

FIG.47 JOINT EFFICIENCY VALUES FOR
ZERO ECCENTRICITY JOINTS



* JOINT EFFICIENCY IN % FOR JOINT TESTED AT U.C. IN 1959

FIG.48 JOINT EFFICIENCY VALUES FOR
NEGATIVE ECCENTRICITY JOINTS