1958

Proposal for tests built-up members - determination of residual stress, June 1958

L. Tall

R. Ketter

Built-Up Members in Plastic Design

TESTS ON LONGITUDINALLY STIFFENED PLATE PANELS

Effect of Residual Stresses and Rotational Restraint by Stiffeners

by

Robert H. Rampetsreiter
Ti-ta Lee
Alexis Ostapenko

This work has been carried out as a part of an investigation sponsored by the Department of the Navy with funds furnished by the Office of Naval Research Contract Nonr 610(03).

Fritz Engineering Laboratory
Department of Civil Engineering
Lehigh University
Bethlehem, Pennsylvania

July 1962

Fritz Engineering Laboratory Report No. 248.5

TABLE OF CONTENTS

ABSTRACT

A description of a series of six tests conducted on longitudinally stiffened plate panels during 1960 and 1961 is presented. This program is a continuation of the tests described in Fritz Laboratory Report No. 248.4.* The test specimens were scale models of typical ship bottom plating. The tests were conducted to investigate the strength of stiffened plate panels as influenced by the following parameters: the degree of rotational restraint furnished by the stiffeners, and residual stresses.

The test results are given in the form of curves and tables. The individual test readings are compiled in a supplementary volume Fritz Engineering Laboratory Report No. 248.5A.

The conclusions for the specimen dimensions and loading used are:

a) The degree of restraint furnished by the stiffeners was found to have some effect on the buckling strain of the plates with b/t = 40 - the stress was equal to the yield stress.

b) Welding residual stresses reduced the axial strength of the stiffened panels by about 13 percent.

- - - - - - - -

* Ostapenko, A., and T. Lee; TESTS ON LONGITUDINALLY STIFFENED PLATE PANELS SUBJECTED TO LATERAL AND AXIAL LOADING, Fritz Engineering Laboratory Report, August 1960.

1. INTRODUCTION

1.1 OBJECTIVES

A research project on the strength of longitudinally stiffened plate panels as used in ship bottom plating has been in progress at Fritz Engineering Laboratory, Lehigh University, since 1958. The overall objectives of this project are to:

a) study the capacity of longitudinally stiffened panels with special emphasis on the effect of lateral pressure.

b) develop an analytical method for the calculation of the strength of such panels.

c) develop a practical design procedure for stiffened panels of actual ship structures, which will utilize results of items a) and b).

In the framework of this project an exploratory experimental investigation of the effect of lateral pressure on the axial strength of scale models of ship bottom plating was completed in 1960. An important part of that phase consisted of the development of the test setup. The results of the first five tests and a detailed description of the test apparatus were reported in 1960.*

---

* Ostapenko, A., and T. Lee; TESTS ON LONGITUDINALLY STIFFENED PLATE PANELS SUBJECTED TO LATERAL AND AXIAL LOADING, Fritz Engineering Laboratory Report No. 248.4, Lehigh University, August 1960.

The present report gives a description and test results of the six specimens tested during 1960 and 1961. Two parameters influencing the axial strength of longitudinally stiffened plate panels were to be investigated in these tests: the effect of the rotational restraint furnished by the stiffeners and the effect of residual stresses.

The degree of restraint furnished by the stiffeners was found to have some effect on the buckling strain of the plates with b/t = 40 - the stress was equal to the yield stress.

Other tests showed that welding residual stresses have a pronounced effect on the strength of stiffened plate panels; the reduction in strength was about 13 percent.

1.2 TEST PROGRAM

Six specimens have been tested since the completion of report 248.4. One specimen, T-11, was used to find the magnitude and distribution of residual stresses. Four specimens, T-7 to T-10 were tested axially, and specimen T-6 was tested under combined axial and lateral loading.

Specimen T-6 was tested to find to what extent the rotational restraint furnished by the stiffeners affected the axial strength of the panels. A comparison was to be made with specimen T-5 from the previous series of tests.

Both specimens had b/t = 40 and were tested axially under a lateral pressure of 6.5 psi. The only difference between these two specimens was that T-5 had box-shaped stiffeners which gave practically complete rotational restraint and T-6 had tee stiffeners which provided essentially simple support.

Specimens T-7 through T-9 were geometrically identical; their residual stress patterns, however, were quite different. Specimen T-7 had residual stresses due to all the causes: rolling, welding, etc. Specimen T-8 was annealed* after fabrication and thus contained no residual stresses to speak of. Specimen T-9 was welded after its component parts had been annealed and thus had residual stresses only due to welding. Whereas residual stresses in specimens T-8 and T-9 were determined from the portions of these specimens which had no visible yield lines after axial testing,a separate specimen, T-11, was used to find residual stresses in specimen T-7. T-11 was fabricated following the same procedure and using the same materials as T-7, and it was assumed that T-11 had the same residual stresses as T-7.

Specimen T-10 was identical to T-7 except that it had a much lower slenderness ratio, L/r, 21 vs. 50. Its purpose was to illustrate that, since all the specimens failed by plate buckling, the specimen strength is practically independent of the slenderness ratio.

- - - - - - - -

* In this report the word "annealing" designates stress relieving by heat.

The basic data and the ultimate axial loads for the ten specimens described in this report and Report 248.4 are listed in Table 1. A qualitative discussion of test results is illustrated with figures and tables. The actual test readings are compiled in a supplementary report, Fritz Engineering Laboratory Report 248.5A which is available on request.

2. TEST SPECIMENS

2.1 DESIGN OF TEST SPECIMENS

Test specimens were designed in accordance with the following criteria:

1. Material: Specimens were to be made of ASTM designation A-7 carbon steel. The material should have properties as uniform as possible.
2. Plate thickness: $t = 1/4$ in. This was considered the minimum acceptable because the stiffeners were to be welded to the plate and a thinner plate would distort excessively.
3. Dimension ratios: Slenderness ratio - $L/r = 50$, with the radius of gyration, r, based on the subpanel cross section and L being the effective specimen length. The word "subpanel" designates a stiffener and a plate the width of which is equal to the stiffener spacing. Ratio of subpanel width to plate thickness (plate slenderness) - $b/t = 60$. Some specimens, T-6 and T-10, did not conform to their requirements.
4. Number of subpanels and conditions of end support: Each specimen should have at least three subpanels and should simulate a pin-ended column with no support on the sides.
5. Lateral loading: Only specimen T-6 of the current test series had lateral loading. The loading was 6.5 psi which corresponds to 15 feet of water head.

The maximum width of the overhanging portions of the plate was limited to three inches in order to avoid local instability, and thus symmetry of the plate about the edge stiffeners was not achieved.

The nominal dimensions of the specimens are shown in Figs. 1, 2, and 3. Table 3 gives the actual dimensions. Tables 4 and 5 show the initial imperfections in the specimens. The maximum out-of-flatness of the plate was approximately 0.18 in. which was considered as tolerable.

2.2 FABRICATION OF TEST SPECIMENS

Specimens T-6 through T-11 were fabricated from material having the same properties.

All five plates were cut from one piece (Fig. 4). The plate was cut by torch, but 3/4 in. of it next to the cut line were sheared off to nullify residual stresses produced by heat.

Tee stiffeners for all specimens were cut from three lengths of rolled beam, 6Jr.4.4, of the same heat number (Fig. 4). The beams were split along the web by torch to give the required depth of 3 5/16 in. of the stiffeners. The effect of cutting by torch was less serious on the web of the beam than on the plate, since the stiffener was later welded to the plate. After the cutting operation the tees curved due to the release of residual stresses. To straighten them, two pieces were put back-to-back, forced together and then tack welded at three locations. The pair was then placed into the furnace with the temperature at approximately 1000°F. When the stiffeners were taken out of the furnace and cooled, they remained straight. In some cases the web plate of one of the two in a pair buckled in the process. The buckled pieces were straightened by applying bars to stiffen the web and putting the deformed stiffeners back into the furnace. These re-straightened stiffeners were used in the fabrication of specimen T-8.

Before welding the tee stiffeners to the plates, the plates were cold bent along the stiffener lines in order to compensate for the warpage due to the welding process. The amount of cold pre-bending required was determined through experiments conducted at the shop on small pieces of material. The welding sequence was such, as to minimize longitudinal deformations due to welding. First, an intermittent weld was made, approximately 1 in. at 6 in. intervals, then the gaps were filled in. Sufficient time was allowed for cooling between individual passes.

Finally the top and bottom end of each specimen were machined plane and parallel to a "smooth finish". The side edges of the specimens were given a "medium finish".

Since it was desired to have specimens with different residual stress conditions, the process of fabrication varied with specimens. Specimens T-6, T-7 and T-11 were welded as described above and thus had welding residual stresses combined with the initial residual stresses which existed in the material. Specimen T-8 was welded and then annealed to eliminate essentially all residual stresses. Specimen T-9 was welded after its component parts, the plate and stiffeners, had been annealed; as a result it contained residual stresses only due to welding.

2.3 MECHANICAL PROPERTIES OF SPECIMEN MATERIAL

Brinell Hardness Number was used as a basis for the selection of the plate and beam pieces with equal properties - the mill reports have proven rather unreliable for this purpose because the pieces of material originated from different sources and probably different techniques were used to determine their properties.

The actual mechanical properties of the material were obtained by conducting 25 tensile coupon tests. The coupons were made from the reserved pieces of plates and tee stiffeners. In Fig. 4 these pieces are marked with letter R. The coupons for stiffeners were taken from the flange and the web since the material properties of these two parts are often different, the web having a higher yield point than the flange. This was found to be the case for both the annealed and unannealed coupons. The dimensions of coupons were specified according to ASTM standards (Designation E8-54T). A gage length of 4 in. was used, and the width of the reduced section was 3/4 in. The tensile coupon tests were conducted on a Tinius Olsen testing machine of 120,000 lb. capacity. In each test, a load-strain curve was automatically plotted using a Tinius Olsen extensometer Type S-1 until the strain hardening curve was well established. Then the extensometer was removed and the strain readings were taken by means of a pair of dividers and a ruler with one hundredth inch divisions. Average strain rate used was 0.02 in./min. before yielding and 0.36 in./min. after yielding.

The yield property of the steel was defined by the static yield stress level, σ_{sy}, that is, the yield stress for a zero strain rate. Results of all the coupon tests are given in Table 2. The average σ_{sy} of the unannealed plate and stiffener material is 39.2 ksi. This would be the σ_{sy} value for specimens T-7 and T-11. The average σ_{sy} of the annealed plate and stiffener is 36 ksi. This would be the σ_{sy} value for specimens T-8 and T-9.

3. TEST SETUP AND INSTRUMENTATION

3.1 TEST SETUP-REQUIREMENTS AND GENERAL ARRANGEMENT

The design of the test setup was guided by the following principal requirements:

1) The setup should provide pin-ended conditions for the specimens.
2) The setup should be capable of applying, simultaneously, a maximum lateral loading of 13.0 psi and an axial force which could go as high as 1,000,000 lb.
3) Under the applied lateral loading the system should be in a state of self-equilibrium so that no additional lateral support would be required.
4) Sufficient clearance should be provided to insure free deformation of the specimen under the action of applied loads.

A detailed description including photographs and drawings of the loading system, end fixtures, and bracing is given in F. L. Report No. 248.4*.

3.2 INSTRUMENTATION

Both dial gages and electric strain gages were used in the tests. This section on instrumentation is only for the axial load tests. The instrumentation for the residual stress measurements is given in Section 6.2.

- - - - - - - - -

* Loc. cit. on p. 1

Dial Gages

All dial gages were AMES dial gages with one thousandth inch divisions and a stroke of one inch. The location of the points at which dial gage readings were made is shown in Figs. 5, 6 and 7. The dial gages were used to measure:

- Lateral deflections of the specimen at a number of points so as to cover, more or less, the whole area of the specimen (Gages 1 through 25, and all C- and E- gages; C = corner, E = end).
- Rotation of the specimen at the ends (S-gages; S=slope).
- Changes in the distance between the ends of the specimen, longitudinal deflection (L-gages; L=length).

All dial gages used for lateral deflection measurements were mounted on a dial gage frame. Drawings and photographs of the frame are shown in F. L. Report No. 248.4*. The dial gage frame itself was firmly attached to the pedestal of the testing machine. Holes 1/16 in. in diameter and 1/8 in. in depth were drilled and tapped on the front face of the specimen at points where lateral deflections were to be measured. Small screws were fitted into these holes. Thin black wire connected the heads of the screws and the tips of the dial gage stems. In this way, lateral movement of the specimen was transmitted to the dial gages, since the distance between the wire ends did not change.

- - - - - - - - -

* Loc. cit. on p.1

It was of interest to measure the rotation of the specimen ends during testing; the S-gages were used for this purpose. At each point (See Figs. 5, 6 and 7) a half inch diameter bar was screwed into the end block and vertical movement of the outstanding end of this bar was measured with a dial gage. Dial gage readings divided by the distance from the bar end to the center of the end block gave the angle of rotation. The effect of the elastic deformation of the end fixtures on the readings was neglected. The dial gages were supported by weights at the bottom end of the specimen and held to the machine cross head by magnets at the upper end of the specimen.

Changes in the distance between the ends of the specimen were measured with two L-gages (L-1 and L-2). This gave the longitudinal deflection of the specimen. Actually, the variation of the distance from the machine cross head to the pedestal was measured, but this introduced a very small inaccuracy since the deformation of the end fixtures compared with that of the specimen was of a negligible magnitude. The distance for the L-gages was bridged with thin black wire, similarly as was done for lateral gages. The upper ends of the wires were attached to the cross head by means of magnets, and the lower ends to the dial gages which, connected to weights, were standing on the pedestal.

Strain Gages

All strain gages were electric resistance SR-4 type A-1 linear gages. The location of the gages on the specimen is shown in Figs. 8, 9, and 10. Table 6 lists which gages were used on which test specimen.

4. T E S T P R O C E D U R E

4.1 PREPARATION OF SPECIMENS FOR TESTING

A brief outline of the steps preparatory to the testing of a specimen is given here. A more detailed description of the procedure can be found in F. L. Report 248.4*.

The specimen was connected to the end blocks and placed on the machine pedestal. The arrangement can be seen in Figs. 11 and 12. SR-4 gages were then cemented and wired up. The specimen was whitewashed in order that the progression of yielding during testing could be observed.

The next step for specimen T-6, which was tested under combined axial and lateral loading, consisted of the attachment of the pressure box to the specimen.

Further steps were common to all specimens. The dial gage frame was erected and the dial gages were connected to the specimen by means of thin wires. Then the pedestal with the specimen on it was rolled into position in the testing machine and the machine head was aligned to produce uniform pressure across the width of the specimen. After this the specimen was ready for testing.

- - - - - - -

* Loc. cit. on p. 1

4.2 TESTING OF SPECIMENS

A description of the testing of specimen T-6 is given. Only T-6 was laterally loaded, therefore, the testing of the other specimens was correspondingly simpler.

The loading procedure started with the application of lateral pressure. The pressure intensity was increased stepwise from zero to the maximum intensity of 6.5 psi which was maintained throughout the test. Then, the machine head was lowered until it made contact with the top platen. An initial axial force of 50 kips was applied, and L and S dial gages were installed. The axial load was then increased, after one more 50 kip increment, in 100 kip steps. Smaller load increments were used when the axial load was approaching its ultimate value. After reaching the ultimate load a sufficient number of readings were taken to define the nature of the post-ultimate behavior. One cycle of unloading and reloading was carried out. The amount of axial deformation was limited by the clearances provided for the free movement of the end blocks. (No such limitation was imposed on specimens T-7 to T-10.) Then the specimen was unloaded axially. At the load of about 50 kips the top S- and L-gages were disconnected. The machine cross head was then raised, and the lateral loading taken off in several steps.

Readings of all gages were taken at each load increment. Load versus deflection curves were continuously plotted for the longitudinal deflections (average of the readings of gages L-1 and L-2) and the lateral deflections of a stiffener and the plate at the mid-height of the specimen (readings of dial gages 8 and 11, stiffener and plate, respectively). These curves served as an illustrative indication of the specimen behavior. At each increment the load was increased slightly above the desired value and then allowed to stabilize itself in order to have a static load reading, that is, at a zero strain rate. The load stabilized quickly in the elastic range, but after some yielding it took about ten minutes or longer until the load became stable and the dial gages showed no detectable movement.

The progress of yielding as indicated by flaking of the whitewash was observed and recorded.

A group of eight persons were needed for the testing of specimen T-6.

Since no lateral loading was applied to the other specimens, the test procedure was correspondingly simplified and fewer men were needed.

The actual testing time for one complete test was, on the average, six hours.

5. TEST RESULTS

5.1 GENERAL

The major parameters, the ultimate axial loads and the mode of failure are listed for each specimen in Table 1. The photographs of the final yield patterns for the front and back faces of each specimen are shown in Figs. 13 to 22. The longitudinal deflection readings are given in Table 7; they are plotted versus non-dimensionalized axial load in Fig. 23. The lateral deflection of stiffeners and plate for a half-width of the specimens is plotted versus axial load in Figs. 24 to 28. Figs. 29 to 33 show the complete deflected cross section at mid-height for different loads. The axial strains at these cross sections are given in Figs. 34 to 38 and discussed in section 5.4. A complete tabulation of all the readings is available in a companion report Fritz Engineering Laboratory Report No. 248.5A.

The general behavior of the specimens is presented in section 5.3. A description is given of the peculiarities in the behavior of the individual specimens: appearance of the yield lines and the mode of failure. The major characteristic of the mode of failure, occurrence or non-occurrence of instability of the plate in the subpanels at the ultimate load, is illustrated by the curves showing the lateral deflection of the plate and stiffeners (Figs. 24 to 33).

5.2 DEFORMATION OF SPECIMENS

Lateral and longitudinal deformations of the specimens are described in this section.

Since, in most cases, the specimen deformed symmetrically except at the ultimate loading, only readings of a small group of lateral deflection gages describing the typical behavior are necessary for the qualitative discussion presented here. The gages used and the graphs pertaining to lateral deformation are shown in Figs. 24 to 33.

Neglecting the initial deformation in the plate, the specimen cross section may be considered perfectly straight before the application of loading. Taking this as the original condition, the lateral deflections of the dial gage points are plotted (Figs. 24 to 28). Actually, these deflections should be corrected for the horizontal movement of the specimen ends (C gages), but the error is negligible.

The load versus lateral deflection curves and cross sections for T-7 and T-10 (Figs. 25, 28, 30, and 33) show a great similarity which was to be expected since both these specimens had the same b/t ratios and the same fabrication procedure.

As a result of closer stiffener spacing the relative deflections between the stiffeners and the plate in specimen T-6 were considerably smaller than in specimens T-7 to T-10.

The most notable characteristic of specimen T-6 in its comparison with specimen T-5 was that buckles appeared in the plate right after the ultimate load was reached. In T-5 the buckles appeared considerably later. It is important to note that in both specimens the plate became unstable after reaching the ultimate load and thus these two specimens failed by general column instability rather than by local plate instability as did the other specimens.

The longitudinal deformation was measured during the application of axial loading and is given in Fig. 23 for all specimens.

5.3 BEHAVIOR OF SPECIMENS DURING TESTING

Since each specimen differed in some way from the others, the behavior of each specimen is discussed separately.

Specimen T-6

T-6 was tested in conjunction with previously tested T-5* to clarify the effect of rotational restraint furnished by the stiffeners. Both these specimens were subjected to lateral loading of 6.5 psi.

As shown in Table 5A, specimen T-6 had a positive initial eccentricity (positive meaning concave on the plate side). As a result the lateral loading increased the initial eccentricity so that the lateral deflection due to the axial loads

- - - - - - - - -

* Loc. cit. on p. 1

started at once. The rate of deflection smoothly increased with an increasing axial load as shown in Fig. 23 for the longitudinal and in Figs. 24 and 29 for the lateral deflections. This continued until the load deflection curve leveled off as the axial load reached its ultimate value of 463 kips. The ultimate load was the maximum stable load obtained.

Yield lines were first noticed at 300 kips on the webs of the tee-stiffeners at the bottom. No new yield lines appeared till close to the ultimate load. The yield lines then extended first across the middle portion of the subpanels and later across the portions by the stiffeners. Some more yielding was observed after the ultimate load. Only then did the plate buckle.

The buckling pattern was of a checkerboard type with alternating concave and convex buckles. The outlines of the buckles can be seen in Figs. 13 and 14. Both specimens, T-5 and T-6, failed by column instability - the plate buckled only after the ultimate load. A lower degree of restraint furnished by the tee-stiffeners in specimen T-6 accounted for a much sooner buckling of its plate after the ultimate load than in specimen T-5 which had box-shaped stiffeners.

Specimens T-7 to T-10

These specimens were tested only under axial load. The specimens differed primarily in the magnitude and distribution of residual stresses, and a comparison was to be made of their axial strength and behavior as influenced by this factor.

Specimen T-7

Specimen T-7 had residual stresses due to welding and rolling.

Having had some initial imperfections in the positive direction (concave on the plate side), it had small lateral deflections due to axial load from the start (Fig. 25).

At a load of 350 kips the first yield lines appeared on the web of the left stiffener in the lower quarter of the length. When the load reached 385 kips all the stiffeners were observed to have yielded, with the yielding not confined to any one specific area. Somewhat later at a load of 410 kips, the flanges also commenced yielding. At P = 425 kips the lower one-fifth of the outer subpanels showed some yield lines.

When the ultimate load P_u = 449 kips was reached, local plate instability occurred in the center subpanel and was immediately followed by the instability of the side subpanels. With the rapidly increasing deflections the axial load dropped. Many yield lines, clearly defining the shape of the buckles, appeared in the process (Figs. 15 and 16 show the yield lines very clearly). At this stage an unloading and reloading cycle was conducted. The unloading and reloading was characterized by the elastic behavior of the specimen, that is, a complete recovery at the end of the cycle (this cycle is not shown in Fig. 23).

The axial load on the specimen was limited by the critical strength of the plate; the local instability in the center plate subpanel triggered the instability in the side subpanels. With the plate so deformed, even if it had been deformed only in one subpanel, the cross section was not only unable to carry any higher load, but was unable to sustain the present load.

<u>Specimen T-8</u>

Residual stresses in specimen T-8 were eliminated by annealing.

This specimen had an initial positive unfairness like T-7, and its lateral deflection curves are very similar to those of T-7 (see Figs. 25 and 26).

At a load of 300 kips yield lines formed in the web at the bottom of the right stiffener. Yield lines appeared in all stiffeners except the left one at 375 kips. Between 460 kips and 480 kips yield lines started to develop at different locations in the plate.

When the load reached P_u = 490 kips, buckles formed and the load dropped off very quickly. The sharp dropping off of the load after the ultimate load was reached can be seen in Fig. 23. The lateral deformation of T-8 can be seen in Figs. 26 and 31.

Specimen T-8 like T-7 failed due to local instability of the plate. After one subpanel buckled, the specimen was "out of commission" as far as sustaining any higher load was concerned. The ultimate load, however, was considerably higher due to the absence of residual stresses.

Specimen T-9

Specimen T-9 contained only welding residual stresses.

Similarly to specimens T-7 and T-8, T-9 had an initial positive unfairness (concave on the plate side).

When the applied load was equal to 350 kips all the webs of the tee stiffeners had yielded. Between the loads of 375 kips and 400 kips the first and second subpanels started to show flaking of the whitewash.

The ultimate load, P_u, was reached at 420 kips. The failure of T-9 was of the same nature as T-8, plate instability.

Figs. 27 and 32 show the lateral deformation of T-9. They show that T-9 had less lateral deflection at the ultimate load than T-8. The percentage of P_y attained by T-9 was about the same as for T-7, but considerably smaller than for specimen T-8 (see Fig. 23).

Specimen T-10

Specimen T-10 was identical with T-7 in every respect except for the L/r ratio. T-10 had an L/r = 20.7, while T-7 had an L/r = 50.

Yield lines started to appear in the webs of the stiffeners at about 300 kips.

At P = 420 kips the left and center panels started to buckle. However, the specimen still continued to carry the load. From P = 435 kips till 472 kips yield lines were observed to be forming in the plate. The specimen failed at P_u = 472 kips. Thus, an additional load could be carried by this specimen after the subpanels started to buckle. Apparently, as the subpanels buckled, the additional load was passed on to the stiffeners. The stiffeners could sustain this increase in load due to their smaller L/r ratio. T-10 developed 4 percent more of its full yield load than T-7.

After P_u was reached, the lateral deformation increased rapidly. Figs. 28 and 33 show the load vs. lateral deflection curves and the shape of the specimen cross section, respectively.

5.4 AXIAL STRAINS

The following paragraphs discuss observations on axial strains in the specimens.

Figs. 34 to 38 show the axial strains at mid-height in the cross section for three consecutive load stages, namely: before, at and after the ultimate load. The curves for specimens T-7 to T-10 illustrate the transfer of strains from the plate to the stiffeners at the ultimate load due to plate buckling. For example, it can be seen in Fig. 36 that the strains at the location of the two inside stiffeners at the mid-height cross section of specimen of T-8 rose well beyond the yield strain while the strains in the plate dropped. This indicates that the ultimate collapse of the whole panel occurred because of the failure of the stiffeners to support the suddenly increased axial load on them after the plate became unstable and could not carry its share of the load.

In specimen T-7 additional gages were mounted on the middle subpanel in order that a more accurate plot of the strain distribution could be made. The strain distribution curves for this specimen are shown in Fig. 35.

The average axial strains in the plates at the plate buckling loads for T-7, T-8, T-9 and T-10 were 950, 1070, 895 and 940 micro-inches per inch, respectively. These values are essentially 88, 100, 84 and 88 percent respectively of the theoretical elastic buckling strain. It is interesting to note that T-8, which had zero residual stress, had a plate strain practically equal to the theoretically computed elastic buckling strain. The strain in the plate of specimens T-7 and T-9 at the ultimate load was less than the elastic buckling strain by the strain corresponding to the compressive residual stresses. This clearly points to the fact that the residual stresses have a direct influence on the strength of the stiffened panels.

In specimen T-10 the left subpanel buckled when the strain was 940 micro-inches per inch at a load of 420 kips. The other subpanels continued to carry more load. However, they buckled one at a time before the ultimate load of 472 kips was reached. The final few load increments after the plate buckled represent the postbuckling strength of the panel.

Specimen T-6 had a distinctly different failure mode than specimens T-7 to T-10 as can be seen in Fig. 34. The plate in the specimen started yielding at about 65% of the ultimate load. Thus the strain measured at this load corresponded to the magnitude of stresses that had to be added to the residual stresses to reach the yield stress level. All subsequent increases in strain took place at the yield stress level and thus did not reflect changes in the stress.

6. RESIDUAL STRESS MEASUREMENTS

6.1 LAYOUT FOR RESIDUAL STRESS MEASUREMENTS

Residual stress measurements were performed on specimens T-8, T-9 and T-11. The basic difference between the three specimens was in the type of heat treatment they received, which affected the magnitude and distribution of residual stresses. Specimen T-8 was annealed after the tee stiffeners were welded to the plate and hence was not expected to have any residual stresses. The plate and stiffeners of T-9 were annealed and only then welded together. As a consequence, only welding residual stresses were developed in it. Specimen T-11 had not been annealed and thus contained both rolling and welding residual stresses (Specimens T-7 and T-10 were assumed to have the same residual stress pattern as T-11).

Figure 39 shows specimen T-11 and the location of the gage sections. The expression "gage section" designates a portion of a specimen 11 inches long which was cut out of the specimen and then sliced for measuring residual stresses.

Two factors were considered in the layout of gage lines: the spacing of gage lines in a gage section and the distance of the gage section from the ends of the plate. The spacing of the gage lines varied from 1/2 in. to 1 1/2 in. The small spacing of 1/2 inches was used next to and including the tee stiffeners. The reason for this was that the residual stress varies quite sharply in this area. The larger spacing was used for the middle portion of the plate between two stiffeners where the residual stress was approximately uniform. The distance of the gage section from the plate ends had to be sufficient to preclude relaxation of residual stresses. To study this effect specimen T-11 had two gage sections: one in the center and one at the end of the specimen. Specimen T-8 and T-9 had been tested to their ultimate axial load before residual stress measurements were taken. Therefore, the gage sections had to be selected in the regions in which no yielding had occurred. For both specimens this was the top end section.

6.2 MEASURING PROCEDURE

Residual stresses were measured with a Whittemore gage and SR-4 electrical gages. SR-4 gages were used primarily to explore the feasibility of their use for measuring residual stresses.

The holes for the Whittemore gage were laid out on the front and back faces with a standard ten inch arc scriber and then drilled with a special drill (No. 57 with the reamer angle of 60°). The reamed depth was equal for all the holes to approximately 0.007 in. The holes were cleaned with carbon tetrachloride and air-blasted.

During measuring with the Whittemore gage precaution was taken to minimize the effect of temperature variation. A standard reference bar of mild steel was laid on the steel to be measured approximately one-half hour before measuring so that it would be at the same temperature as the specimen. By taking readings on the reference bar at frequent intervals, temperature effects could be detected, and corrections to the readings in any one sequence could be made.

The effect of bending in the plate after sectioning was taken into account by averaging readings taken on the front and back faces of the plate.

At each set of gage holes three readings were taken. Readings on the standard reference bar were taken at time intervals corresponding to approximately thirty readings.

After initial readings were taken the gage holes were taped up to keep them clean. The plate was sectioned and the holes were uncovered and cleaned again for another set of readings. Taping and cleaning of the holes was performed each time some work on the plate had to be done.

SR-4 gages were used on two-thirds of the center section of specimen T-11. This was considered sufficient to indicate reliability and desirability of their use compared to the Whittemore gage. As with the Whittemore gage, first, a set of initial readings were taken. Three readings were taken on each gage. After taking readings on all gages the wire leads had to be cut before sectioning the plate. The wire leads were resoldered after sectioning and new readings were taken. Fig. 40 shows the center gage section of specimen T-11 after slicing and ready for residual stress measurements using SR-4 gages.

The changes in the strain between the initial and final readings multiplied by the modulus of elasticity gave the residual stresses in the specimen in the longitudinal direction. Residual strains in the transverse direction were assumed to be negligible and thus of little influence on longitudinal residual stresses.

6.3 RESULTS OF RESIDUAL STRESS MEASUREMENTS

6.3.1 Residual Stresses in Specimen T-11

The most extensive investigation was made on T-11. It had two gage sections, center and end as shown in Fig. 39. The distribution of residual stresses at these sections based on the Whittemore gage readings is shown in Fig. 41. The values plotted in the curves are the averages of the readings on the front and back faces of the plate. The compressive residual stress in the center gage section has values ranging from 2 to 12 ksi, with a weighted average of approximately 4.5 ksi. In the end gage section, the compressive residual stress had values ranging from 3 to 6 ksi with an average of approximately 4 ksi.

The maximum measured tensile residual stress for the center and end gage section was 38 ksi and 33 ksi, respectively. The greater magnitude of compressive residual stresses at the outside tee stiffeners may be attributed to the fact that less area of the plate was available around the outside than inside stiffeners. Hence in order to have equilibrium, higher compressive stresses were needed on the smaller plate area since the tensile residual stress was the same at all stiffeners.

Figure 42 shows the residual stress patterns found before and after the final sectioning. The final sectioning entailed the slicing of the 11 in. x 51 in. gage section into strips 11 in. long by 1/2 in. to 1 1/2 in. wide. This operation released more than half of the tensile residual stress. The compressive residual stress was not affected as greatly. The reason for this is that, less restraint is needed on adjoining strips in the compressive region where the residual stress is fairly constant, than in the tensile area where there is a steep variation of residual stresses.

A comparison of SR-4 and Whittemore gage readings for the center gage section is shown in Fig. 43. The readings indicate that the magnitude and distribution of residual stresses are approximately the same. However, the values for the SR-4 gages are more widely scattered than for the Whittemore gage. This is due to the fact that an SR-4 gage gives average strains for approximately a 3/4 in. gage length while a Whittemore gage has the advantage of giving an average value for a ten-inch gage length. Thus, SR-4 gage readings, are easily influenced by local stress conditions. Since in general the values of overall average residual stresses are needed it is obvious that the Whittemore gage should be preferred. Furthermore, its use is easier and less time consuming and thus less expensive.

6.3.2 Residual Stresses in Specimens T-8 and T-9

The residual stress distribution obtained for T-11 included the effects of rolling and welding. Specimens T-8 and T-9 were sectioned to show the effect of annealing and the magnitude of welding residual stresses, respectively.

The gage section for Specimens T-8 and T-9 was selected at their top ends. Specimen T-8, which was annealed, had hardly any residual stresses, as can be seen in Fig. 44. A comparison of the welding residual stresses in specimen T-9 (Fig. 45) with the combined residual stresses in the center gage section of specimen T-11 indicates that essentially all residual stresses were due to welding.

7. SUMMARY

The objective of this group of tests was to investigate the effect of residual stresses on the axial strength of longitudinally stiffened plate panels. In addition, one specimen, T-6, was tested to establish the effect of the degree of rotational restraint furnished by the stiffeners on the panel strength. This specimen was to be compared with a specimen, T-5, from the previous series of tests.*

This report is concerned with the presentation of the test results with only a short qualitative interpretation. Later reports will give a thorough analysis of the obtained data and a correlation with theoretical studies.

Altogether five specimens were tested by subjecting them to either axial or combined axial and lateral loading.

Specimens T-7 to T-10 had identical cross sections but different residual stress conditions. They all were tested axially. With a b/t = 60 the failure in them was triggered by local plate instability.

Specimens T-7 and T-9 had very similar residual stress patterns although in T-7 residual stresses were produced by rolling and welding and in T-9 only by welding. Specimen T-8 was stress relieved (annealed) after fabrication and had no

- - - - - - - - - - - - -

* Loc. cit. on p. 1.

residual stresses. The buckling strength of the plate in the specimens, and thus, the axial strength of the specimen was found to depend on the magnitude of the compressive residual stress. In T-8 it corresponded to the theoretical buckling stress, and in T-7 and T-9 it was equal to the theoretical buckling stress less residual stress. Quantitatively, the reduction amounted to about eight percent.

Specimen T-10, having the same residual stress condition as T-7, had an axial strength about four percent higher than T-7 due to the postbuckling strength resulting from the low slenderness ratio L/r.

Some insight into the effect of the rotational restraint furnished by the stiffeners on the plate behavior in the plastic range was afforded by the test results of specimens T-5 and T-6. Both of them had b/t = 40 and were tested under a constant lateral pressure of 6.5 psi. The basic difference between the specimen consisted of the stiffener cross section; specimen T-5 had box-shaped stiffeners, and T-6 had tee stiffeners. Thus the plate between stiffeners in T-5 was fully restrained and in T-6 essentially simply supported.

The plate in both specimens had undergone considerable yielding by the time the ultimate load was reached. At the ultimate load the strain in the plate differed markedly: in T-5 it was about 0.0027 in./in. and in T-6 about 0.0022 in./in. (the yield strain is 0.0013 in./in.) If the strains due to residual stresses are added to the above strains, the difference in the ultimate strains in T-5 and T-6 would rise from 0.0005 in./in. to about 0.0008 in./in.

In both specimens the failure was due to general column instability. The plate in both specimens became unstable but only after reaching the ultimate load. In T-6 the buckles appeared right after the ultimate load, whereas in T-5 considerably later. The buckling pattern was different in the two specimens; in T-6 it was of a checkerboard type with alternating concave and convex buckles; in T-5 it was irregular. Thus, the influence of a respectively weak and strong rotational restraint furnished by the stiffeners of T-6 and T-5 was reflected in the plastic buckling strain of the plate.

Some important observations were made during measurement of residual stresses. Although the residual stress patterns were found to be different in the end and center gage sections of specimen T-11, it is interesting to note that the average values of compressive residual stresses are approximately equal. Thus, as is often the need the magnitude of compressive welding residual stresses can be determined, at some saving, from an end gage section instead of from a center gage section.

The other observation concerns the use of SR-4 strain gages versus a Whittemore gage. Since the Whittemore gage works over a much longer gage length than an SR-4 gage (10 in. vs. 3/4 in.), it gives readings with considerably less scatter. Furthermore, a Whittemore gage requires less care and time.

On the basis of the obtained results some tentative qualitative conclusions can be drawn.

1. Residual stresses play an important part in the elastic buckling of plates and thus in the ultimate load carrying capacity of longitudinally stiffened panels. However, their effect on the plastic buckling of plates with a low plate slenderness ($b/t \leq 40$) is negligible.

2. For plates with low b/t the rotational restraint furnished by the stiffeners affects only the plastic buckling strain, and therefore, has no influence on the ultimate strength of panels with such plates.

Development of a method of theoretical analysis is currently (1962) underway, and a correlation of the test results (T-1 to T-10) and theory will be given in future reports.

8. ACKNOWLEDGEMENTS

This report presents results of six tests conducted on longitudinally stiffened plate panels during 1960 and 1961. This test series is a part of the research program on Built-Up Members in Plastic Design currently being conducted at the Fritz Engineering Laboratory of which Professor William J. Eney is Head and Dr. Lynn S. Beedle is Director.

The program is being carried out under the general direction of Dr. Lynn S. Beedle. The research is sponsored by the Department of the Navy under the Office of Naval Research Contract Nonr 610 (03). The study was initiated by Mr. John Vasta of the Bureau of Ships. His interest in and support of the project are gratefully acknowledged.

The specimens were fabricated at the Bethlehem Foundry.

The authors wish to express their deep gratitude to Mr. K. R. Harpel with his crew of technicians and to Mr. I. J. Taylor with his Instruments Group for their cooperation and assistance in preparation and execution of the tests.

Thankful acknowledgement is also due Gordon C. Eckley who helped reduce the test data and recognition is extended to Jun Kondo and Richard N. Sopko who drew the figures. The manuscript was typed with care by Mrs. Lillian Morrow.

9. TABLES AND FIGURES

Table 1: BASIC SPECIMEN DATA (T-1 to T-10)

Specimen No.	Date Tested	A* (in.^{2})	I* (in.^{4})	Parameters: b/t	Parameters: L/r*	Parameters: Rotat. restr. by stiffeners	Parameters: Latrl. ldg. q (psi)	Variable Parameter	Ultimate Axial ld. test (kips)	Mode of Failure
1	2	3	4	5	6	7	8	9	10	11
T-1	2/24/59	17.75	24.41	60	52	low	0	q (T-1 to T-4)	532	Plate Instability
T-2	4/3/59	17.75	24.41	60	52	low	6.5		450	Plate Instability
T-3	4/12/59	17.75	24.41	60	52	low	13.0		400	Plate Instability
T-4	5/14/59	17.75	24.41	60	52	low	6.5	b/t (T-4, T-5)	475	Plate Instability
T-5	7/2/59	21.34	29.52	41	52	high (full fixity)	6.5	Rotational Restraint (T-5, T-6)	684	Column Instability
T-6	6/3/60	16.96	24.54	40	51	low	6.5		463	Column Instability
T-7	7/7/60	15.56	17.58	60	50	low	0	Residual Stress (T-7, T-8)	449	Plate Instability
T-8	8/8/60	15.56	17.58	60	50	low	0		493	Plate Instability

Table 1: BASIC SPECIMEN DATA (T-1 to T-10) (Cont'd)

Specimen No.	Date Tested	A* (In.^{2})	I* (in.^{4})	Parameters				Variable Parameter	Ultimate Axial ld. test (kips)	Mode of Failure
				b/t	L/r*	Rotat. restr. by stiffeners	Latrl. ldg. q (psi)			
1	2	3	4	5	6	7	8	9	10	11
T-9	8/16/60	15.56	17.58	60	50	low	0	Residual Stress	422	Plate Instability
T-10	1/11/61	15.56	17.58	60	20.7	low	0		472	Plate Instability

* The areas, moments of inertia and L/r ratios are based on the whole cross section, however, L/r for T-1 to T-4 would be 54 if based on a subpanel width of 15" with T-stiffener at center of 15".

Table 2. TENSION COUPON TEST RESULTS (T-6 to T-10)

Coupons Taken From	Coupon Number	σ_{sy} (ksi)	σ_u (ksi)	E (10^3ksi)	E_{st} (10^3ksi)	E_{st} (in./in.)	% Elongation	% Reduct. of Area
1	2	3	4	5	6	7	8	9
	As Delivered							
Plate	Pc-8	40.8	61.3	34.2*	0.522	0.007	21.1*	54.7
	Pc-9	41.4	62.3	31.6	0.539	0.007	32.2	56.1
	Pc-10	40.3	60.7	31.0	0.408	0.007	31.8	59.4
	Pc-11	37.8	59.2	29.2	0.510	0.013	31.3	57.4
	Pc-12	42.0	62.3	29.8	0.655	0.014	28.8	57.4
	Pc-16	37.8	59.5	28.8	0.775	0.011	30.4	53.2
	Pc-17	38.0	60.5	29.6	0.493	0.011	29.8	59.5
	Pc-18	37.9	59.8	29.5	0.650	0.012	31.2	57.2
	Average	39.5	60.7	29.9	0.569	0.010	30.8	56.9
	Annealed							
Plate	Pc-13	35.9	59.4	29.5	0.561	0.022	33.4	55.7
	Pc-14	36.5	60.0	31.7	0.356	0.021	31.4	53.2
	Pc-15	36.8	59.9	33.0	0.507	0.023	32.2	60.0
	Average	36.4	59.8	31.4	0.475	0.021	32.3	56.3
	As Delivered							
Stiffener Flange	Fc-6	32.8	54.1	30.1	0.555	0.021	31.0	56.0
	Fc-7	35.2	58.6	28.1	0.655	0.017	26.9	41.8*
	Fc-8	36.8	58.7	32.2	0.489	0.021	23.5	57.4
	Fc-10	38.2	62.4	29.9	0.769	0.021	25.6	54.6
	Fc-12	36.7	58.6	29.8	0.718	0.016	24.8	47.0
	Average	35.9	58.5	30.0	0.637	0.019	26.4	53.8

Table 2. TENSTION COUPON TEST RESULTS (T-6 to T-10) (Cont'd)

Coupons Taken From	Coupon Number	σ_{sy} (ksi)	σ_u (ksi)	E (10^3ksi)	E_{st} (10^3ksi)	ϵ_{st} (in./in.)	% Elongation	% Reduct. of Area
1	2	3	4	5	6	7	8	9
	Annealed							
Stiffener Flange	Fc-9	31.7	48.0	33.6	0.449	0.022	30.5	59.3
	Fc-11	34.7	49.3	33.1	0.615	0.019	27.4	-
	Average	33.2	48.6	33.4	0.532	0.020	29.0	59.3
	As Delivered							
Stiffener Web	Wc-4	40.9	67.0	34.6	0.481	0.017	25.5	46.9
	Wc-5	38.6	62.4	29.4	0.356	0.021	33.2	50.1
	Wc-6	40.1	60.0	28.8	0.592	0.029	28.8	45.5
	Wc-8	42.0	64.2	32.2	0.574	0.030	29.6	53.6
	Wc-9	36.8	60.0	-	-	-	30.8	60.5
	Wc-10	39.7	59.9	29.1	0.465	0.026	33.7	57.0
	Average	39.7	62.2	30.8	0.494	0.025	30.3	52.3
	Annealed							
Stiffener Web	Wc-7	34.8	54.7	30.4	0.731	0.029	29.0	-

* These values are not included in averages

Table 3. ACTUAL SPECIMEN DIMENSIONS

	Plate			Stiffeners			
Specimen	Width in.	Length in.	Avg. Thickness in.	Flange Width in.	Flange Thickness in.	Depth in.	Web Thickness in.
1	2	3	4	5	6	7	8
T-6	51	58.5	0.2553	1.88	0.161	3.32	0.120
T-7	51	50.5	0.2529	1.93	0.162	3.30	0.122
T-8	51	50.5	0.2512	1.86	0.161	3.31	0.118
T-9	51	50.5	0.2530	1.89	0.161	3.33	0.119
T-10	51	19.43	0.2514	1.93	0.162	3.29	0.115

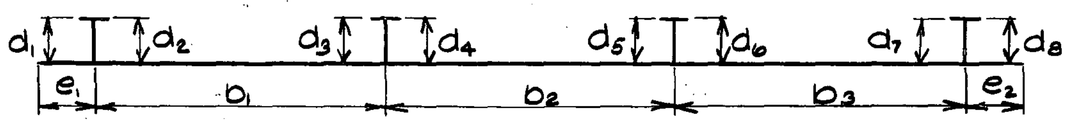
Note: For nominal dimensions, see Figs. 1, 2, and 3.

Table 4. INITIAL TILTING AND SPACING OF STIFFENERS

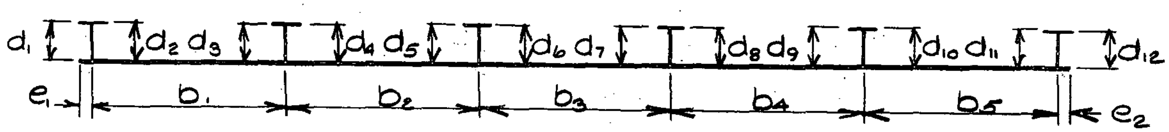
a. Initial Spacing of Stiffeners (in.)

Specimen		e_1	b_1	b_2	b_3	b_4	b_5	e_2
T-6	Top	.50	9.97	10.00	10.06	9.97	10	.50
	Bottom	.43	10.06	9.91	10.03	10.03	10	.50
T-7	Top	3.02	15.00	15.00	15.00			2.95
	Bottom	2.97	15.00	14.97	15.03			2.99
T-8	Top	2.97	15.02	15.00	14.97			3.02
	Bottom	2.99	15.00	15.00	14.99			3.00
T-9	Top	2.99	15.02	15.00	14.99			3.02
	Bottom	2.97	15.03	15.03	14.94			3.03
T-10	Top	3.00	15.00	15.00	15.00			3.00
	Bottom	2.95	14.99	15.00	15.02			3.05

Cross - Section



Specimens T-7 to T-11



Specimen T-6

Table 4. INITIAL SPACING AND TILTING OF STIFFENERS (Cont'd)

b. Initial Tilting of Stiffeners (in.)

Specimen		d_1	d_2	d_3	d_4	d_5	d_6	d_7	d_8
T-7	Top	3.31	3.27	3.34	3.28	3.34	3.28	3.29	3.28
	Bottom	3.32	3.32	3.35	3.34	3.28	3.29	3.29	3.29
T-8	Top	3.31	3.30	3.28	3.32	3.28	3.31	3.29	3.30
	Bottom	3.30	3.31	3.32	3.28	3.31	3.31	3.28	3.36
T-9	Top	3.35	3.30	3.35	3.30	3.30	3.31	3.34	3.36
	Bottom	3.30	3.32	3.33	3.31	3.30	3.26	3.31	3.31
T-10	Top	3.26	3.30	3.32	3.32	3.28	3.32	3.28	3.32
	Bottom	3.26	3.28	3.29	3.30	3.28	3.31	3.28	3.29

Specimen		d_1	d_2	d_3	d_4	d_5	d_6
T-6	Top	3.31	3.26	3.32	3.28	3.31	3.34
	Bottom	3.30	3.35	3.29	3.30	3.31	3.34

Specimen		d_7	d_8	d_9	d_{10}	d_{11}	d_{12}
T-6	Top	3.35	3.39	3.28	3.36	3.29	3.31
	Bottom	3.31	3.32	3.20	3.31	3.25	3.32

Table 5A. INITIAL UNFAIRNESS OF PLATE (SPECIMEN T-6)

(10^{-3} in.)

a. Horizontal Sections

Sect.	Points 1	2	3	4	5	6	7	8	9
HT	-2	-30	-51	-79	-100	-94	-46	-21	-14
HC	-10	-57	-49	-95	-90	-104	-49	-49	0
HB	-18	-48	-93	-152	-159	-174	-111	-74	-36

b. Vertical Sections

Sect.	Points 1	2	3
VR	47	62	55
VC	93	118	96
VL	46	81	50

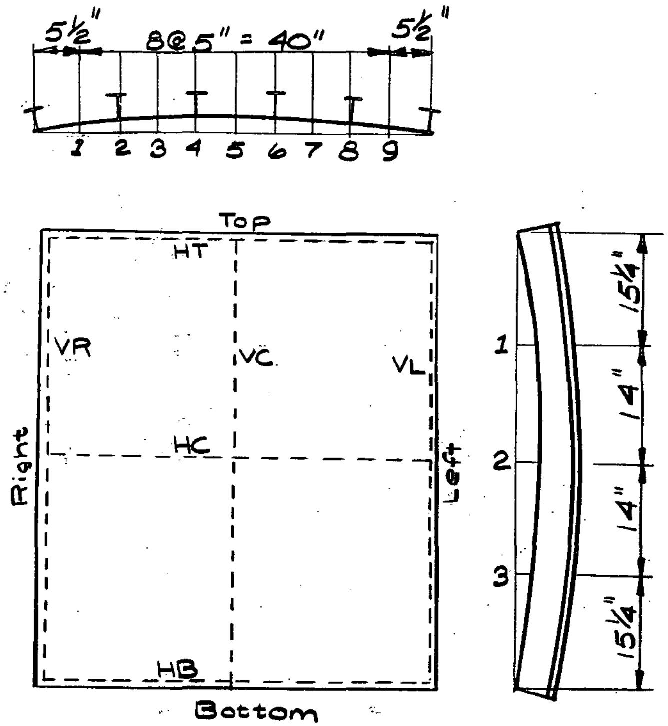


Table 5B. INITIAL UNFAIRNESS OF PLATES (SPECIMENS T-7 to T-9)

(10^{-3} in.)

a. Horizontal Sections

Spec.	Sect.	Points 1	2	3	4	5	6	7
T-7	HT	63	59	80	36	60	-5	25
	HC	68	111	101	84	59	153	64
	HB	80	66	83	1	-7	-12	27
T-8	HT	-16	-9	-15	-24	-37	14	-22
	HC	-64	-30	-37	-20	3	-4	-54
	HB	35	138	42	3	16	-8	-15
T-9	HT	-29	-111	-162	-141	-119	-65	-16
	HC	-98	-80	-180	-139	-169	-126	-113
	HB	-42	-84	-117	-63	-73	-137	-81

b. Vertical Sections

Spec.	Sect.	Points 1	2	3
T-7	VR	1	12	-2
	VC	42	41	45
	VL	-50	-1	20
T-8	VR	30	104	84
	VC	88	84	11
	VL	40	57	39
T-9	VR	39	68	23
	VC	41	29	17
	VL	55	53	53

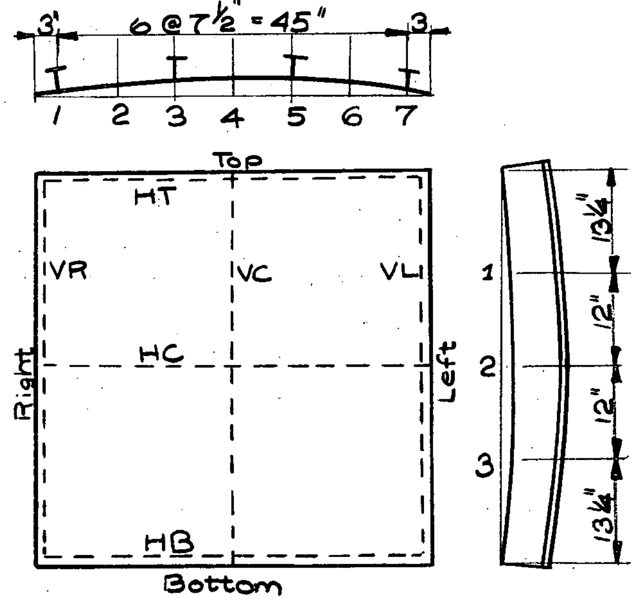


Table 6. INITIAL UNFAIRNESS OF PLATE (SPECIMEN T-10)

(10^{-3} in.)

a. Horizontal Sections

	Points						
Sect.	1	2	3	4	5	6	7
HT	-132	-177	-171	-185	-149	-120	-43
HC	-92	-128	-148	-107	-136	-85	-40
HB	-87	-136	-134	-84	-106	-89	-57

b. Vertical Sections

	Points		
Sect.	1	2	3
VR	0	9	15
VC	21	23	23
VL	12	-4	-9

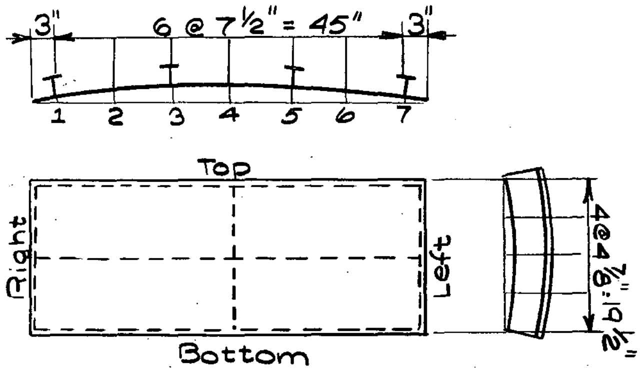
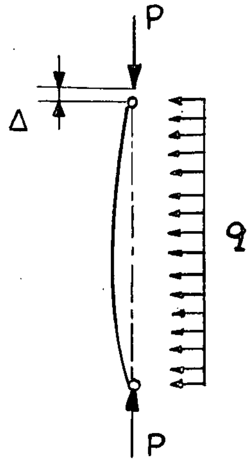


Table 7: LONGITUDINAL DEFLECTIONS



Deflection = Average of Gages L-1 and L-2

Note: Longitudinal deflection readings were made only during the application of the axial load, therefore, none are given for Specimen T-6 for a few first (and last) load numbers, Ld. No., at which the lateral loading was put on (and off).

Ld. No.	T-6 Load P kips	T-6 Defl. 0.001 in.	T-7 Load P kips	T-7 Defl. 0.001 in.	T-8 Load P kips	T-8 Defl. 0.001 in.	T-9 Load P kips	T-9 Defl. 0.001 in.	T-10 Load P kips	T-10 Defl. 0.001 in.
1	0	-	0	-	0	-	0	-	0	-
2	0	-	50	0	20	0	20	0	50	-
3	0	-	50	0	20	0	20	0	50	0
4	0	-	100	7	50	6	50	6	100	6
5	50	0	150	15	100	14	100	16	150	10
6	100	10	200	22	150	22	150	24	200	15
7	200	27	300	37	200	28	200	32	250	19
8	300	42	350	44	250	35	250	39	300	23
9	400	60	375	50	300	42	300	46	350	27
10	423	69	385	52	350	49	350	54	375	29
11	442	76	389	52	375	53	375	58	390	30
12	450	80	394	54	400	57	400	63	400	31
13	458	87	403	55	425	60	410	66	410	31
14	460	90	406	56	450	64	420	72	350	29
15	462	92	411	57	460	66	380	80	390	31
16	463	95	417	58	470	67	370	80	410	32

Table 7: LONGITUDINAL DEFLECTIONS (Cont'd)

Ld. No.	T-6 Load P kips	T-6 Defl. 0.001 in.	T-7 Load P kips	T-7 Defl. 0.001 in.	T-8 Load P kips	T-8 Defl. 0.001 in.	T-9 Load P kips	T-9 Defl. 0.001 in.	T-10 Load P kips	T-10 Defl. 0.001 in.
17	453	103	425	59	480	69	350	77	420	33
18	422	116	430	60	485	71	300	70	426	33
19	397	115	436	61	431	66	250	62	431	34
20	330	108	442	62	450	67	200	55	437	35
21	297	100	447	64	485	72	150	47	442	35
22	348	106	449	66	490	74	100	39	446	36
23	398	113	443	70	360	94	50	29	452	37
24	398	125	418	83	340	100	20	22	455	37
25	263	167	382	98	323	108	0	-	461	38
26	54	118	349	93	200	87			465	39
27	0	-	299	84	100	68			467	39
28	0	-	200	68	200	84			465	41
29			298	82	325	107			472	43
30			348	92	308	116			465	47
31			382	98	294	128			443	60
32			368	106	200	111			423	69
33			341	122	20	71			373	66
34			200	96					300	60
35			30	59					200	51
36			0	186					300	59
37									423	69
38									402	81
39									399	86
40									43	50
41									0	-

Table 8 EFFECT OF RESIDUAL STRESS ON THE STRENGTH OF LONGITUDINALLY STIFFENED PANELS-TEST PROGRAM

Test No.	Condition of Specimen	State of Residual Stress	Nature of Test
T-7	As welded	Rolling and Welding	
T-8	Welded then Annealed	None	Axial Compression
T-9	Parts Annealed then welded	Welding	
T-11	Same as T-7		Residual Stress Measurement

Table 9 EFFECT OF RESIDUAL STRESS ON THE STRENGTH OF LONGITUDINALLY STIFFENED PANELS-TEST RESULTS

Test No.	State of Residual Stress	σ_e* Ksi	σ_y ksi	P_u kips	P_u/A ksi	P_{cr}/A_{cr} ksi
T-7	Rolling & Welding	31.9	39.5	449	28.6	29.3
T-8	None	31.9	36.4	493	31.9	31.9
T-9	Welding	31.9	36.4	422	27.0	28.4
T-10	Rolling & Welding	31.9	39.5	472	30.5	24.6

* Elastic buckling stress based on:

$$b/t = 60, \; E = 30 \times 10^3 \text{ ksi}, \; k = 4.23$$

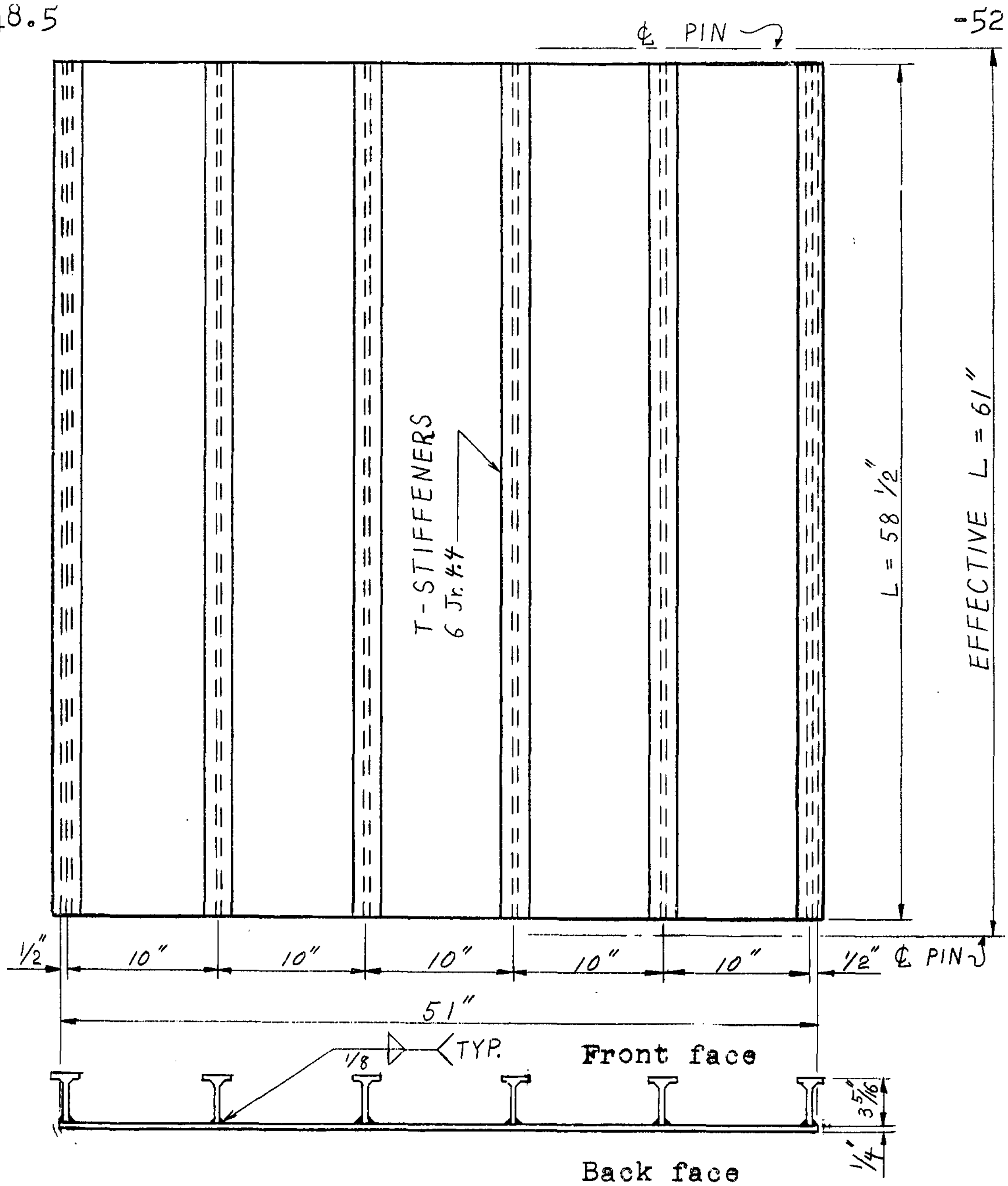


Fig. 1 TEST SPECIMEN DIMENSIONS (T-6)

Scale: 1"=1'-0"

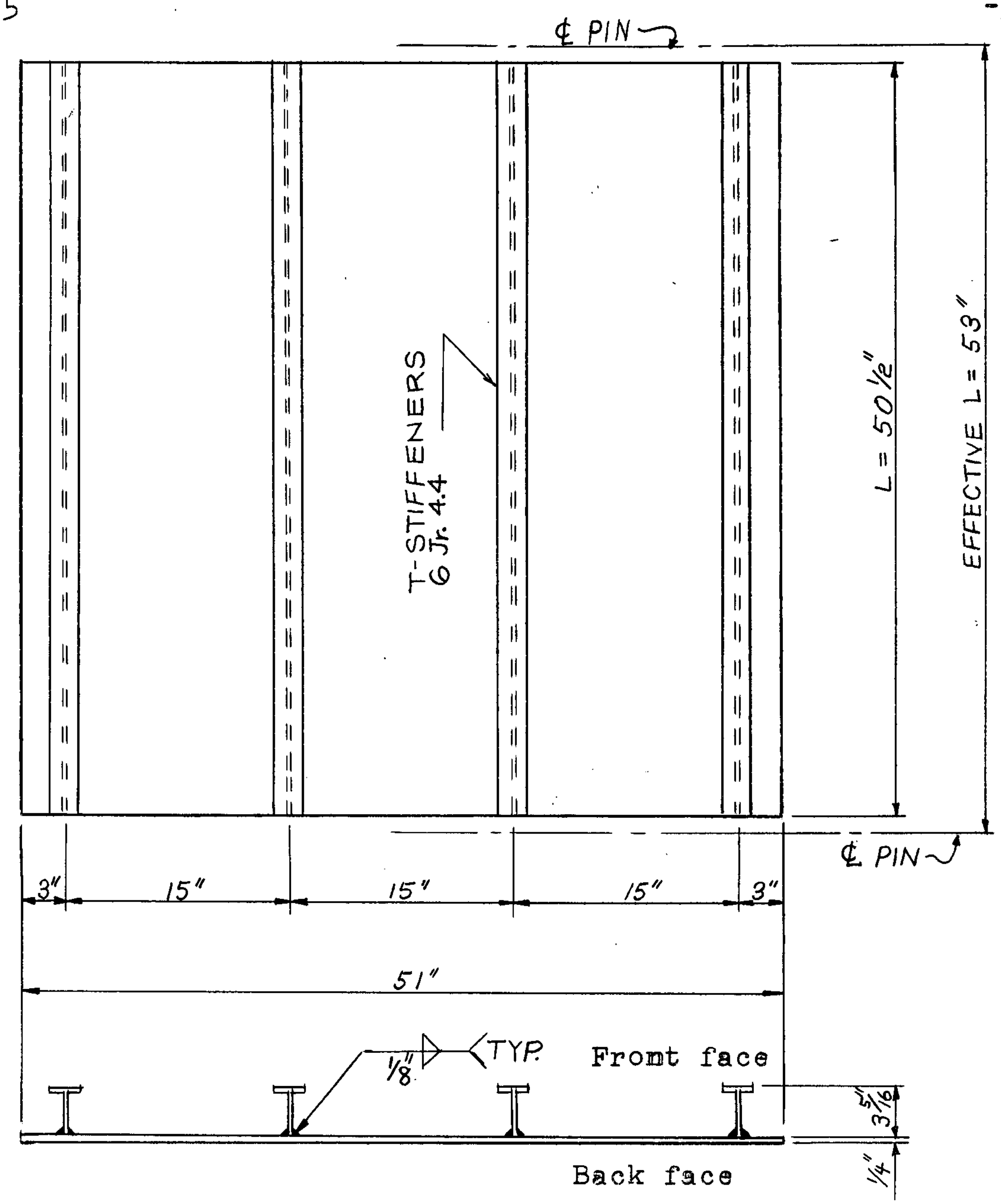


Fig. 2 TEST SPECIMEN DIMENSIONS (T-7, T-8, T-9)
Scale 1"=1'-0"

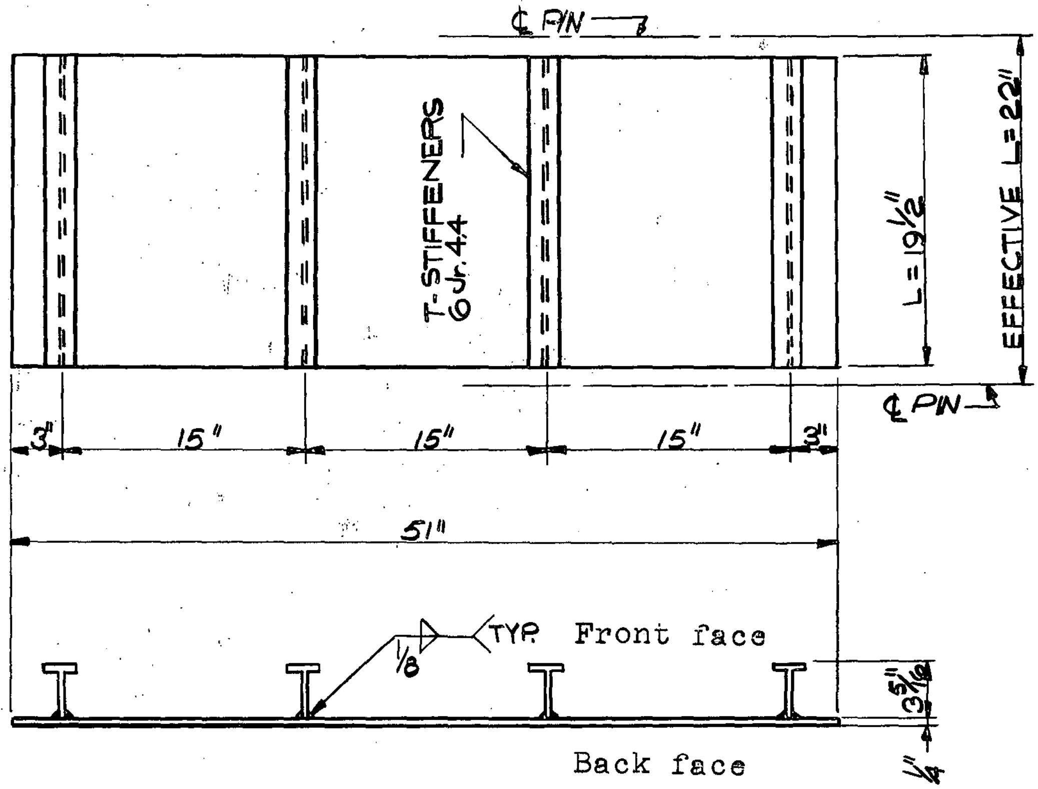
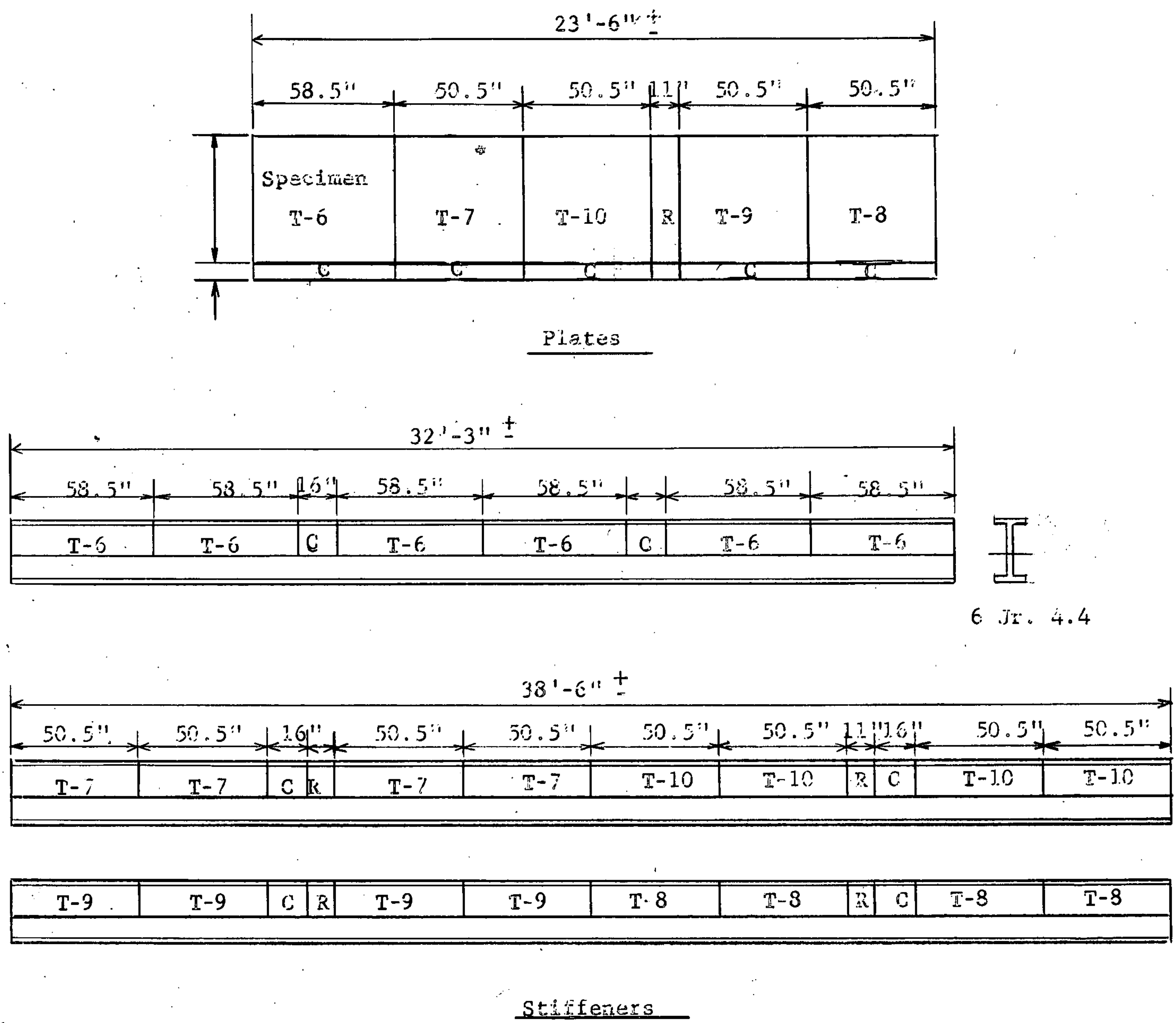


Fig. 3 TEST SPECIMEN DIMENSIONS (T-10)
Scale 1, = 1'-0"



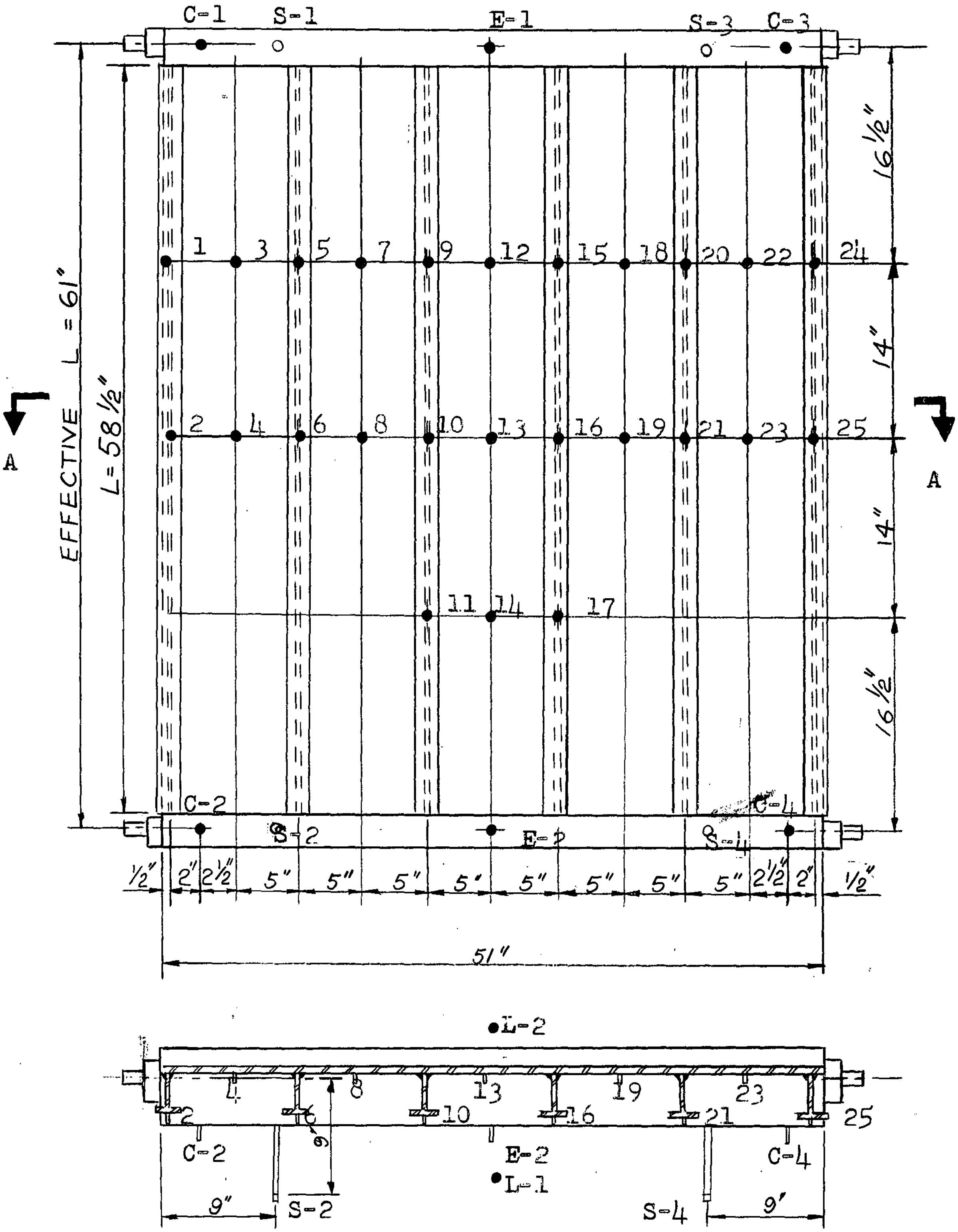
Note:

R: Reserved pieces for residual stress measurement

C: Reserved pieces for coupon tests

No Scale

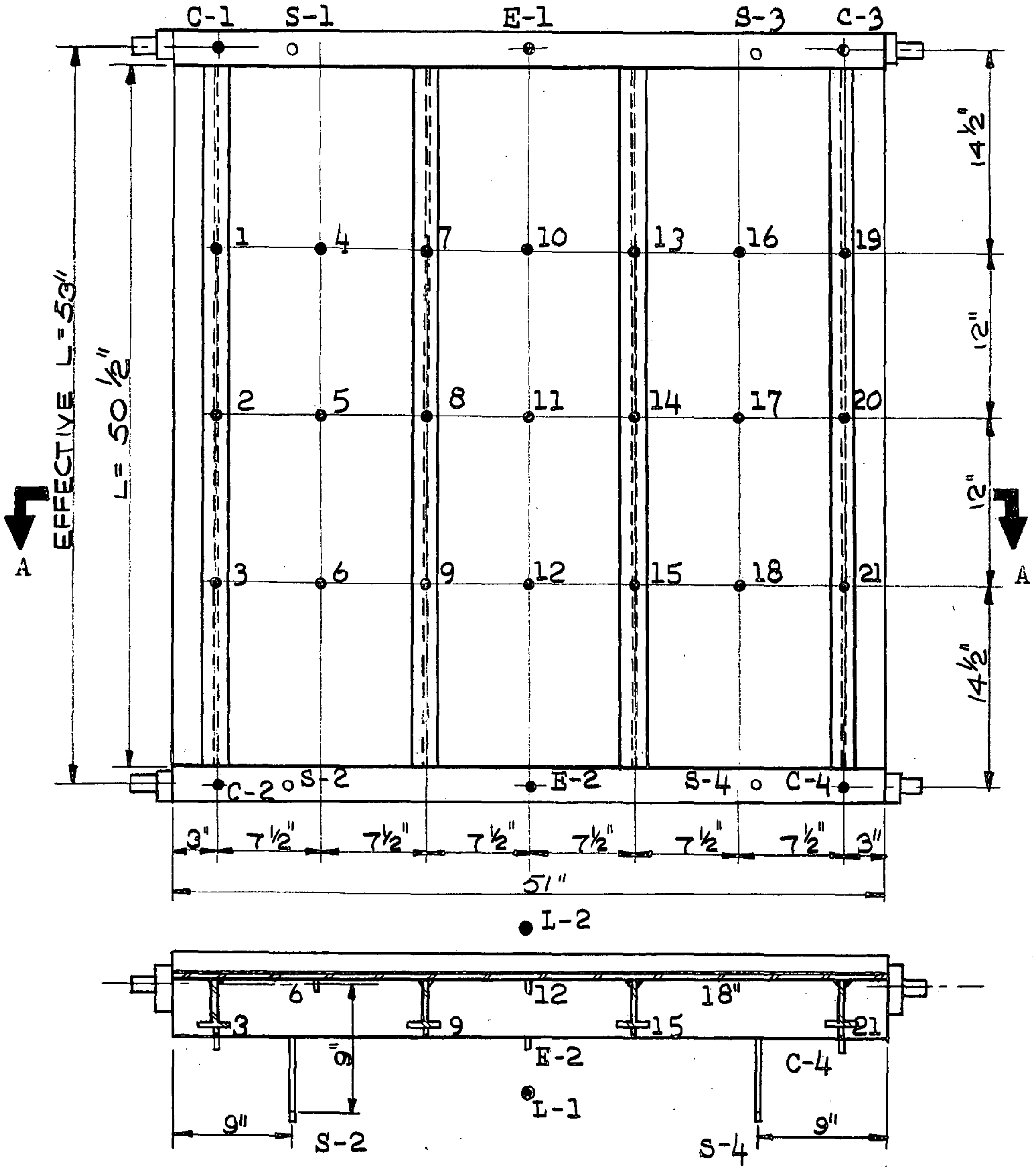
Fig. 4 MATERIAL CUTTING DIAGRAMS



Section A-A

Fig. 5 LOCATION OF DIAL GAGES (T-6)

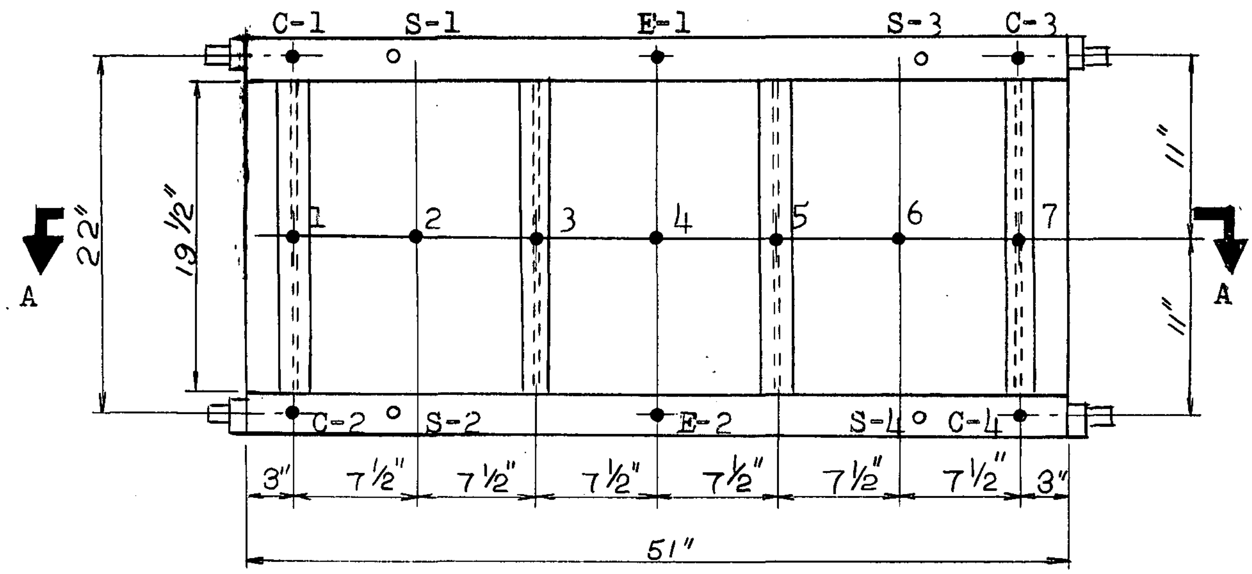
Scale: 1"=1'-0"

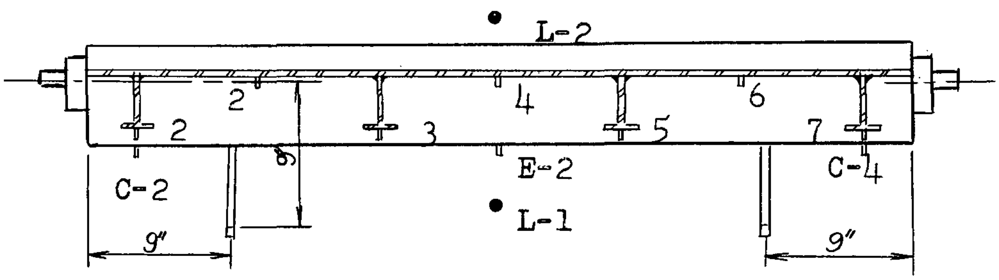


Section A-A

Fig. 8 LOCATION OF DIAL GAGES (T-7, T-8, T-9)

Scale: 1"=1'-0"

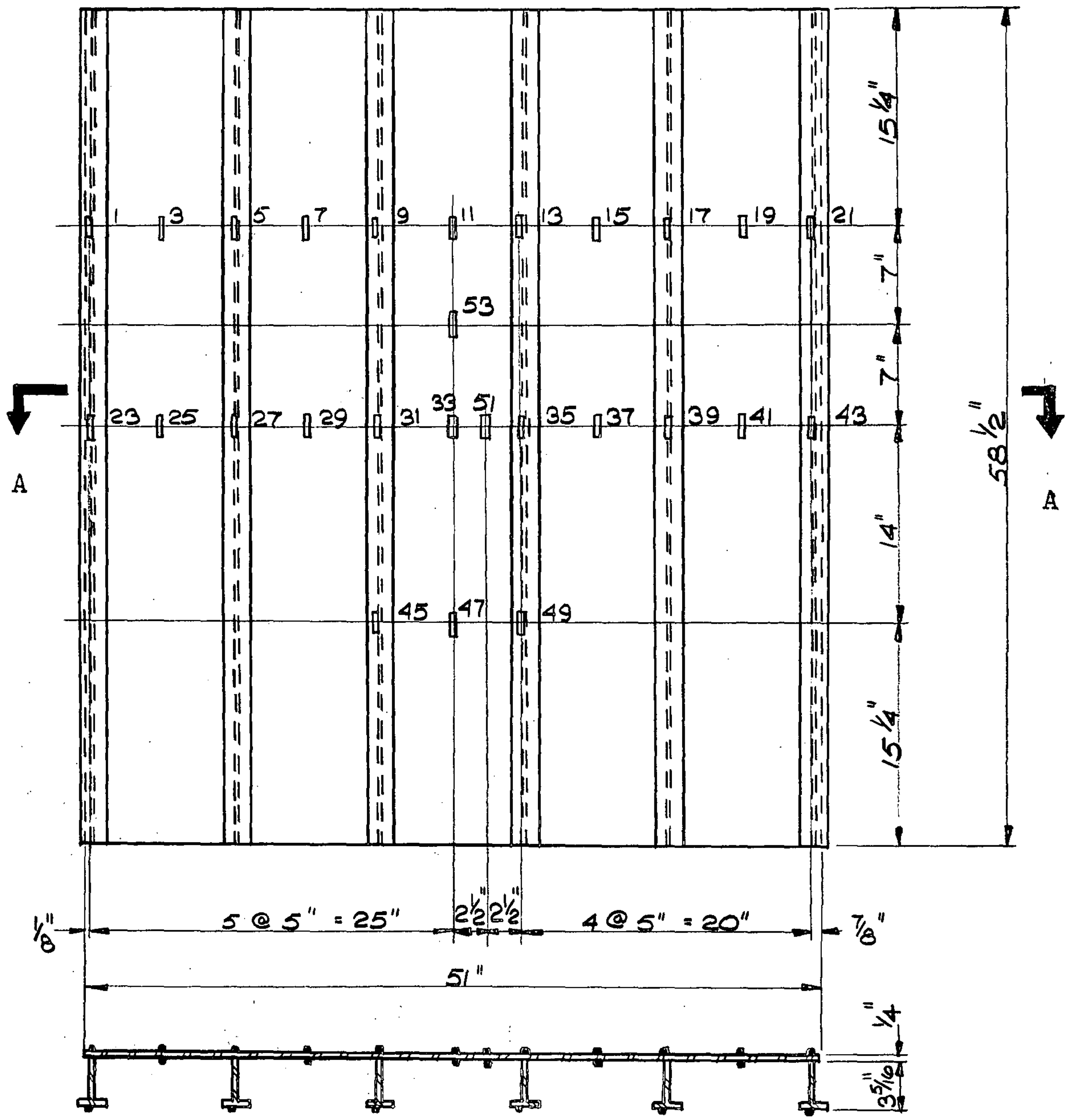




Section A-A

Fig. 7 LOCATION OF DIAL GAGES (T-10)

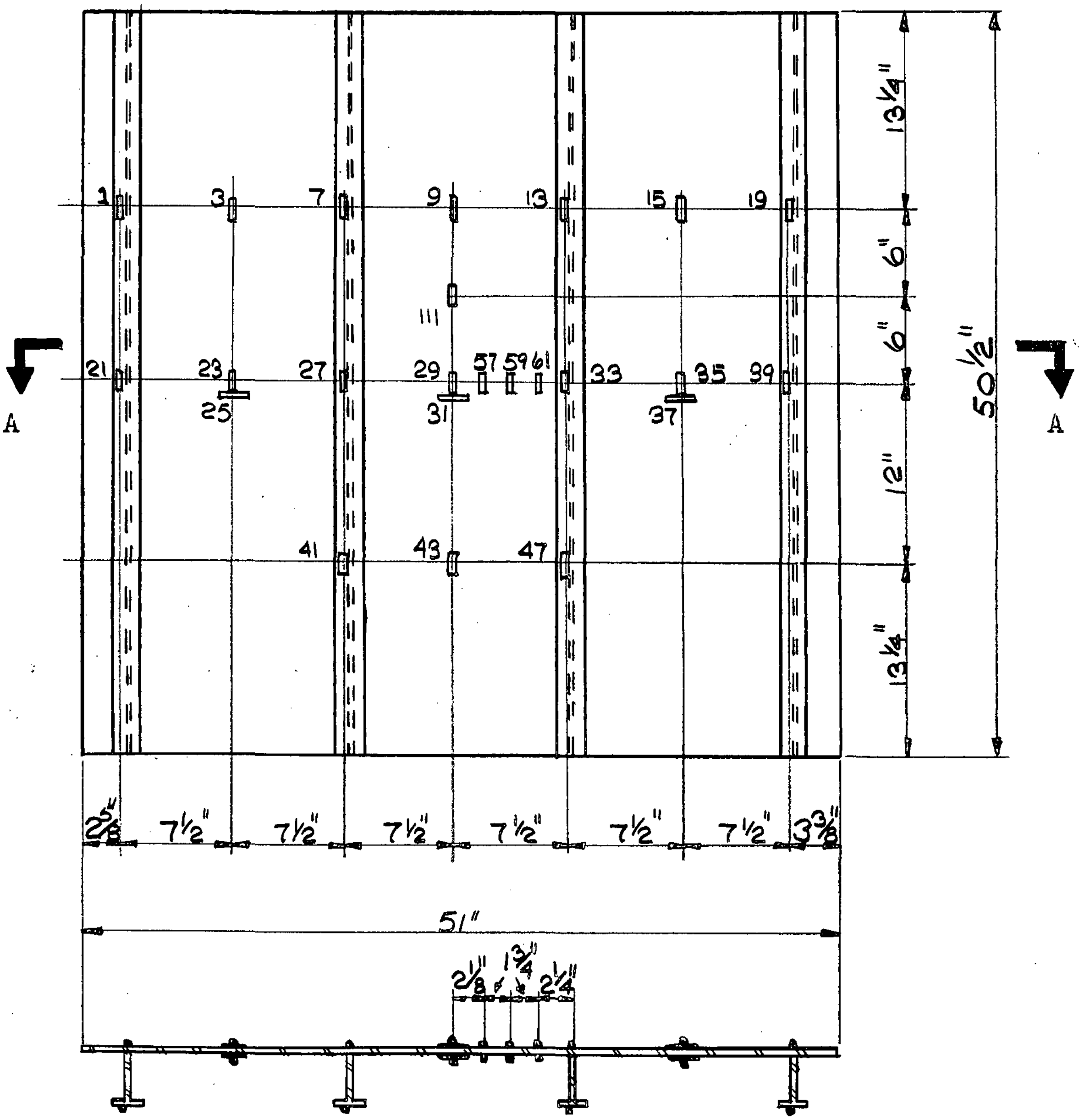
Scale 1" = 1'-0"



Section A-A

Fig. 8 LOCATION OF SR-4 STRAIN GAGES (T-6)

Note: For each gage on the front face there is a corresponding gage on the back face. The gage number on the back face is the following even number to that of the gage on the front face.

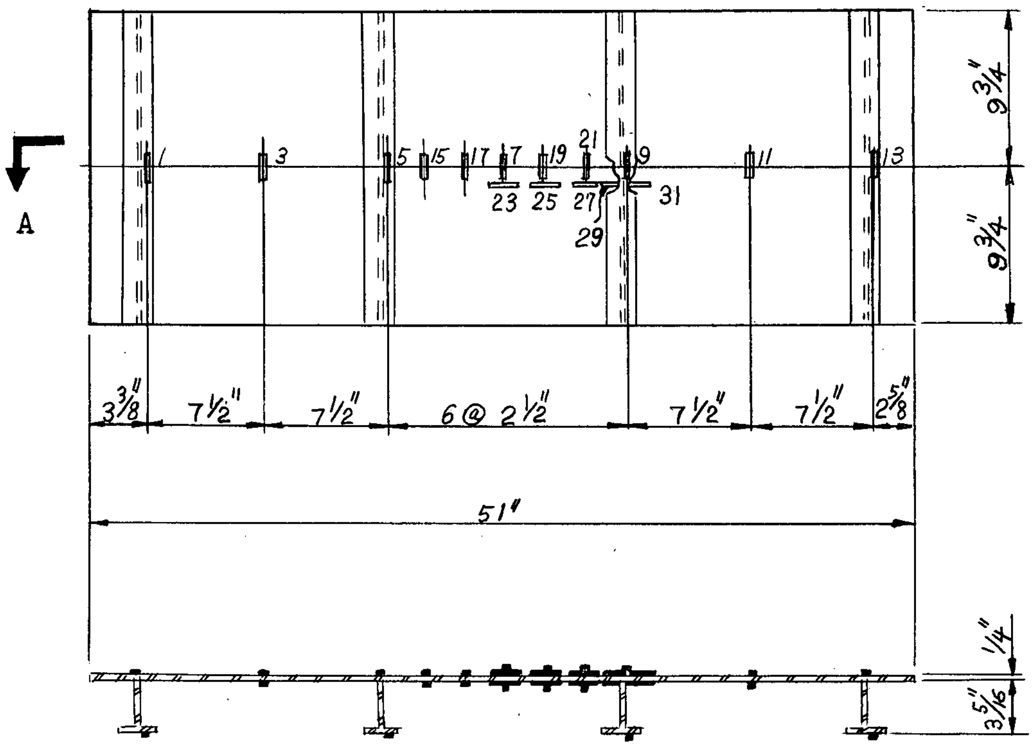


Section A-A

Fig. 9 LOCATION OF SR-4 STRAIN GAGES (T-7, T-8, T-9)

Notes: 1. For each gage on the front face there is a corresponding gage on the back face. The gage number on the back face is the followimg even number to that of the gage on the front face.

2. Table A shows which gages were used on which specimen.



Section A-A

Fig. 10 LOCATION OF SR-4 STRAIN GAGES (T-10)

Note: For each gage on the front face there is a corresponding gage on the back face. The gage number on the back face is the following even number to that of the gage on the fron face.

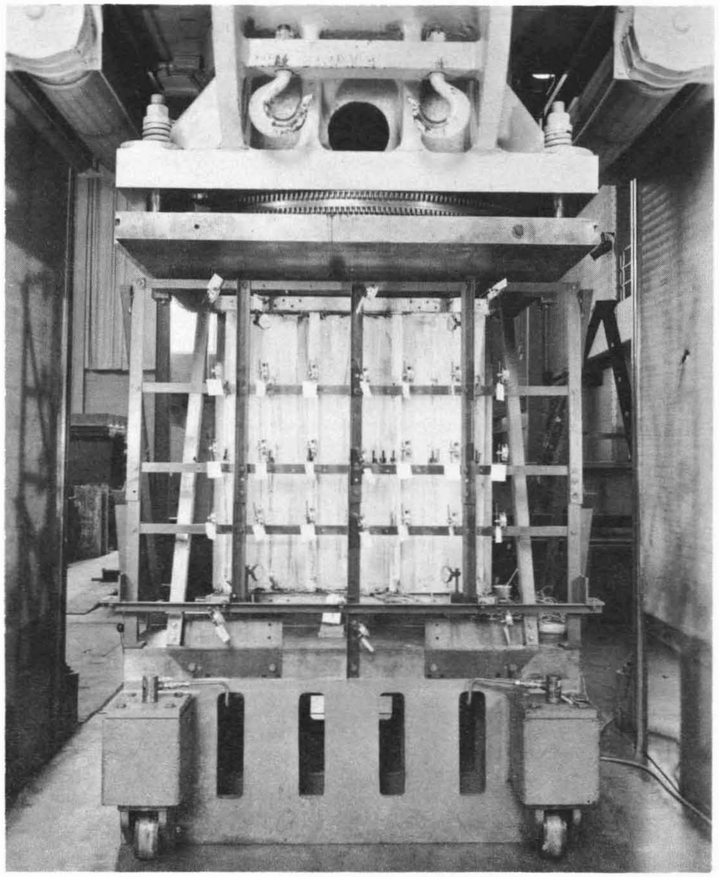


Fig. 11 TEST SETUP - FRONT VIEW

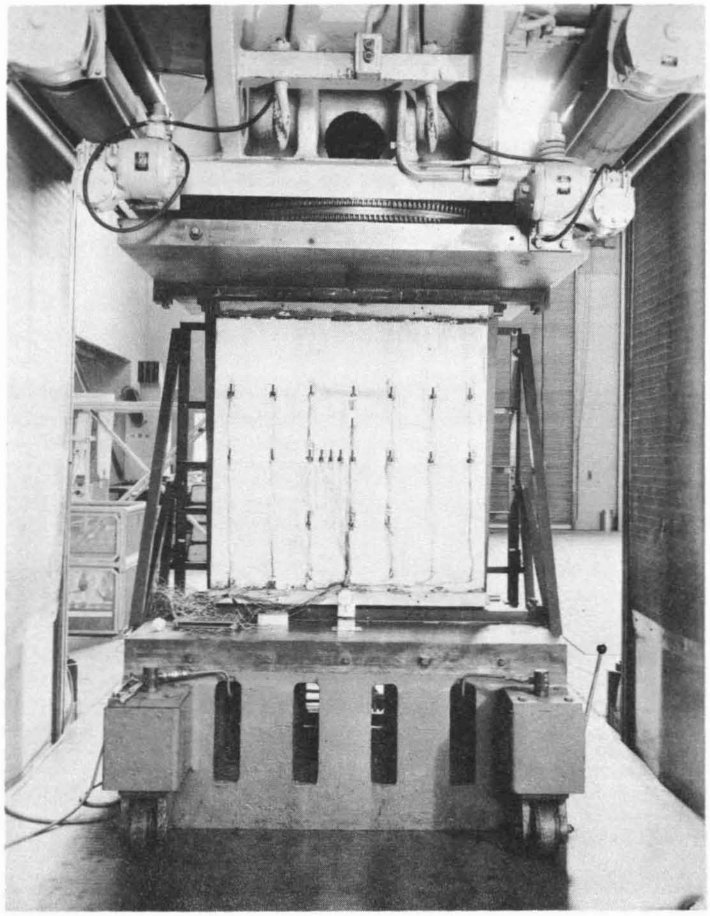


Fig. 12 TEST SETUP - REAR VIEW

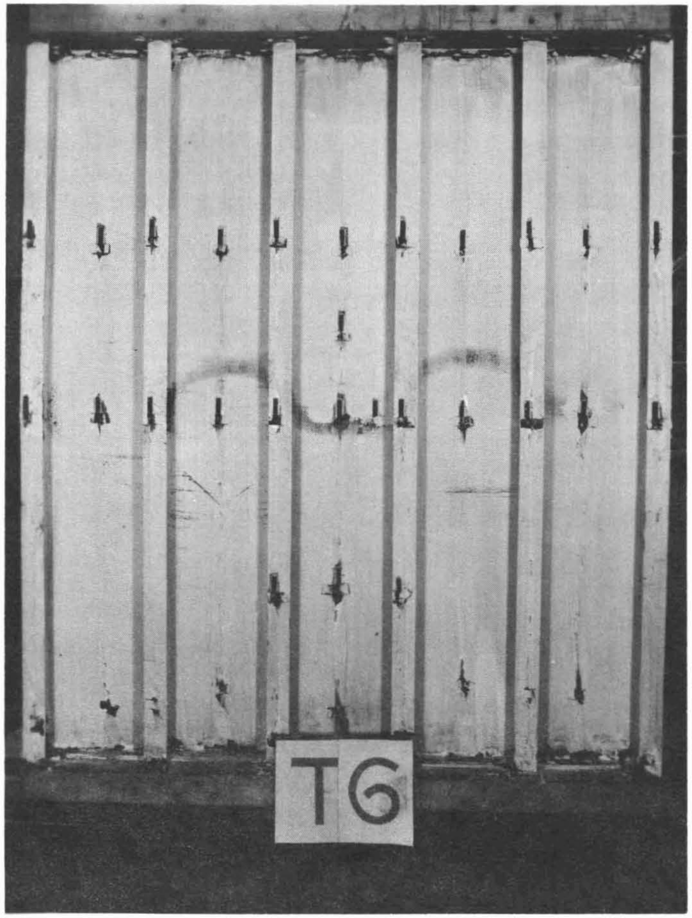


Fig. 13 SPECIMEN T-6 AFTER TEST
FRONT FACE

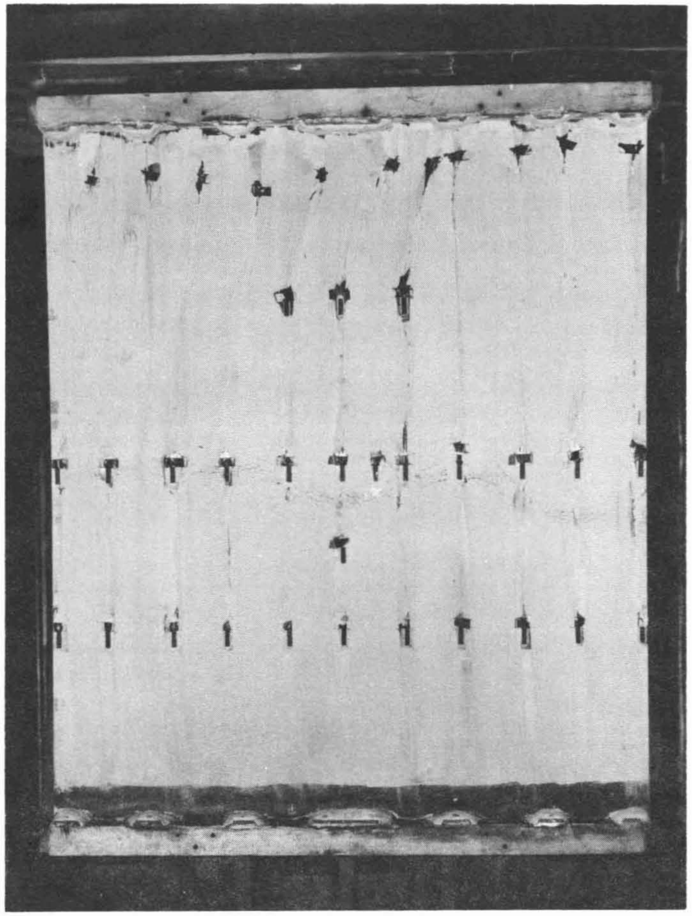


Fig. 14 SPECIMEN T-6 AFTER TEST
BACK FACE

Fig. 15 SPECIMEN T-7 AFTER TEST
FRONT FACE

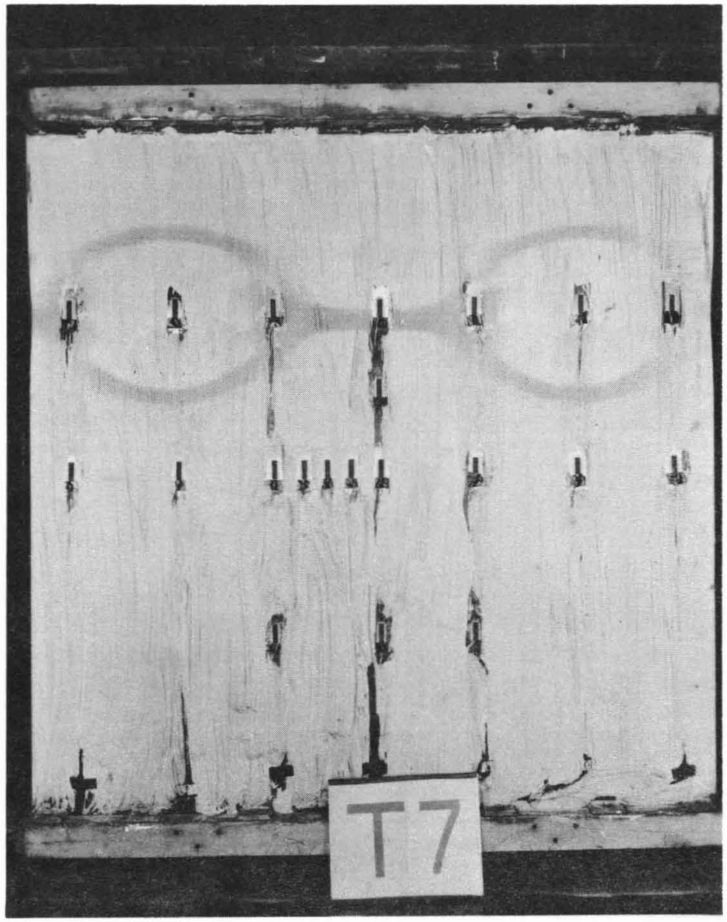


Fig. 16 SPECIMEN T-7 AFTER TEST
BACK FACE

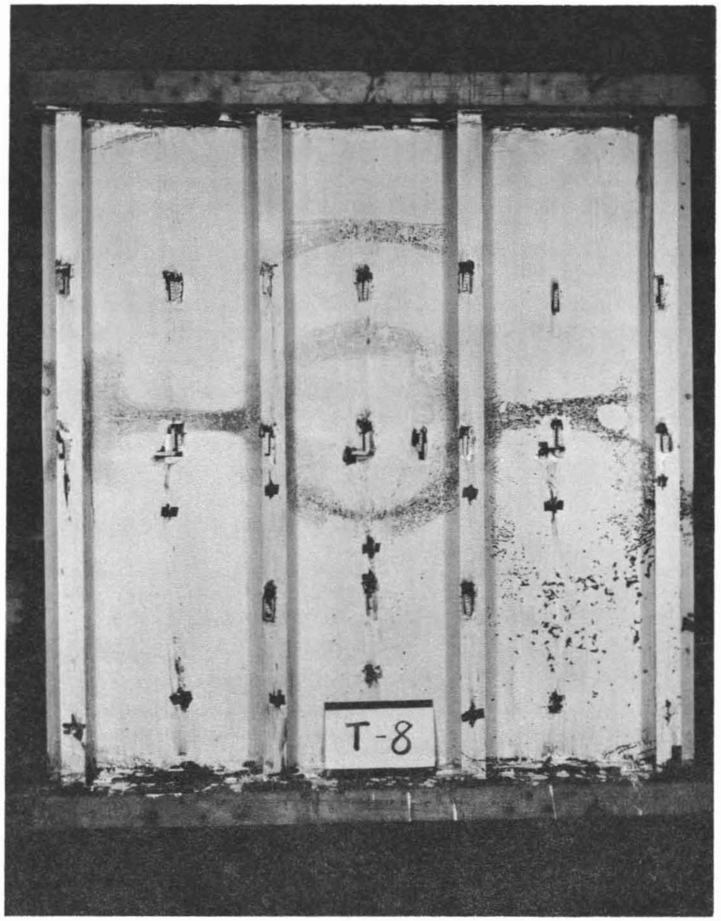


Fig. 17 SPECIMEN T-8 AFTER TEST
FRONT FACE

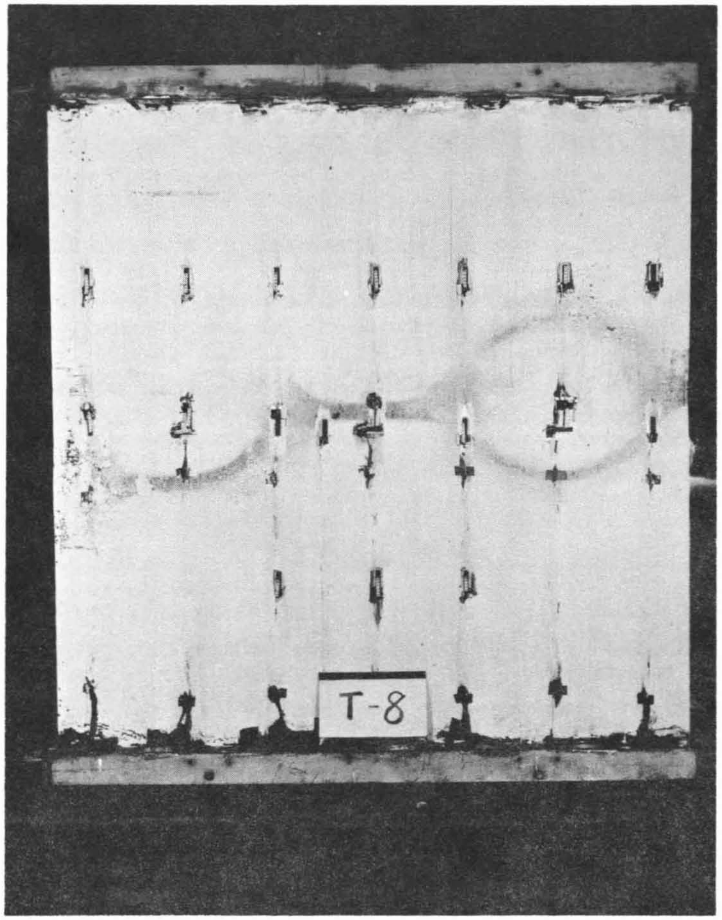


Fig. 18 SPECIMEN T-8 AFTER TEST
BACK FACE

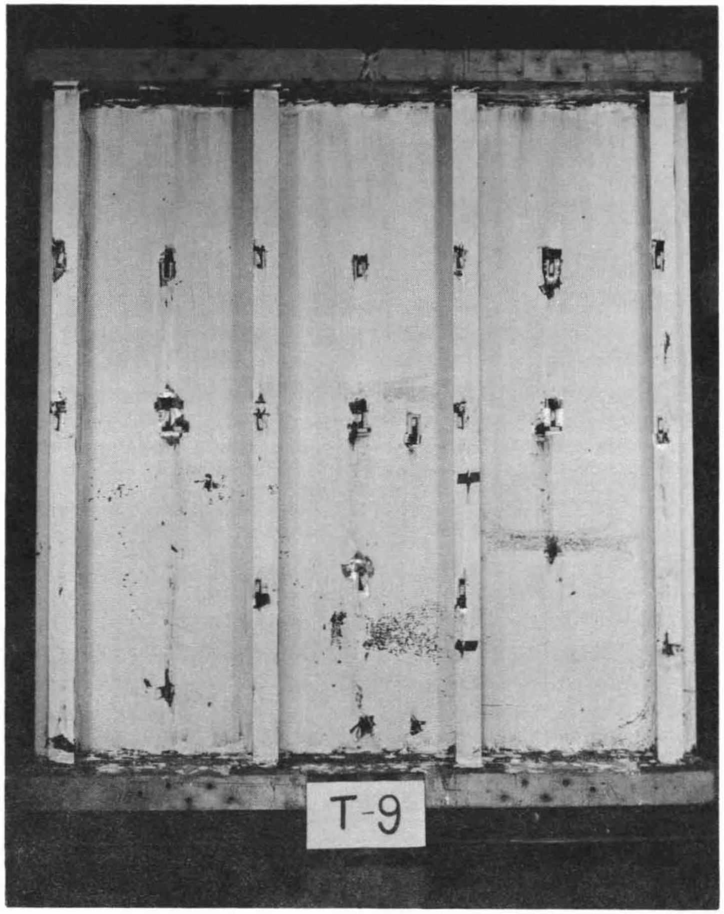


Fig. 19 SPECIMEN T-9 AFTER TEST
FRONT FACE

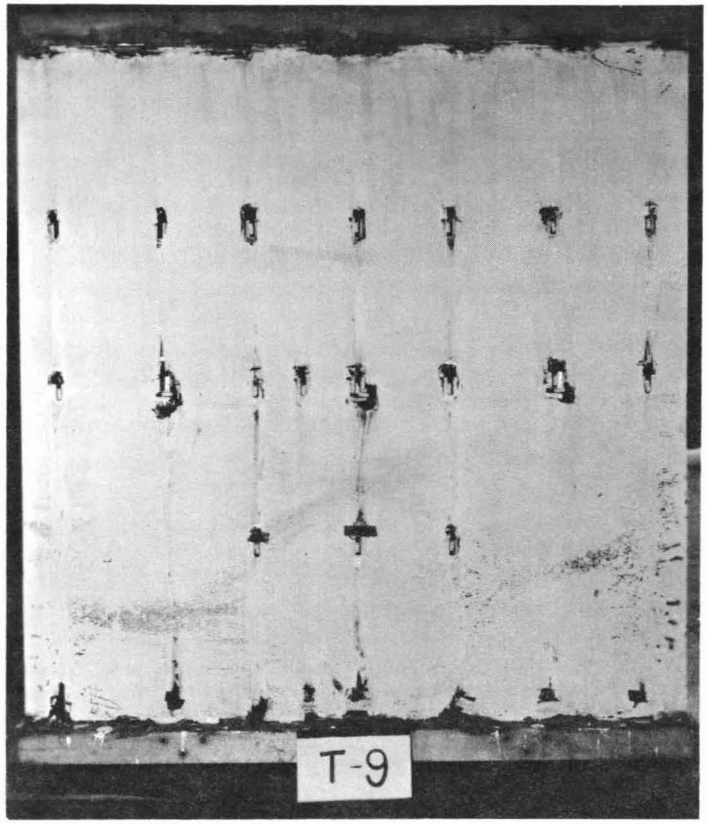


Fig. 20 SPECIMEN T-9 AFTER TEST
BACK FACE

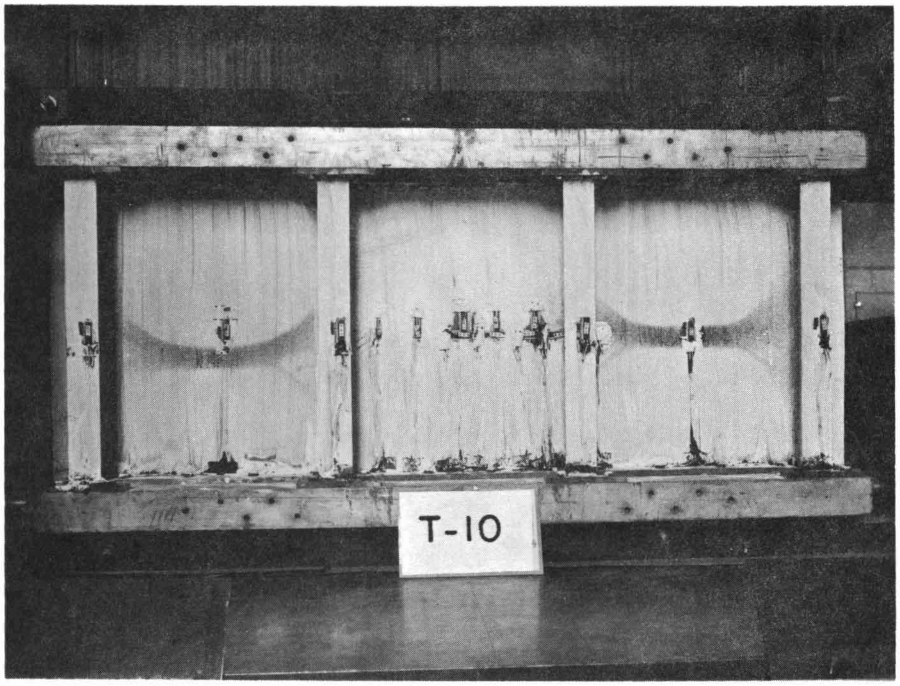


Fig. 21 SPECIMEN T-10 AFTER TEST-FRONT FACE

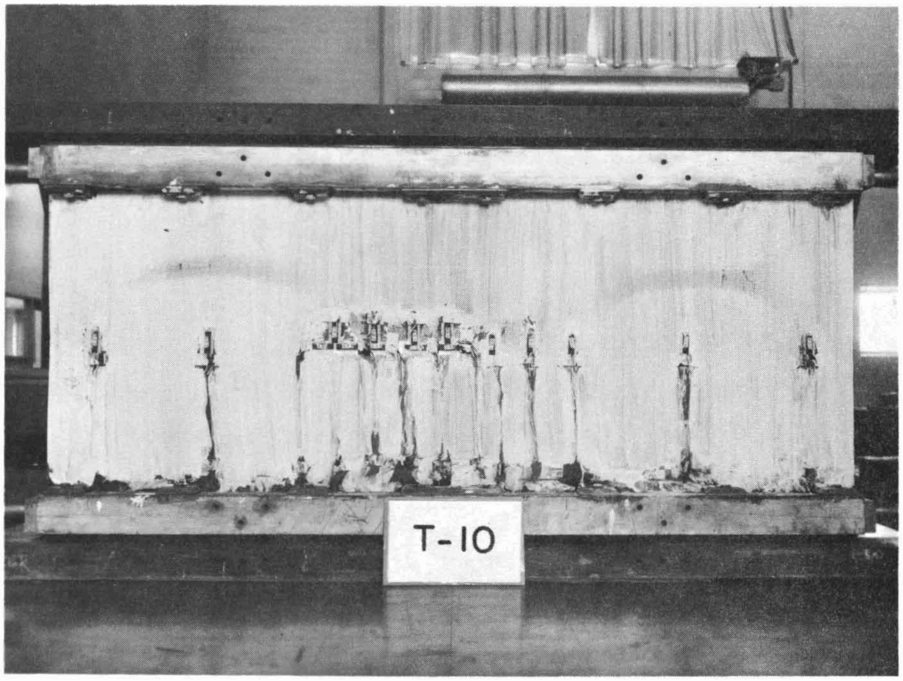


Fig. 22 SPECIMEN T-10 AFTER TEST-BACK FACE

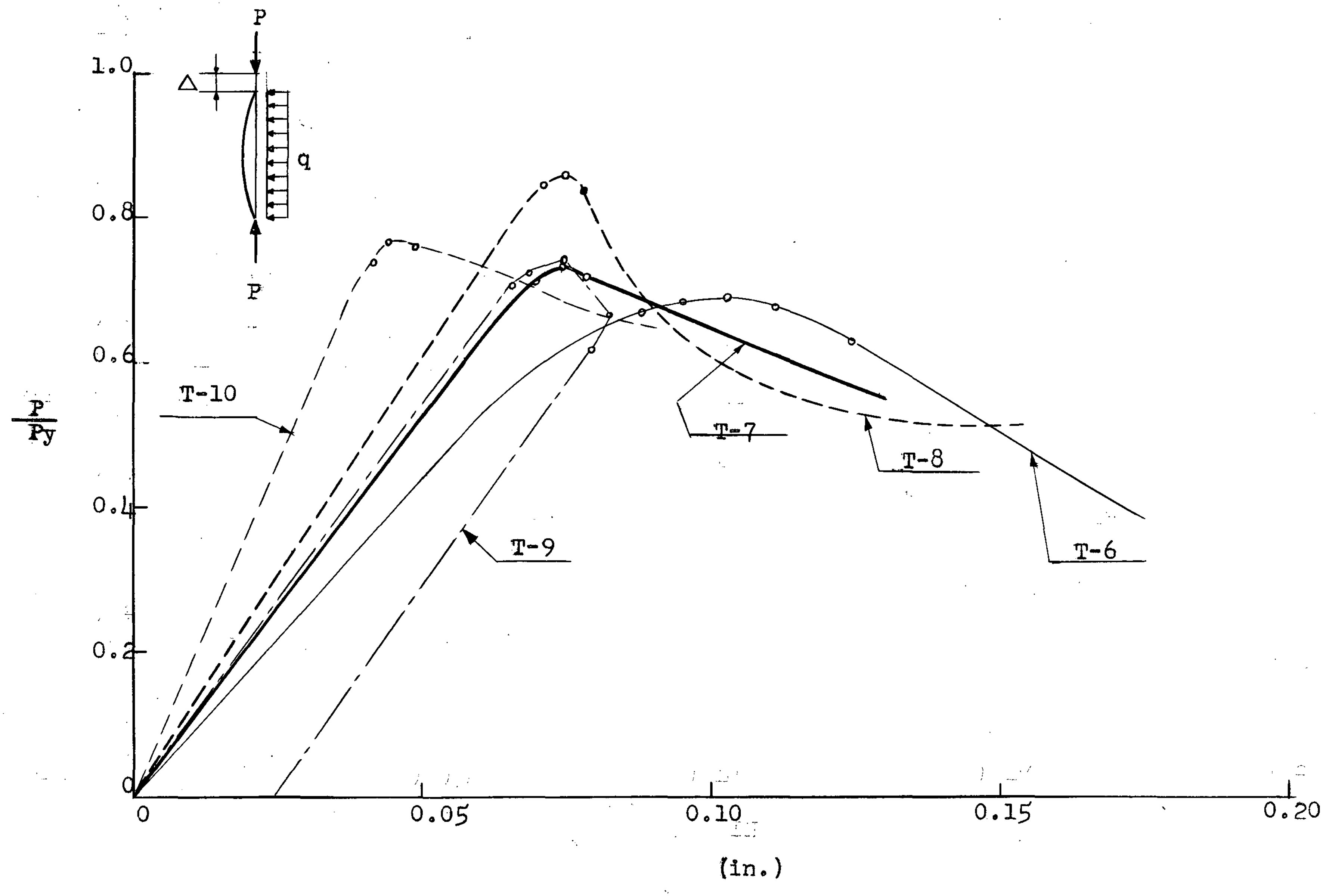


Fig. 23 LONGITUDINAL DEFLECTION, SPECIMEN T-6 to T-10

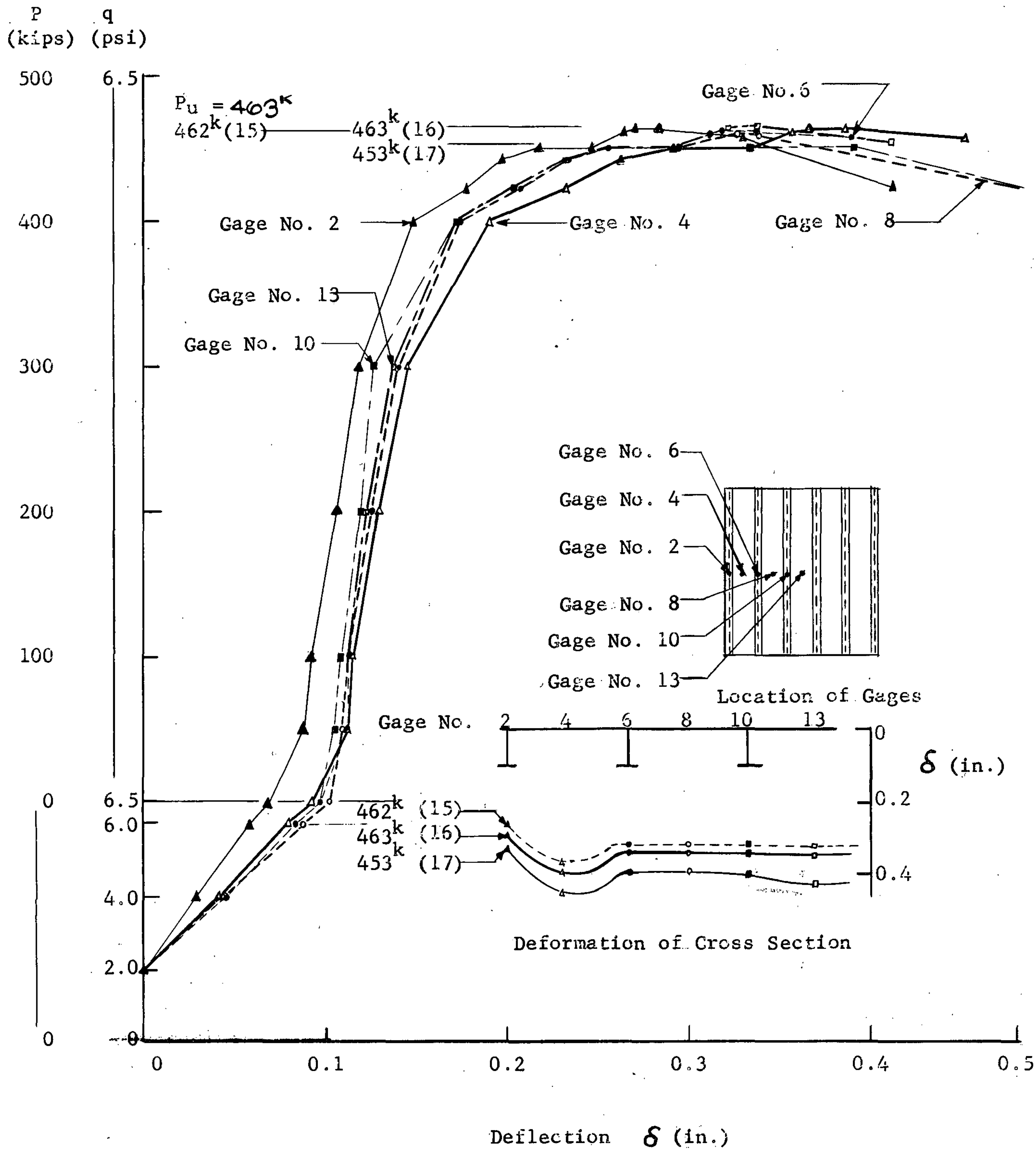


Fig. 24 LATERAL DEFLECTION, SPECIMEN T-6

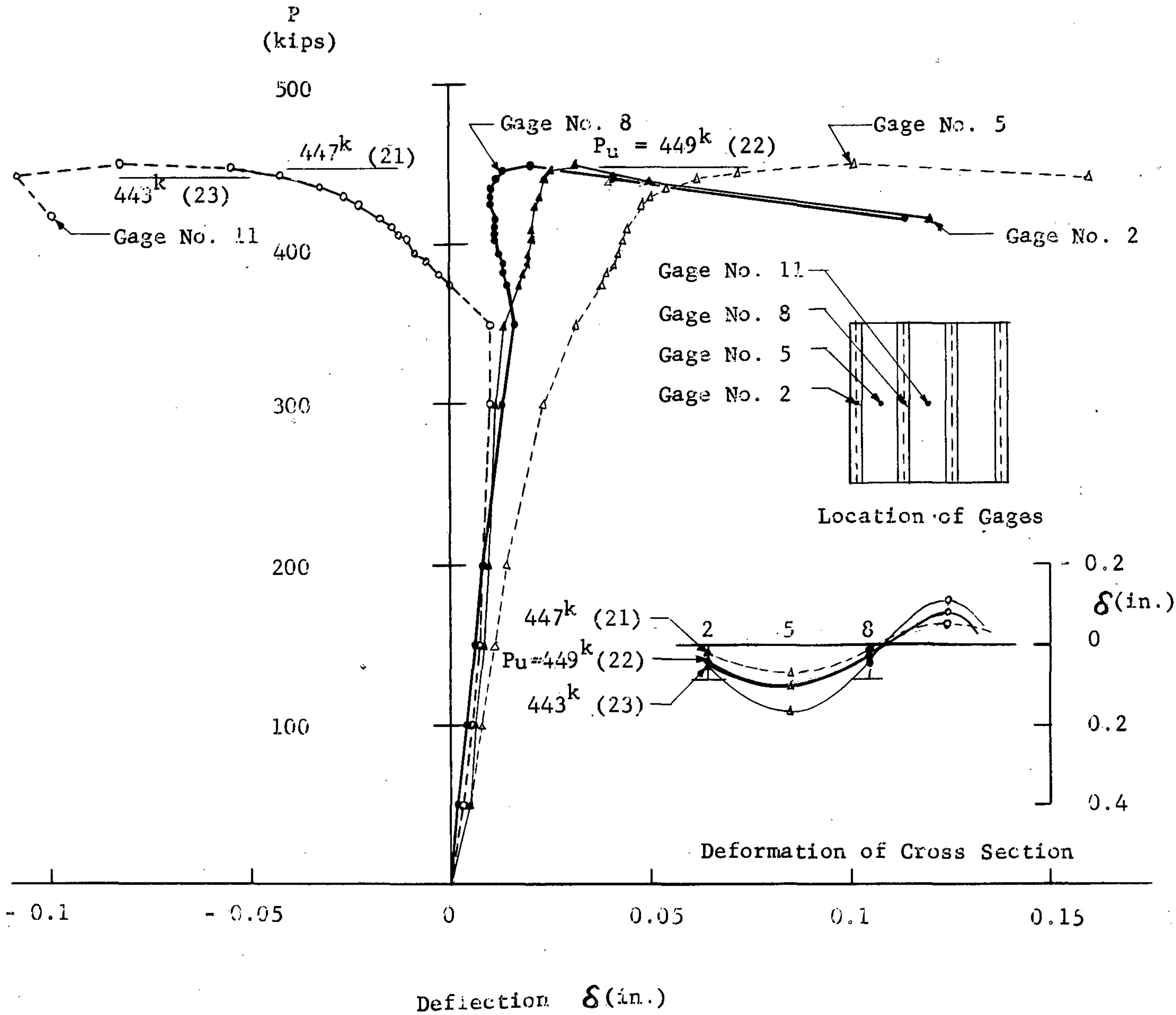


Fig. 25 LATERAL DEFLECTION, SPECIMEN T-7

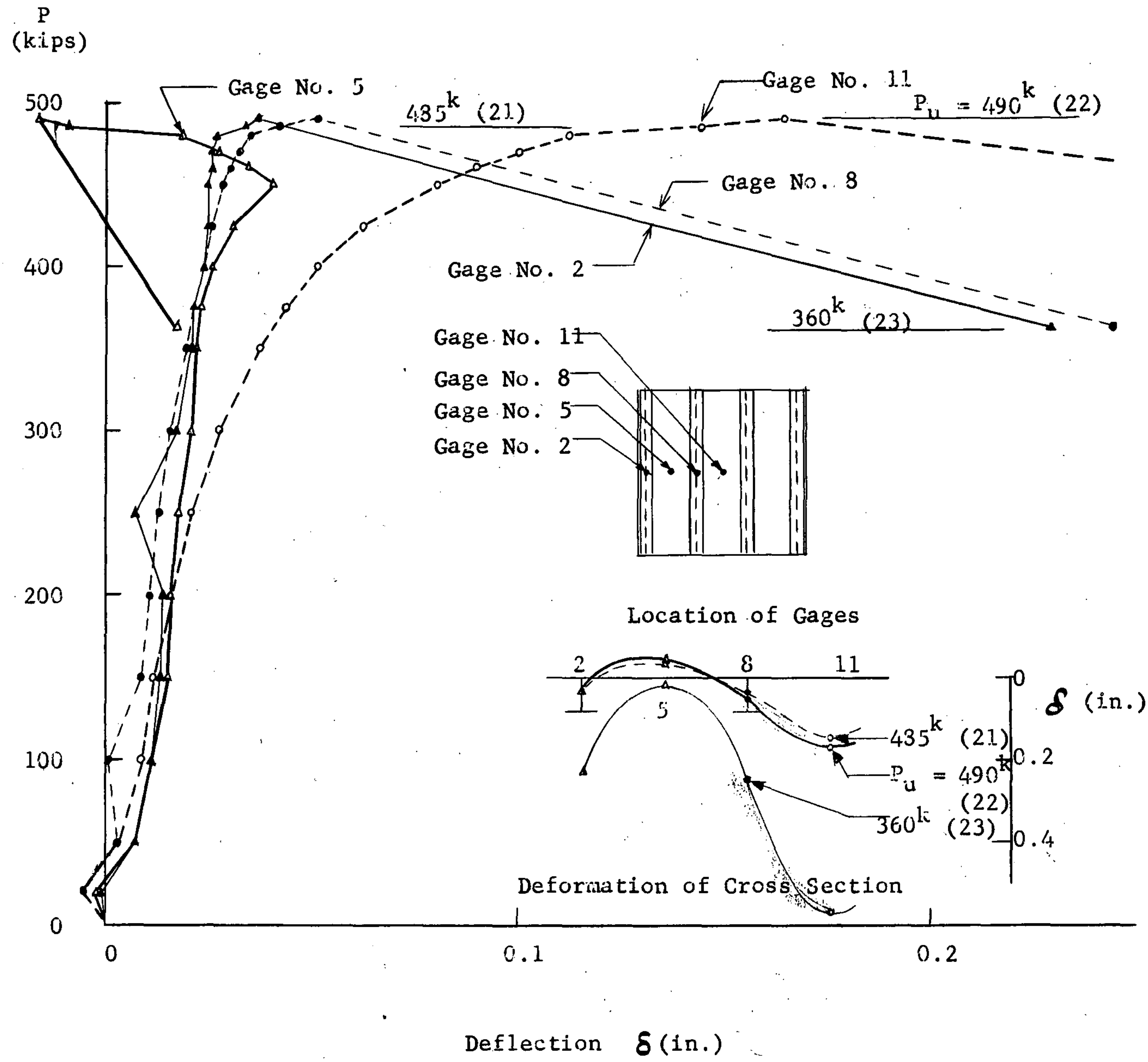


Fig. 26 LATERAL DEFLECTION, SPECIMEN T-8

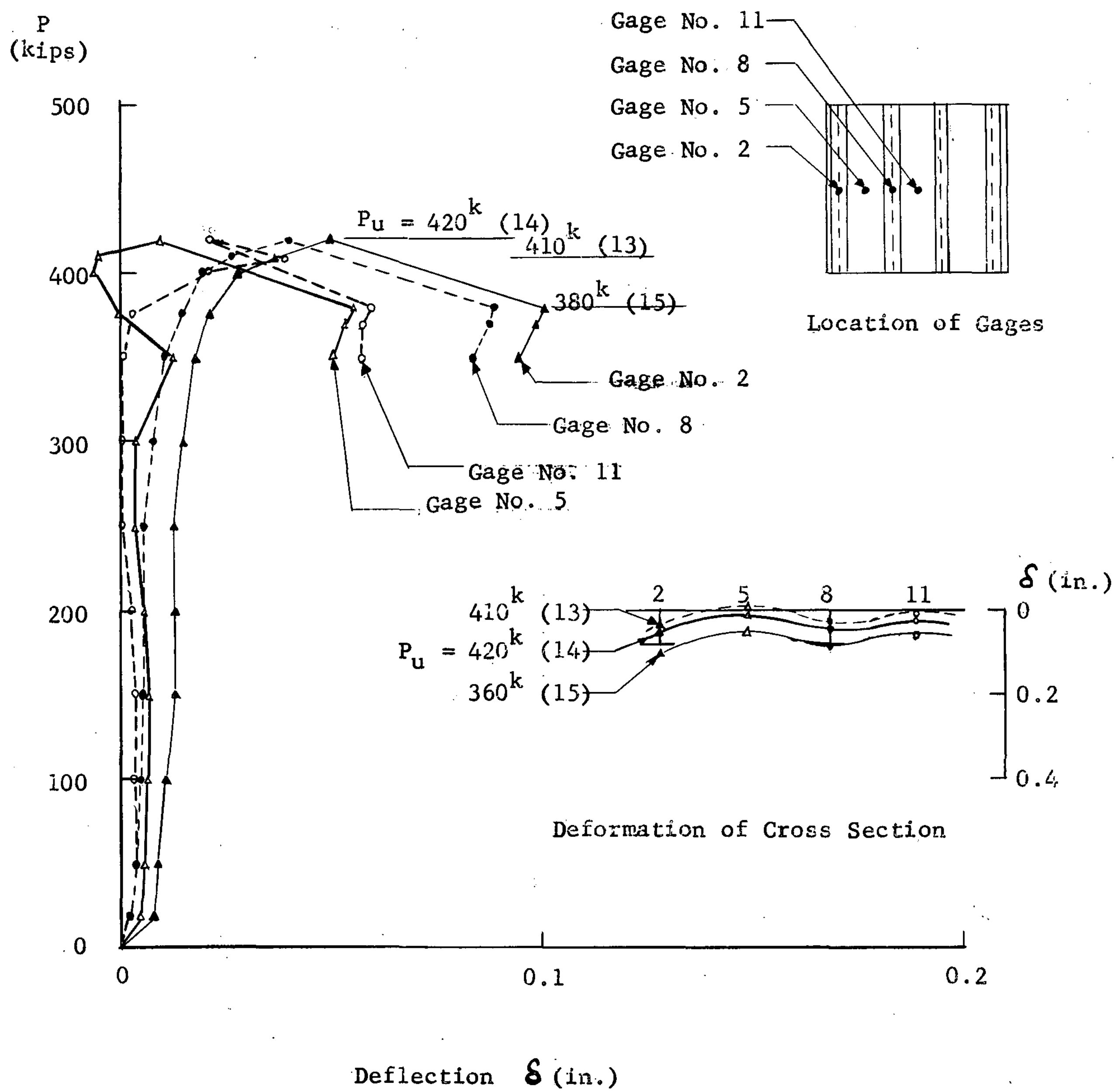


Fig. 27 LATERAL DEFLECTION, SPECIMEN T-9

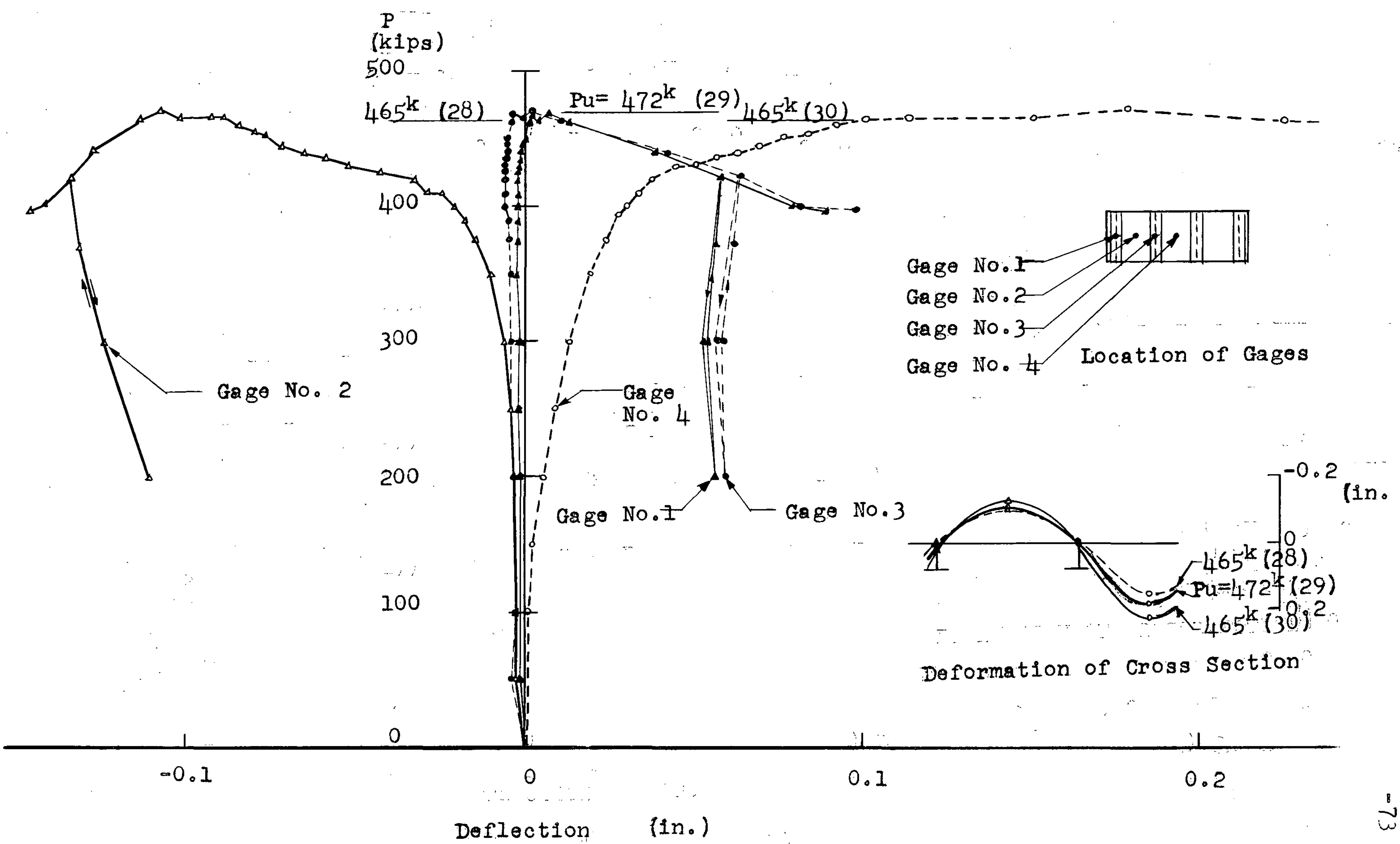


Fig. 28 LATERAL DEFLECTION, SPECIMEN T-10

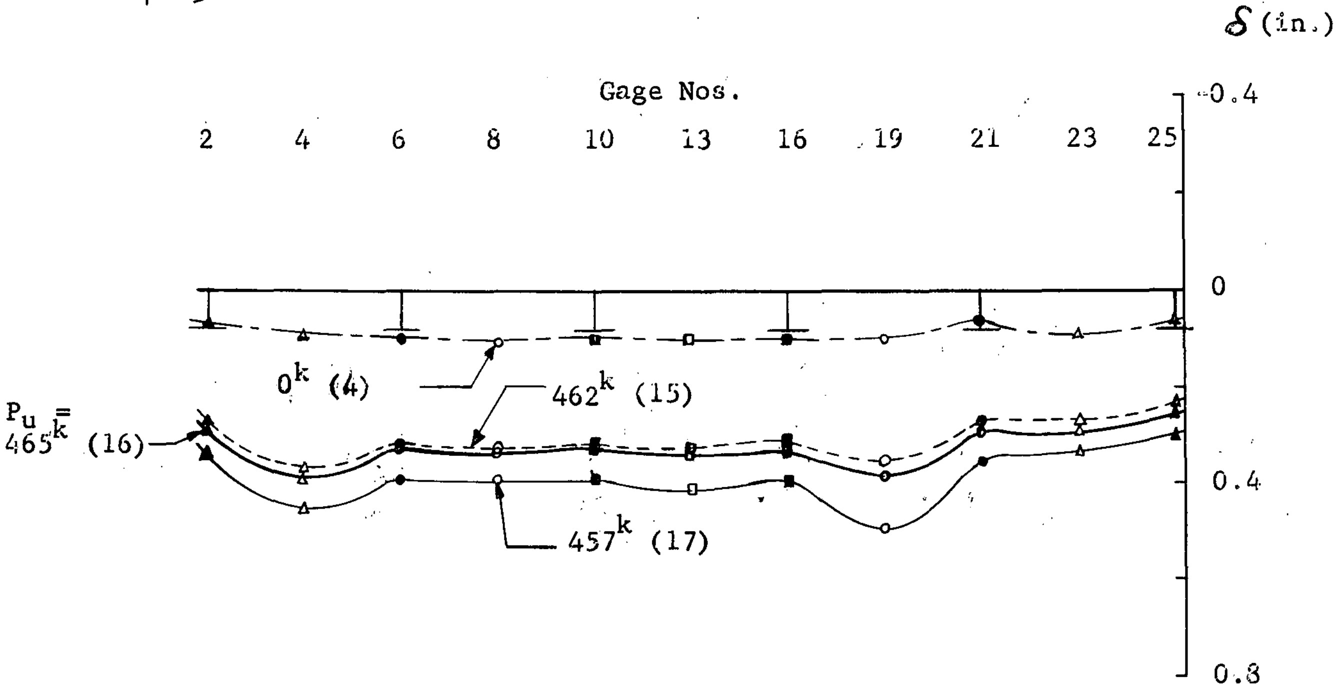


Fig. 29 DEFORMATION OF MID-HEIGHT CROSS SECTION, SPECIMEN T-6

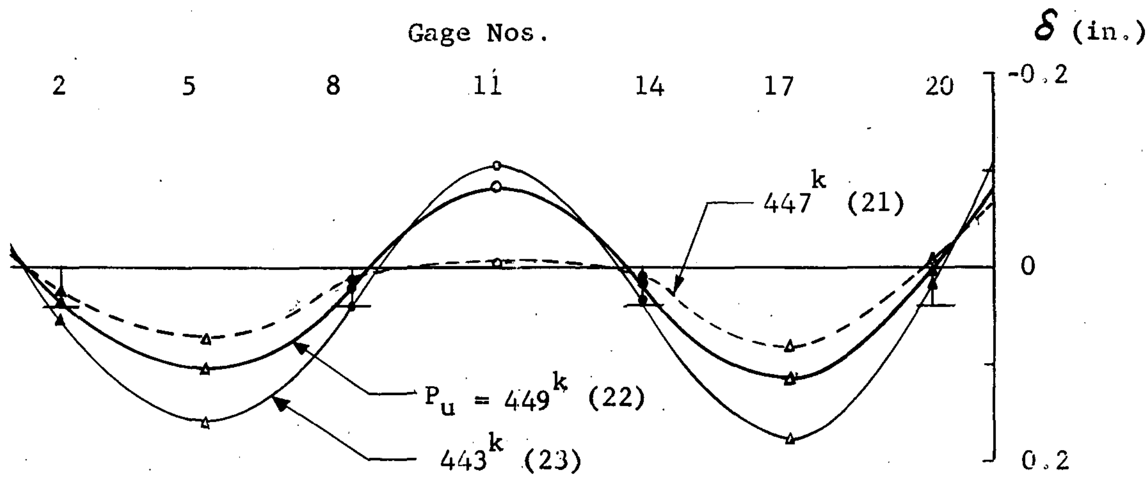


Fig. 30 DEFORMATION OF MID-HEIGHT CROSS SECTION, SPECIMEN T-7

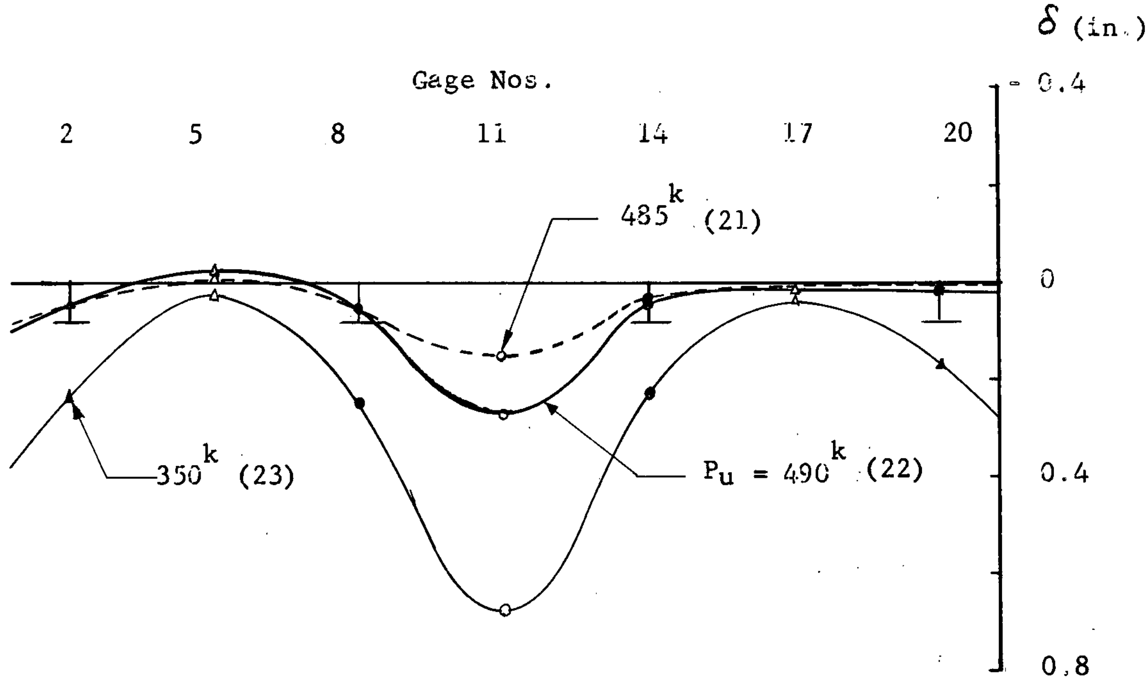


Fig. 31 DEFORMATION OF MID-HEIGHT CROSS SECTION, SPECIMEN T-8

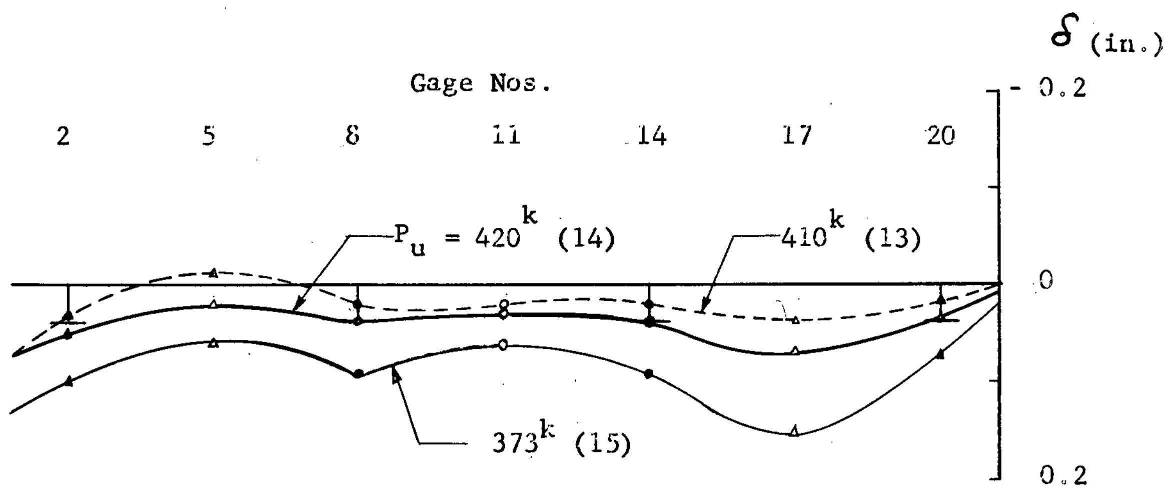


Fig. 32 DEFORMATION OF MID-HEIGHT CROSS SECTION, SPECIMEN T-9

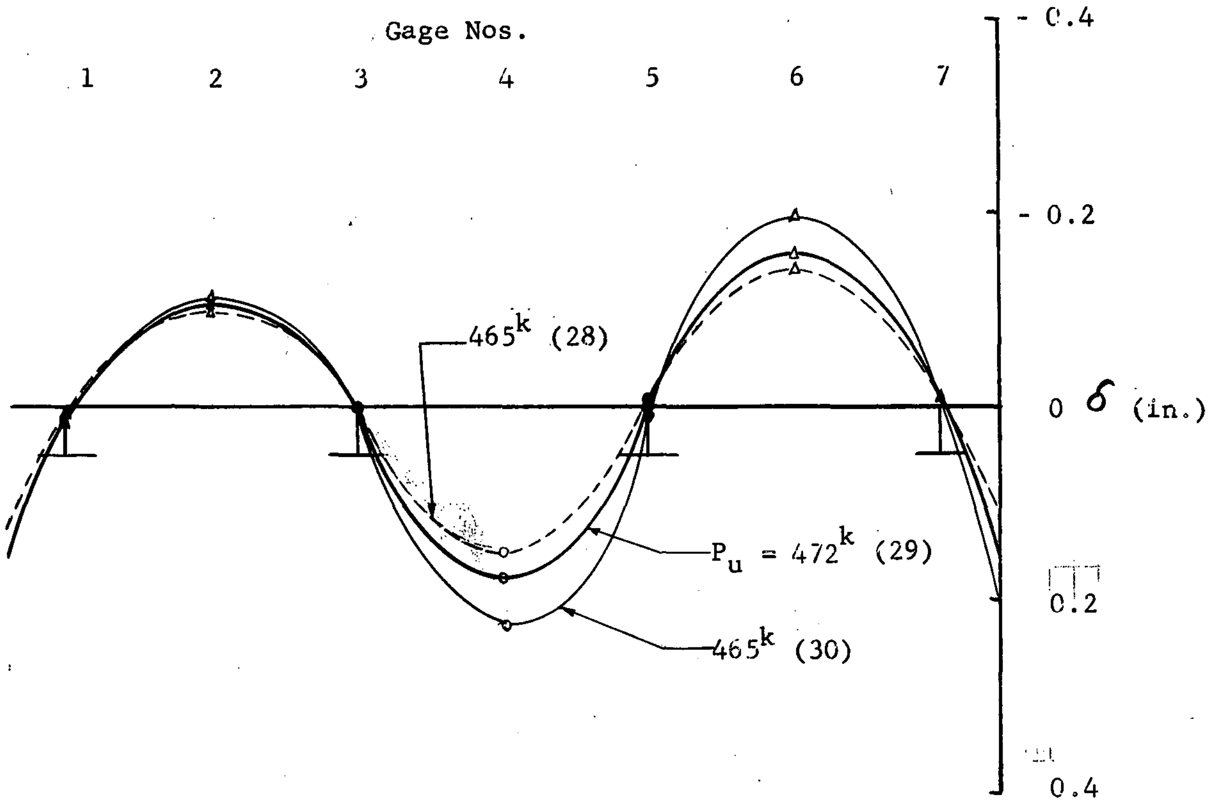


Fig. 33 DEFORMATION OF MID-HEIGHT CROSS SECTION, SPECIMEN T-10

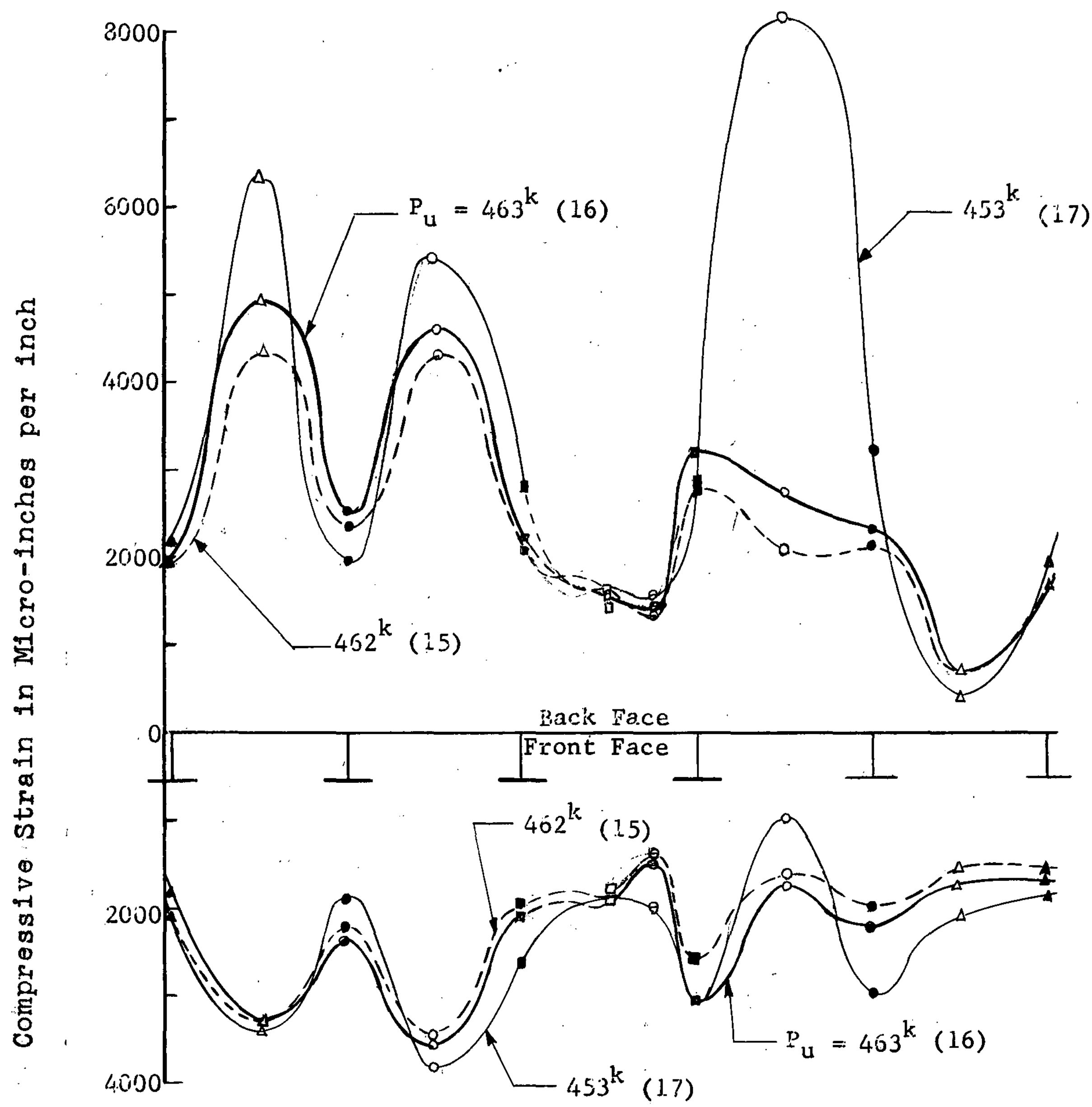


Fig. 34. AXIAL STRAIN IN PLATE OF SPECIMEN T-6, MID-HEIGHT

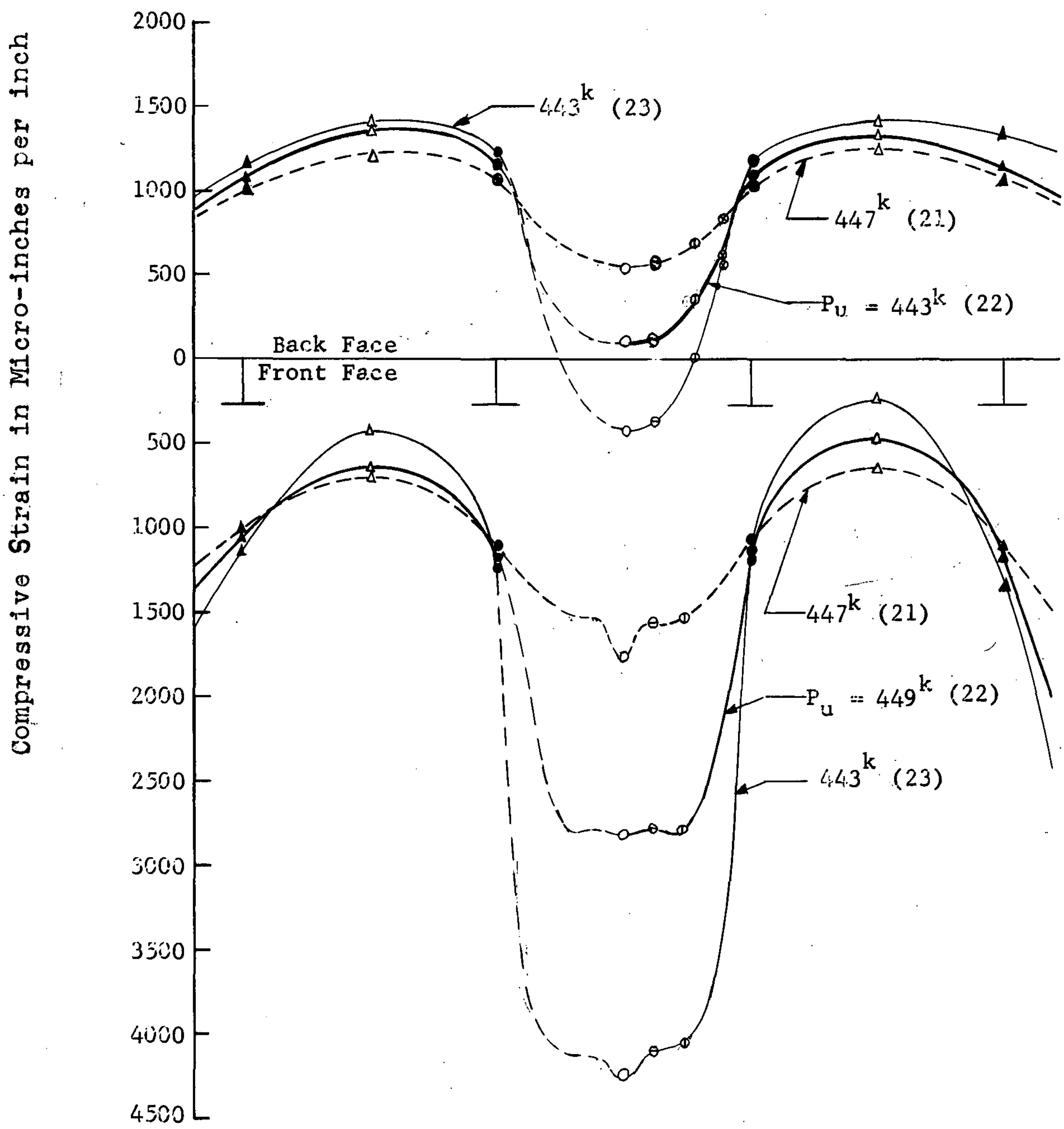


Fig. 35 AXIAL STRAINS IN PLATE OF

SPECIMEN T-7, MID-HEIGHT

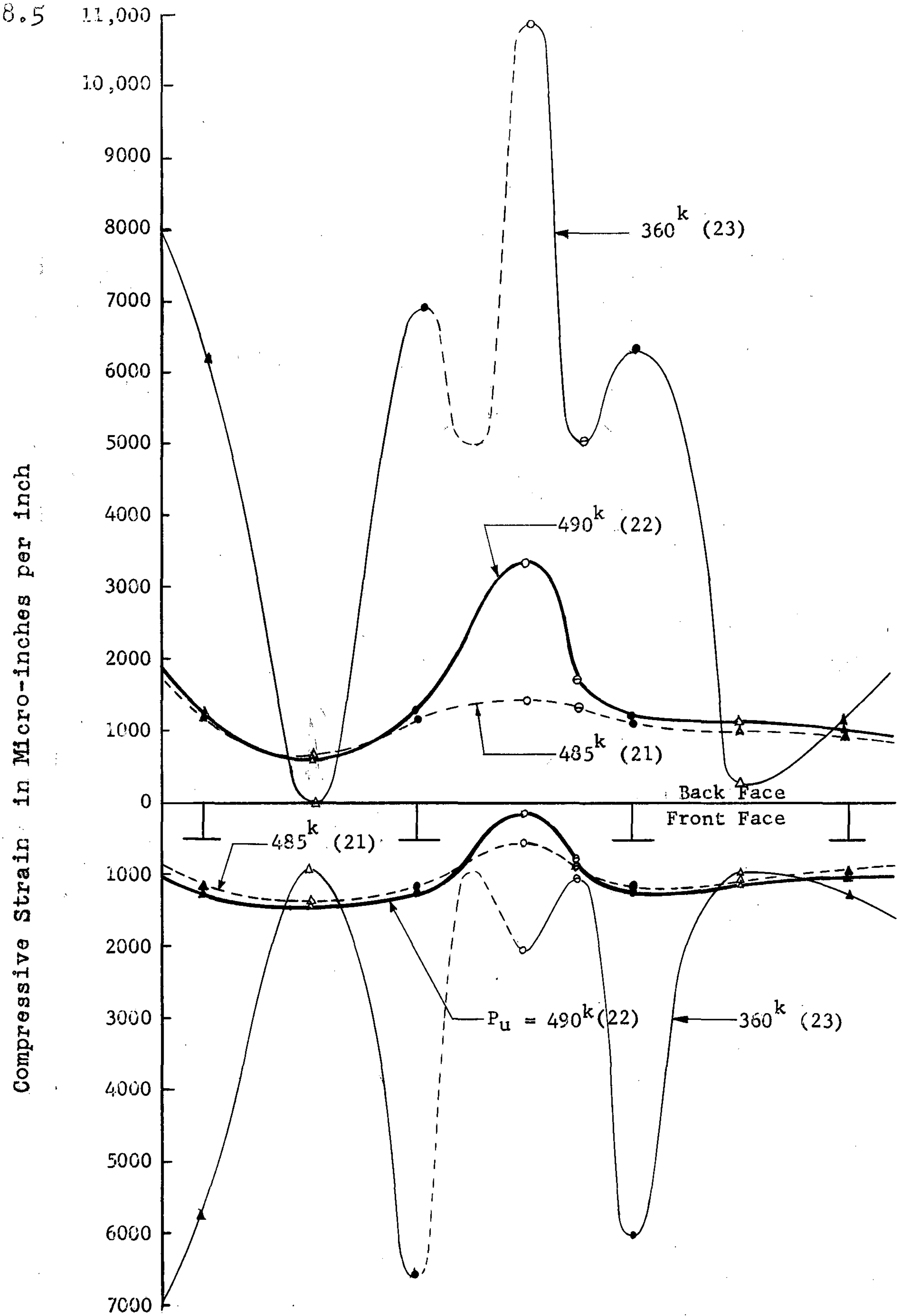


Fig. 36 AXIAL STRAINS IN PLATE OF SPECIMEN T-8, MID-HEIGHT

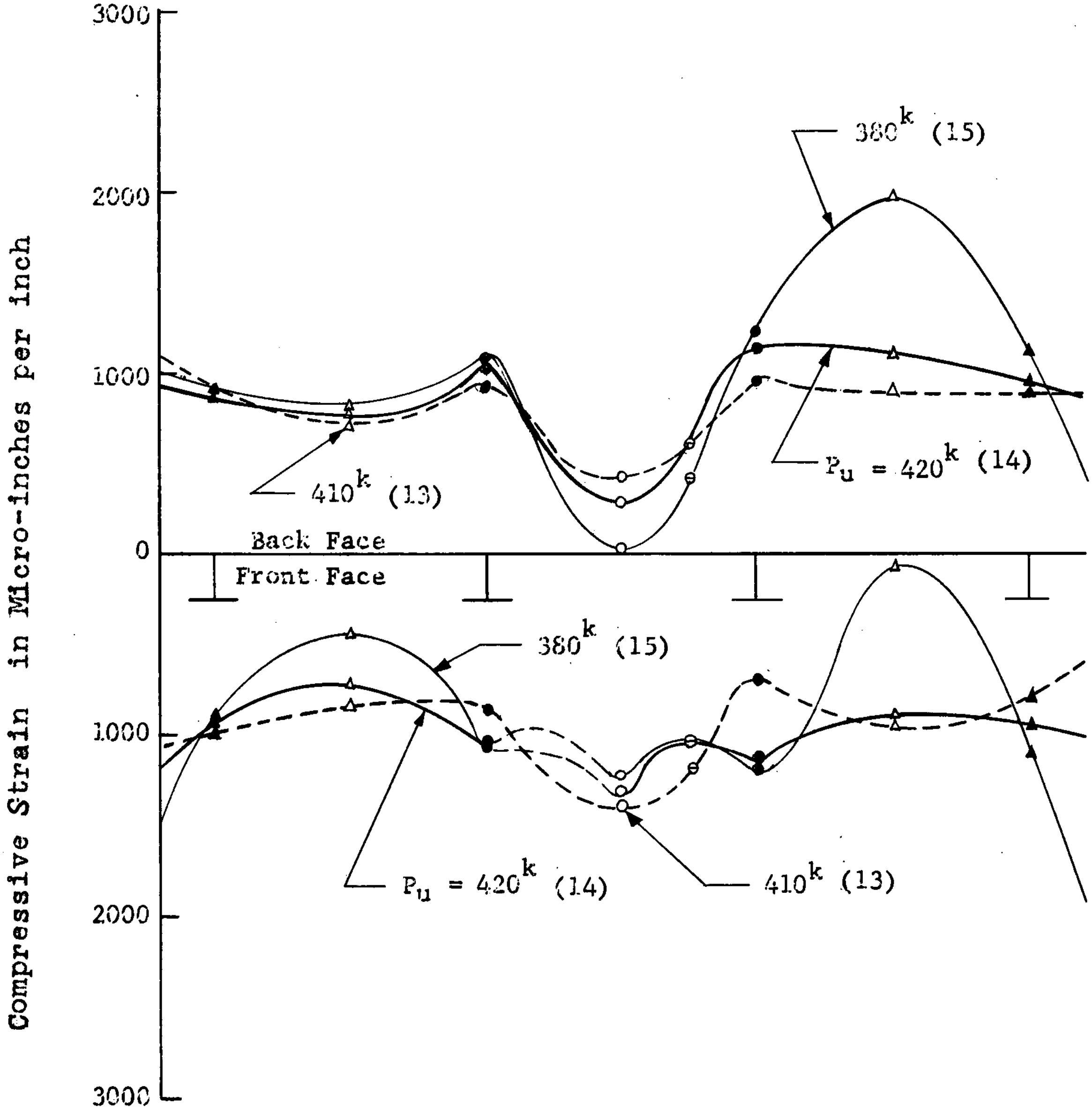


Fig. 37 AXIAL STRAINS IN PLATE OF SPECIMEN T-9, MID-HEIGHT

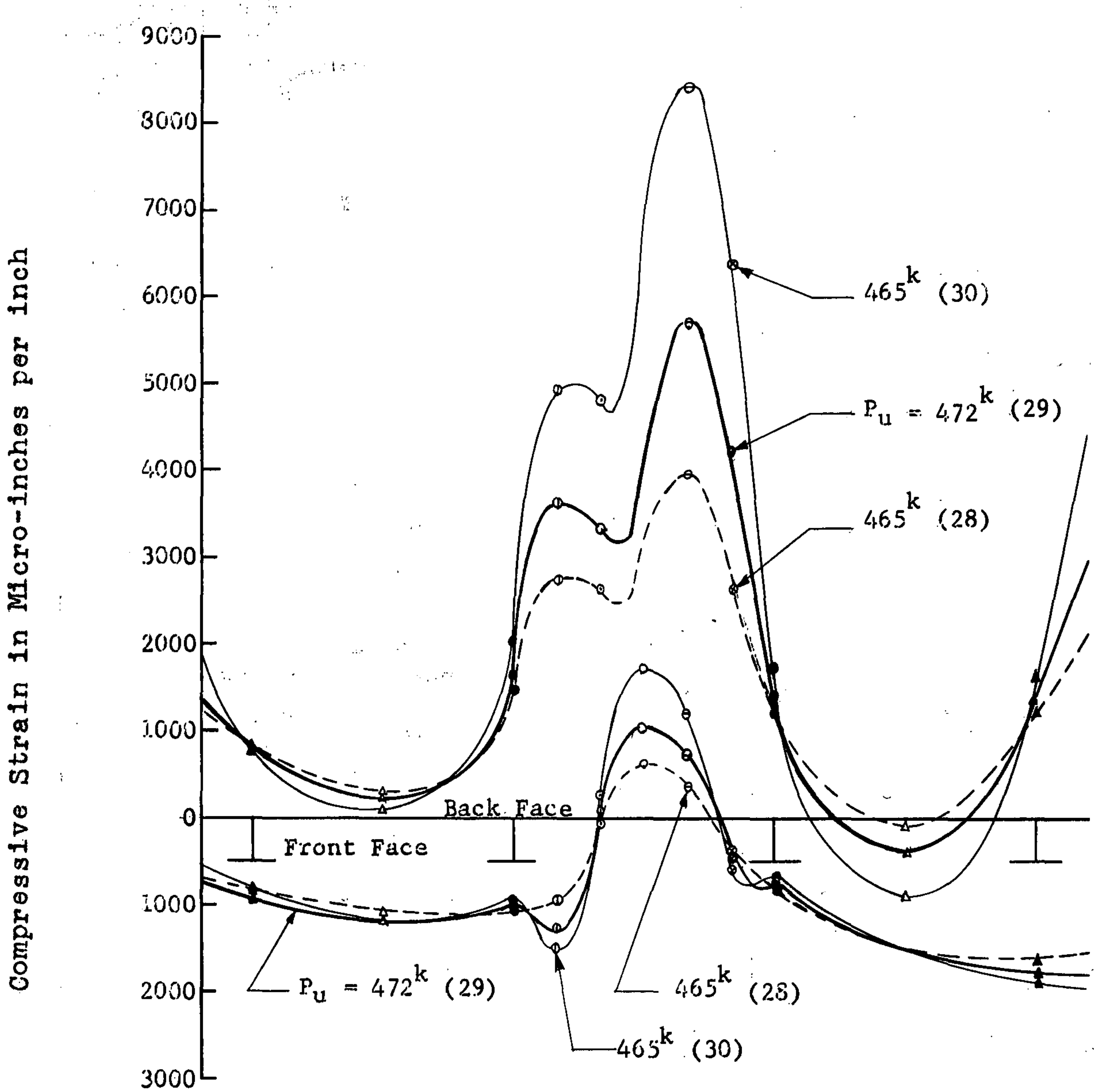


Fig. 38 AXIAL STRAINS IN PLATE OF SPECIMEN T-10, MID-HEIGHT

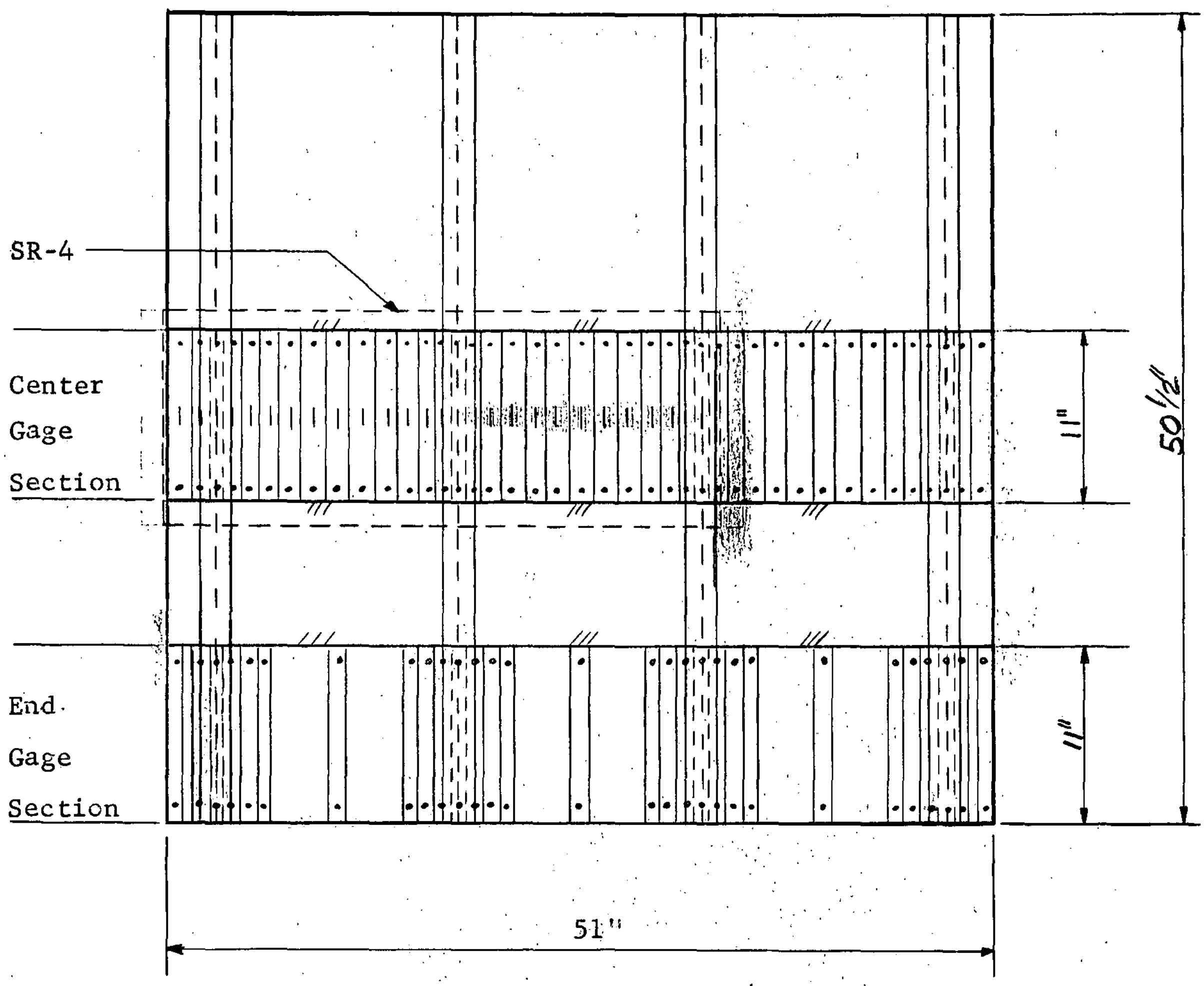


Fig. 39 SPECIMEN FOR RESIDUAL STRESS MEASUREMENT (T-11)

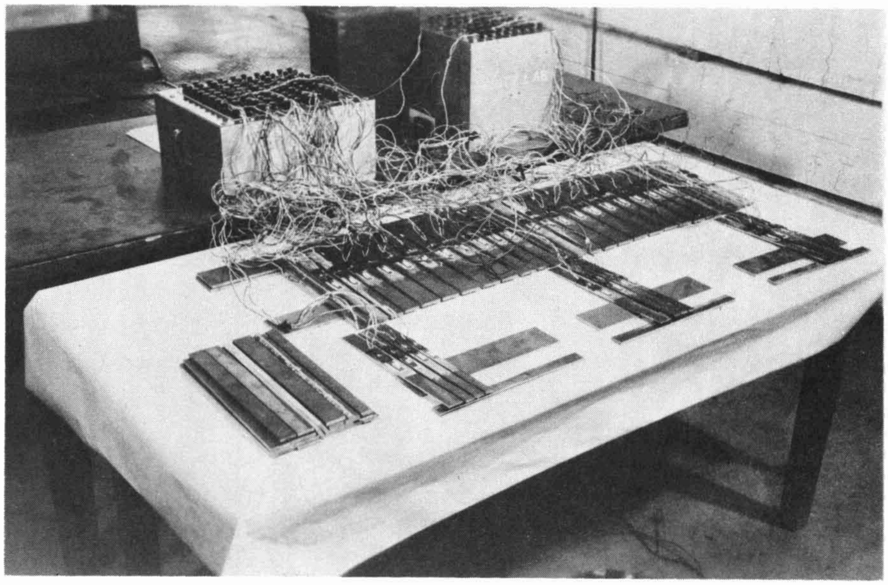


Fig. 40 CENTER GAGE SECTION - SPECIMEN T-11 ARRANGEMENT FOR RESIDUAL STRESS MEASUREMENTS WITH SR-4 STRAIN GAGES

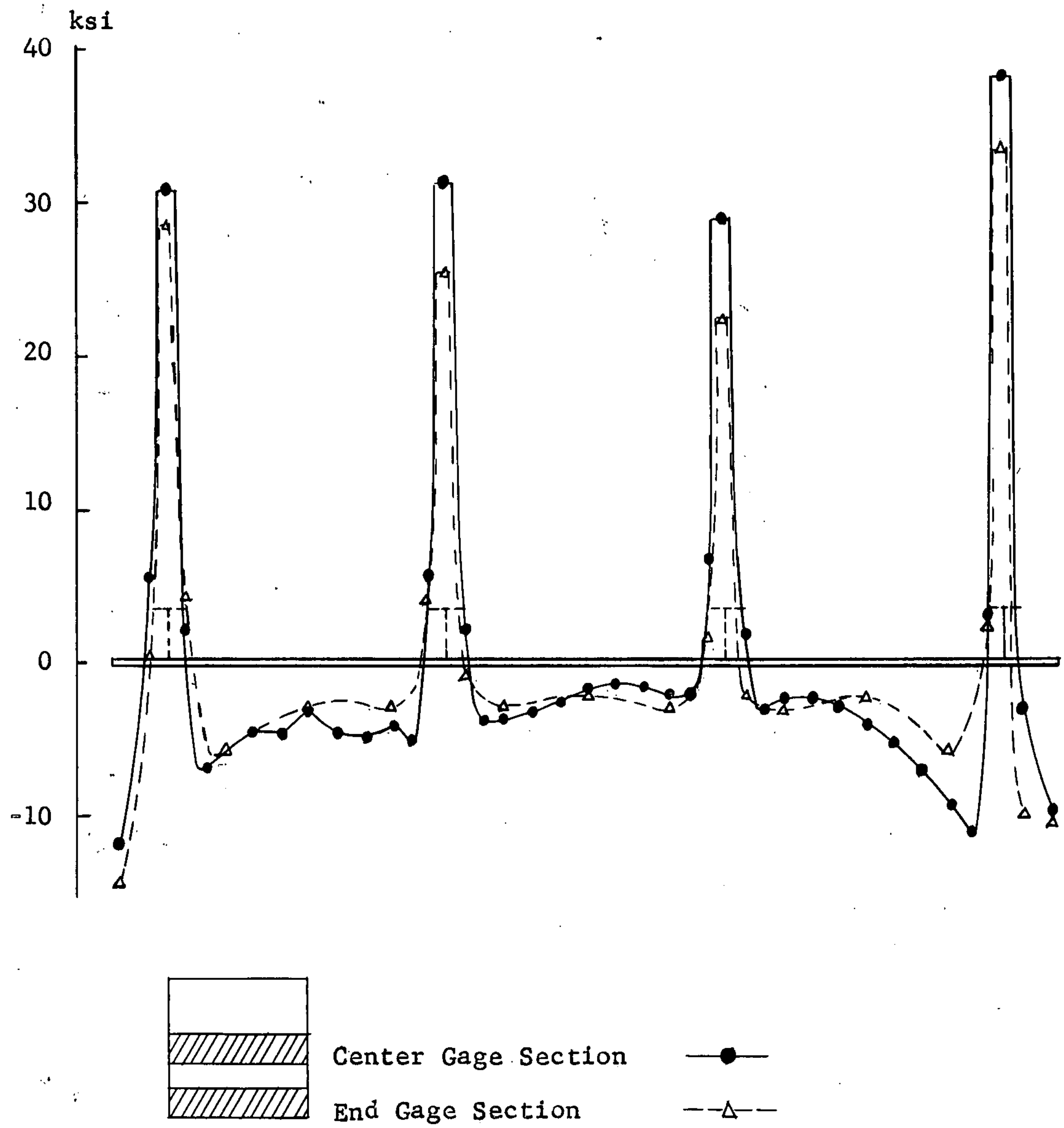


Fig. 41 RESIDUAL STRESS AT CENTER AND END GAGE SECTIONS

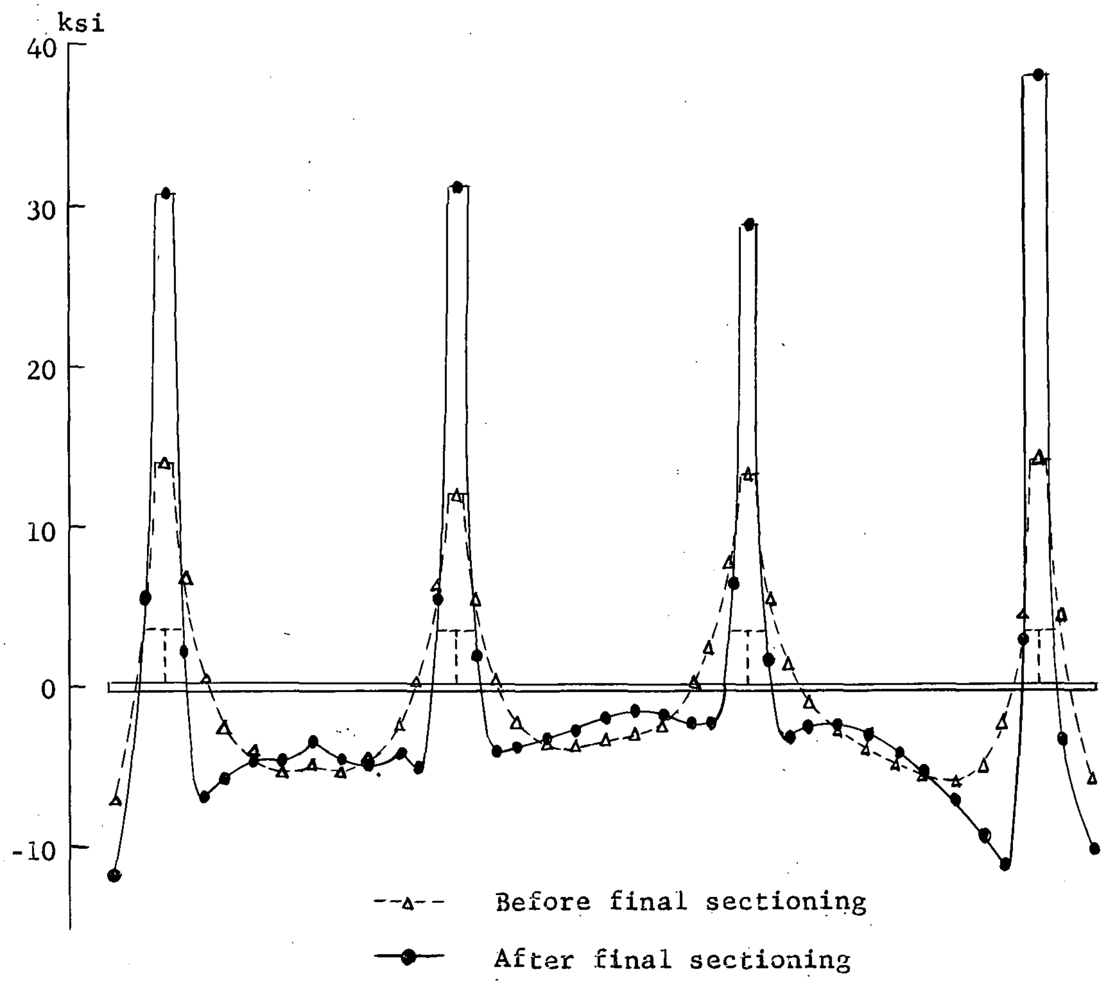


Fig. 42 RESIDUAL STRESS READINGS BEFORE AND AFTER THE FINAL SECTIONING

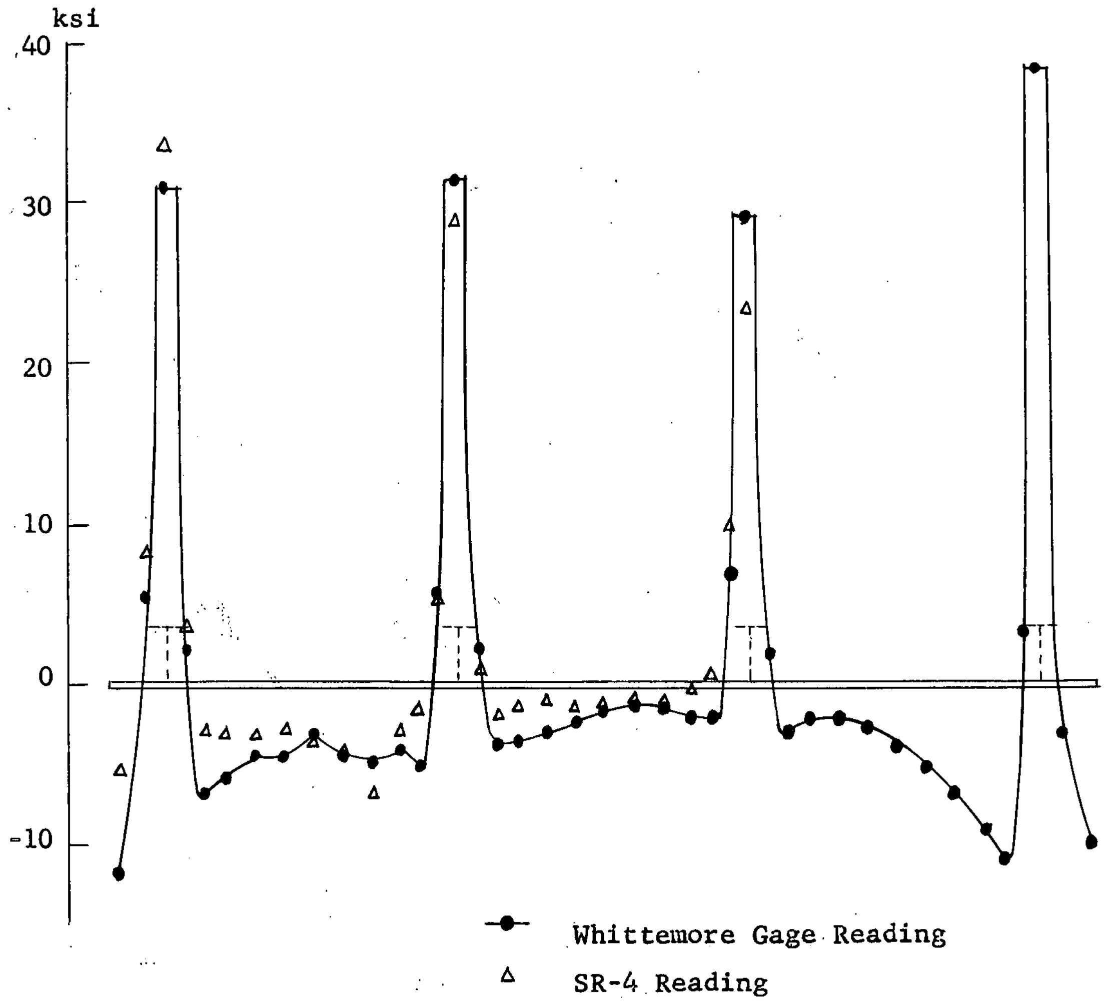


Fig. 43 COMPARISON OF READINGS FROM WHITTEMORE AND SR-4 GAGES, SPECIMEN T-11

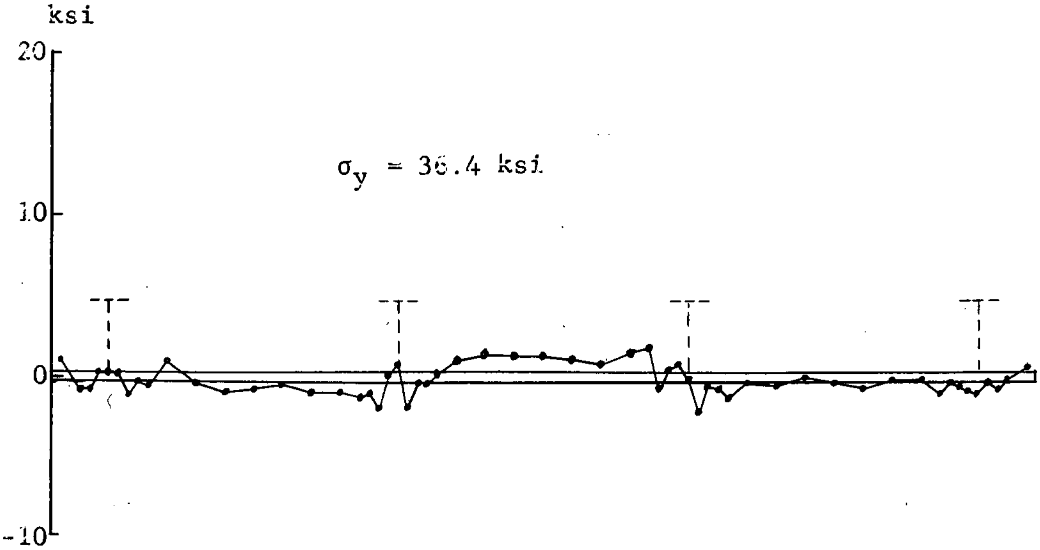


Fig. 44 RESIDUAL STRESS PATTERN

SPECIMEN T-8

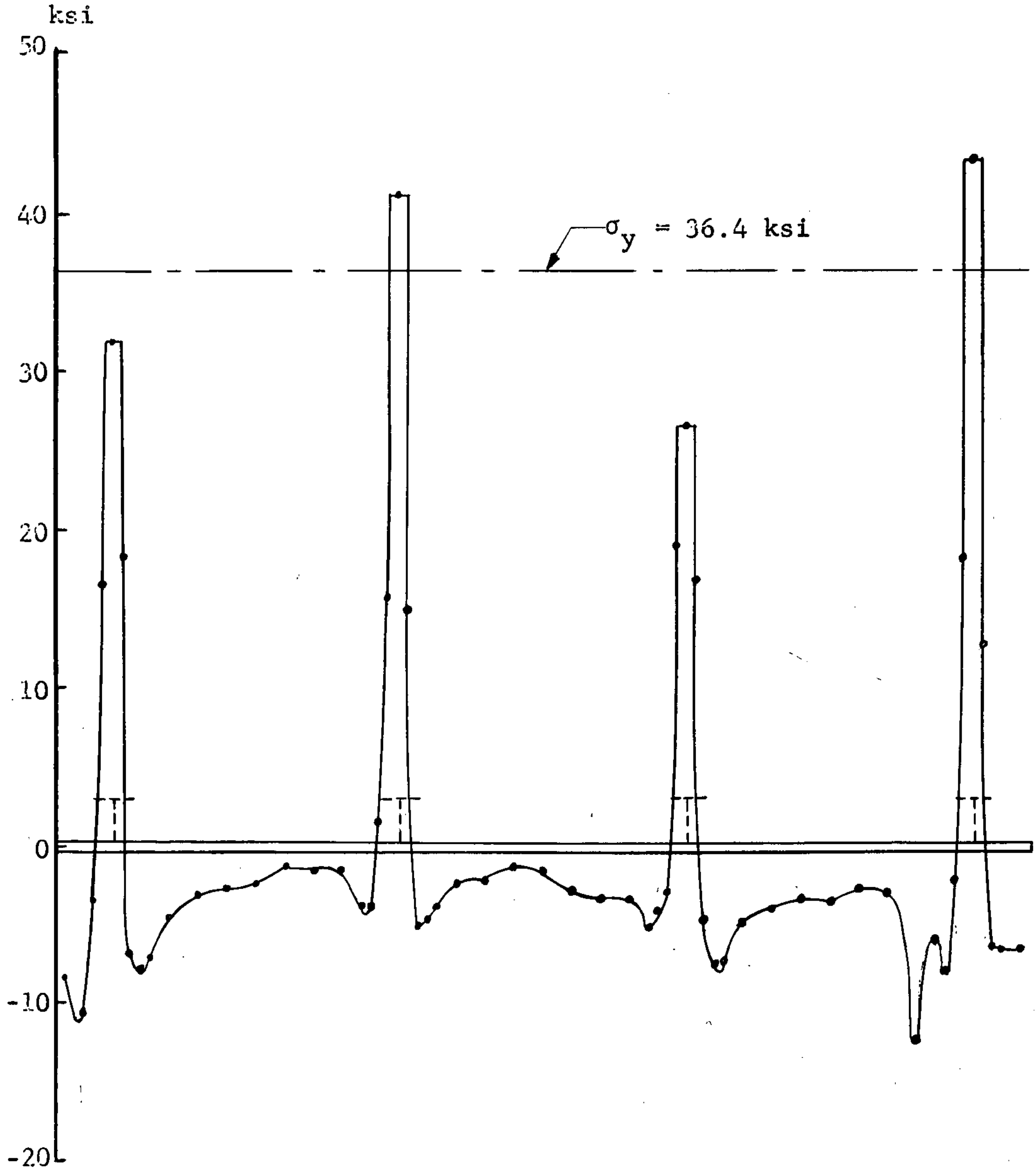


Fig. 45 RESIDUAL STRESS PATTERN

SPECIMEN T-9