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This work has been carried out as part of an investigation sponsored jointly by the Column Research Council, the Pennsylvania Department of Highways, The U.S. Department of Commerce - Bureau of Public Roads and the National Science Foundation

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ABSTRACT

This report is a summary of the experimental investigation conducted on columns built-up by welding from universal mill plates of A7 steel. Particular attention was given to columns of medium-size (10" x 10") box shape cross section, and their behavior is compared with medium size (9" x 10") H shapes and box shapes and H shapes of smaller sizes. The investigation included tensile coupon tests, residual stress measurements, stub column tests, and actual column tests. It was concluded that welded columns are weaker than corresponding rolled columns.

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1. INTRODUCTION

1.1 Scope of Study

A study of the effect of welding on the strength of built-up columns is presented. Welded built-up members are being used more frequently in steel construction due to economy, convenience and aesthetics. It is only recently that a true insight into the behavior of columns under load has shown that the residual stress distribution inherent in the cross section plays a major role in the column strength characteristics. Welded shapes have residual stress magnitudes and distribution different from those of rolled shapes and yet design formulas prepared for rolled structural shapes are being applied to welded columns. The investigation was concerned with welded box and welded H shapes of medium cross section and varying slenderness ratios. These shapes were built up by welding universal mill plates of ASTM A7 steel.

1.2 Factors Influencing Column Strength

Earlier studies have shown that the variables influencing column strength are numerous. However, the major factors are as follows:

1) the magnitude and distribution of residual stress,

2) the basic (static) yield stress level,

3) the strain hardening modulus (for short columns), and

4) initial out-of-straightness which includes unsymmetrical residual stress distribution and accidental eccentricities.

The influence of these factors has been discussed in Refs. 1, 2, and 3.

2. PRELIMINARY INVESTIGATION

In order that the carrying capacity of the columns tested could be predicted, preliminary tests were made which included tensile coupon tests to obtain the static yield stress level, residual stress measurements to determine the magnitude and distribution of residual stresses and stub column tests to obtain a stress-strain diagram which includes the effect of residual stresses.

2.1 Coupon Tests

Tensile coupon tests were made as a routine check on the static yield stress level of the material used for the sections. ASTM specifications and recommendations(4) for standard rectangular tensile test specimen with 8-inch gage length were followed on all tests except for 24 small coupons. These small coupons were sections cut for residual stress measurement.

Table 1 gives the test results in detail. Figure 1 is a schematic diagram of the location of the coupons with respect to the cross section.

2.2 Residual Stress Measurements

The method of "sectioning"(5) was used to obtain the experimental or measured values of residual strains (and consequently residual stresses). A series of 10-inch gage holes were laid out on the specimen and measured with a 1/10,000 Whittemore strain gage. The difference in length before and after the sectioning is a measure of residual stress. Figure 2 shows a typical layout for the sectioning process. The 11-inch section cut from the beam is at a sufficient distance from the ends to offset any edge effect.[1] Reference 5 also shows that an edge effect does exist, the residual stresses being undistrubed at a distance from the edge approximately equal to the width of the plate.

The residual stress distribution was also checked insofar as the following factors were concerned:

1) the variation of residual stress along the length,
2) the effect of different edge preparations of the plate before welding, and
3) the effect of thickness, that is, the variation between stresses on the two sides of the plate.

A 15-foot test piece designated C5 was used for the study of the variation of residual stress along the length of the member. Residual stresses were measured at those sections marked A, B and C in Fig. 3.

To check the effect of different plate edge preparation on the residual stress distribution, two methods of preparing the edge of the joints were used. The preparations were either by machining or by flame cutting. Edge preparation by machining is more laborious and hence a more expensive operation not normally used in fabrication. In this case, the fabrication facilities available set a 30-foot limit on the length that could be machined. Since flame cutting is the standard operation, all the test pieces (except for seven pieces) were edge-prepared by flame cutting. There was concern that flame cutting would introduce a change in the residual stress distribution; this was the reason for the machined plates which were used for comparison purposes. Fabricated piece Nos. 1 to 7 were machine-prepared and the rest were prepared by flame cutting (refer to Table 2).

Direct measurements of strain inside the box shape were not possible so that an indirect method was used to find the residual stress distribution of the inside face of the column. Two sets of residual stress specimens were taken each from fabricated pieces No. 11 and No. 12. Figure 4 shows the sections used in the study. Section E and F were taken from piece No. 11 and sections G and H from piece No. 12. The sections were cut into L shapes according to the detail shown in the figure. Additional gage holes were laid out on the inside faces of the L shape before final sectioning was done. Measurements were made prior to each cutting operation.

2.3 Stub Column Tests

Prior to the testing of any column, a stub column test was made on a section from the same piece from which the actual column was cut. The length of the stub column is such that column instability cannot occur[6] but was sufficiently long to retain the original residual stress distribution of the section. The stub column test gives a stress-strain curve showing the effect of residual stress. The proportional limit, the static yield stress level and the elastic and the elastic-plastic moduli are the important data furnished by the curve. Data from the stub column test is necessary for the prediction of column strength.

The stub column specimens were tested in an 800,000 lb. screw type testing machine. Bearing plates were provided at the top and at the base to obtain a uniform application of stress. Figure 5 shows the instrumentation of the stub column. Four 1/1000 inch dial gages (Nos. 1 to 4) are attached at the four corners to measure the strain over the whole length. Two 1/10,000 inch dial gages are mounted on opposite sides to measure the strain over a 10" gage length at the mid-height. This data is used to determine the stress-strain relationship.

The four corner gages are used for alignment. The alignment of the specimen was made at loads not exceeding one-third of the expected yield stress level, this being an estimate of the proportional limit based on the measured residual stress distribution. A constant check was made of the whitewash on the specimen to detect any premature yielding. The alignment was considered satisfactory if the deviation of any of the four corner gage readings did not exceed 5% of the average value at the maximum alignment load.

The loads were applied in appropriate increments dictated by the continuously plotted stress-strain curve of the test. Above the proportional limit, a load relaxation diagram (load versus time) was plotted as shown in Fig. 6. The curve for load relaxation is asymptotic to a load value which is the stabilized load. The strain gages were read when the load approached stabilization or a minimum of 20 minutes after the load was applied. An additional 10 minutes was required to obtain all the readings and in which time no appreciable changes in the data were observed.

As the specimen was loaded, a qualitative picture of the yield pattern could be seen from the flaking of the mill scale as detected by the cracking of the whitewash (hydrated lime) painted on the specimen.

3. COLUMN TESTS

The pilot program on welded built-up columns included three tests of welded H sections (9" x 1/2" web and 9" x 3/4" flanges) with slenderness ratios of 59, 78 and 103. The results of the test are shown in Table 2 and Fig. 7. The following conclusions were drawn from the tests[7]:

1) Welded H-shaped members may have high compressive residual stresses.

2) Columns built-up by welding will contain tensile residual stresses close to the yield point.

3) The strength of the welded H-column is less than that of the riveted or as-rolled column.

A later test with the same cross section but with a slenderness ratio of 12.5 indicated that the ultimate strength of the column was in excess of that given by the yield stress level, failure being by local buckling.[8]

The column specimens were fabricated from structural steel of ASTM designation A7, universal mill plates and according to the schedule given in the Appendix. The welding details are given in Fig. 8. The joints were machine welded employing an automatic feed unionmelt of the submerged arc type. For the 10" x 10" box shape, a first pass at the root was deposited manually. In all cases, small tack welds were first deposited to fix the shape. Figures 9, 10, and 11 show the process of flame cutting the edges, fixing the shape in the jig with tack welds, and welding of the joint with the automatic welder.

A summary of the fabrication data and the schedule of specimens are given in Table 3.

3.1 Test Set-up

A total of 12 full scale column tests were conducted. All the columns, except four, were tested in an 800,000 pound screw-type universal testing machine. Columns C6, C10, C11 and C12 were tested in a 5,000,000 pound hydraulic-type universal testing machine.

The columns were tested with pinned-end supports in the "weak axis" direction and fixed-end supports in the perpendicular axis. The "weak axis" of a welded box shape is the axis perpendicular to the narrower plate (see Fig. 12a).

The end fixtures used were standard column fixtures developed in the laboratory. The main cylindrical bearing was designed so that the radius of the surface had its center at the mid-point of the column ends.[9] Figure 12b shows the end fixture action as the column bends. It can be seen from this figure that at any stage of the test, the load passes through the same point.

Before testing, the following preparations were made on the column:

1) The external dimensions of the column were measured and checked for any variation not within the acceptable tolerance of 0.05 in.

2) The column was whitewashed with hydrated lime to indicate undesirable yielding that might occur in the process of aligning the column. The flaking of the whitewash also gives an indication of the extent of yielding during the actual test.'

3) The initial out-of-straightness of the column with respect ot its neutral axis was determined.

The instrumentation consisted of strip scales and dial gages to measure lateral deflection, mechanical and SR-4 gages to measure strain, level bars to measure end rotation and dial gages to measure cross head movement in the vertical direction.

Strip scales, about 12 inches long, were attached to the column at quarter points or sixth-points. The scales were read with a theodolite to obtain a measurement of lateral deflection along the length of the column. As an added precaution, a short strip scale was attached to the fixed cross head of the testing machine to check lateral movement of the testing machine. A floor standard was used to check any disturbances of the theodolite setting.

Lateral deflection was also measured at the mid-height of the column with a fixed 1/1000 inch dial gage attached with taut thin wire to a small screw tapped-in at the centerline of the column width. The set-up for the dial gage measurement of the lateral deflection is shown in Fig. 13.

SR-4 strain gages were attached at various levels of the column, four at each end and eight at the mid-height level as shown in Fig. 14. Due to their longer length, columns C6, C11 and C12 were provided with four more strain gages each at the quarter and three-quarter points.

The strain gage data gave an indication of strain distribution across the cross section and along the length of the column. This was used both for alignment and for testing. At the mid-height, a strain gage on three 10-inch gage holes laid out on one face of the column and perpendicular to the axis of bending, as shown in Figs. 13 and 14.

The rotation about the test axis was measured at the ends of the column with level bars mounted on support brackets welded to the base plate and the top plate of the column. Angle changes were measured by centering the level bubble with the micrometer screw. A vertical dial gage attached to the end of the level bar indicated the rotation of the bar over a 20-inch gage length at various states of deformation of the column.

3.2 Alignment

As the first trial position in the alignment, the column was centered geometrically in the testing machine. It was then loaded in increments up to a load value which was considerably less than the proportional limit of the section. The alignment was based on the four corner gages at each end and at the mid-height. No particular difficulty was encountered in determining the adjustments on the end fixtures necessary to attain an even strain distribution at the different alignment loads. The column was considered aligned when at each load level, the maximum deviation of any of the four gage readings from the average value did not exceed 5%. Since the specimens had some slight initial out-of-straightness, it was also necessary to check the lateral deflection during the alignment procedure. By balancing the eccentricity between the ends and the mid-height, a position was attained where the column was uniformly loaded and the lateral deflection was negligible up to the maximum alignment load.

3.3 Test Procedure

After the alignment or centering of the column, the test was started with an initial load of about 40 kips. All the dial gages were adjusted to zero readings and initial readings were taken on the deflection scales, the SR-4 strain gages and the 10-inch gage holes. Besides recording the above data, a point by point plot of the load-deflection curve and the load-strain diagram was made during the test. The load-deflection curve was used to determine the appropriate load increments throughout the test. The plot of load versus strain at mid-height (from measurements of the 10-inch gage holes) showed the value of the proportional limit and also indicated the occurrence of first yield. A check on the whitewash also indicated the occurrence and progression of yielding.

As in the stub column, a load relaxation diagram was plotted for each load above the proportional limit. The readings were taken only after the load has stabilized. At this stage also, the deflection readings were observed carefully in loading the specimen to make sure that the peak (ultimate) load of the column would be clearly defined in the load-deflection diagram. Three or four more points were plotted in the unloading stage past the ultimate load. A complete release of the load on the column followed and the permanent deformations were observed and recorded.

3.4 Test Results

The column test program involved in this investigation is summarized in Table 4. A total of 12 columns were tested with slenderness ratios varying from 30 to 105. The tests were expected to provide information for comparison with theoretical studies made in Ref. 2.

In addition to actual column tests, studies were made also on material properties, residual stress distribution and stub column characteristics.

A total of 43 standard 8-inch coupons and 24 non-standard 2-inch coupons were tested in a 120-kip mechanical screw-type testing machine. The strain was recorded and plotted automatically. The 2-inch coupons were actually sections cut for residual stress measurement, and 12 of these non-standard coupons were taken from the welded joint as shown in Fig. 1.

The average static yield stress of the standard 8-inch coupons was 37.3 ksi with a maximum deviation of 2.7 ksi. The tests on the non-standard coupons gave a static yield stress of 35.9 $\pm$ 1.5 ksi. The test of the coupons taken from the weld revealed that the static yield stress of the deposited weld metal was about 46.5 $\pm$ 2.8 ksi. This indicated that the deposited weld metal was about 30% stronger than the parent material.

Figures 15 and 16 show typical stress-strain curves of the non-standard 2-inch coupons taken from the parent material and from the deposited weld metal respectively. Figure 17 is a stress-strain curve recorded from a test on a standard 8-inch coupon.

The residual stress distribution of 16 sections were measured; one each for the 6" x 6" box shape and the 6" x 7" H shape and 14 for the 10" x 10" box shape. Figure 18 shows the residual stress distribution typical of the sections. The residual stress magnitudes shown are from outside measurements for the box sections and the average of the measurements on two faces of the H-shape.

The box shapes had a residual stress pattern quite uniform for all the sections investigated. The middle portion of the plates contained approximately uniform compressive residual stresses and abruptly decreasing and changing to tensile residual stresses at the edges. The compressive residual stress at the center of the plate was about 30 ksi and the tensile residual stress at the edge was about 38 ksi.

The H shape had a residual stress pattern similar to that of the standard rolled shapes[1] although with much greater magnitudes. The greater residual stress values are due to the localized heat of welding.

The findings of Refs. 3 and 10 were used as a correlation with this investigation. These references describe the formation, magnitude and distribution of residual stresses in welded plates. Reference 2 indicated that, for welded shapes built-up from similar plates, the effect of restraint is negligible. Hence, the distribution of residual stress in such a welded shape may be obtained from the residual stress distribution of the separate component plates.

The following is a summary of the results of the studies conducted on the 10" x 10" box shape:

Variation of residual stress along the length of the column

The measurement on sections A, B and C of column C5 showed that there is no significant difference in the residual stress distribution at different points along the length of a column. All the test pieces showed high compressive residual stresses (a maximum of 36 ksi) at about the center line of the welded (narrower) plate and also high tensile residual stresses at the edges. The side (wider) plates showed a more even distribution of compressive residual stress (about 28 ksi) over the middle three-quarters of the plate, with high tensile stresses (about 35 ksi) at the edges. Figure 19 shows that the residual stress distribution of the three sections are essentially the same.

Effect of plate edge preparation for welding

The manner of preparing the edge of the plate had little effect on the residual stress distribution as the specimens showed very negligible differences between the residual stress distribution of the specimen fabricated from machined plates and the specimen fabricated from flame-cut plates.

Difference between residual stress on the outside and the inside face

Measurements on the L sections cut from the box shape showed only a slight variation in the magnitude of residual stresses measured on the outside face and on the inside face.

The effect of weld size and type of welding is not considered in this report. However, a study of the effect of these factors in the formation of residual stress and the strength of welded built-up columns is included in future studies.

The result of eight stub column tests are shown in Figs. 20, 21, and 22. Figure 20 is the average of six tests made on the

10" x 10" box shape. Figures 21 and 22 are results of tests on the 6" x 6" box shape and the 6" x 7" H shape respectively.

The yield load of the 10" x 10" box shape was about 710 kips, using the 0.5% strain offset method of determining the yield stress level. This corresponds to a stress of about 37.4 ksi which agrees very well with the yield stress of 37.3 ksi obtained from the standard coupon tests. From the load-strain curve, it was noted that the proportional limit was 210 kips (11 ksi) which implies a maximum compressive residual stress of 26 ksi. Residual stress measurement on the section showed compressive residual stress of about 28 ksi. The load-strain curve also displayed a tendency to rise continuously even at the fully plastic stage until it finally reached the strain hardening range. This tendency to rise continuously is typical of welded shapes and is probably caused by the higher strength of the deposited weld metal.

The stub column test on the 6" x 6" box shape gave a load-strain curve very similar to that of the 10" x 10" box shape, except for the fact that strain hardening was not attained due to the onset of local buckling at about 0.007 in./in. strain. The yield load of the section was 320 kips.

The yield load of the 6" x 7" H shape was about 440 kips. The load strain curve was very similar to the 10" x 10" box shape and no local buckling was experienced.

The results of the column tests are summarized in Table 5. The data given in the table includes the slenderness ratio, the column strength (P/P_y), and the initial out-of-straightness of each of the twelve columns tested in the program. The initial out-of-straightness ranged from a minimum eccentricity ratio, e/b of 0.001 for C4 to a maximum of 0.024 for C6. Figure 23 shows the variation of the initial out-of-straightness along the length of the column.

The load versus mid-height deflection curves are shown in Figs. 24 and 25. The test curves show that the deflections were negligible for the low loads, as expected, because the eccentricity was balanced between the ends and the mid-height in the alignment procedure.

A notable feature of the load deflection curves is the unloading portion; for the longer columns, the slope of the unloading curve is very slight whereas for the shorter columns, after the ultimate strength is attained, the rate of drop in the load is very pronounced. This indicates that the longer columns can carry the ultimate load for a wider range of deflection than the shorter columns.

A comparison can be made on the load-deflection curves of columns C6 and C10, both of which had slenderness ratios of 80. Column C6 was fabricated from plates edge prepared by machining while column C10 was fabricated from plates edge prepared by flame cutting. Columns C10 had a slightly higher ultimate load (0.65 versus 0.63) occurring at mid-height deflection of 1.1 inches. Column C6 had a flatter peak with the ultimate load occurring at mid-height deflection of 1.6 inches. At the unloading stage, the two curves were more or less coincident.

It may be concluded that the use of either machined or flame-cut plates in the fabrication does not affect column strength.

The data shown in Fig. 26 gives the stress-strain curve at the mid-height section of the extreme fibers and the fiber at the center line. Part of the stress-strain curve of the stub column is also plotted in the figure. The features of the stress-strain curves are typical of each column and Fig. 26 is the result of the test on column C6. Note that the strains are uniform up to about the proportional limit. Once the column started deflecting the strains of the extreme fibers started deviating from the average value up to a point where the fiber on the convex side of the bent column experienced strain reversal. The divergence of the stress-strain curves is due to the initial eccentricity of the column. If the column was perfectly straight and homogeneous, the curves of the three fibers would coincide up to the point of bifurcation. This was shown by Shanley in his classical paper on columns failing in the inelastic range.[11]

The data above can also be plotted in a manner as shown in Fig. 27. The stress distribution across one of the plate elements of the column are plotted as the load increases. The significant features of this figure are: (1) the initial state of uniform stress, (2) the occurrence of strain regression prior to attaining ultimate load, and (3) the inward movement of the point of zero strain regression.

The theoretical computations of the ultimate carrying capacity of welded built-up columns are given in Ref. 2. The computations are based on the equilibrium of external and internal forces and moments at the mid-height cross section. The effect of residual stress is taken into account by assuming an idealized residual stress distribution based on the actual measured residual stress distribution.[2]

In Fig. 28 the results of the column tests are plotted. The tangent modulus load curve and the ultimate load curve for the welded box section[2] are also shown. On the basis of these results, it can be seen that the ultimate load prediction is too optimistic. The experimental results show that the actual ultimate load of columns with medium slenderness ratios appears to be about 20% less than the predicted values. This discrepancy is caused mainly by the initial out-of-straightness of the column and the presence of non-symmetrical residual stress distribution in the section.

3.5 Discussion

(a) It was shown in Ref. 2 that the theoretical analysis did not give satisfactory results due to the presence of initial out-of-straightness in the column specimens and to a lesser degree, due to the assumption of an idealized residual stress distribution.

(b) In Fig. 29, the column curves for the eccentrically loaded box column were plotted for eccentricity ratios, e/b equal to 0.01 and 0.05. A comparison of these column curves with the column curve for the axially loaded column shows the very appreciable effect of initial out-of-straightness.

In all the columns tested, initial out-of-straightness was present. If the initial out-of-straightness of each test column is taken into account, a good correlation can be shown to exist between the ultimate strength of the test column and the expected ultimate strength of a column with the equivalent eccentricity. A discussion of this aspect of column strength will be presented in a future report on the theoretical study of welded built-up columns.

(c) As far as the welded 10" x 10" box sections were concerned, the deviation from the specified dimensions was satisfactory, with a maximum of $\pm$ 0.05 inch. As can be seen in Fig. 23, the straightness of the column was not perfect. However, the deviations in dimension and straightness were well within the allowable tolerances given by the specifications (1956 AWS Specification, Sec. 507).[12,13]

The same remarks can be made on the dimensions and straightness of the 6" x 6" box shape. In the case of the 6" x 7" H shape, the geometry of the cross section was noticeably out of shape due to excessive pre-cambering introduced to overcome the anticipated welding distortions. The edges of the 6" flange were flared to as much as 0.02 inch (see Fig. 30). This was not serious as the columns were tested about the weak axis of bending.

(d) In Fig. 31, the test results are plotted with the Basic Column Curve proposed by the Column Research Council,[1,14] together with results of tests of WF shapes. This column curve is the basis of allowable stresses for columns given by the 1961 Specification of the American Institute of Steel Construction.[15] It can be seen from the figure that except for the shortest columns, the test points fall below the predicted values.

The column specimens were tested in the as-fabricated condition, that is, without undergoing any cold-bending. It was shown for wide-flange shapes that cold-straightening causes an alteration of the residual stress pattern which is more favorable to column strength.(1) For the welded built-up columns, cold-straightening will at least minimize the initial out-of-straightness. It is also possible that the residual stress pattern will be altered favorably. A study into the effect of cold-bending on residual stress formation and the strength of welded built-up columns is planned for the future.

4. SUMMARY AND CONCLUSIONS

The tests conducted in this investigation involved columns built-up by welding from universal mill plates of ASTM designation A7. Particular attention was given to columns of medium size box-shape cross section and their behavior is compared with medium size H-shapes, and box shapes and H shapes of smaller sizes.

In this report, the following problems were investigated experimentally:

a) the magnitude and distribution of residual stresses of welded built-up columns,

b) the effect of residual stress on column strength, and,

c) the strength of welded built-up columns of medium slenderness ratios.

Based on the results of the studies made in the investigation, the following conclusions can be stated:

1) The variation of residual stress distribution for a particular section is not appreciable, there being negligible differences between sections taken from different fabricated pieces. (Fig. 19)

2) Flame cutting does not affect column strength; the strength of box columns of similar slenderness ratios made from machined and from flame cut plates is the same.

3) The effect of eccentricity on welded built-up shapes is considerable in the medium slenderness ratios. (Fig. 28)

4) For the medium slenderness ratios, the results showed that the welded box columns were stronger than the welded H columns by 5 to 15% (Compare Fig. 28 with Fig. 7).

5) Except for the shortest columns, these welded members exhibited a strength less than that implied by the CRC column curve by amounts varying from 8% to 26%. (Fig. 31)

6) The results of this study have indicated that future work is needed to evaluate:

   a) The effect of cold-straightening on the residual stress distribution and on the strength of welded built-up columns

   b) The strength of welded columns built-up from thick plates. The residual stress distribution in this case may vary across the thickness and possibly may not play as great a role in the strength of the column.

5. ACKNOWLEDGEMENTS

This report presents the results of an experimental study of the effect of welding on built-up columns. The project is part of a research program designed to determine the relationship between material properties and the strength of columns.

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6. DEFINITIONS

Buckling:	Buckling load may be defined as that load at which the theoretically straight column assumes a deflected position.
Static Yield Stress Level:	The static yield stress level is the yield stress level for zero strain rate.
Ultimate Load: (Maximum Load)	The maximum load a column will carry. It is not coincident with the buckling load for an axially loaded column.
Yield Strength:	The yield strength is the stress corresponding to the load which produces in a material, under the specified conditions of the test, a specified limiting strain. (ASTM Standard A370-54T, 1958)
Yield Stress Level:	The yield stress level is the stress corresponding to a strain of 0.5%. This stress will usually correspond to the constant stress under yield when the stress-strain relationship does exhibit such yielding.

7. APPENDIX

The column specimens were fabricated from structural steel of ASTM designation A7, universal mill plates according to the following schedule:

Item (1) 6" x 6" Box Shape

Sets (a) and (b). 6" x 1/4" plate, 4 lengths of 30'0"

5 1/2" x 1/4" plate, 4 lengths of 30'0"

Machine the plate edges straight. NO FLAME CUTTING.

Four corner welds, full penetration.

Sets (a) and (b) will be fabricated into 2 columns, each 30'0" long.

Item (2) 7" x 6" H Shape

Set (a)	6" x 1/2" plate, 2	lengths	of	22'0"
	6" x 3/8" plate, 1	"	"	22'0"
Set (b)	6" x 1/2" plate, 2	"	"	16'0"
	6" x 3/8" plate, 1	"	"	16'0"

Machine the plate edges straight. NO FLAME CUTTING.

Two - 3/16" fillet welds at each joint.

Set (a) will be fabricated into a column, 22'0" long.

Set (b) will be fabricated into a column, 16'0" long.

Item (3) 10" x 10" Box Shape

	9" x 1/2" pl.	10" x 1/2" pl.	Length
Set (a)	2 lengths	2 lengths	15'0"
(b)	"	"	52'0"
(c)	"	"	30'0"
(d)	"	"	40'0"
(e)	"	"	40'0"
(f)	"	"	45'0"
(g)	"	"	50'0"
(h)	"	"	60'0"

Make edges straight for 10" plate and for the 9" plate.

Make straight, with bevel, as specified.

Four corner welds, with slight reinforcement.

Sets (a) and (b) will be machined for all edge preparations.

Sets (b), (c), (e), (f) and (g) will be edge prepared and beveled by flame cutting. Use double track burner.

Set (h) will undergo no fabrication operations at this stage, but will be kept for future use.

Each 40'0" plate of set (d) will be cut into a 30'0" and a 10'0" length to simplify machining. These plates will be fabricated into two columns, one 30'0" long, and the other 10'0" long. (Note: Column (d) will be used as a direct comparison to column (e), one being prepared by machining, and the other by flame cutting).

Set (a) will be fabricated into a column 15'0" long.

Set (b) will be fabricated into a column 52'0" long.

Set (c) will be fabricated into a column 30'0" long.

Set (d) will be fabricated into a column 30'0" long
and a column 10'0" long.

Set (e) will be fabricated into a column 40'0" long.

Set (f) will be fabricated into a column 45'0" long.

Set (g) will be fabricated into a column 50'0" long.

Set (h) will not be fabricated.

To standardize the fabrication of the sections, the following specifications were also set forth:

1) Each set of plate lengths used to make a column should come from the same rolling or from the same position in the ingot, so that their chemical and physical properties are more or less identical.

2) The universal plates should undergo a minimum possible mill straightening. Any other process which can in any way alter the distribution of residual stress should be avoided.

3) The columns should be fabricated as straight as possible, and should undergo no straightening of any form.

4) The final cross sectional dimensions shall be those designated except that slight weld reinforcement of the box shapes should not be ground off to make the sides flush.

8. TABLES AND FIGURES

TABLE 1 RESULTS OF TENSILE COUPON TESTS

Column	Coupon No.	y (ksi)	Average y	u (ksi)	Average u	Remarks
No. 1	C-1-1	51.5	(50.8)	79.8	(79.8)	Standard 8" Coupons
	C-1-2	51.9		80.1		
	C-1-3	50.5		79.2		
	C-1-4	49.8		80.2		
No. 3	C-3-1	--		80.3		Standard 8" Coupons
	C-3-2	48.3		80.6		
	C-3-W	46.8		77.0		
No.5	C5 A1	37.3	(37.7)	65.7	(65.4)	Standard 8" Coupons
	C5 A2	37.9		65.5		
	C5 A3	37.9		65.0		
	C5 A4	40.1		66.8		
	C5 B1	36.8	(37.9)	66.1	(66.2)	Standard 8" Coupons
	C5 B2	39.1		67.1		
	C5 B3	37.5		65.3		
	C5 B4	38.3		66.4		
No. 6	C61	37.0	(37.2)	66.2	(66.5)	Standard 8" Coupons
	C62	38.1		67.0		
	C63	37.1		66.2		
	C64	36.6		66.6		
No. 7	C71	37.3	(37.4)	65.0	(65.4)	Standard 8" Coupons
	C72	37.6		65.4		
	C73	37.0		64.6		
	C74	37.6		66.4		
No. 8	B10	34.6	At the weld - 46.8	63.1	At the weld - 68.2	2" Coupons*
	B21	47.2		68.9		
	B30	37.2		63.9		
	B39	48.3		69.4		
	B50	35.0	Between welds - 36.0	64.3	Between welds - 64.0	
	B60	44.8		66.4		
	B70	37.0		64.6		
	B78	65.6		73.9		
	C8(1)	35.4	(37.0)	64.3	(65.4)	Standard 8" Coupons
	C8(2)	36.3		65.5		
	C8(W1)	38.2		65.5		
	C8(W2)	37.9		66.2		

*Non-standard - σ_R sections tested in tension

TABLE 1 - CONTINUED

Column	Coupon No.	y (ksi)	Average y	u (ksi)	Average u	Remarks
No. 9	10 21 30 39 50 60 70 78	34.5 41.0 36.2 45.6 34.1 49.3 36.4 47.2	At the weld - 47.3 Between welds - 35.3	61.4 69.8 61.9 67.4 60.9 70.4 62.6 68.2	At the weld - 61.7 Between welds - 68.9	2" Coupons
	C9(1) C9(2) C9(W1) C9(W2)	35.3 35.0 36.8 37.1	(37.1)	62.3 62.5 62.4 63.4	(62.4)	Standard 8" Coupons
No. 10	A10 A21 A30 A39 A50 A60 A70 A78	34.4 44.0 36.7 46.6 36.6 45.1 37.4 45.6	At the weld - 45.3 Between welds - 36.3	61.4 65.8 63.2 69.3 62.5 68.0 64.3 68.5	At the weld - 62.8 Between welds - 67.9	2" Coupons
No. 11	C11-1 C11-2 C11-3 C11-4	34.4 40.0 33.9 38.4	(36.7)	61.0 64.6 61.6 64.4		Standard 8" Coupons
No. 12	C12-1 C12-2 C12-3 C12-4	35.4 38.0 35.8 38.4	(36.9)	63.4 65.3 63.3 65.0		

TABLE 2 RESULTS OF PILOT TEST

Plates	Section	L/r	P/P_y
9" x 1/2"		12.5*	1.25
9" x 3/4"	9" x 10" H	59	0.64
		78	0.62
		103	0.50

*Part of test on low slenderness ratio

TABLE 3 SCHEDULE OF SPECIMENS

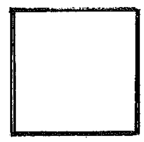
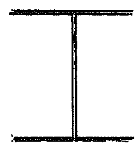
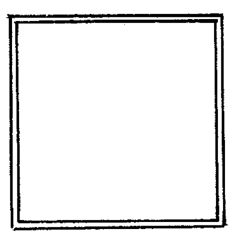
Piece No.	Length	Description	Col. No.	Specimens
1	30'	6" x 6" box 	1 2	10' 6" column 6' 6" column residual stress coupons stub column
2	30'			(store)
3	22'	6" x 7" H 	3 4	6' 6" column 4 0" column residual stress coupons stub column
4	16'			(store)
5	15'	10" x 10" box 	5	Coupons (2 sets) residual stress (3)
6	30'		6	26' 7 5/8" column residual stress coupons
7	10'		7	coupons residual stress stub column
8	52'		8 13 14	13' 3 3/4" column stub column residual stress coupons 10' 0" column 16' 8" column
9	30'		9	20' 1 1/4" column stub column coupons residual stress
10	40'		10	26' 7 1/8" column residual stress stub column

TABLE 3 CONTINUED

Piece No.	Length	Description	Col. No.	Specimens
11	45'	10" x 10" box	11	31' 10 7/8" column stub column coupons residual stress (2)
12	50'		12	35' 3 1/8" column stub column coupons residual stress (2)
13	60'	(Reserve piece - not fabricated)		

NOTE: Piece Nos. 1 to 7 were fabricated from plates edge prepared by machining and the rest were from flame cut plates.

TABLE 4 COLUMN TEST PROGRAM

Item	Plates	Section	L/r
(1) Box Shape No. 1	6" x 1/4" 5 1/2" x 1/4"	6" x 6"	32 51
(2) H Shape	6" x 1/2" 6" x 3/8"	6" x 7"	32 53
(3) Box Shape No. 2	10" x 1/2" 9" x 1/2"	10" x 10"	30 40 50 60 80 (2) 95 105

TABLE 5 RESULTS OF COLUMN TEST

Column No.	L/r	$P_{max.}$ (kips)	P/P_y	e/b	Shape
1	51	241	0.75	0.004	
2	32	297	0.93	0.002	6" x 6" box
3	53	298	0.63	0.002	
4	32	353	0.80	0.001	6" x 7" H
6	80	439	0.63	0.024	
8	40	606	0.84	0.005	
9	60	547	0.77	0.005	
10	80	450	0.65	0.020	10" x 10" box
11	95	388	0.55	0.010	
12	105	354	0.51	0.020	
13	30	672	0.94	0.004	
14	50	589	0.82	0.012	

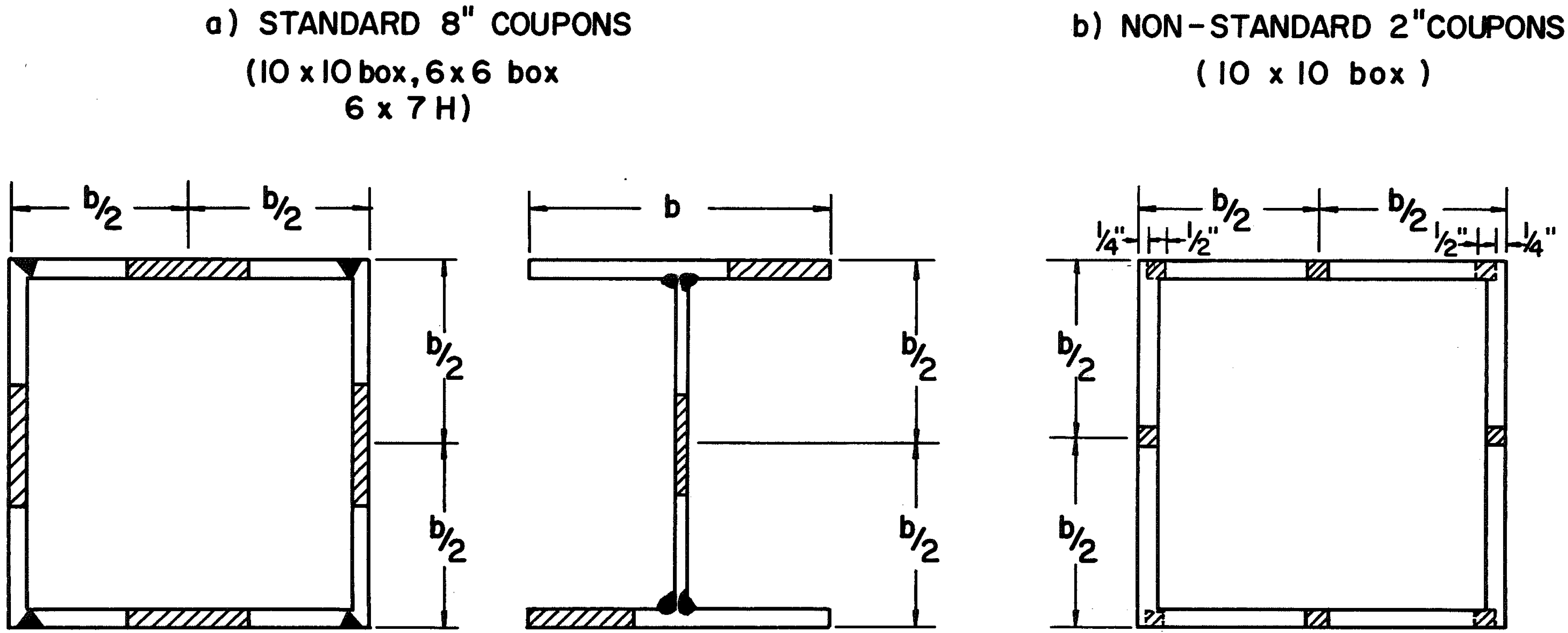


FIG. 1 LOCATION OF TENSILE COUPONS

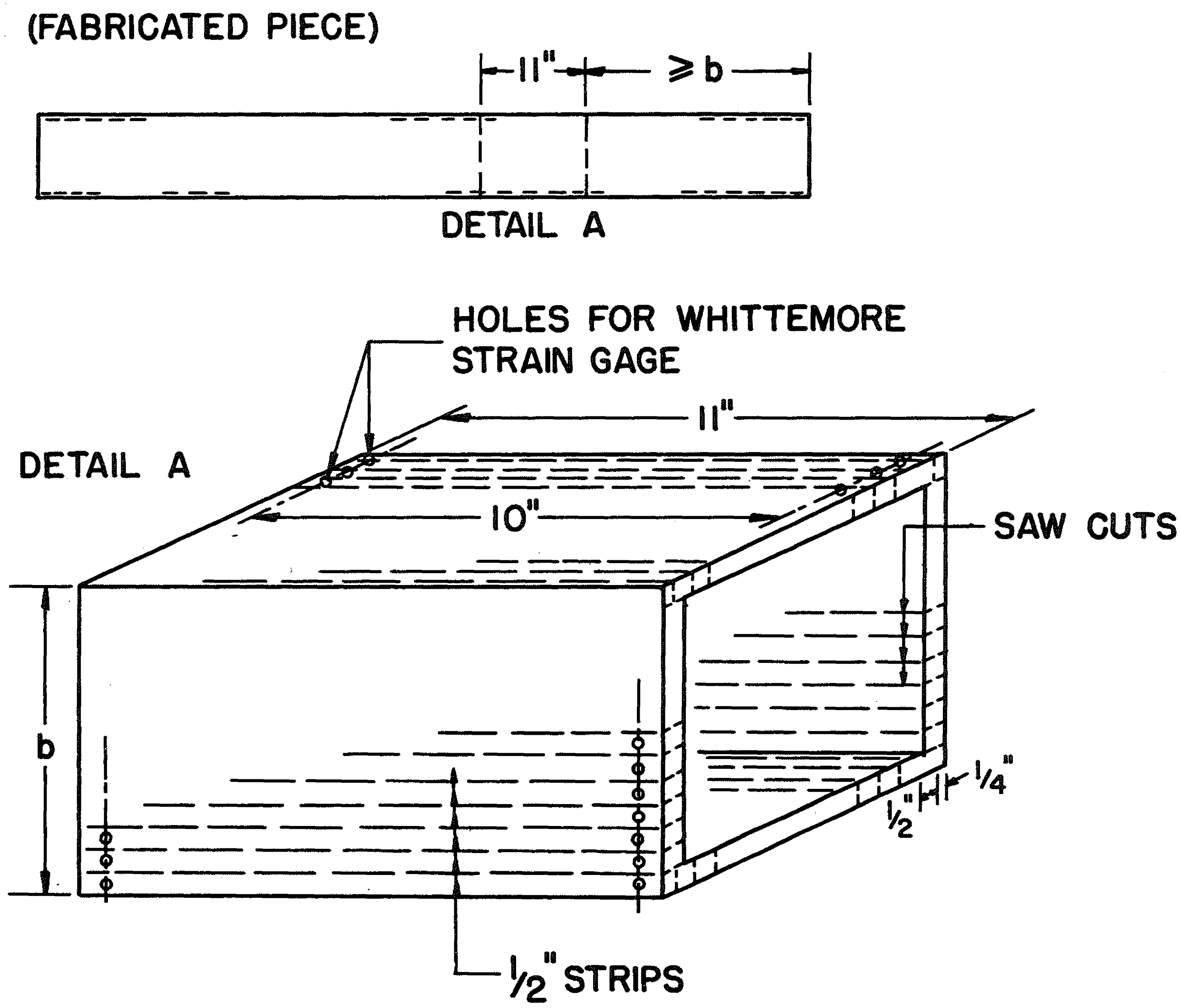


FIG. 2 LAYOUT FOR RESIDUAL STRESS MEASUREMENT

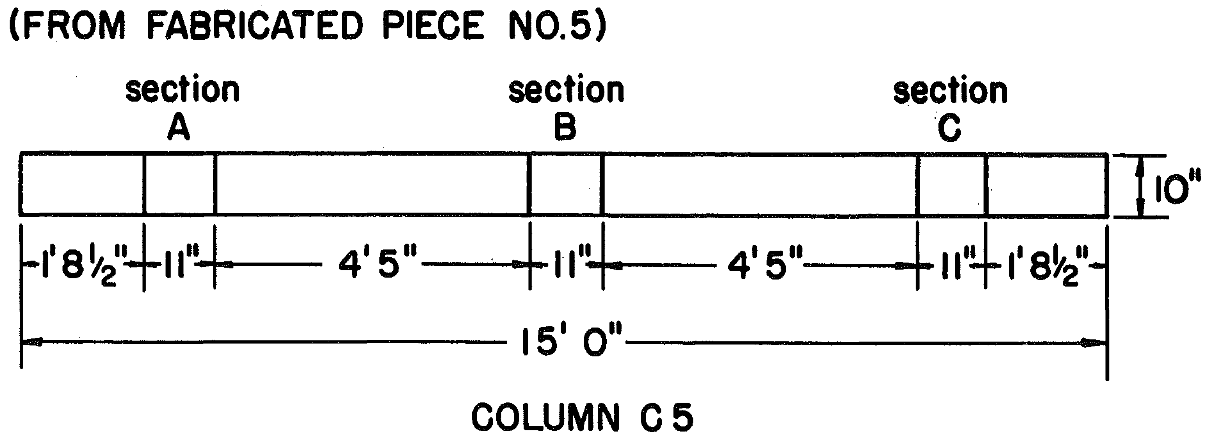


FIG. 3 LAYOUT FOR RESIDUAL STRESS MEASUREMENT

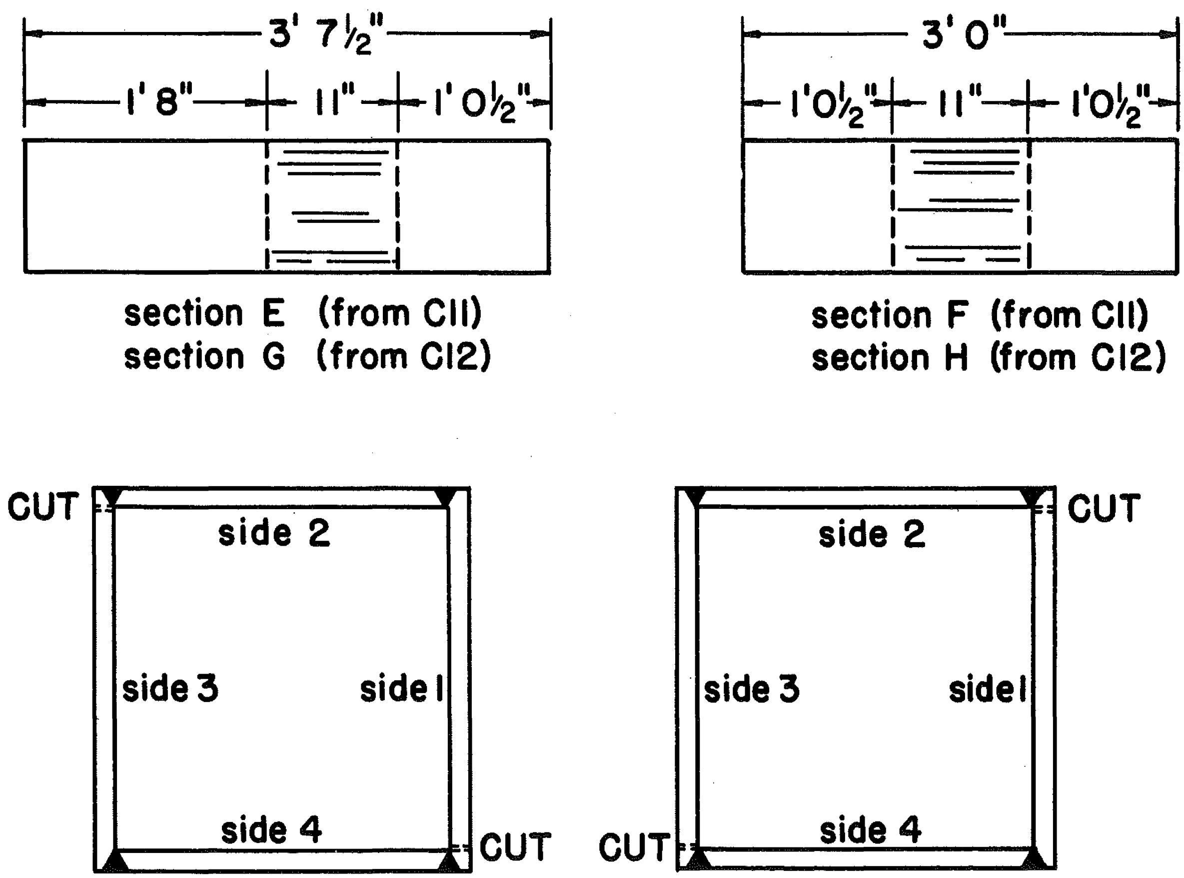


FIG. 4 LAYOUT FOR RESIDUAL STRESS MEASUREMENT

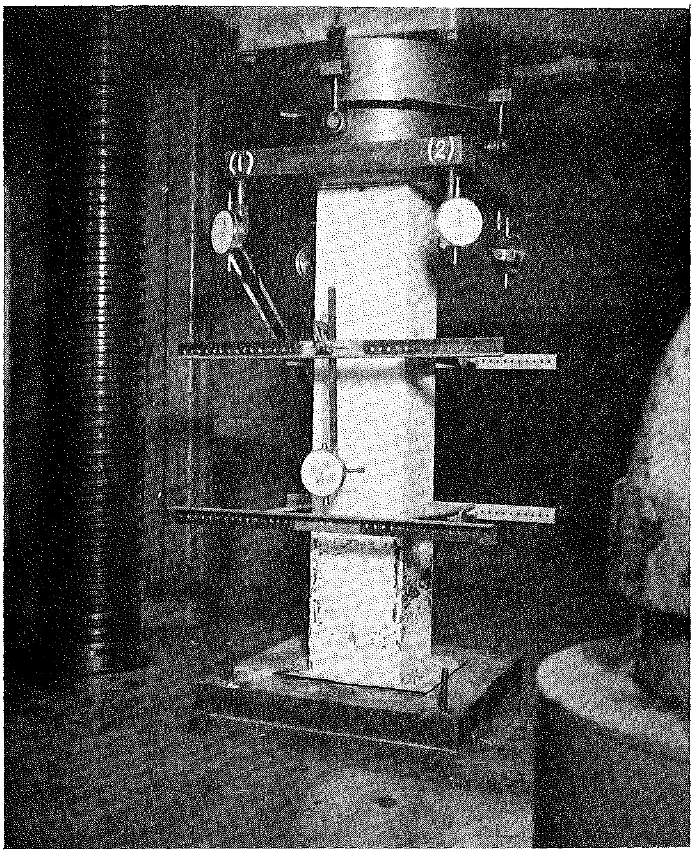


FIG. 5 INSTRUMENTATION OF STUB COLUMN

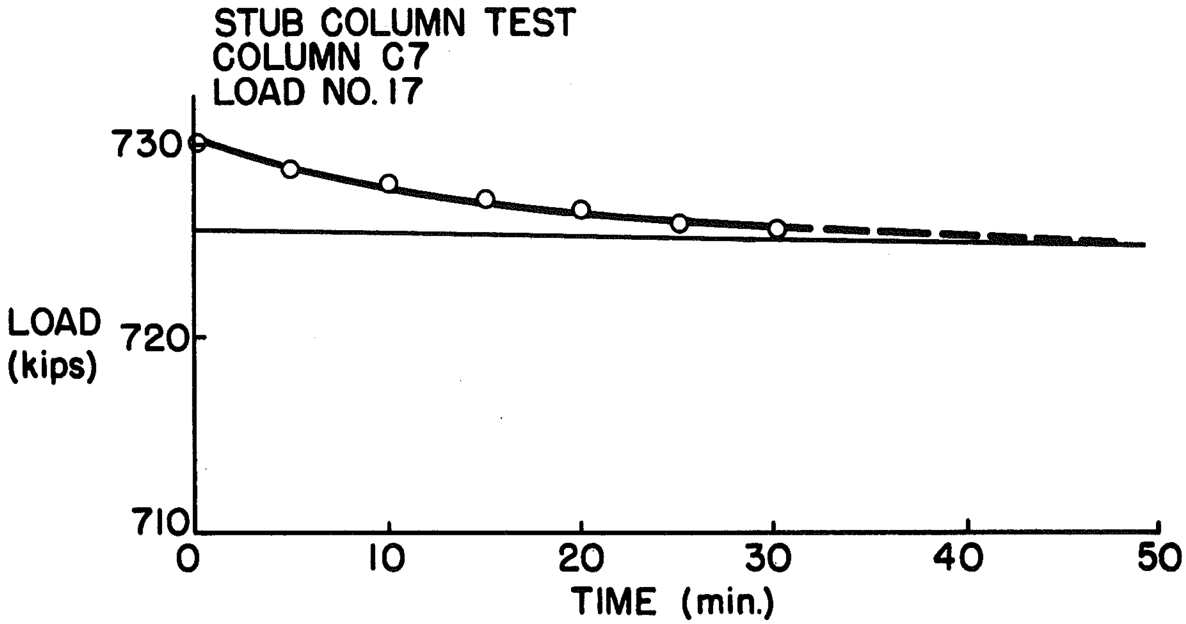


FIG. 6 TYPICAL LOAD RELAXATION DIAGRAM

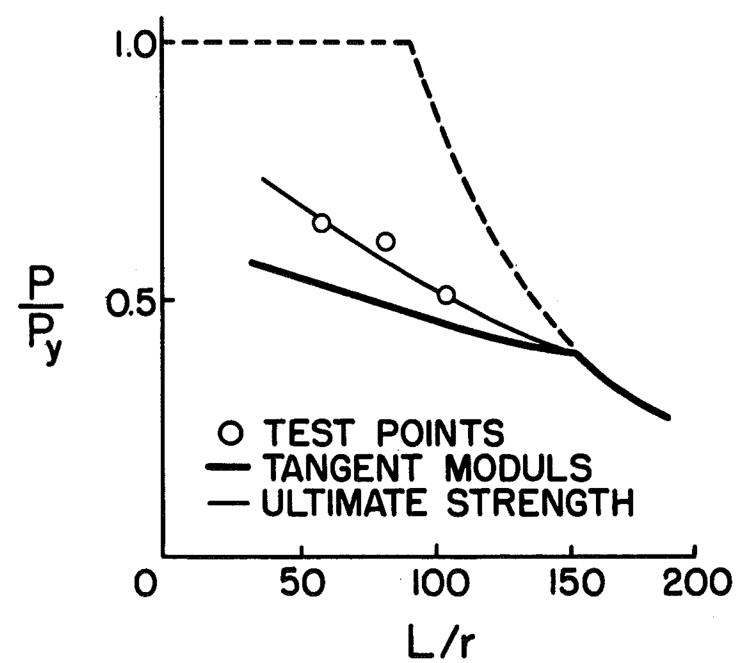


FIG. 7 STRENGTH OF WELDED H COLUMN

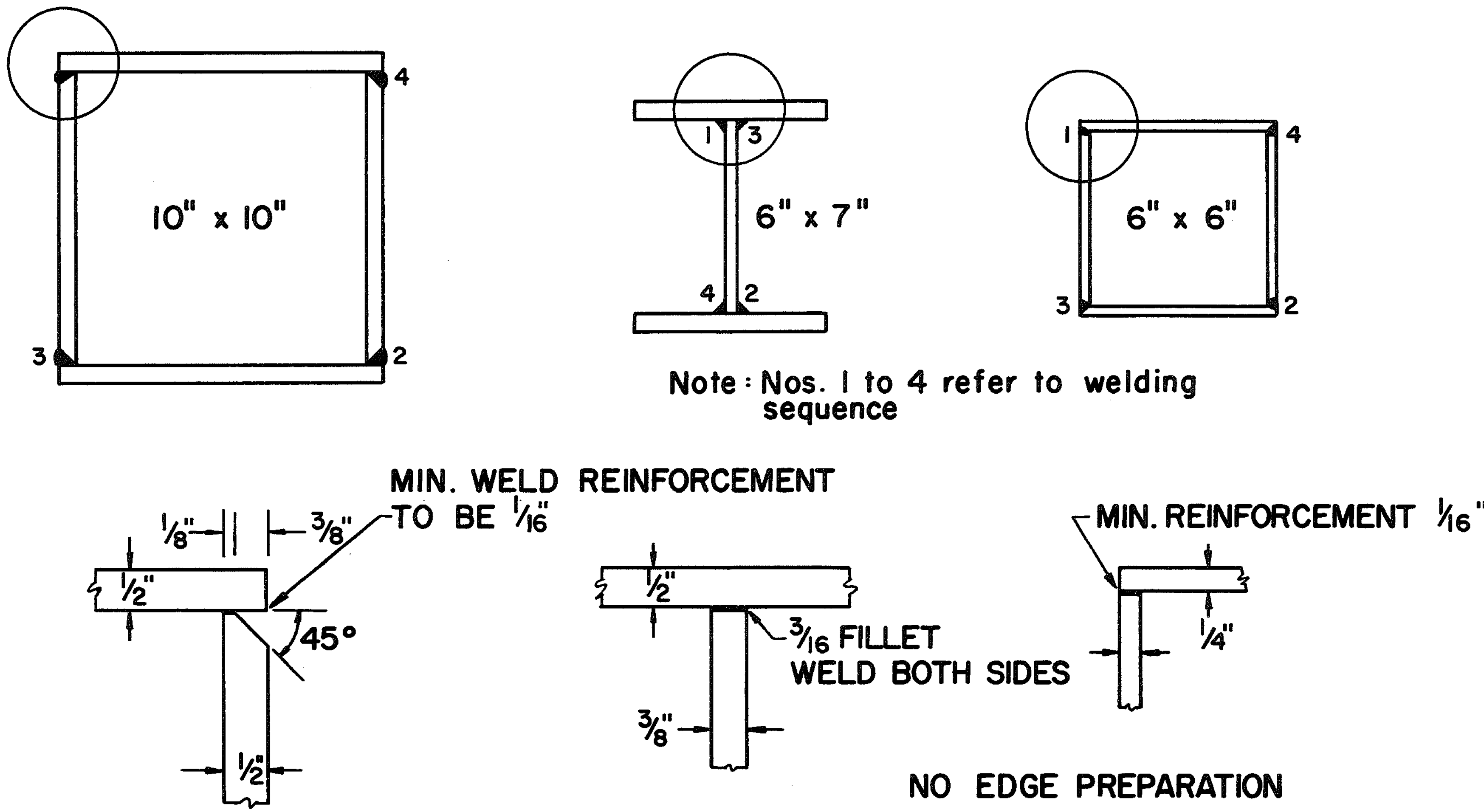


FIG. 8 WELDING DETAILS

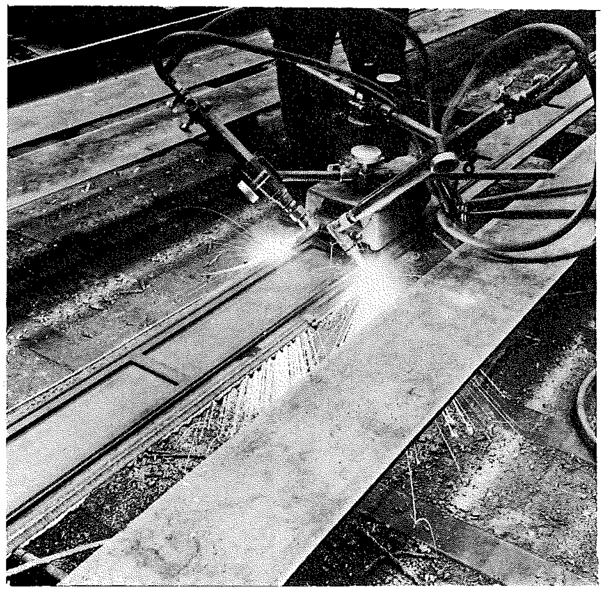


Fig. 9 FLAME CUTTING THE EDGES

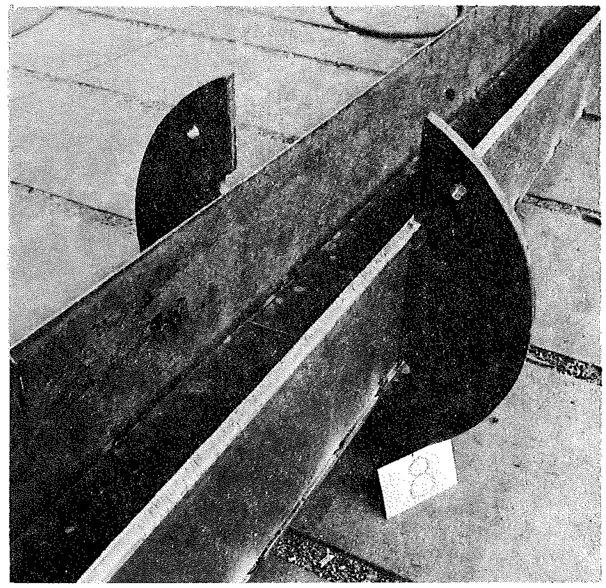


Fig. 10 TACK WELDING ON THE JIG

Fig. 11 AUTOMATIC WELDING OF JOINTS

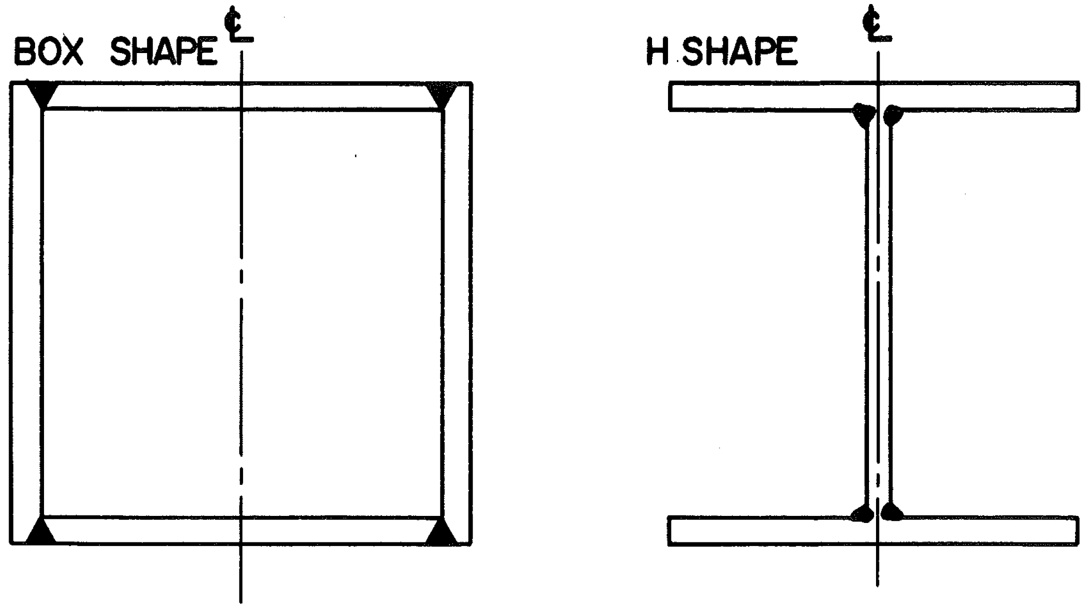


FIG. 12(a) END FIXTURE ACTION

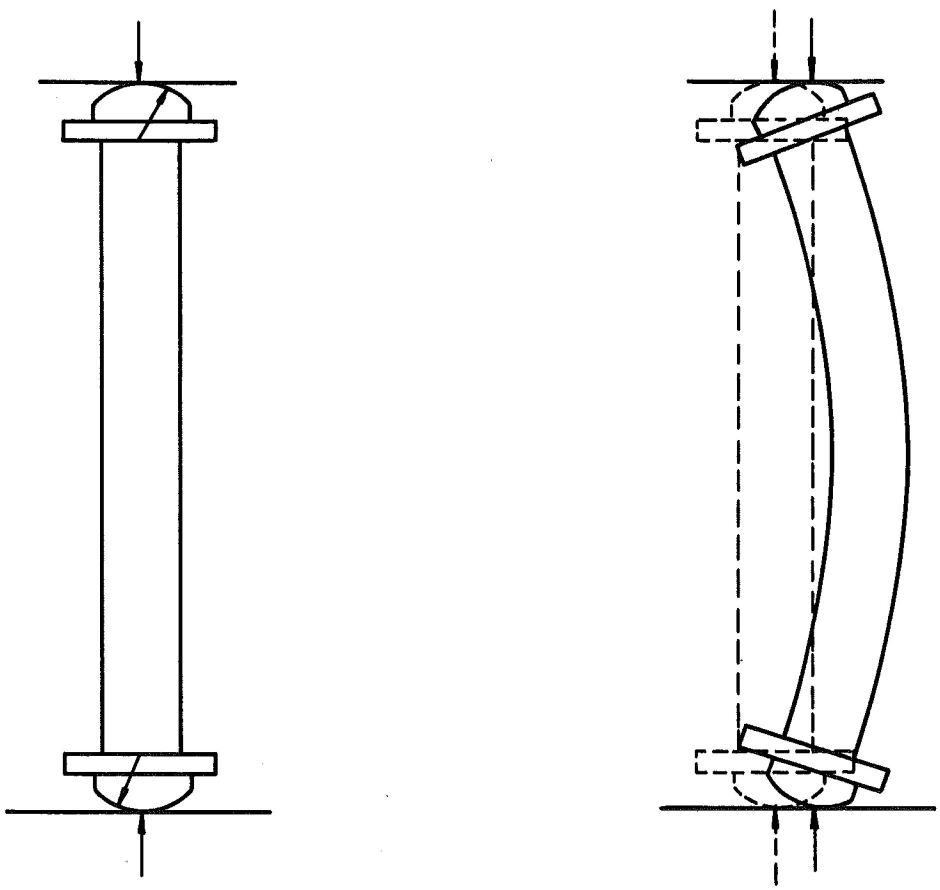


FIG. 12(b) END FIXTURE ACTION

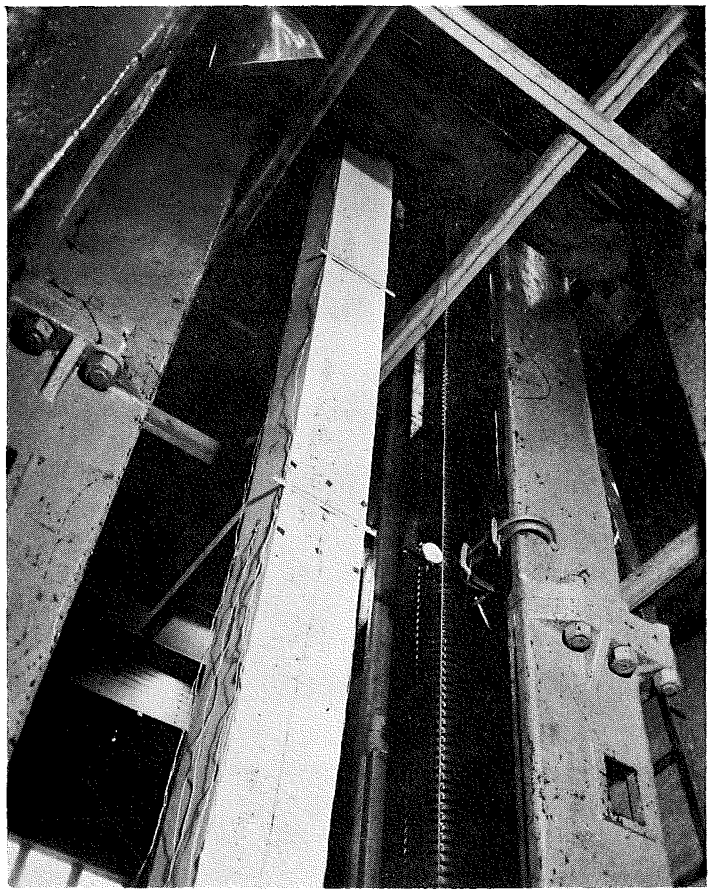
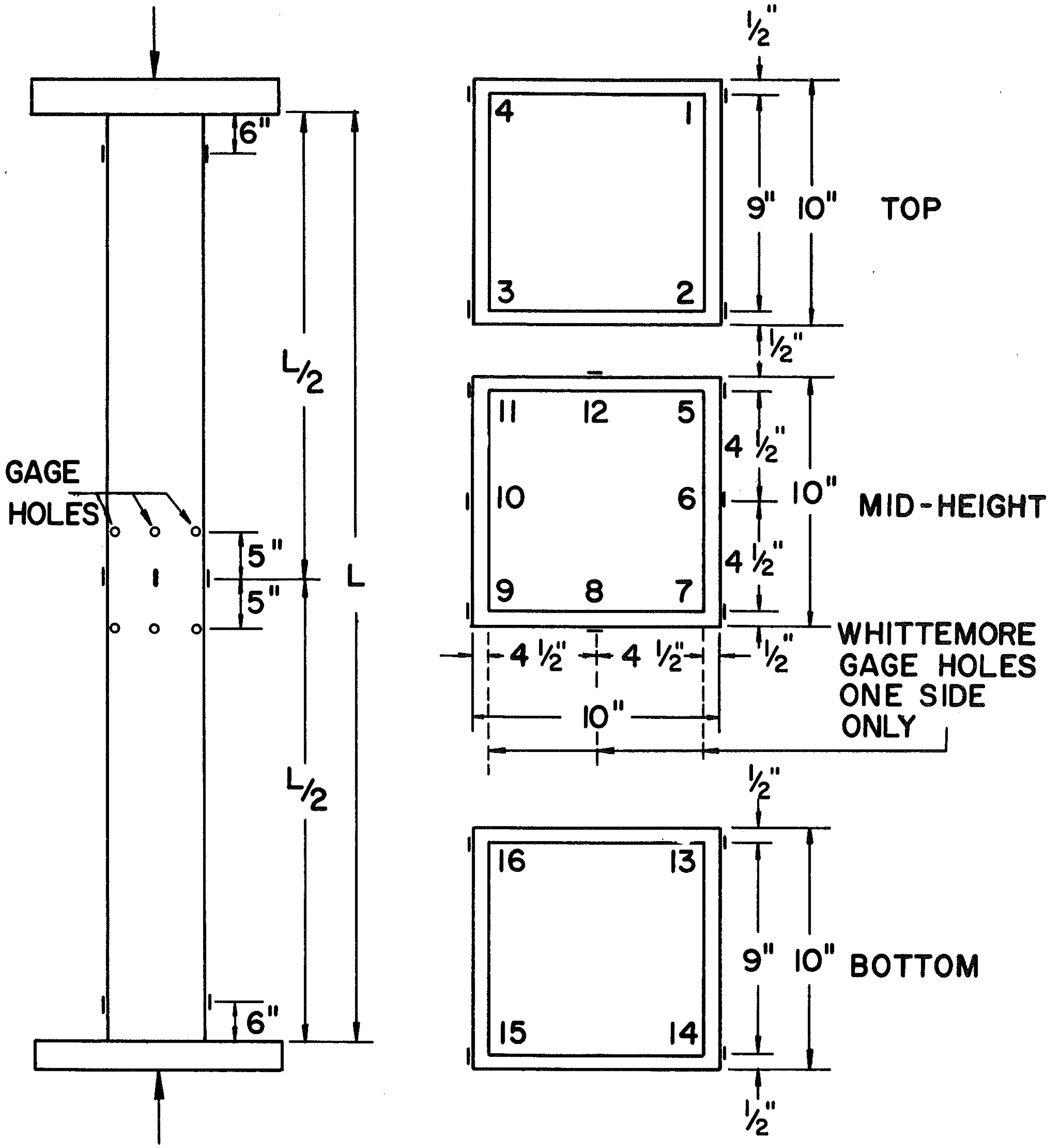


FIG. 13 MEASUREMENT OF LATERAL DEFLECTION



Note : Nos. 1 to 16 refer to SR4 strain gages

FIG. 14 LOCATION OF SR4 GAGE AND WHITTEMORE GAGE HOLES

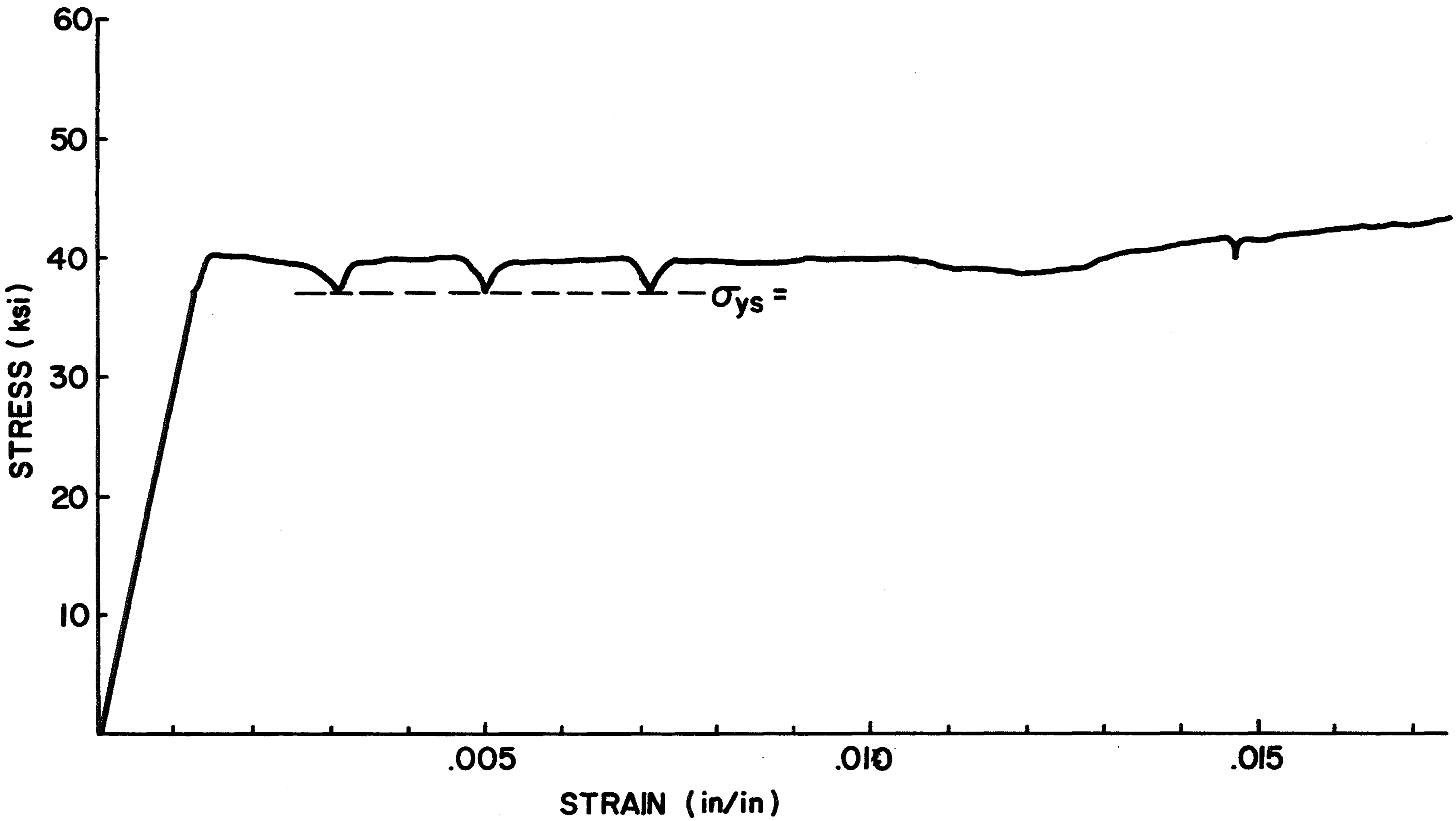


FIG. 15 STRESS STRAIN CURVE FOR NON-STANDARD COUPON

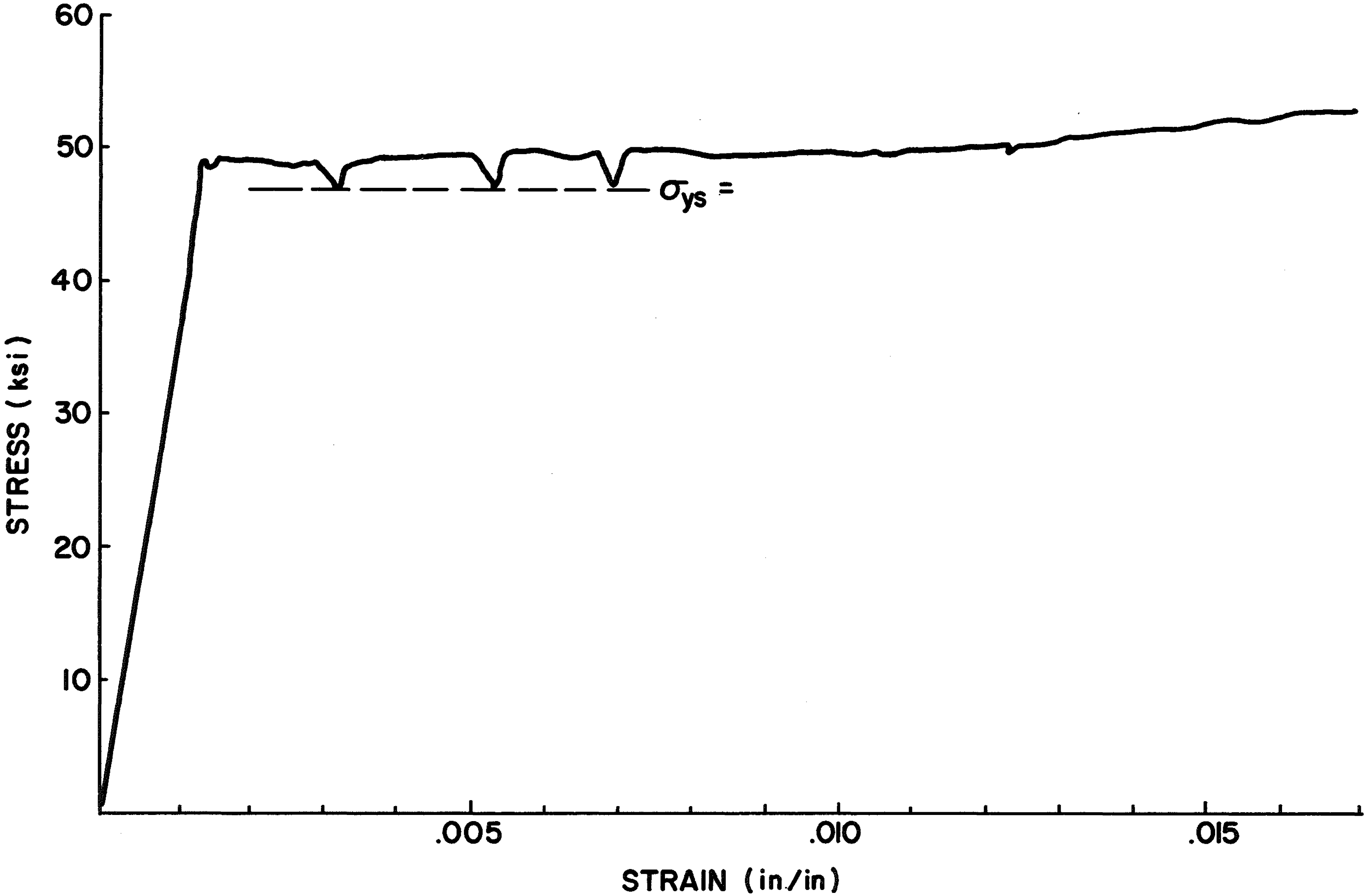


FIG. 16 STRESS STRAIN CURVE FOR NON-STANDARD COUPON
(TAKEN FROM THE WELDED JOINT)

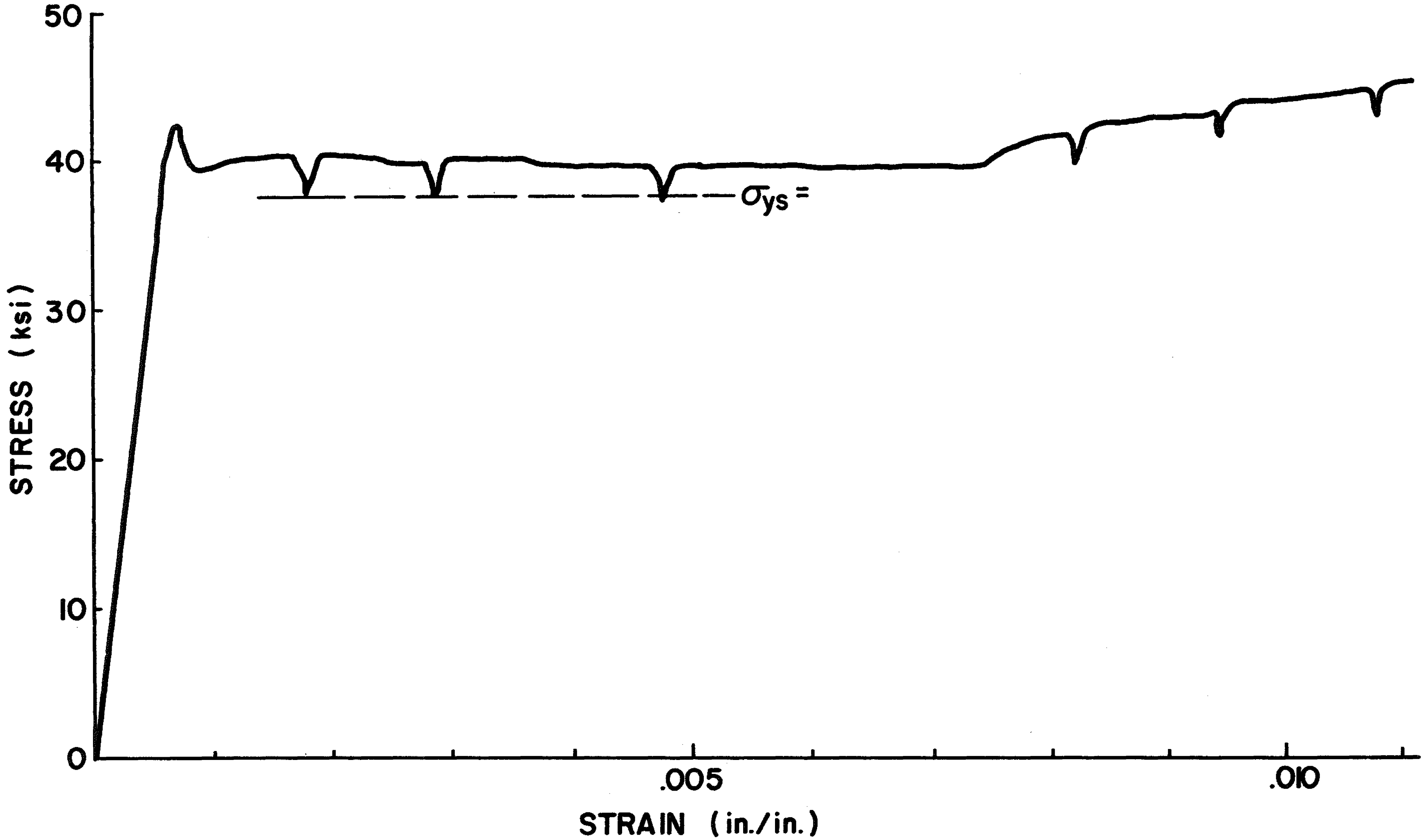


FIG. 17 TYPICAL STRESS STRAIN CURVE FOR STANDARD COUPON

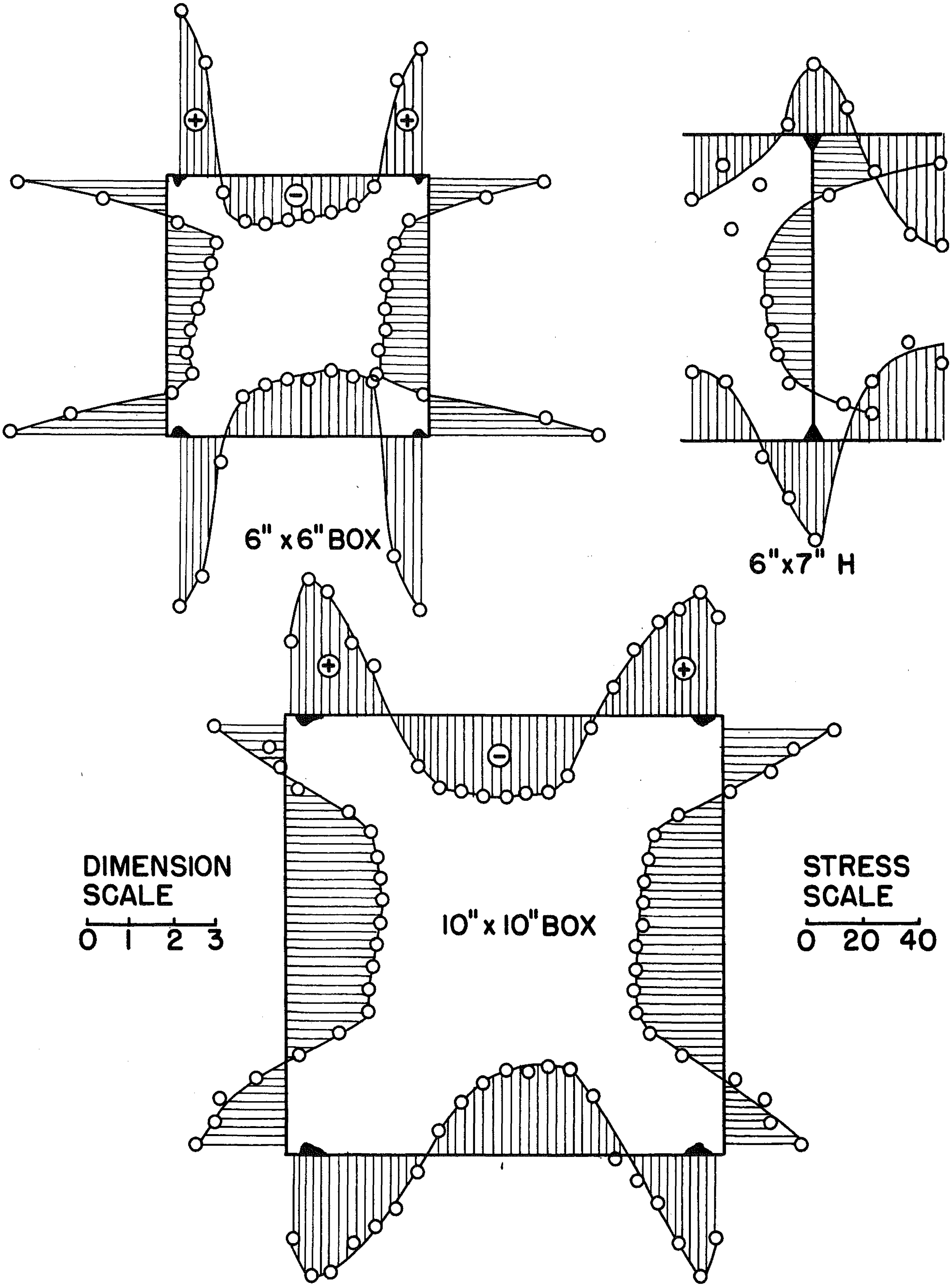


FIG. 18 TYPICAL RESIDUAL STRESS DISTRIBUTION

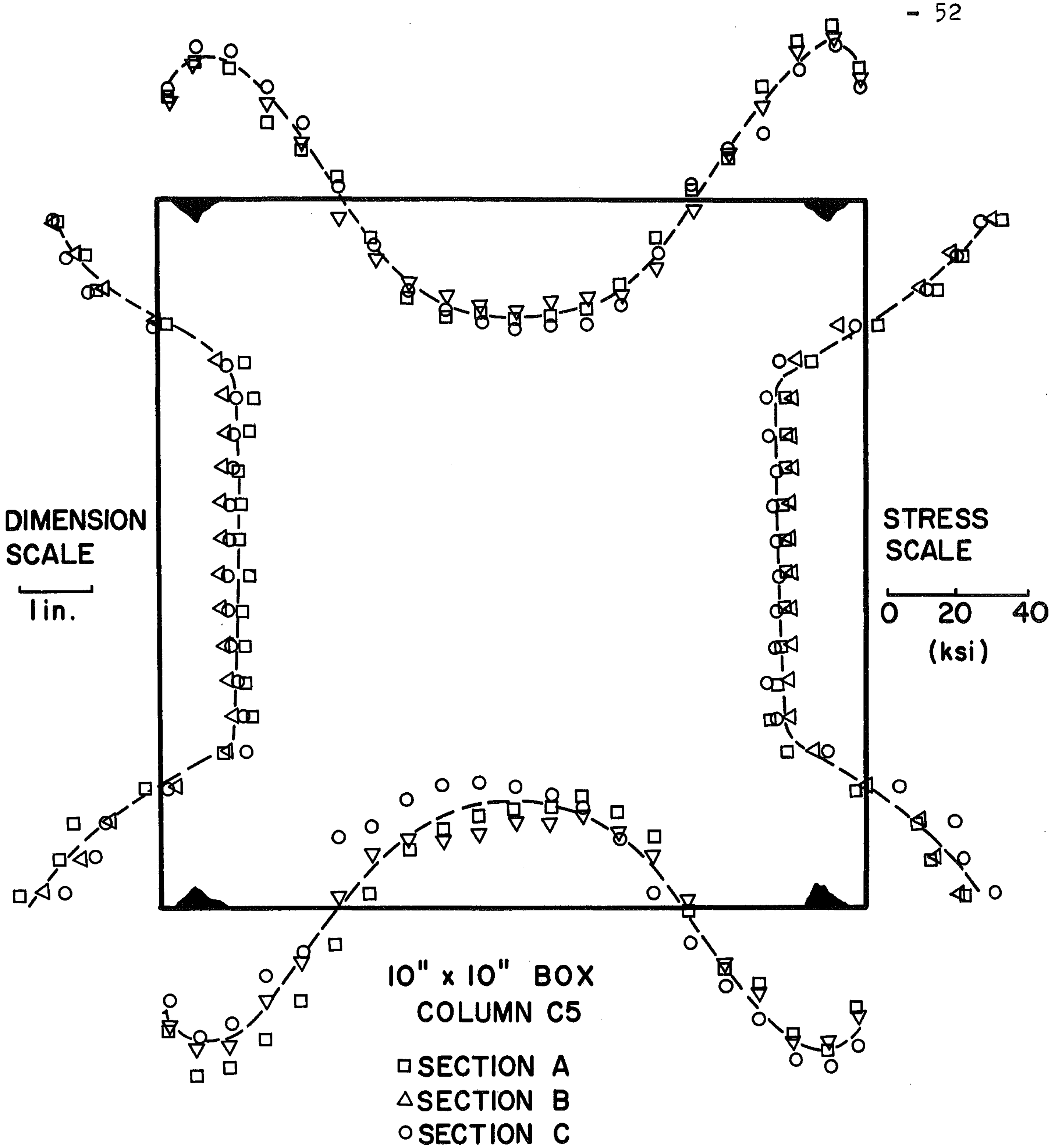


FIG. 19 EXPERIMENTAL RESIDUAL STRESS DISTRIBUTION

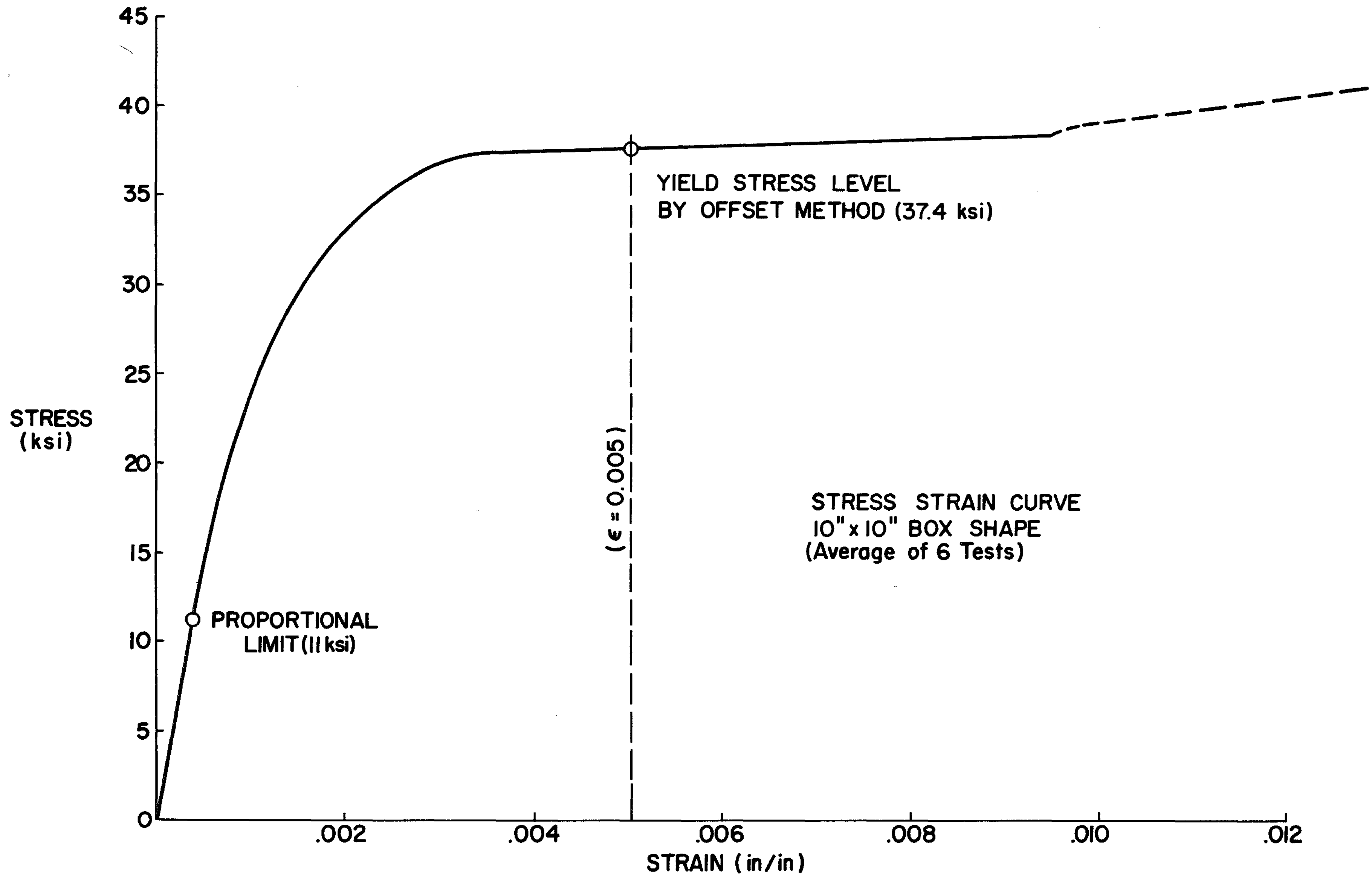


FIG. 20 EXPERIMENTAL RESULT OF STUB COLUMN TEST

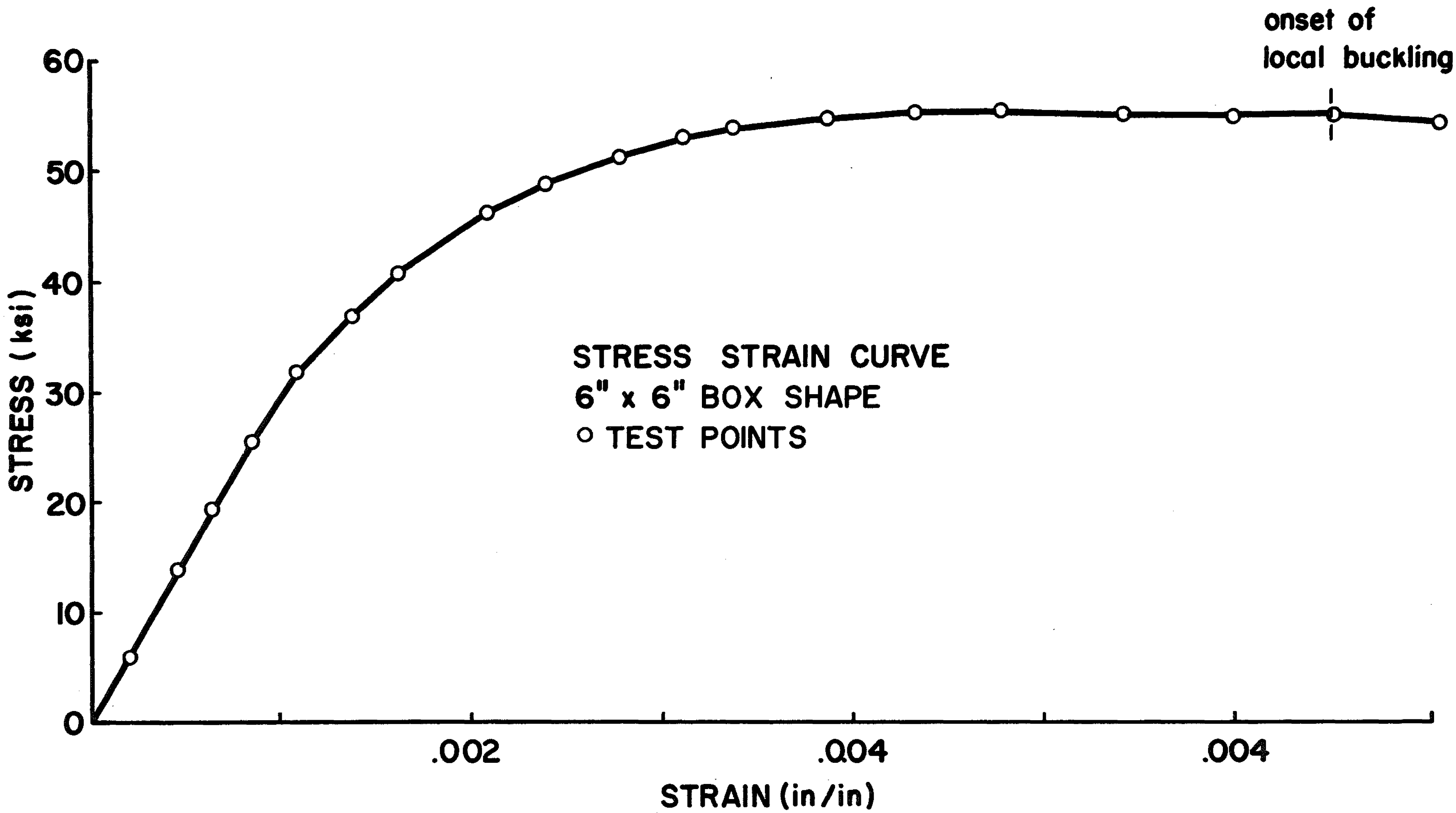


FIG. 21 EXPERIMENTAL RESULT OF STUB COLUMN TEST

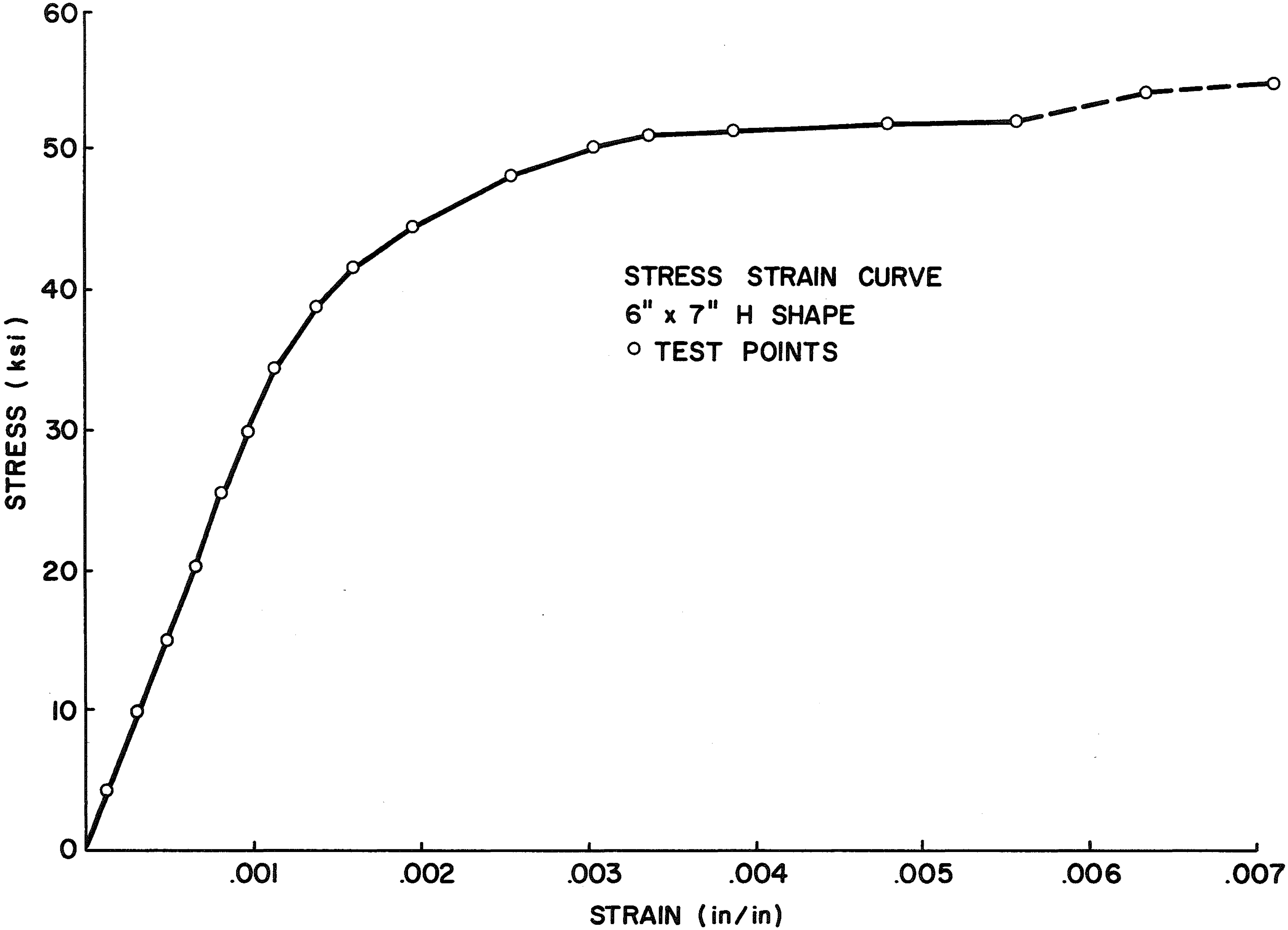


FIG. 22 EXPERIMENTAL RESULT OF STUB COLUMN TEST

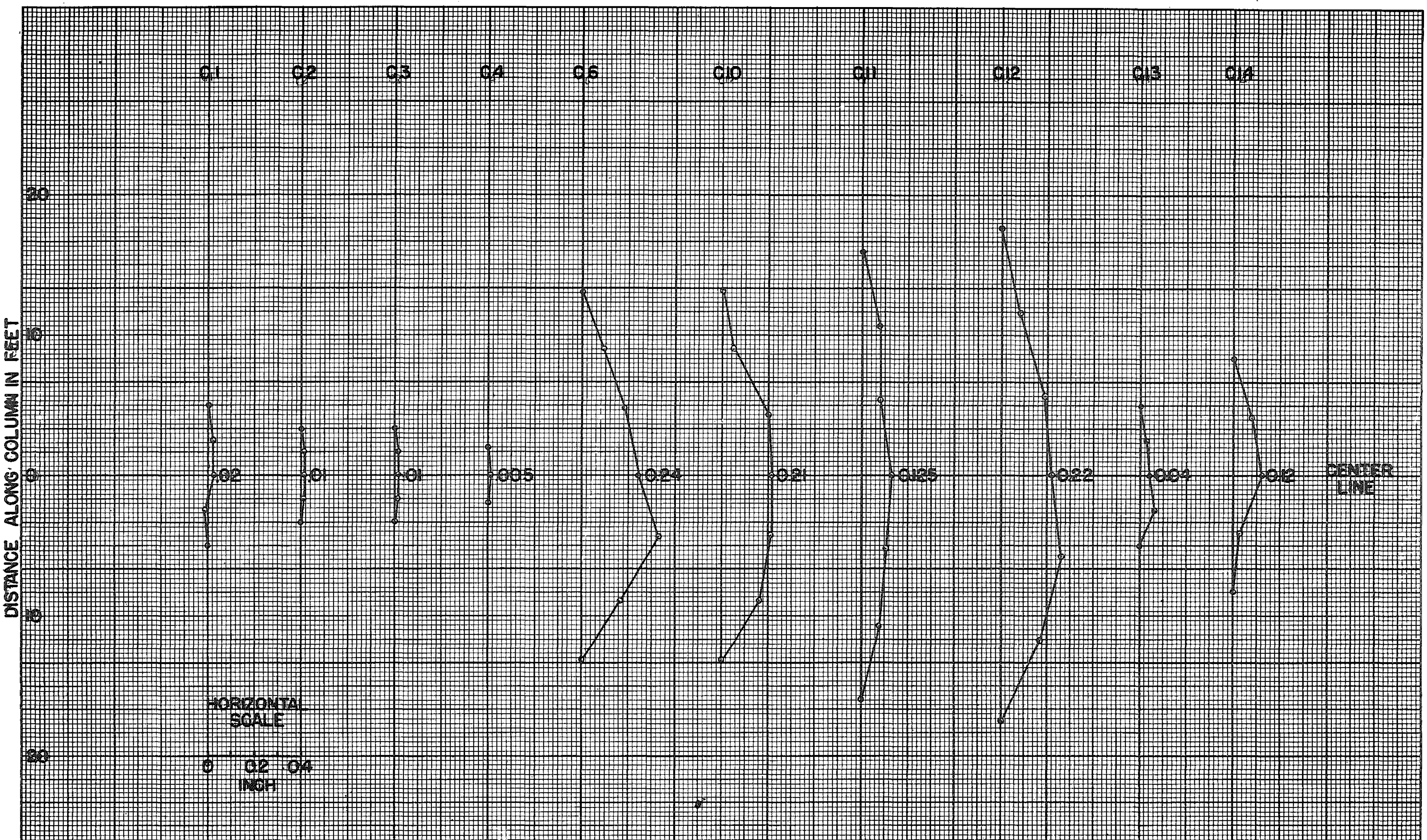
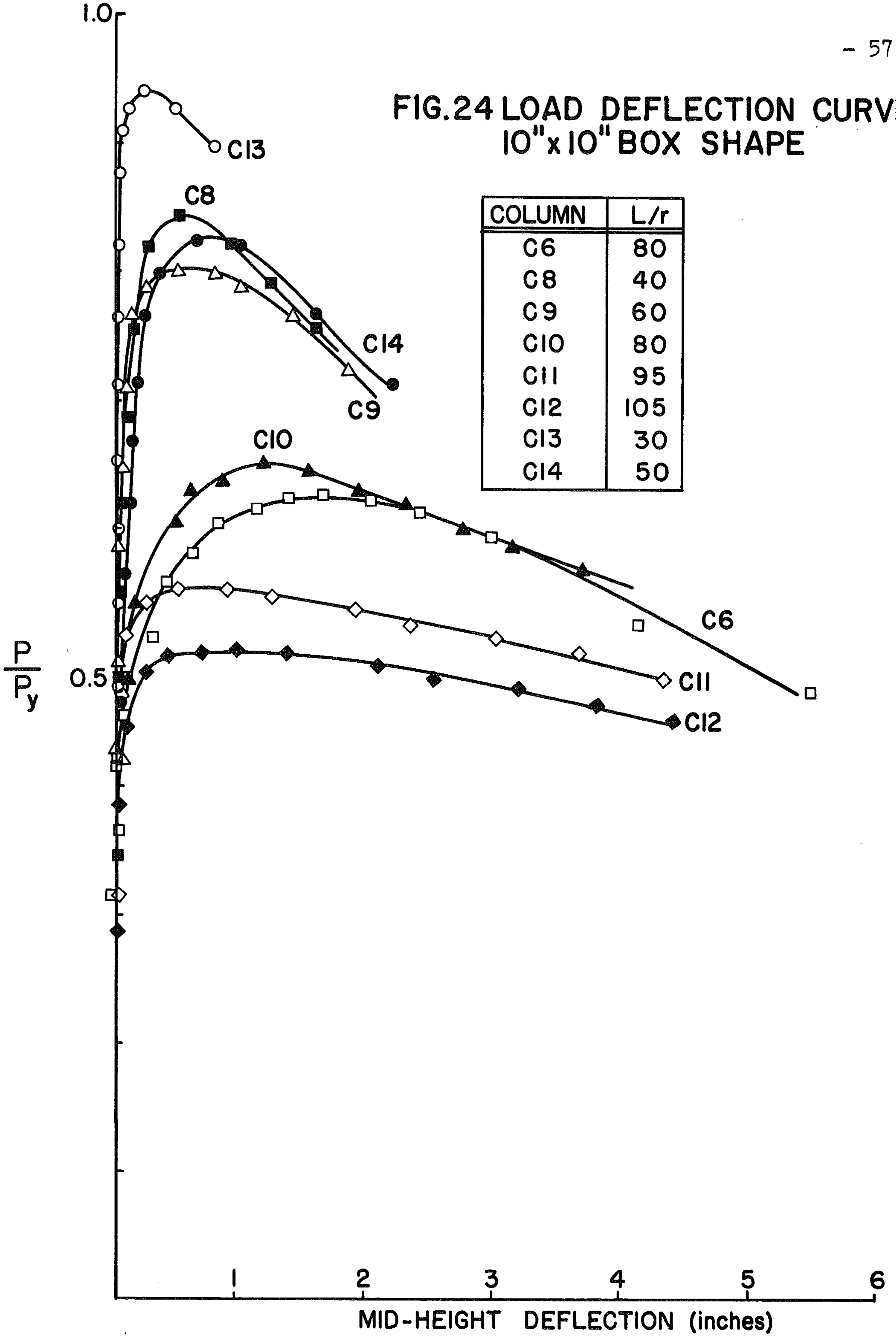


FIG 2.3 INITIAL OUT-OF-STRAIGHTNESS OF TEST COLUMNS

FIG.24 LOAD DEFLECTION CURVES 10"x10" BOX SHAPE



COLUMN	L/r
C6	80
C8	40
C9	60
C10	80
C11	95
C12	105
C13	30
C14	50

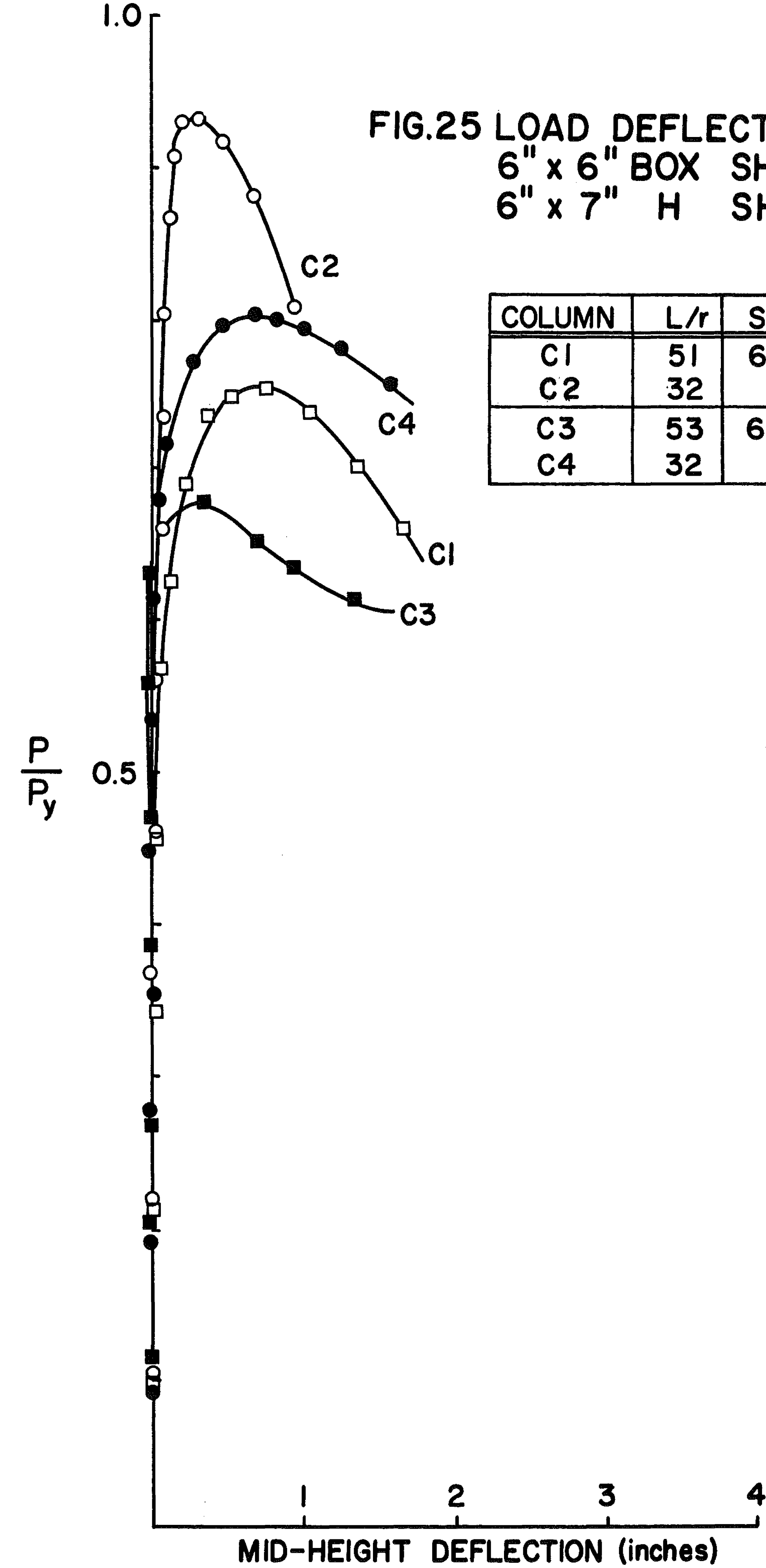


FIG.25 LOAD DEFLECTION CURVES
6" x 6" BOX SHAPE
6" x 7" H SHAPE

COLUMN	L/r	SHAPE
C1	51	6" x 6"
C2	32	Box
C3	53	6" x 7"
C4	32	H

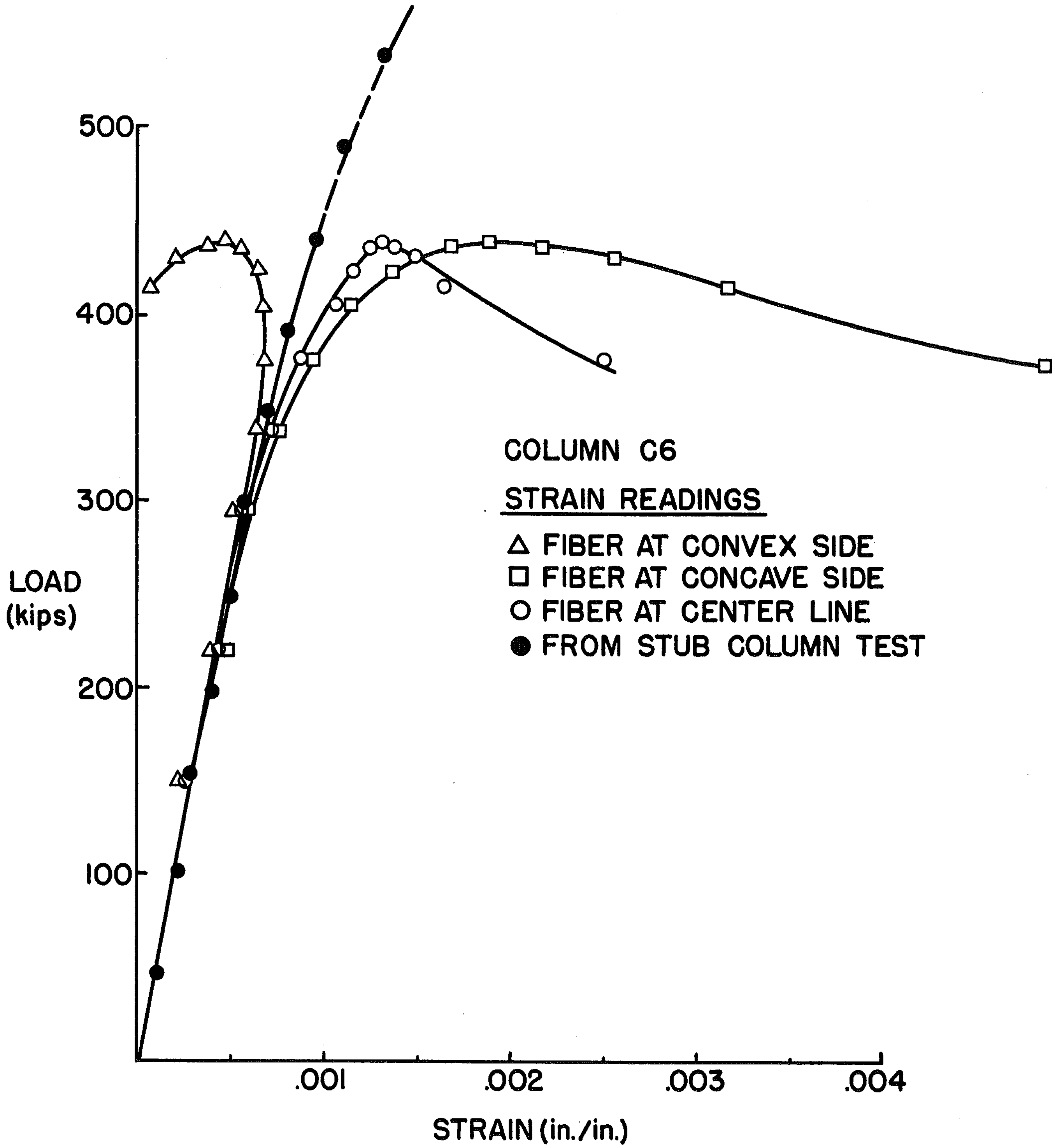


FIG. 26 FIBER STRAINS

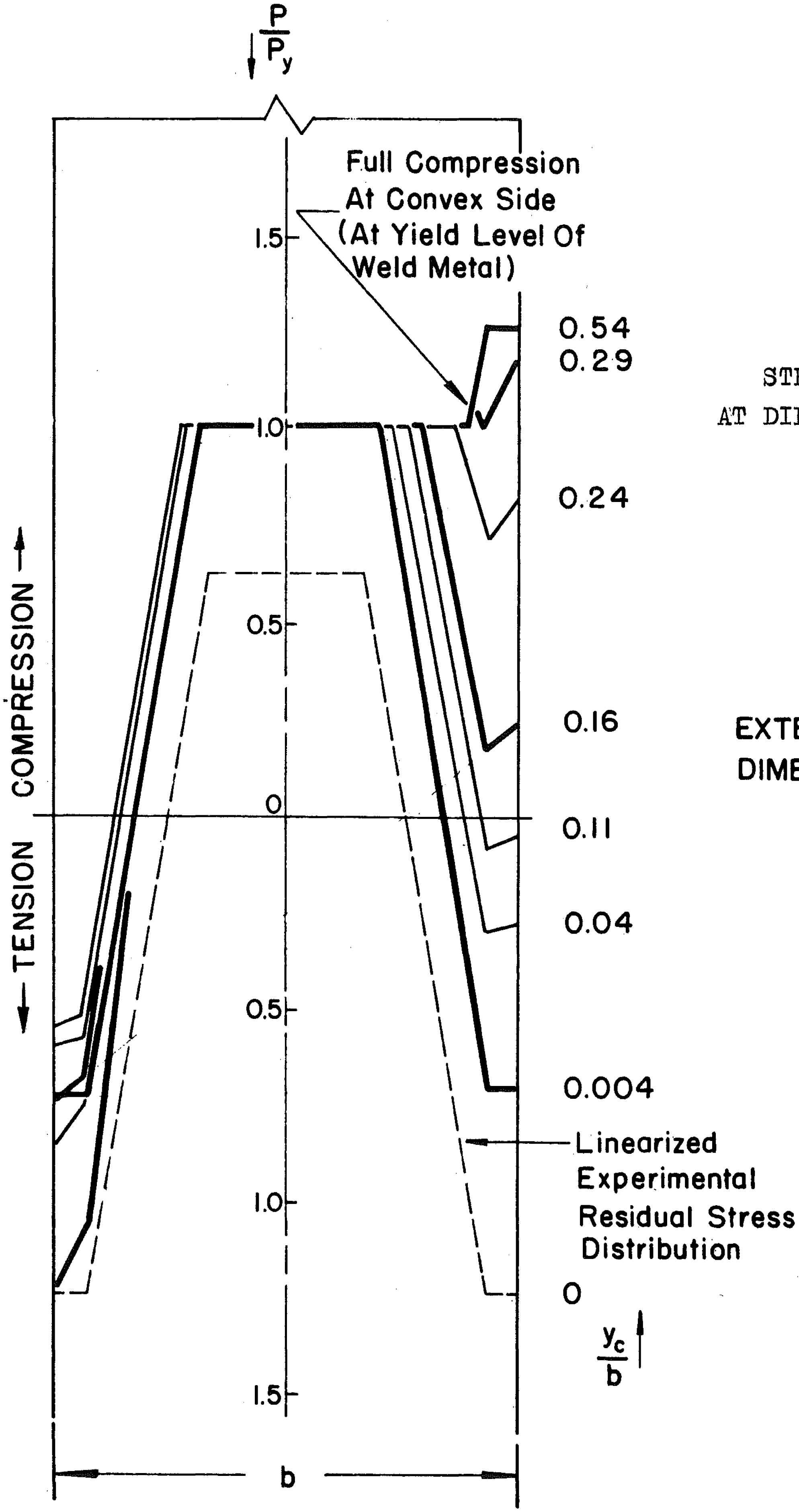


FIGURE 27

STRESS DISTRIBUTION

AT DIFFERENT LOAD LEVELS

$L/r = 80$

$e/b = 0.024$

$\frac{P_u}{P_y} = 0.63$

EXTERNAL DIMENSION : 10"x 10"

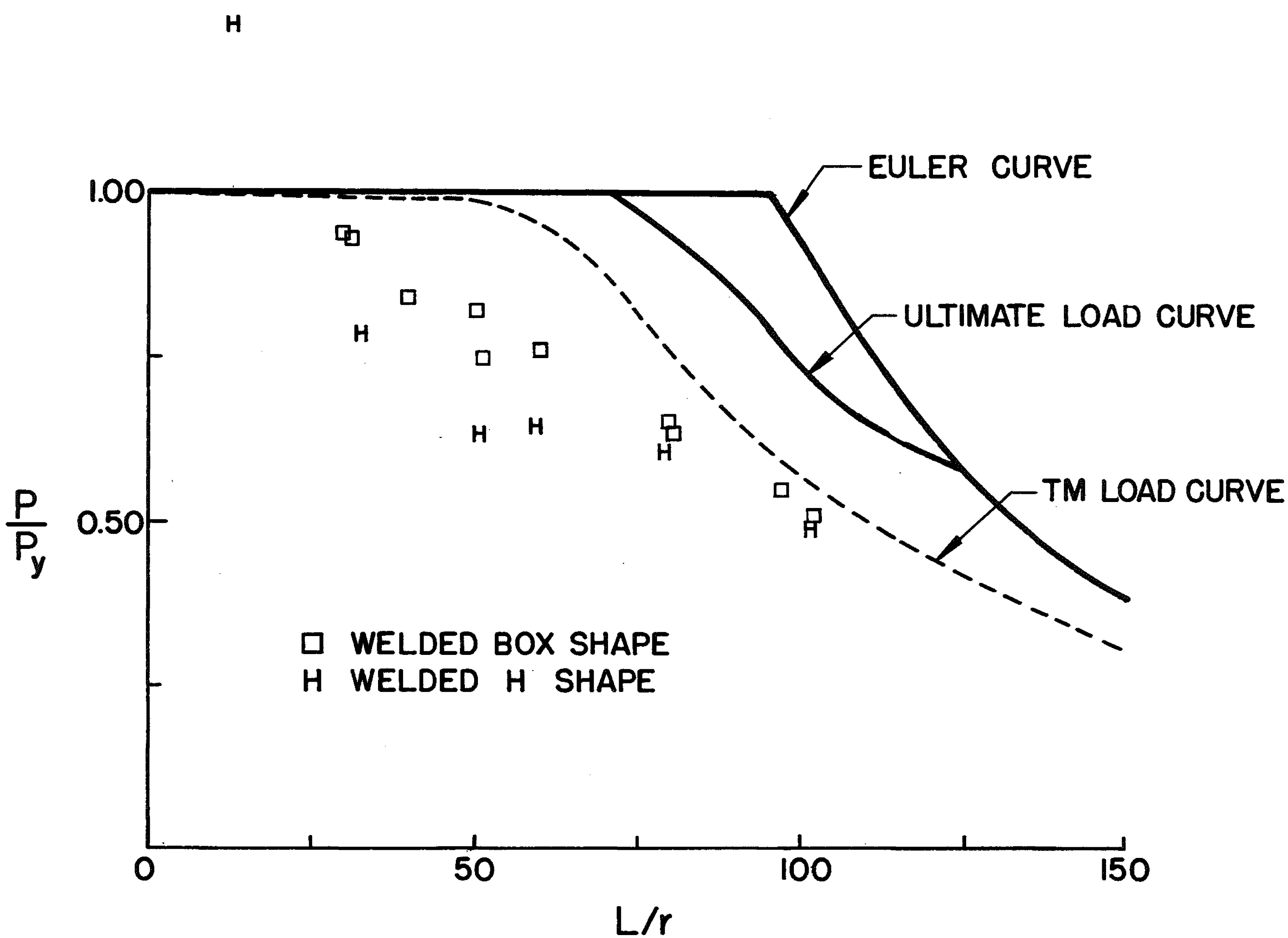


FIG. 28 STRENGTH OF WELDED BULT-UP COLUMNS

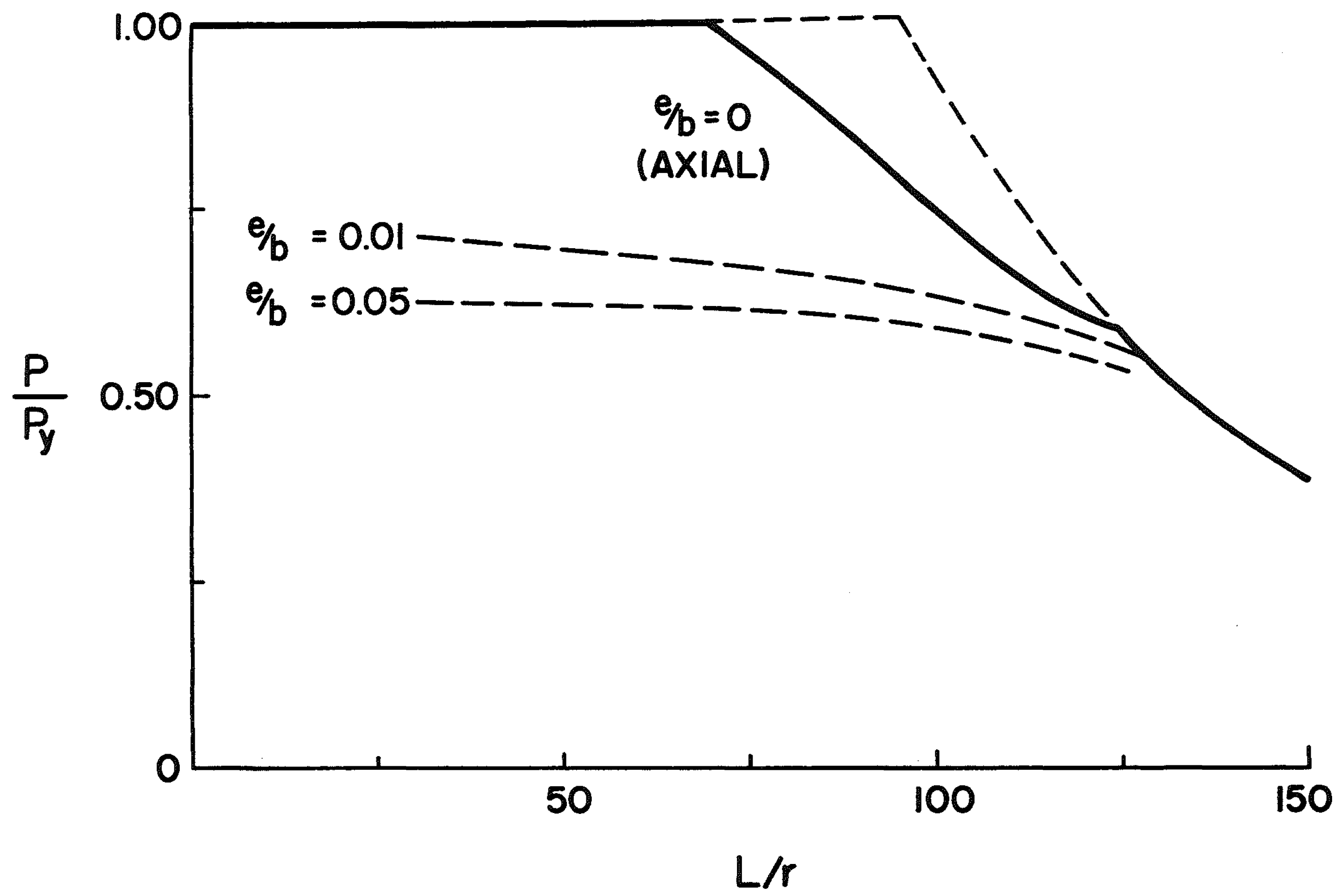


FIG. 29 ULTIMATE LOAD CURVES FOR A BOX COLUMN

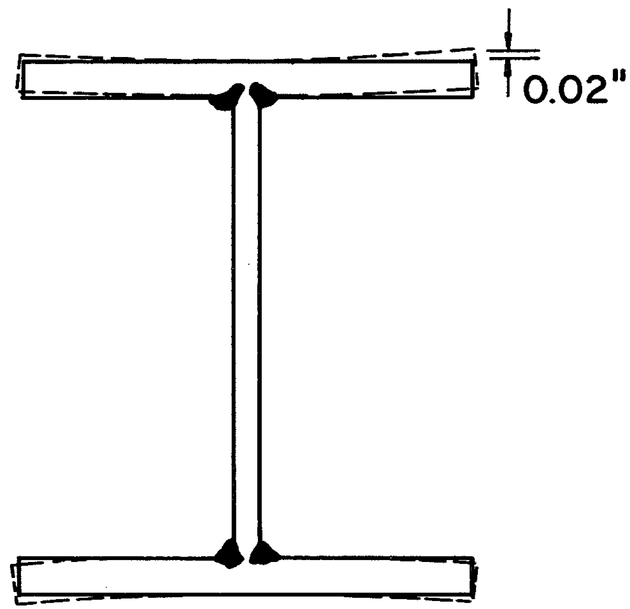


FIG. 30 DISTORTION OF H SHAPE

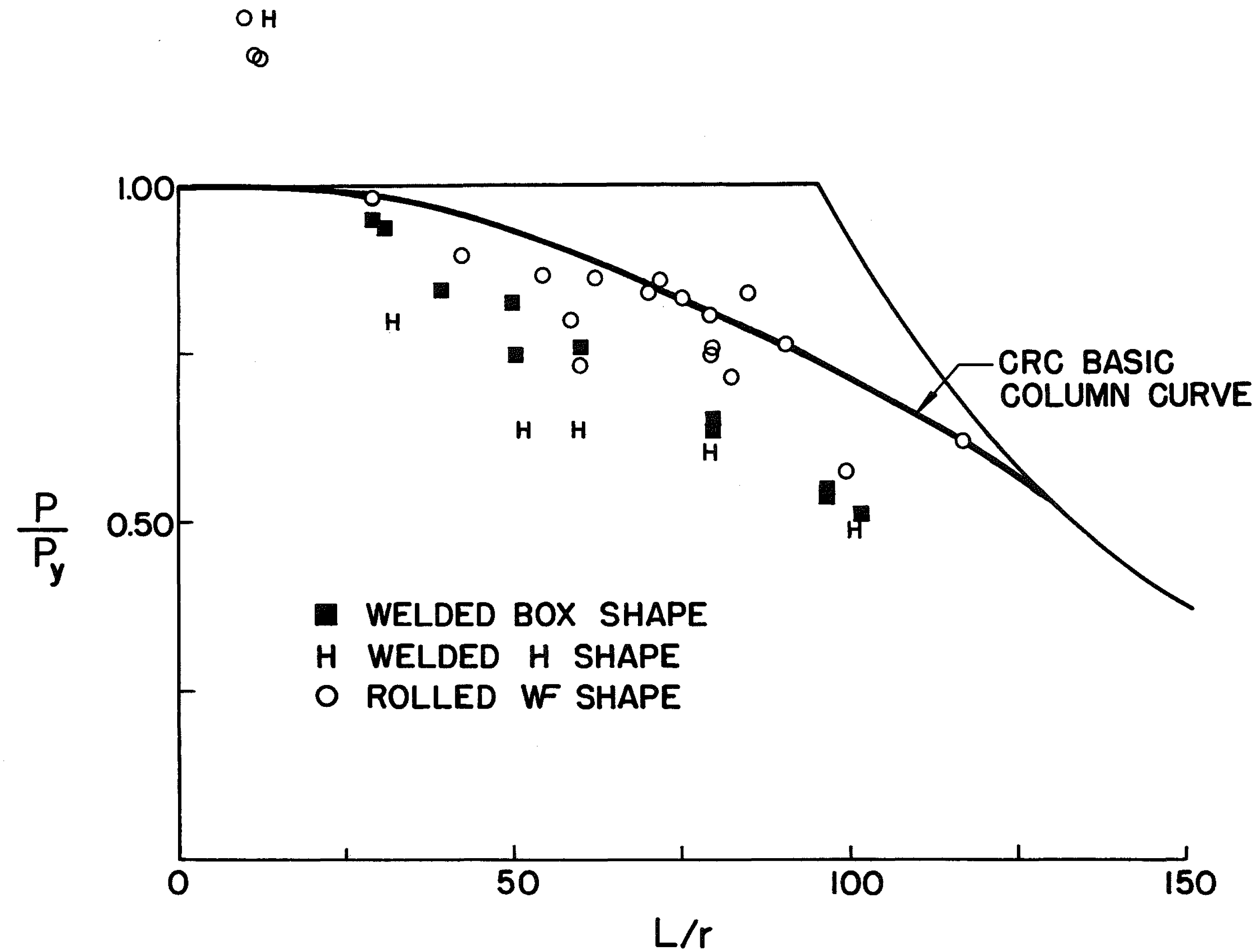


FIG. 31 WELDED COLUMNS AND THE CRC COLUMN CURVE

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