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OFFICE OF RESEARCH

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Fritz Engineering Laboratory Report
No. 290.9

Welded Built-Up and Rolled Heat-Treated T-1 Steel Columns

EXPERIMENTAL INVESTIGATION OF THE STRENGTH OF T-1 STEEL COLUMNS

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Fumio Nishino

Lambert Tall

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ABSTRACT

The results are presented of a study on columns of T-1 constructional alloy steel, (ASTM design A514/A517).

The tests conducted involved columns both rolled and heat-treated as well as built-up by welding from flame-cut and sheared-edge plates. Particular attention was given to the effect of residual stresses on the carrying capacity of centrally-loaded columns with medium size box- and H- cross sections. The strength of these columns is compared with the results obtained in similar studies of mild steel (ASTM A7) welded columns.

The results may be summarized:

1. there are tensile residual stresses in the area of the weld and flame-cut edge
2. compressive residual stresses are of a relatively small magnitude when compared to the yield point of the material
3. welded box-columns are stronger than welded H-columns bent about the weak axis
4. the strength of medium-size T-1 steel columns is closely represented by the CRC curve, which is the basis for the AISC design curve

5. the torsional properties may play a role in defining the strength of an H-column of T-1 steel
6. columns of T-1 steel are stronger than those of A7 steel, compared on a non-dimensionalized basis.

1. INTRODUCTION

The strength of centrally loaded steel columns has been studied extensively in the past decade. Both theoretical and experimental studies were carried out on a wide variety of rolled and welded built-up columns of structural carbon and low-alloy high-strength steels.[1 through 7] These studies have shown that the residual stress distribution inherent in the cross section plays a major role in determining the strength of steel columns.

With the continued developments in steel making, constructional alloy steels of ASTM designation A514/A517 steels have been introduced for structural use. These steels are heat-treated and the yield strength exceeds 100 ksi. With the increasing necessity of determining the strength of compression members made of constructional alloy steels, the authors measured residual stresses present in welded plates of "T-1" constructional alloy steel*[8] and studied theoretically the buckling strength of centrally loaded columns made of this steel.[9,10] The strength of centrally loaded columns is the most basic and the most fundamental study for compression members, and is the basis for the design of columns and beam-columns.

The investigation was concerned with the experimental study of the strength of centrally loaded columns of T-1 constructional alloy steel. Columns of welded built-up box and H-

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*"T-1" steel meets the requirement for ASTM A514/A517 steel.

shapes, and rolled H-shapes, of medium cross section were studied for various slenderness ratios.

Earlier studies have shown that the variables influencing the strength of centrally loaded steel columns are numerous. However, the major factors are as follows:[4,6,7]

(1) the static yield stress,

(2) the magnitude and distribution of residual stress,

(3) the unavoidable initial out-of-straightness,

which includes unsymmetrical residual stress distribution and eccentricity. The first two are factors characteristic to steels of different strength or made with different processes. The experiments were performed to minimize the effect of unavoidable initial out-of-straightness when possible so that the effect of residual stress is pronounced.

The purpose of this report is to describe the tests on rolled and welded built-up columns of T-1 steel and to discuss the results. Another report will describe the studies on beam-columns made of T-1 steel. These studies are part of a major investigation of "Welded Built-up and Rolled Heat-Treated "T-1" Columns," under way at Lehigh University.

2. PRELIMINARY TESTS

A number of preliminary tests were performed on the material prior to the column tests. The purpose of the tests was to determine the mechanical properties of the sections used in the column tests to predict the strength of the columns. These preliminary tests included tensile specimen tests to obtain the static yield stress, 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 stress and the yield loads of the sections tested.

2.1 Tension Specimen Tests

The main tool used in the determination of the mechanical properties was the tensile specimen test. ASTM specification and recommendations[11] for standard rectangular tensile test specimen with 1-1/2" width and 8 inch gage length were followed on all tests.

Table 1 summarizes the test program in detail. The tests were performed on a screw type machine and an automatically recorded load-strain curve was obtained. Three or four tensile specimens were tested from each fabricated piece in order to know the static yield stress of all component plates. Also, six small compression specimens were tested for comparison.

2.2 Residual Stress Measurements

The "method of sectioning"[12] was used to obtain the distribution of residual strains and consequently residual stresses; it is simple and gives the average strains within the gage length. A series of 10 inch gage holes were laid out on the specimen and were measured with a 1/10,000 inch Whittemore strain gage. The spacing of the gage holes were arranged to give more readings in regions of stress variation than in regions of constant stress. For instance, a large stress variation is expected near the weld and edges of the plates.

Figure 1 shows a typical layout for the sectioning process. The 11 inch section cut from the specimen is at a sufficient distance* from the ends so that a uniform state of stress existed in that portion where the residual strains were measured.

The strain readings were made on both faces of the component plates for the H-shapes, however, only the strains on the outside surface were read on the box shapes, since direct measurements of inside strains were not possible and since similar measurements on A7 welded box shapes,[13] where indirect measurements were made on the inside surface, showed only a slight variation in the magnitude of residual stresses measured on the outside face and on the inside face. Since the variation of residual stress along the length is expected to be small,[6,13]

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*The length of a specimen was at least twice the maximum dimension of the component plates plus 11 inches so that residual stresses were measured at least at a distance from the edge equal to the width of the widest plate composing the shape.

measurements were made at one convenient section along the length for each fabricated piece. The program of residual stress measurements is shown in Table 2.

2.3 Stub Column Tests

Prior to the testing of any column, a stub column was tested for each shape. The lengths of the stub column were chosen such that column instability could not occur (upper limit) and, at the same time, such that the end disturbances would not effect the distribution of residual stresses (lower limit). The stub column test gives a stress-strain curve showing the effect of residual stress. This stress-strain relationship can be correlated with the magnitude of the measured residual stress distribution, and with column strength.

All the stub column specimens were tested in a 5,000,000 lb. hydraulic type testing machine, except for the 6 x 6 box column which was tested in an 800,000 lb. screw type testing machine. The specimens were tested in the as-placed end condition with bearing plates at the top and at the bottom to obtain a uniform application of stress. The average strain was measured by two 1/10,000 inch dial gages mounted on frames at opposite sides of the columns over a 10" gage length at the mid-height. Another 1/10,000 inch dial gage was used to control the head movement of the hydraulic testing machine, which was necessary to obtain the static load-strain relationship because of unavoidable slight leakage of oil. Such a gage was not necessary in the screw type machine. In addition to the dial gages, four SR-4 strain gages were attached at the flange tips for the H-shaped columns and at the corners for the box columns, for column alignment. Figure 2 shows the instrumentation of a stub column.

After the milled-end specimen was centered in the testing machine, the alignment was made by adjusting a set of wedge-disks in the movable head of the hydraulic testing machine. For the test on the 6 x 6 box column, a set of wedge-disks were placed between the top bearing plate and the head of the screw-type machine. A load of approximately one half of the expected yield load was applied during the alignment, this was a load far below the estimate of the proportional limit based on the measured residual stress distribution. The alignment was checked and adjustments were made until the strains recorded by the four SR-4 gages showed a maximum deviation of 5% from the average readings at the maximum alignment load. No particular difficulty was experienced in alignment.

The loads were applied in appropriate increments until the proportional limit was reached. Above the proportional limit, the loadings were controlled by appropriate increments of average strains dictated by a continuously plotted load-strain curve of the test. After each increment, the loading was stopped and readings were taken after the whole system was static, or in a minimum of 20 minutes.

3. COLUMN TESTS

The test program is summarized in Table 2. It includes two rolled shapes and five welded shapes, with a total of 16 pinned-end column tests. In all cases the cross sections may be regarded as being small-to-medium in size. The shapes were identical to those of A7 steel previously studied, so that meaningful comparisons could be made. The slenderness ratios ranged from 30 to 60 so that test results would furnish points distributed throughout the transition part of the column curve between the Euler curve and the yield line.

The welded column specimens were fabricated from flame-cut T-1 steel plates; in addition to this, some column specimens were fabricated from sheared-edge plates so that comparison could be made between the behavior of columns of flame-cut plates and of sheared-edge plates. The welding was carried out according to normal practice. The joints were welded by automatic submerged-arc welding. In all cases, small tack welds were first deposited to fix the shapes. The fabrication was made by standard procedures. Figures 3, 4 and 5 show the process of flame cutting the edges, tack welding and welding of the joint.

3.1 Test Set-Up and Instrumentation

Among the 16 columns tested, eight were welded H-shapes, four were welded square box columns and four were rolled WF shapes.

The H-shapes were tested as shown in Table 3 either with pinned-end supports about the weak axis* and fixed-end supports about the strong axis* or vice versa. Because of the symmetry of the cross section, box-columns were tested with pinned-end supports in one of the principal axes and with fixed-end supports for the other. A set of plates, approximately two inches thick and milled flat, were welded at both ends of the column specimens and then the columns were placed in the end fixture. The end fixtures used were standard column fixtures developed in the laboratory.[(14)]

Preceding the set-up of specimen in a testing machine, the external dimensions of the column were measured and the initial out-of-straightness of the column with respect to its neutral axis was determined.

The instrumentation consisted of strip scales and a dial gage to measure lateral deflection, SR-4 gages to measure strain, and level bars to measure end rotation.

Lateral deflection was measured at the mid-height of the column with a fixed 1/1000 inch dial gage on the testing machine attached with taut thin wire to the specimen.

Strip scales were also attached to the column at quarter points or at sixth-points. The scales were read with a theodolite to obtain a measurement of lateral deflection along the length of

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*The weak axis, for the case of the H cross section, is one of the principal axes parallel to the web plate; the other axis is denoted as the strong axis.

the column. Sufficiently long scales, about 12 inches long, were used so that any large amount of instantaneous increase of lateral deflection by buckling could be read without re-adjustment. As a 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.

SR-4 strain gages were attached at three levels of the column; two levels at 6 to 10 inches from both ends and at mid-height. Four SR-4 gages were attached, at the four corners of the box column at all three levels, while four gages were attached at the outside faces of flange tips of H-columns at both ends, and eight gages attached at the mid-height. These are shown in Fig. 6 . The strain gage data gave an indication of strain distribution through the cross section and along the length of the column. This was used both for alignment and for testing.

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 and top plates of the column.

3.2 Alignment

The column was first carefully placed in the center of the testing machine. It was then loaded up to a load which was approximately one third of the expected failure load. The alignment was made by adjusting a set of wedges both at top and bottom end fixtures and by sliding the end plates based on readings from the four corner SR-4 gages at the ends and at the mid-height and the dial gage at mid-height for lateral movement. The first procedure was to attain an even strain distribution at these three levels where SR-4 gages were attached. A maximum deviation of less than 5% from the average value on any of the gage readings was the objective and was attained without any particular difficulty.

3.3 Test Procedure

After the alignment, the test was started with an initial load of about 5% to 10% of the expected failure load. During the tests, increments of load were chosen in the elastic range with the help of a point-by-point plot of the load-deflection curve and the load-strain diagram. After the load at which yielding penetrated into the column was reached, the increments of loading were controlled by increments of axial strain and, at the same time, careful observation was made for any significant increase of lateral deflection. The readings were taken in 20 minutes after the application of loading in order to stabilize the load and yielding.

Once the load-deflection relationship indicated a relatively sharp round off, the increments of loading were carefully controlled by the increase of lateral deflection so that the peak load of the column would be clearly observed on the load-deflection curve. A few additional points were plotted in the unloading stage past the ultimate load whenever these readings were possible.

The complete test preparation and procedure is described in detail in Ref. 15.

4. TEST RESULTS AND DISCUSSIONS

4.1 Preliminary Tests

A total of 30 standard tension specimens and 6 compression specimens were tested in a 120,000 lb. screw type testing machine. The test results are summarized in Table 1.

A typical stress-strain relationship is shown in Fig. 7 for a tension specimen test, which was recorded automatically. Other tests[16] have shown the existence of an inflection point in the diagram towards the limit of strains indicated in Fig. 7, that is, between 1% and 2% strain, and that a maximum strain-hardening modulus of about 250 ksi is reached at 2% to 3% strain.

The residual stress magnitude and distribution were measured for each shape. The distribution of compressive residual stress and the ratio of the magnitude of compressive residual stress to the static yield stress are important factors relating to the study of column strength. The results of measurements on two geometrically similar columns fabricated at different times showed very little difference. A typical example is shown in Fig. 8, which presents the results of measurements on a 10H61 shape from pieces D-1 and D-2. 6H27 shapes were fabricated from plates of two different edge preparations: two with flame cut plates and two with sheared edge plates. Figure 9 shows the difference in the residual stress distribution in 6H27 shapes due to this difference in edge preparation of the component plates. Figure 10 shows the residual stress distributions in the two welded box shapes. Only the residual stress distribution from the outside surface is shown for the box sections, while readings on both surfaces are shown for the H shapes. Residual stress measurements for the rolled 8WF31 shape are shown in Fig. 11.[17]

The residual stress pattern shows tensile residual stress at and in the vicinity of the weld metal for welded shapes and at the juncture of flange and web for the rolled, heat-treated shapes; and also at the flange tips in the case of H-shapes fabricated from flame-cut plates. Compressive residual stresses were distributed over the rest of the portion of the cross section. The 6H27 shape, whether made of flame-cut plates or of sheared plates, showed a similar stress pattern except at the flange tips, where the residual stress pattern of one face of a sheared edge is totally different from the other. This appears to be a characteristic pattern resulting from the shearing of the edges.[8] The tensile residual stresses at the weld metal and heat-affected zone varied from 40 ksi to as high as the yield strength of the material,* while the tensile residual stresses at the flame-cut flange tips were somewhat smaller in magnitude with the heat-affected zone smaller than that at the weld metal. Compressive residual stresses covered a relatively large portion of the

*The yield strength of weld metal was not measured but it is around 90 ksi.[8]

cross section of welded shapes with a rather uniform distribution and values not exceeding 25 ksi in any case except at a few localized points. The magnitudes of residual stress in rolled heat-treated shapes were usually less than 5 ksi.(17)

The compressive residual stresses in the 6H27 shape with flame-cut plates had an average value of 20 to 22 ksi extending over wide portions of both the flanges and the web, while those in the same shape with sheared-edge plates showed a distribution over a similar portion of the cross section but with a varying intensity of a relatively smaller magnitude.

The average value of the compressive residual stresses in the 10H61 was the smallest among the welded shapes and was around 10 ksi.

Since welding was made with the L70 electrode, the yield strength of weld metal, which is a combination of electrode and parent metal, can be expected to be slightly less than that of the parent metal. The smaller magnitude of tensile residual stress at the weld metal compared to that nearby as seen in patterns of box shapes, can be understood with the above in mind. The 6" x 6" box shape showed a relatively uniform distribution of compressive residual stress over 80% of the total width of the component plates varying from 24 to 28 ksi. In the larger box shape, the 10" x 10" box shape, the pattern was similar to that of the smaller box shape with a small magnitude of compressive residual stress distributed over a wider portion of the component plates.

As far as the magnitude of tensile residual stress at the weld metal and its neighboring area is concerned, no particular difference was observed among the shapes of various geometry.

However, the shapes with narrower component plates showed comparatively large compressive residual stresses. This is clearly seen on comparing the patterns for the 6H27 and 10H61 shapes and the patterns for the 6" x 6" and 10" x 10" box shapes in Figs. 8, 9, and 10. Since the distribution of the tensile residual stress around the weld metal is independent of shape, the distribution of compressive residual stress must depend on geometry in order to give equilibrium of residual stresses.

A study of residual stresses in welded A7 shapes, and applicable to A36 steel, was made at Lehigh University.[6, 13] It is of interest to compare the results of this study with those of the study on A7 steel since the shapes are of identical geometry. Figure 12 shows the residual stresses in the A7 steel welded shapes, where the 6H27 shape was fabricated with sheared edge plates and the plots of results is based on the average reading of both surfaces. The general pattern of the residual stress is similar for both A7 and A514 steels. However, for the A514 steels the magnitude is slightly more in compressive residual stress and one half to two thirds more in tensile residual stress when compared to A7 steel. The compressive residual stress covers a slightly narrower portion of the plates in A7 shapes.

Although the value of the compressive residual stress is slightly higher and it covers a wider portion of the section in A514 shapes, nevertheless, it is a much smaller fraction of the yield strength. The effect of residual stress on the carrying capacity of A514 columns will be less pronounced as compared to the effect on columns of A7 and A36 steels, on a non-dimensional basis.

The stub column tests were carried out to obtain the yield load of the cross sections. Table 4 summarizes the results Figure 13 shows typical load-strain relationships for the 6H27 shapes, STWA and STWB. The linear part of the relationship is more than 2/3 of the yield load for A514 steel, which shows that for identical shapes of A7 steel is less than 1/3.[6]

4.2 Column Tests

The results of the column tests are summarized in Table 3. The data given in the table include the slenderness ratio, the initial out-of-straightness, and the column strength. The maximum deviation of the center line of a column from a straight line ranged from a minimum eccentricity ratio, e_{max}/L of 0.0001 to a maximum of 0.001 for column DWZ. It is noted that all these columns are within the tolerance limit of 0.001 as specified by AISC.[18] Figure 14 shows the variation of the initial out-of-straightness along the length of the columns.

The load versus mid-height deflection curves are shown in Figs. 15, 16, and 17. The horizontal arrow in the curves shows that the column failed instantaneously at that point after the -oading was stopped; the distance shown beside the arrow indicated the mid-height deflection after this failure. The test curves show very small deflection for lower loads indicating good alignment. It is noted that, in all cross sections tested, the mid-height deflection of shorter columns increased gradually with the increase of the load reaching the maximum load and then kept increasing with decreasing load. To the contrary, however, the longer columns showed an abrupt increase of the deflection at the maximum load. When the maximum load was applied, the mid-height deflection of the columns started to increase gradually, kept increasing for a couple of seconds to as long as one minute, then the deflection jumped instantaneously as much as fifty to a hundred times the previous total deflection with a corresponding sharp decrease of the load. Figure 18 shows column AWI at 99 percent of the maximum load and the column after the abrupt failure at the maximum load; a significant change of configuration is noted. Actually all of the columns with slenderness ratios of more than 50 failed instantaneously, whereas columns with a slenderness ratio of less than 45 failed gradually.

All of the box columns and H columns tested on weak axis bending failed as intended. However, for the two 6H27 columns, AW3 and BW3, tested under pinned-end conditions about the strong axis and fixed for weak axis bending and twisting, both bending about the strong axis and twisting were observed at the maximum load. Figure 20 shows one of the columns at failure.

The method of computing the buckling strength of centrally loaded columns is presented in Refs. 9 and 10, and considers the effect of residual stress. The theoretical column buckling strengths were computed for the 6H27 columns based on the measured residual stress patterns with a slight idealization such that the equilibrium* of the residual stress and geometrical symmetry** of the distribution are satisfied.

Figure 20 shows the tangent modulus buckling strengths in the form of non-dimensionalized column curves for 6H27 columns made both of plates with sheared edges and with flame-cut edges. The solid lines are for strong axis bending, and the broken lines are for weak axis bending. The predictions for the columns with flame-cut plates are shown with the thick lines; the thin lines are for the columns with sheared edge plates. Also shown in the figure are the test results for these columns.

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*Because of an out-of-equilibrium of measured residual stress, a slight adjustment was necessary.

**Since simultaneous welding of the cross section was not employed, the distribution of residual stress was not perfectly symmetric about the geometrical axis.

On the transition curve between the Euler curve and the yield line, it is expected that a tangent modulus curve predicts higher failure loads for a longer column and lower loads for a shorter column.[9] The tendency is more pronounced for columns with compressive residual stresses uniformly distributed over a wide portion of a cross section, as are the cases for these test columns. The test results for weak axis bending in Fig. 20, where the two longer columns show points below the predictions, and the two shorter columns above the predictions, may be explained on this basis. Two test results for the strong axis bending give results below the predictions, although the slenderness ratios are the smallest among the test columns. The discrepancy is due to the torsional property of the test columns. Torsional buckling may have played a role in the failure of these two columns as seen in Fig. 19.

Figure 21 shows the relationship of the tangent modulus column curves for the strong axis bending and for torsional failure on test columns and the column test results of AW3 and BW3. The figure is plotted for non-dimensionalized stress against length of test columns, of which the end conditions are simply supported for strong axis bending and fixed for twist. The flexure failure is dominant for longer columns, while the torsional failure governs for shorter columns. Both flexural and torsional strengths are so close to each other for this length of test columns, 88 inches long, that both buckling modes may have played a role in the failure as can be seen in Fig. 19.

The strength of columns fabricated from flame-cut plates and from sheared plates may be different as can be seen from the column curves in Fig. 20; however the tests have been made on such column lengths for which the difference is not significant, so that no particular difference was observed in the test results.

In Fig. 20, it is more important to compare the test results obtained on T-1 columns with those on A7 columns. Also shown in Fig. 20 are the results of similar tests on the identical shape of A7 columns,[6] which makes possible a direct comparison of the welded H-columns of T-1 and A7 steel. It is clearly seen that T-1 columns are stronger than A7 columns, when they are compared on a non-dimensionalized basis.

All of the test results are plotted in Fig. 22 together with the CRC Basic Column Curve[19] and with the test results of similar A7 columns of the same geometry.[6]

Figure 23 compares the strength of the rolled heat-treated T-1 shapes with those of rolled shapes of A7 steel.

The box columns of T-1 steel are stronger than the welded H columns of T-1 steel forced to buckle about the weak axis. An H column forced to buckle about the strong axis should, theoretically, behave in a manner similar to the box column, provided the column fails by bending. The two H columns tested on the strong axis, as shown with triangles in Fig. 22, are considerably weaker than the test results of box columns. The discrepancy is due to the torsional property of the cross section and the yield strength of the steel; the column has failed by torsional buckling as pointed out previously. The fact that thw two H columns carried significantly less loads than the box columns and that twisting was observed at the failure suggests the importance of consideration of torsional properties for the column design of open cross sections. This is true for any higher strength steel. The theoretical results of the buckling analysis are shown in Fig. 24 for an 8WF31 shape with idealized residual stresses of the welding type as shown in the same figure.[10] The figure indicates that a relatively short 8WF31 column may fail torsionally if it is only buckling about the weak axis that is prevented.

The results of the box column and rolled shape tests are slightly above the CRC Curve, while the results of welded H columns buckled about the weak axis are slightly below the CRC curve. Nevertheless, it can be concluded that the experimental results fit the CRC curve well.

Comparison of the test results for T-1 columns and those for A7 columns in Figs. 22 and 24 shows that T-1 columns are stronger than A7 columns when they are compared on a non-dimensionalized basis. This can be best explained by the difference in the ratios of the average magnitude of compressive residual stress distributed over a wide portion of the column cross section and the yield strength. Theoretical analysis of column buckling considering the effect of residual stress predicts this difference in strengths between T-1 and A7 columns.[10,20]

5. SUMMARY AND CONCLUSIONS

The report presents the results of a study on columns of T-1 constructional alloy steel. The tests conducted in this study involved columns both rolled and heat-treated and built-up by welding from flame-cut and sheared edge plates. Particular attention was given to the effect of residual stress on the carrying capacity of centrally loaded T-1 columns with medium size box and H cross sections. The strength of T-1 columns was compared with the results obtained in similar studies of A7 welded columns.

The experimental investigation of this report is summarized as follows:

1. Tension and compression specimen tests were conducted on the component plates of test specimens.

2. The residual stress present in welded built-up columns of T-1 constructional alloy steel were measured in four medium size cross sections made of flame-cut plates; two box sections and two H sections and on one H section made of sheared edge plates. Residual stresses were measured in a number of rolled shapes, including the two reported on here.

5. Welded box columns are stronger than welded H-columns bent on the weak axis.

6. For an H column of T-1 steel, the torsional properties of the section may play a role in the failure.

7. T-1 columns are stronger than A7 columns compared on a non-dimensionalized basis.

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7. TABLES AND FIGURES

TABLE 1 RESULTS OF TENSILE COUPON TESTS

Cross Section	Piece No.	Coupon No.	Location	Yield Strength σ_y (ksi)	Average σ_y*	Ultimate Strength σ_u (ksi)	Average σ_u*
6H27 (With Sheared Plates)	A-1	AW1	F	110.0		122.0	
		AW2	F	108.1	108.7	120.6	121.8
		AW3	W	108.0		122.8	
	A-2	AW5	F	107.1	107.1	120.6	120.6
6H27	B-1	BW1	F	106.4		119.8	
		BW2	F	105.6	106.2	119.7	119.6
		BW3	W	106.6		119.4	
	B-2	BW4	F	105.4		119.9	
		BW5	F	103.4	105.1	119.7	119.7
		BW6	W	106.4		119.4	
10H61	C-1	CW1	F	106.2	105.7	119.3	119.3
		CW2	W	105.2		119.3	
10H61		C5 Cut From		110			
		C6 3/4" PL's		122			
		C7 before		121			
		C8 welding		122			
6" x 6" Box	D-1	DW1		117.0		129.6	
		DW2		117.9		129.2	
		DW3		118.8	117.7	129.5	129.3
		DW4		117.0		129.0	
10"x10" Box	E-1	EW1		106.8		120.6	
		EW2		106.4		119.6	
		EW3		106.8	106.2	120.6	120.1
		EW4		104.8		118.9	
	E-2	EW5		103.7	103.7	116.9	116.9

*Direct average (not weighted)

TABLE 1 RESULTS OF TENSILE COUPON TESTS - CONTINUED

Cross Section	Piece No.	Coupon No.	Location	Yield Strength σ_y (ksi)	Yield Strength Average σ_y*	Ultimate Strength σ_u (ksi)	Ultimate Strength Average σ_u*
Welded Box 10"x10"	E1	C1	Cut from 1/2" PL's before welding	108			
		C2		110			
		C3		110	109		
		C4		110			
8WF31	T-R-B	TRB1	F	115.0		121.7	
		TRB2	W	111.0		121.5	
		TRB3	F	113.9		126.2	
		TRB4	F	113.3	112.8	122.3	122.5
		TRB5	W	110.4		119.8	
		TRB6	F	112.2		123.5	
12WF120	T-R-F	TRF1	F	105.4		116.4	
		TRF2	W	87.5	93.2	105.2	109.3
		TRF6	F	86.7		106.4	

*Direct average (<u>not</u> weighted)

TABLE 2 SUMMARY OF TEST PROGRAM

Cross Section	Piece No.	Length (ft.)	Col.No.	Specimen
6H27	A-1	20	AW1 STWA	7'4" column 2' stub column a set of residual stress three tensile coupons
2,6"x1/2" 5-1/2"x3/8" (Sheared Plates)				
	A-2	20	AW2 AW3	5'7" column 7'4" column a set of residual stress three tensile coupons
6H27	B-1	20	BW1 STWB	7'4" column 2' stub column a set of residual stress three tensile coupons
2,6"x1/2" 5-1/2"x3/8"				
	B-2	20	BW2 BW3	5'7" column 7'4" column a set of residual stress three tensile coupons
10H61	C-1	20	CW1	10'4" column a set of residual stress three tensile coupons, two compression coupons
2,9"x3/4" 9" x 1/2"	C-2	20	CW2 STWC	6'7" column 3'4" stub column a set of residual stress three tensile coupons

TABLE 2 SUMMARY OF TEST PROGRAM - CONTINUED

Cross Section	Piece No.	Length (ft.)	Col. No.	Specimen
6"x6" box	D-1	20	DW1 STWD	7'11" column 2'1" stub column a set of residual stress four tensile coupons
2,6"x1/4" 2,5-1/2"x1/4"				
	D-2	20	DW2	12'0" column a set of residual stress four tensile coupons
10"x10" box	E-1	20	EW1 STWE	9'7" column 3'4" stub column a set of residual stress four tensile coupons, four compressive coupons
2,10"x1/2" 2,9"x1/2"				
	E-2	20	EW2	16'3" column a set of residual stress four tensile coupons
8WF31	T-R-B	40	STB RB1 RB2	10'0" column 6'8" column 2'10"stub column 2 sets of residual stress three tensile coupons
12WF120	T-R-F	36	RF1 RF2 STF	7'10" column 13'0" column 4'0" stub column 2 sets of residual stress three tensile coupons

TABLE 3 RESULTS OF COLUMN TESTS

Cross Section	Test No.	Bending Axis	Slenderness Ratio	Out-of-Straightness e_{max}/L 10^{-3}	P_{max} (kips)	P/Py	Remarks
6H27	AW1	Weak Axis	60	0.2	605	0.66	Instantaneous Failure
	AW2	Weak Axis	45	0.1	750	0.82	
(Sheared Plates)	AW3	Strong Axis	30	0.2	761	0.83	Both bending on strong axis and twisting at the failure
6H27	BW1	Weak Axis	60	0.1	626	0.69	Instantaneous Failure
	BW2	Weak Axis	45	0.2	729	0.80	
	BW3	Strong Axis	30	0.2	764	0.84	Both bending on strong axis and twisting at the failure
10H61	CW1	Weak Axis	55	0.3	1655	0.79	Instantaneous Failure
	CW2	Weak Axis	35	0.4	1902	0.90	
6"x6" Box	DW1	One of Principal Axes	40	0.7	576	0.91	
	DW2	One of Principal Axes	60	1.0	460	0.69	Instantaneous Failure, Crack in the Weld at the Failure
10"x10"Box	EW1	One of Principal Axes	30	0.1	1897	0.94	
	EW2	One of Principal Axes	50	0.5	1773	0.87	Instantaneous Failure
8WF31	RB2	Weak Axis	40		966	0.92	
	RB1	Weak Axis	60		810	0.77	
12WF120	RF1	Weak Axis	30		3230	0.89	
	RF2	Weak Axis	50	0.2	2960	0.82	Instantaneous Failure

TABLE 4 STUB COLUMN TEST RESULTS

Cross Section*	Test No.	Area (in^2)	Yield Load** (kips)	Yield Stress (ksi)
6H27(s)	STWA	8.83	918	104
6H27	STWB	8.74	908	104
10H61	STWC	19.0	2110	111
6" x 6" box	STWD	6.17	669	107
10" x 10" box	STWE	19.7	2035	103
8WF31	STB	9.18	1016	111
12WF120	STF	35.3	3510	99.4

*All the shapes were fabricated with flame-cut plates except 6H27(S) shape which was fabricated with sheared plates.

**Yield loads were determined at an average compressive strain of 0.005 in./in.

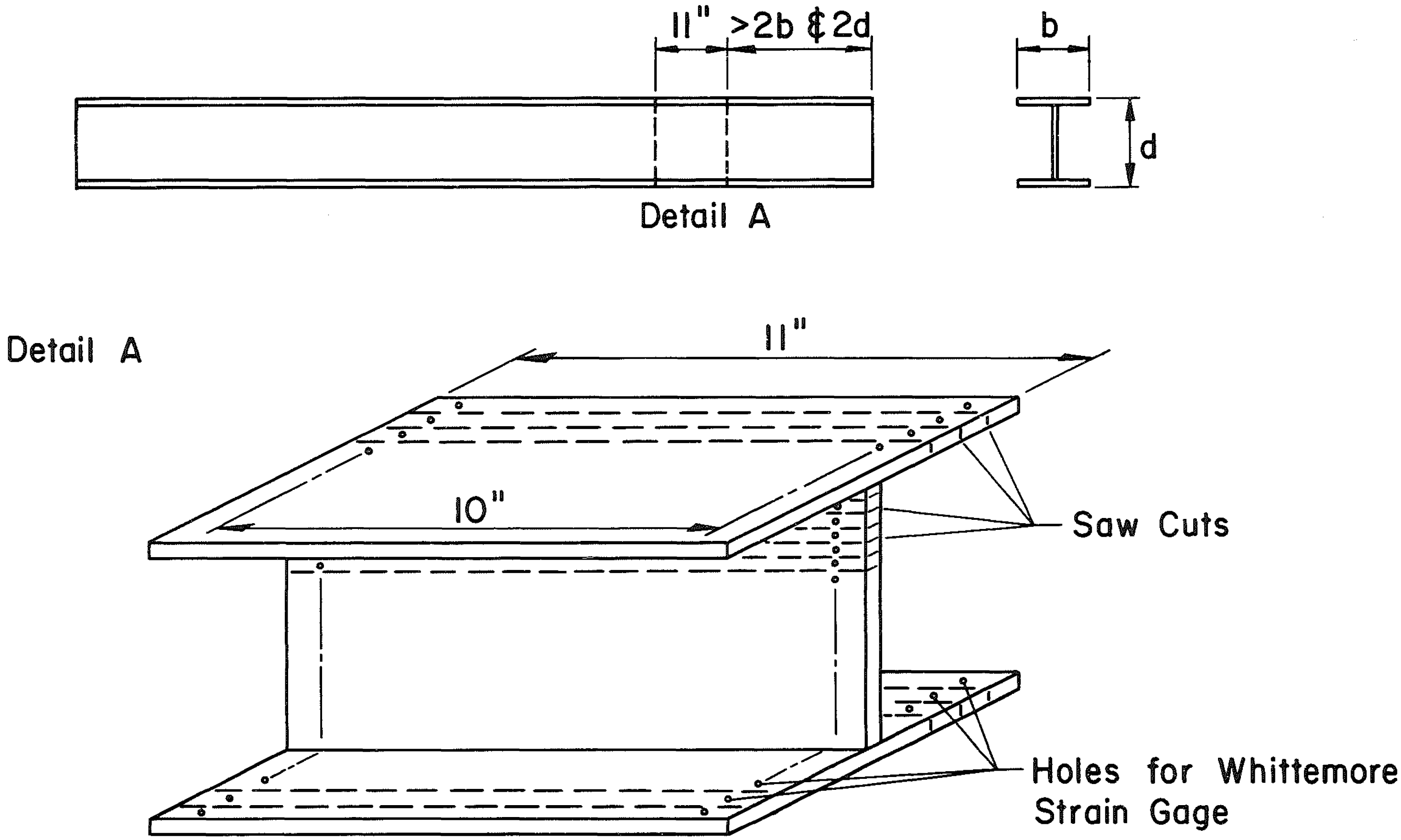


Fig. 1 Layout for Residual Stress Measurement

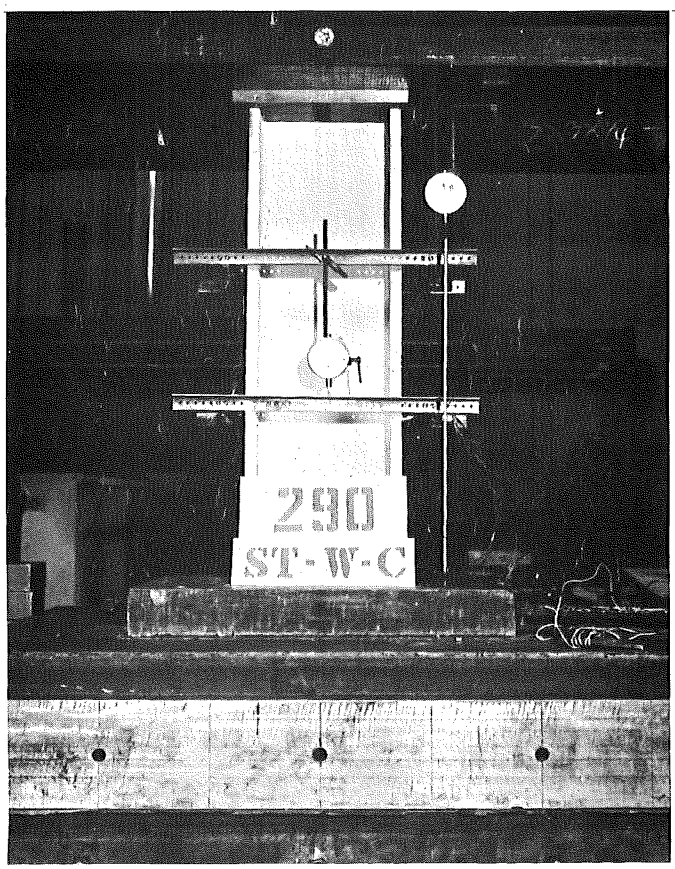


Fig. 2 Instrumentation of Stub Column Test

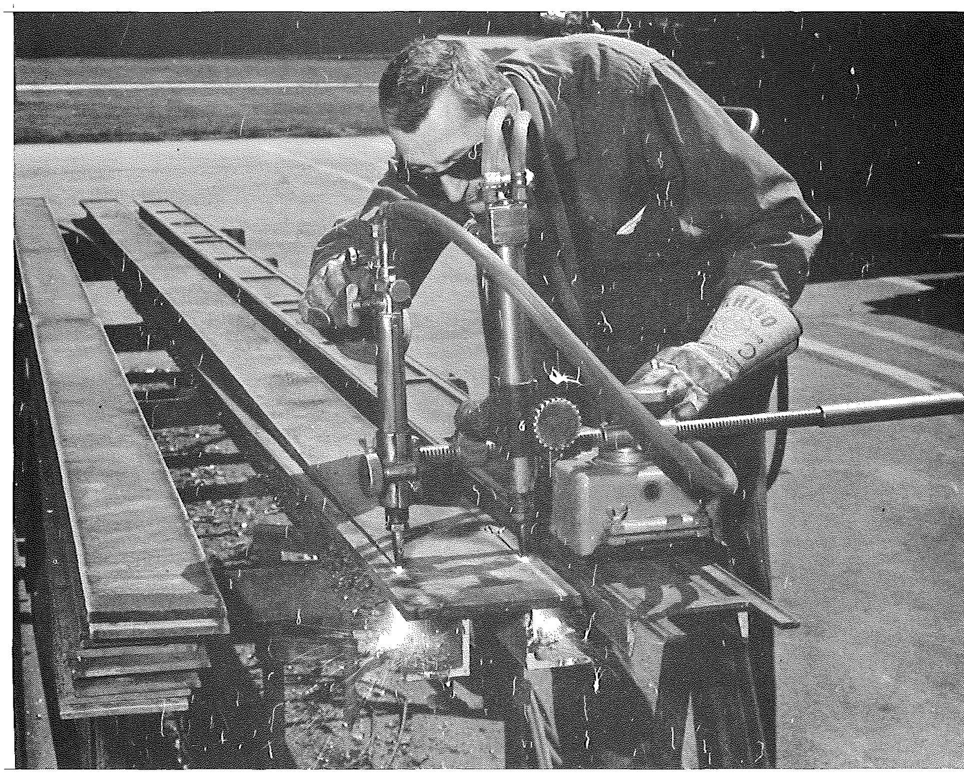


Fig. 3 Flame Cutting of Edges

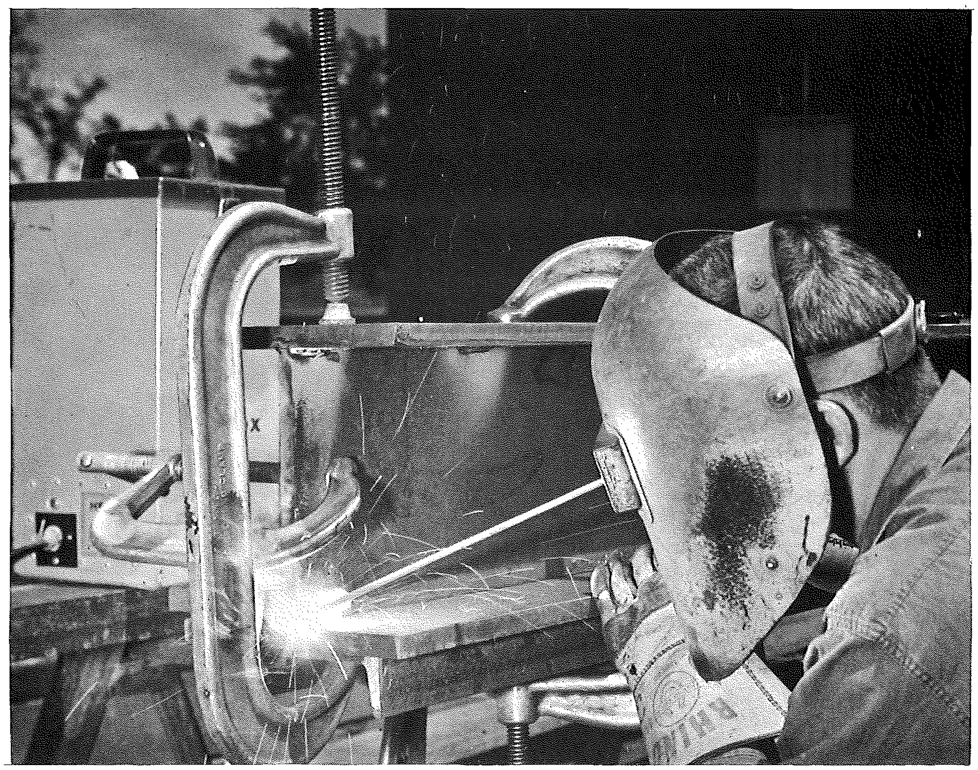


Fig. 4 Tack Welding of a Specimen

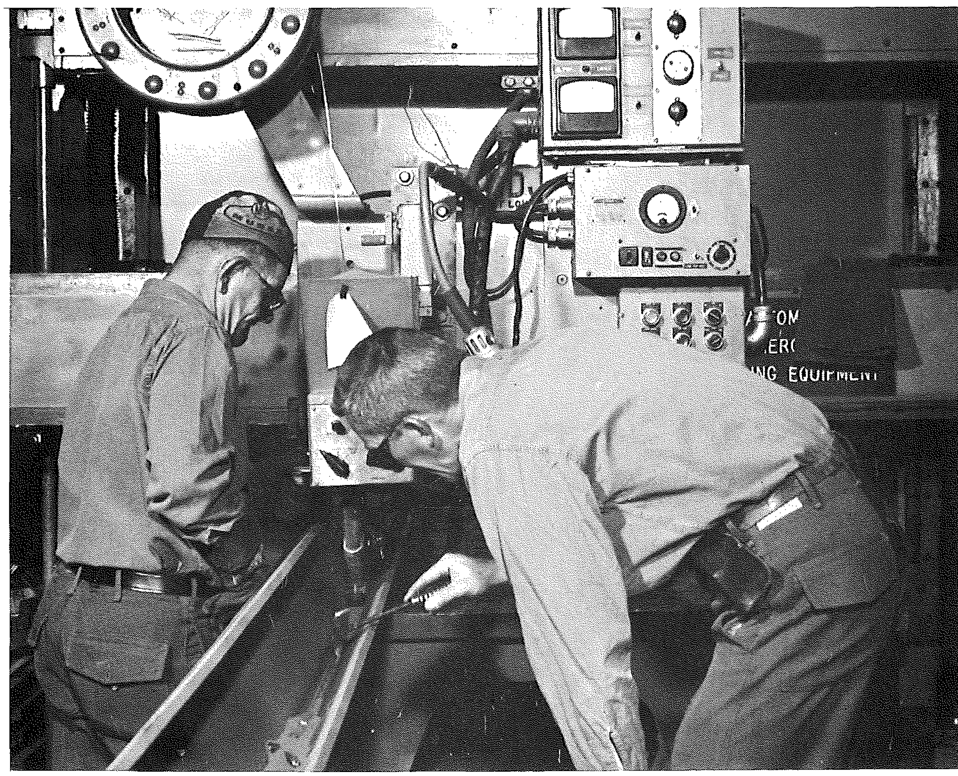


Fig. 5 Welding of a Specimen

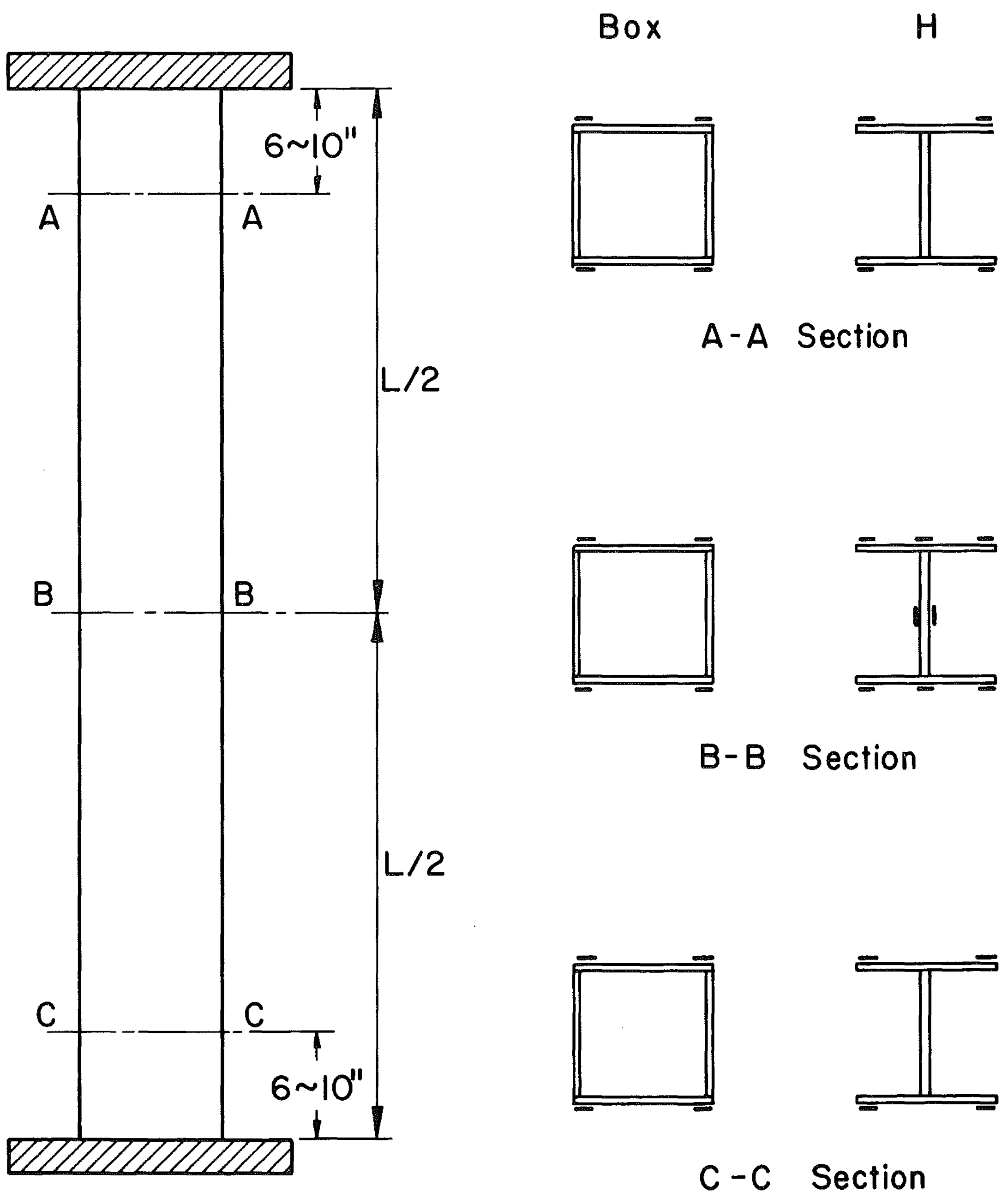


Fig. 6 Location of SR-4 Gages

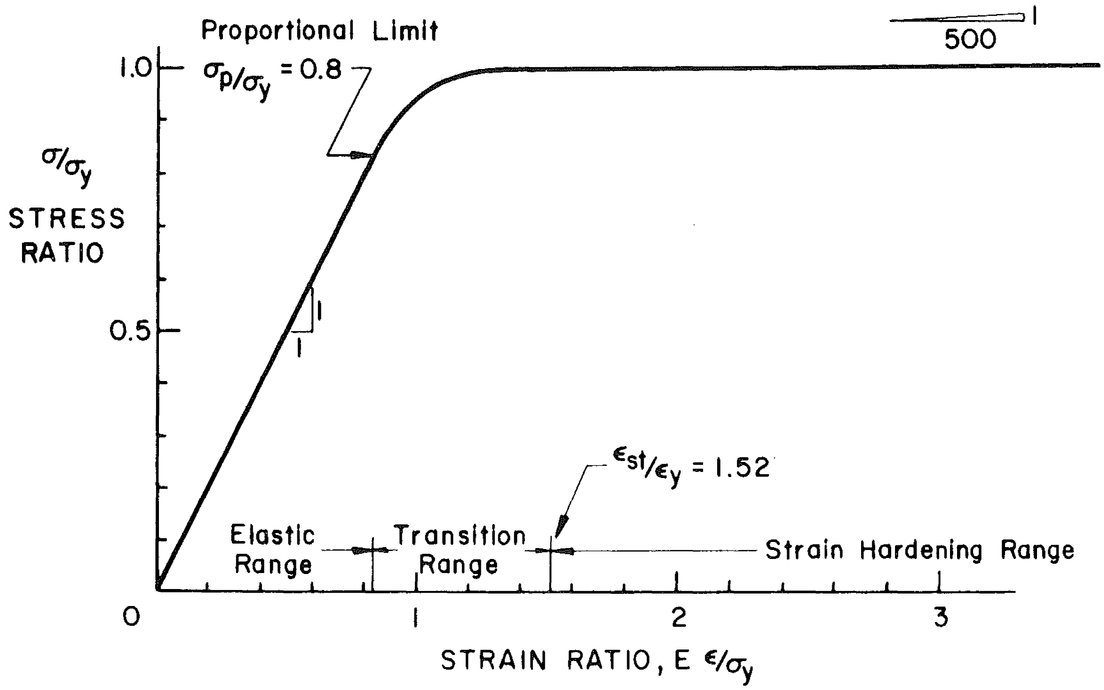


Fig. 7 Typical Stress-Strain Relationship for A514 Steel Obtained from Tension Specimen Test

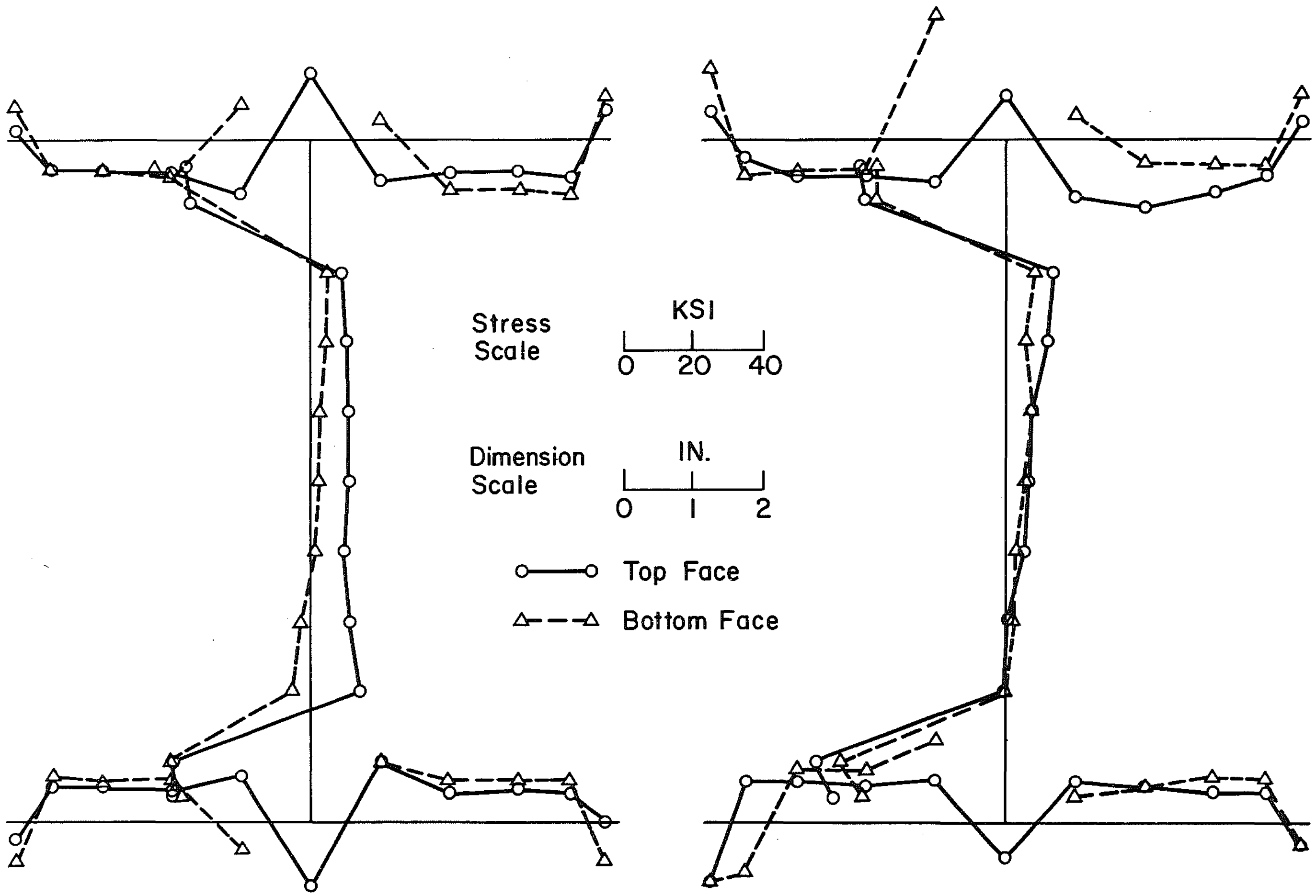


Fig. 8 Residual Stress Distribution in Two 10H61 Shapes

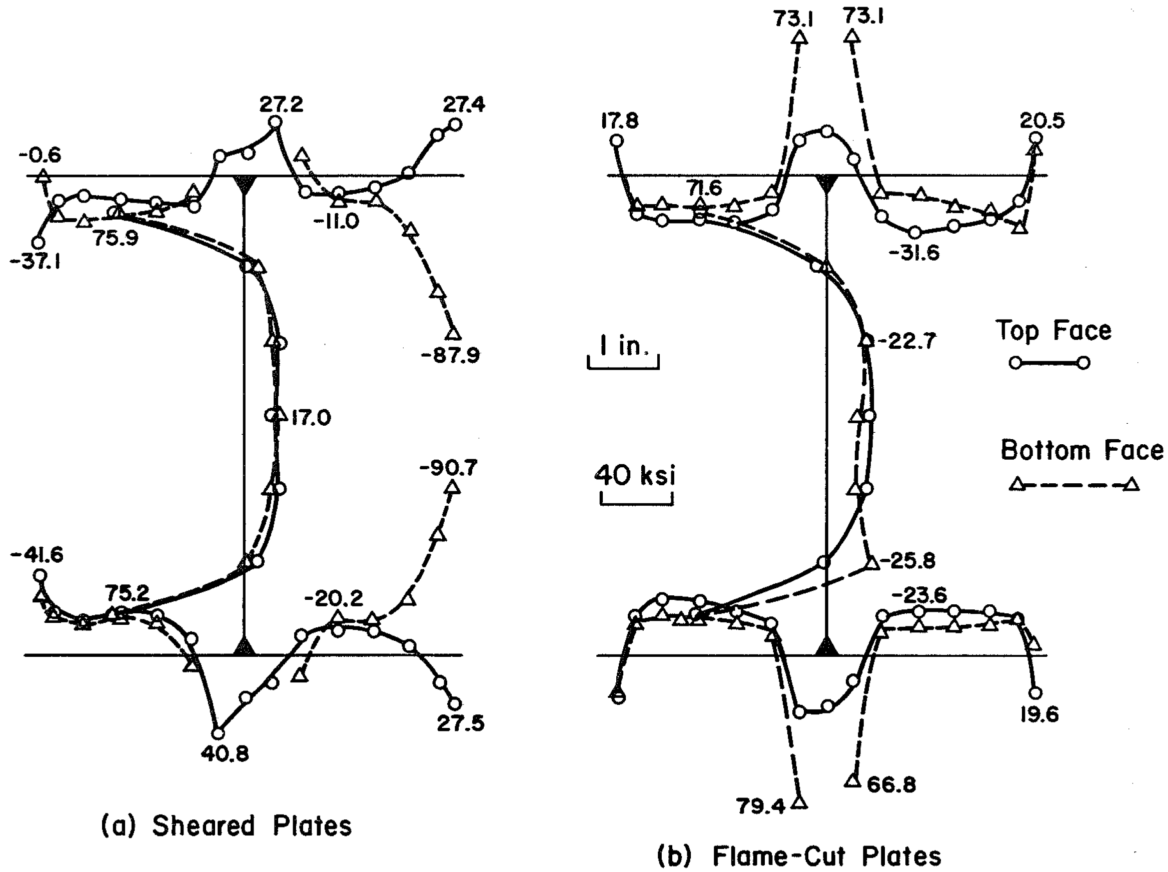


Fig. 9 Residual Stress Distribution in 6H27 Shapes

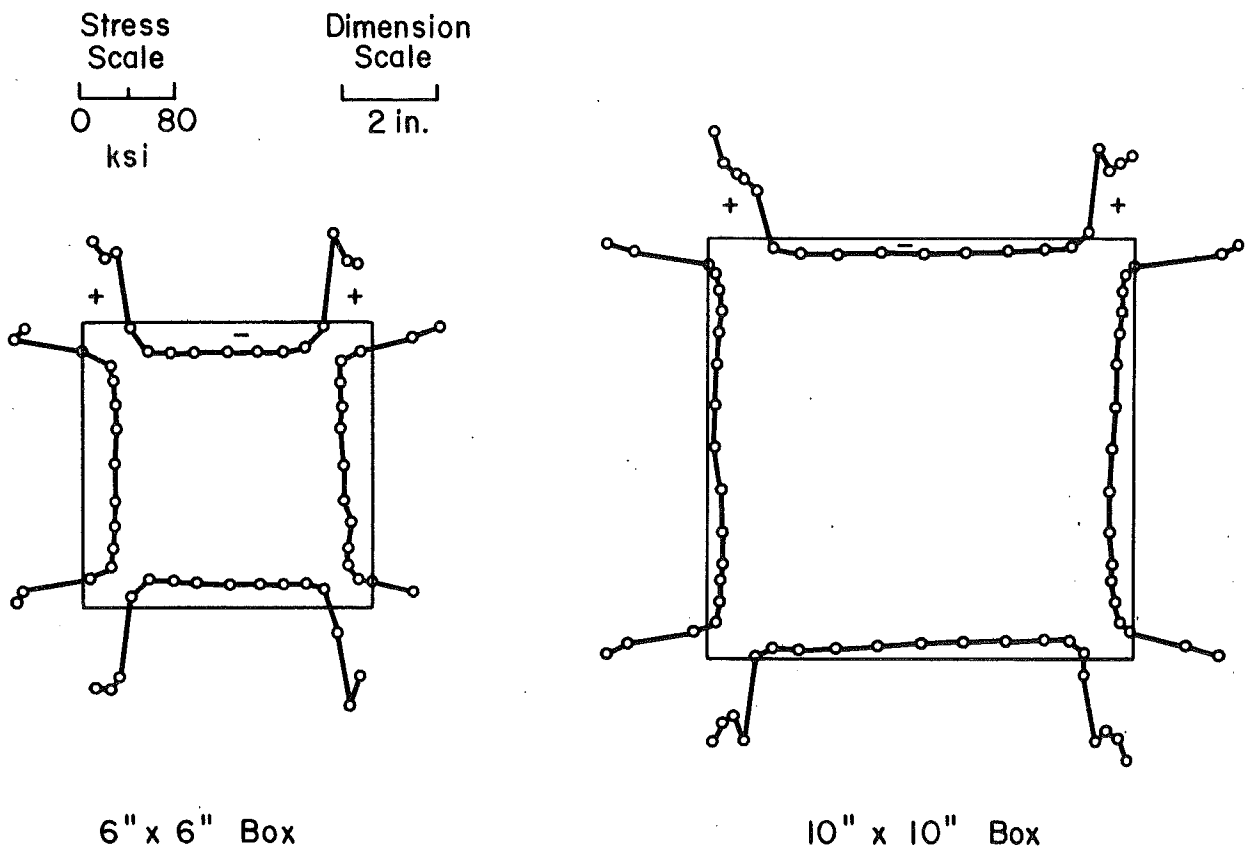


Fig. 10 Residual Stresses in Box Shapes

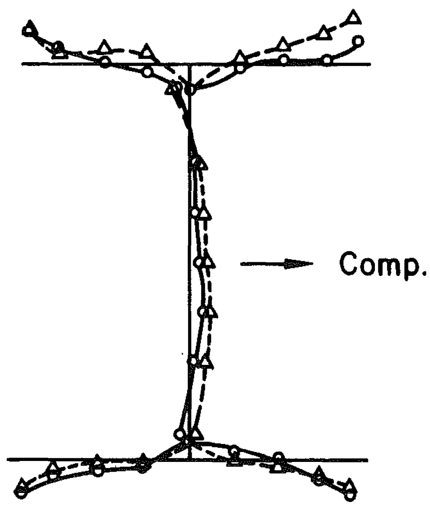


Fig. 11 Measured Residual Stresses

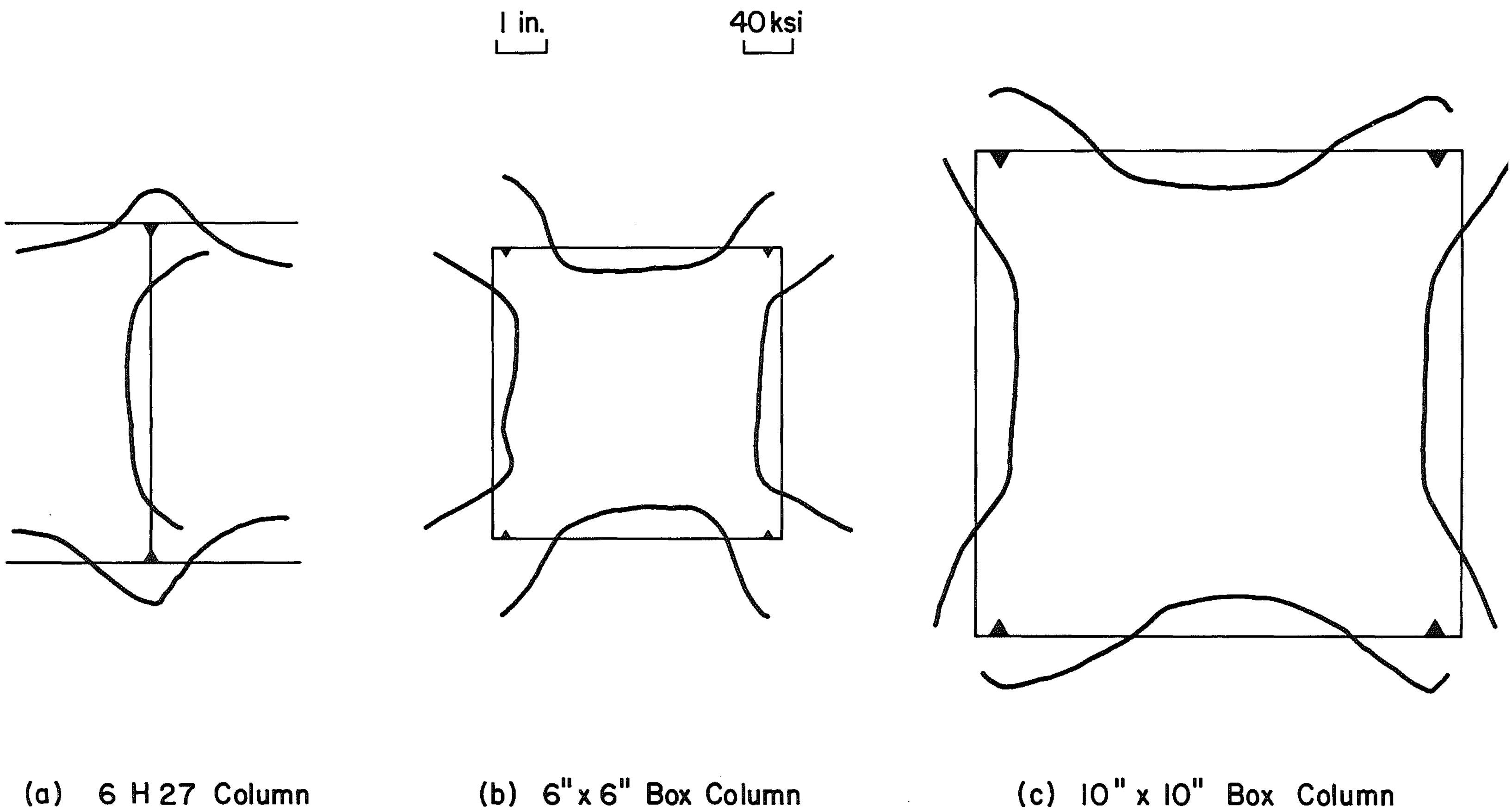


Fig. 12 Residual Stress Distribution in A7 Welded Shapes

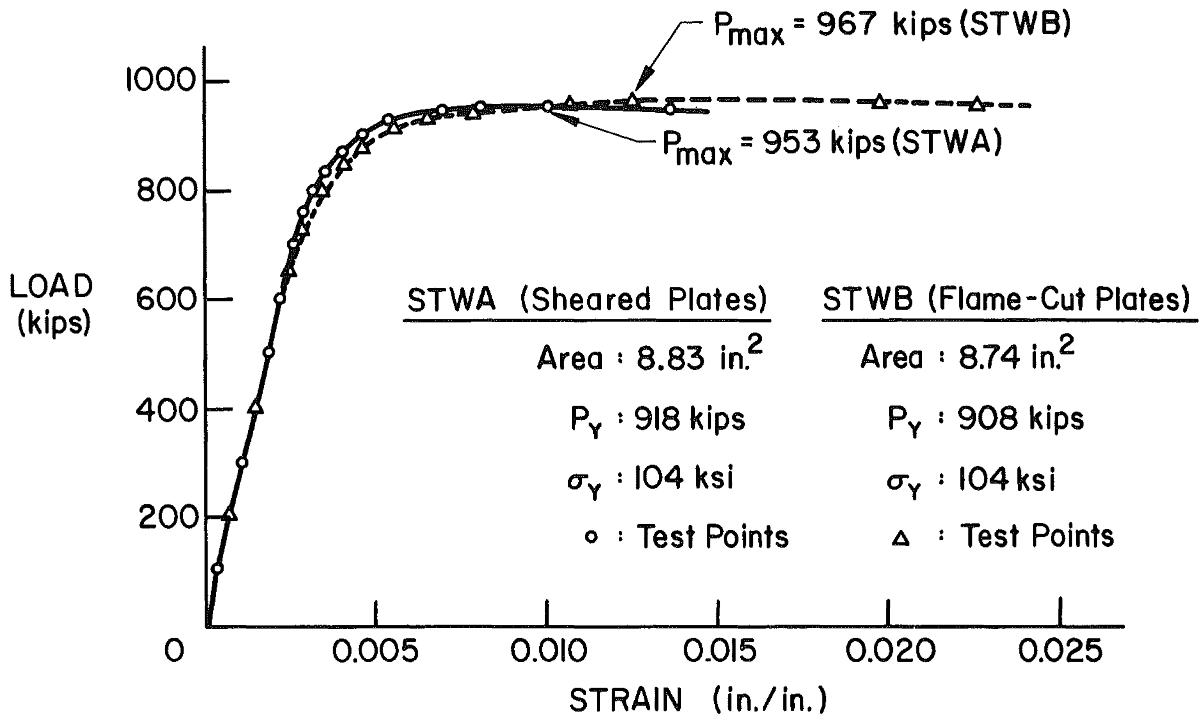


Fig. 13 Stub Column Tests of 6H27 Columns

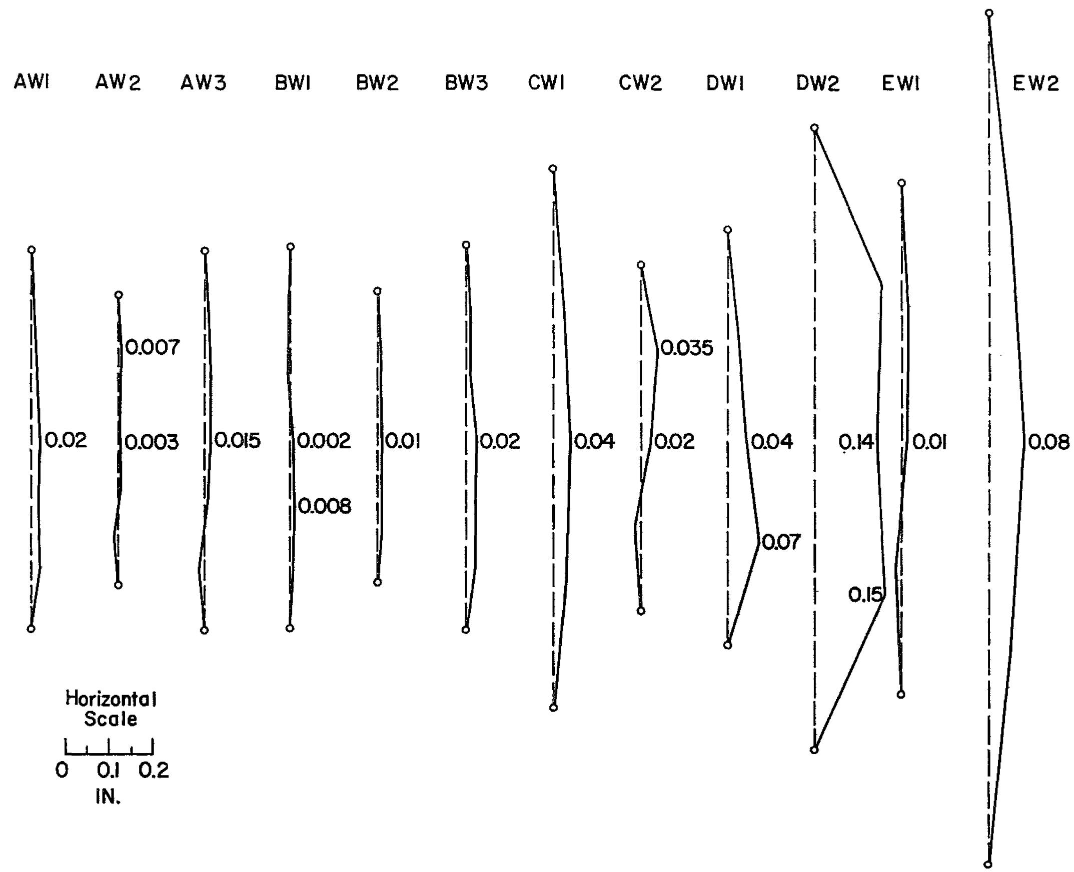
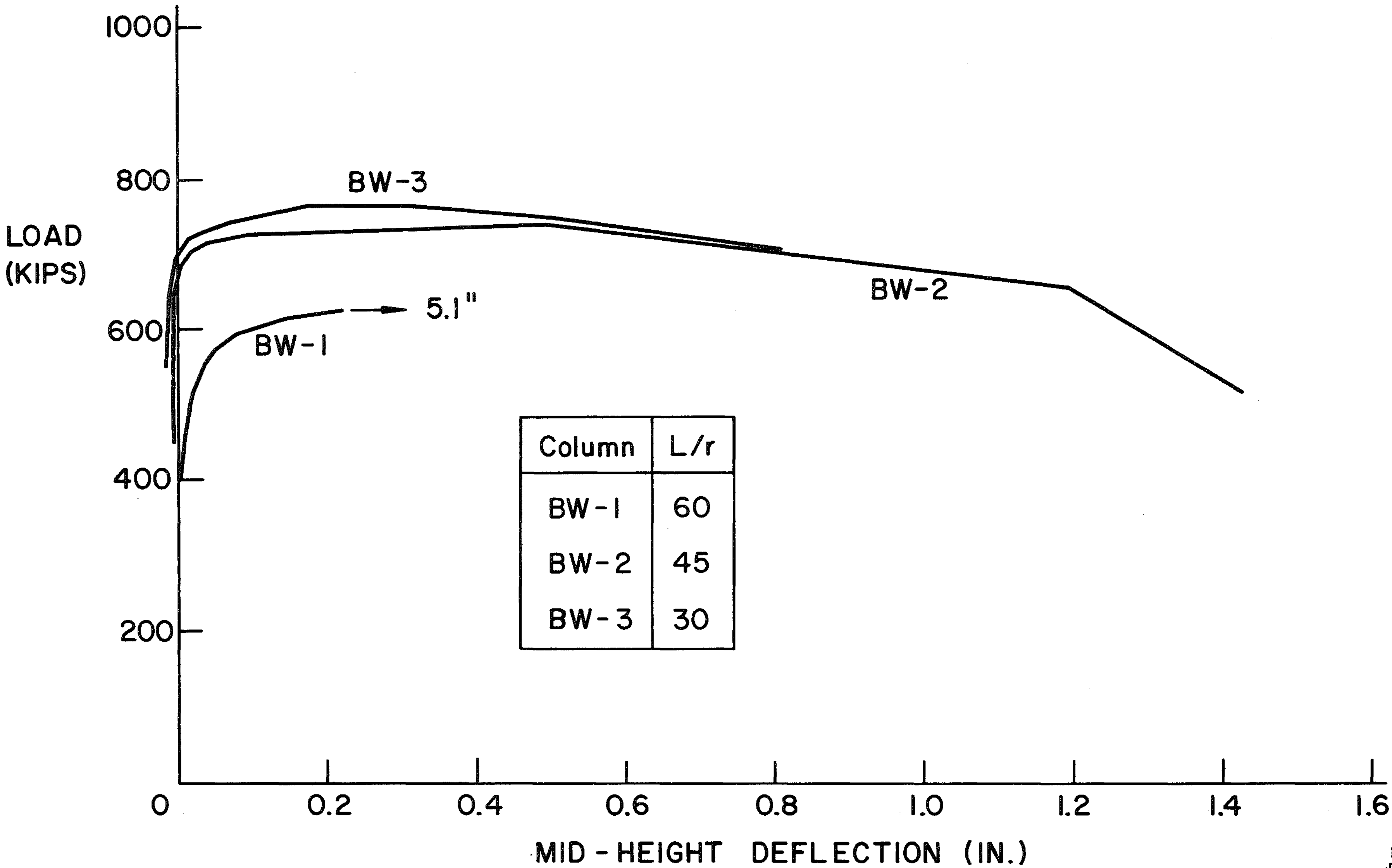


Fig. 14 Initial Out-of-Straightness of Test Columns



Column	L/r
BW-1	60
BW-2	45
BW-3	30

Fig. 15 Load-Deflection Curves - 6H27 Columns

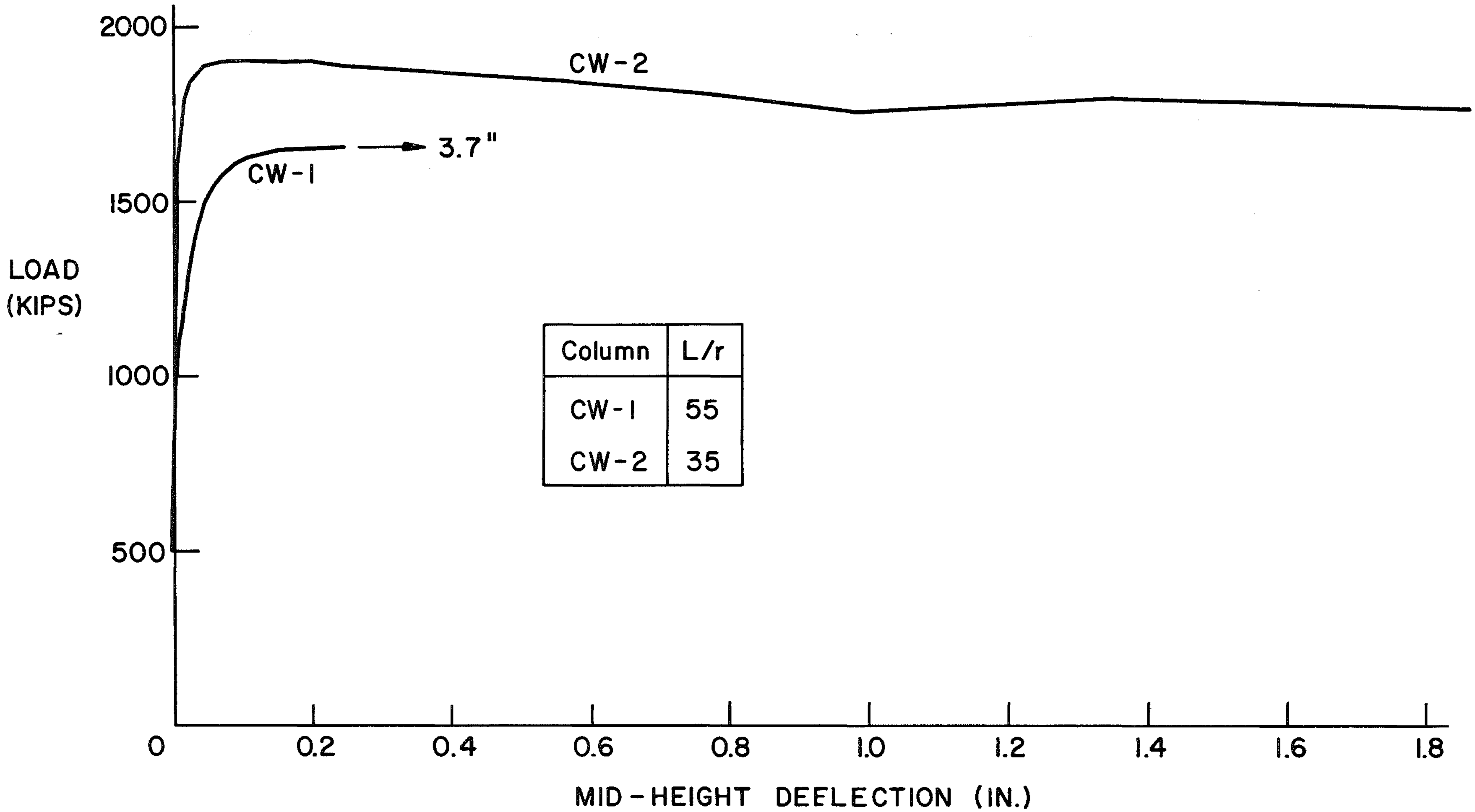


Fig. 16 Load-Deflection Curves - 10H61 Columns

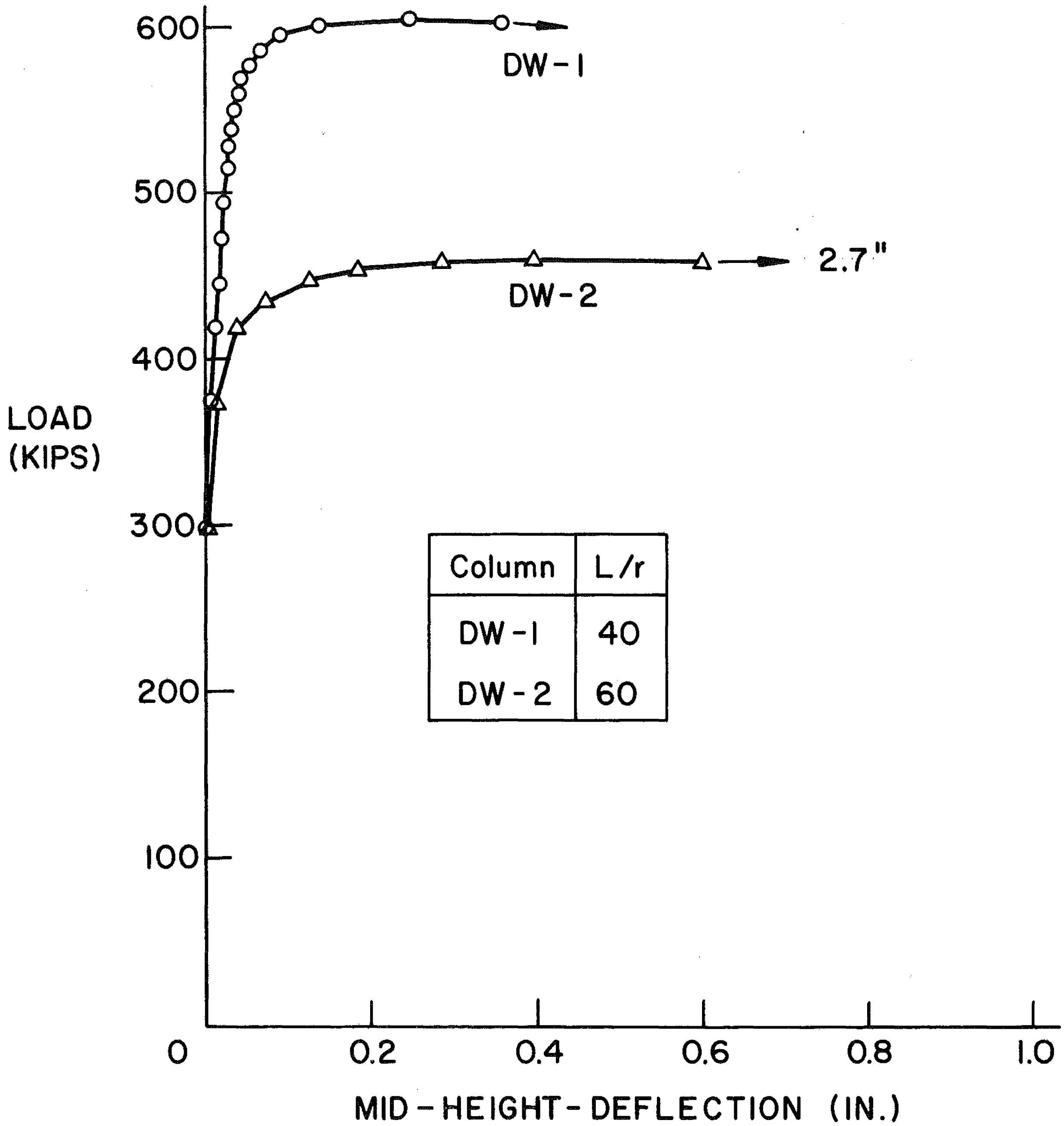
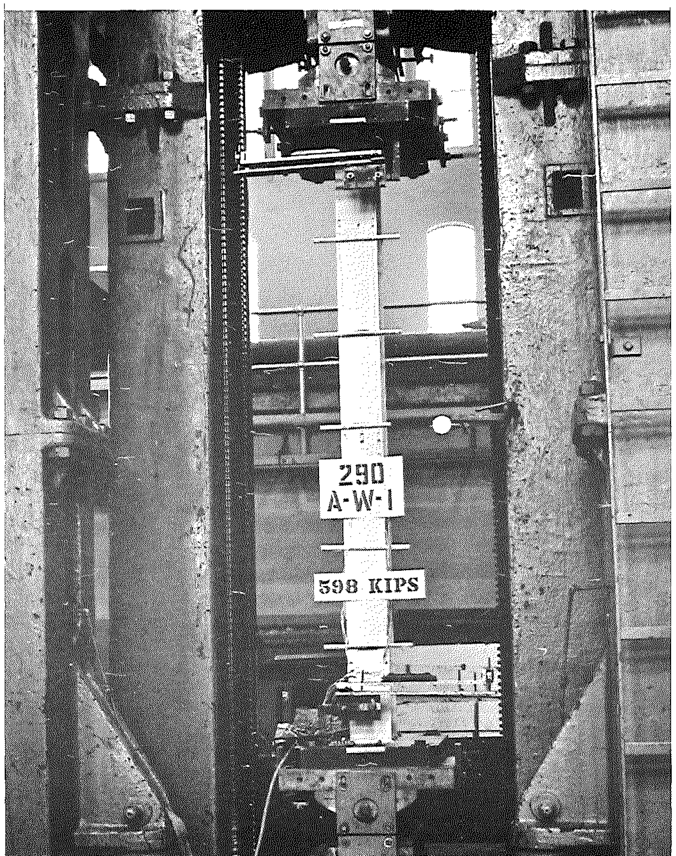
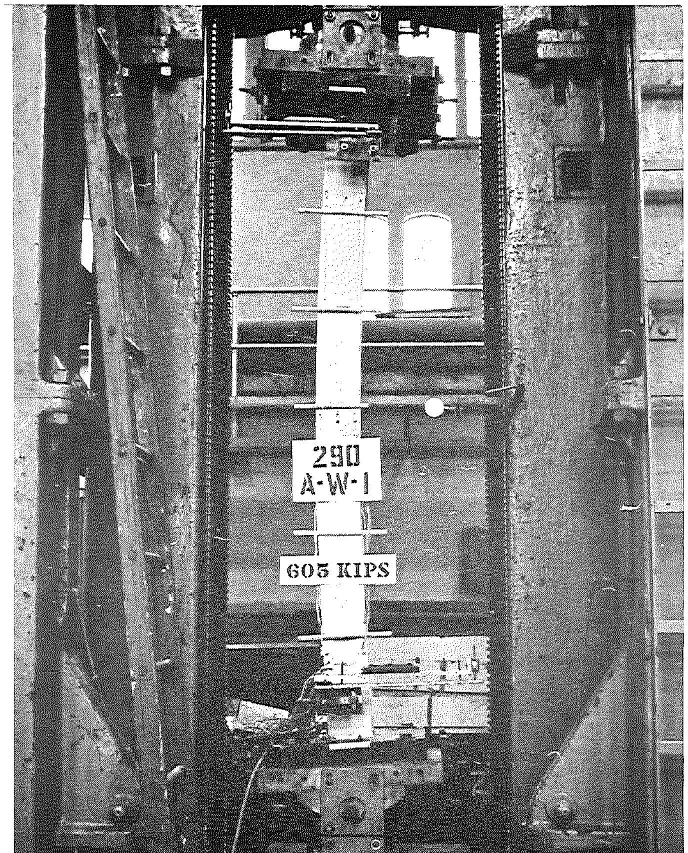


Fig. 17 Load Deflection Curves (6"x6" Box Columns)



(a) At 99% of Maximum Load



(b) Immediately After Abrupt Failure

Fig. 18 Column in Testing Machine

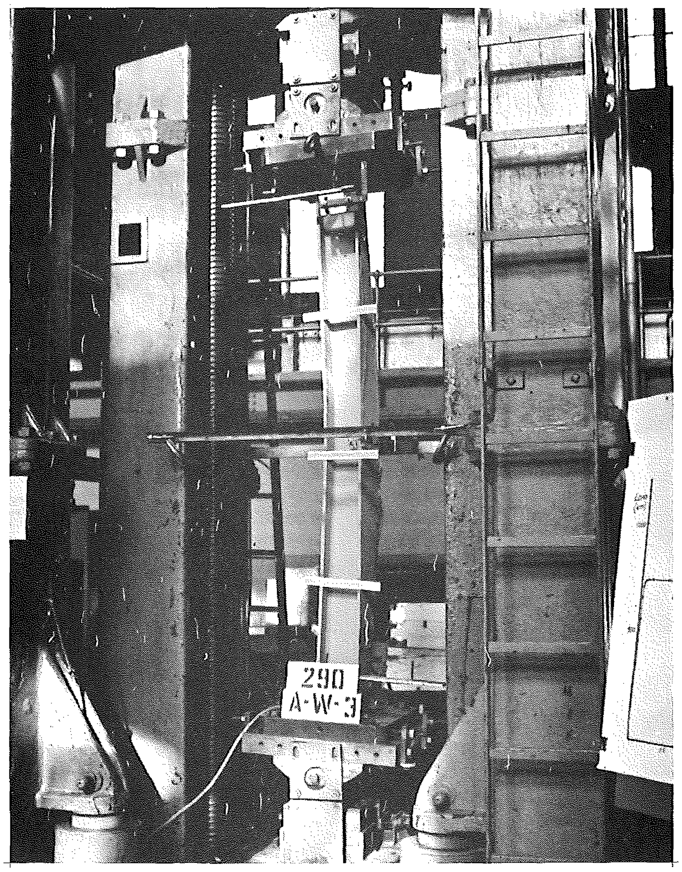


Fig. 19 Twisting in Failure

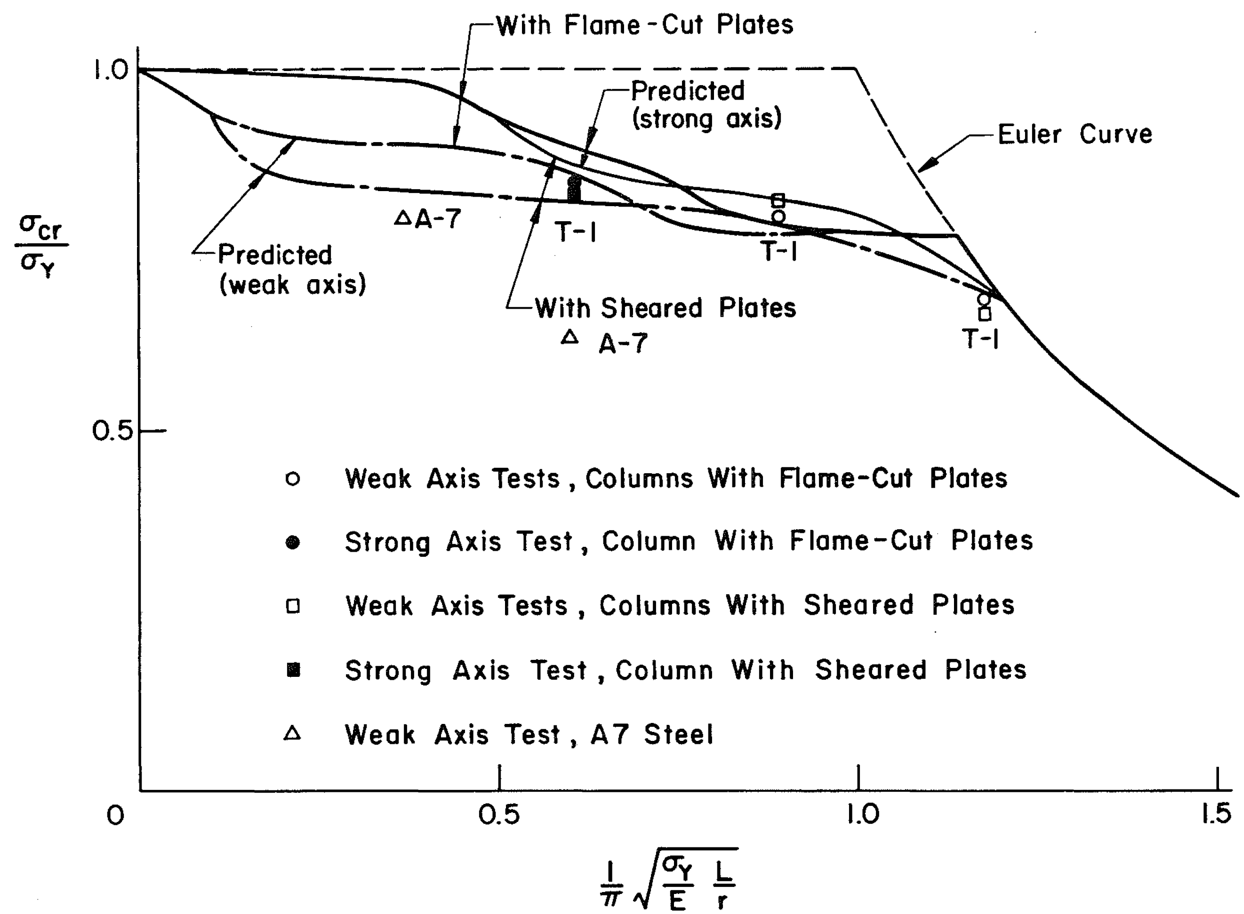


Fig. 20 Column Curves and Test Results - 6H27 Columns

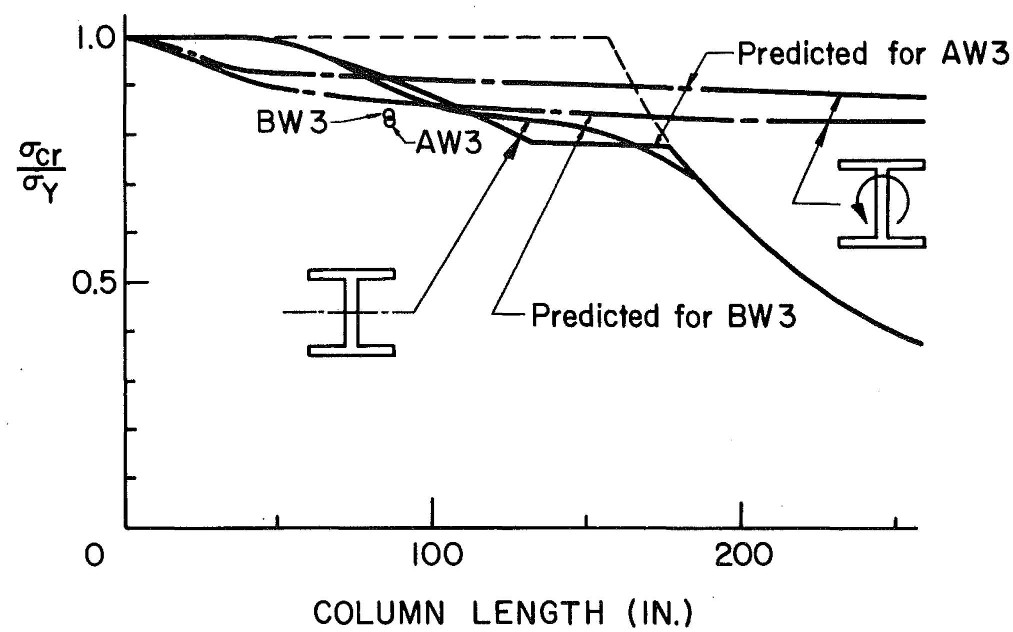


Fig. 21 Column Curves and Test Results for Tests AW3 and BW3

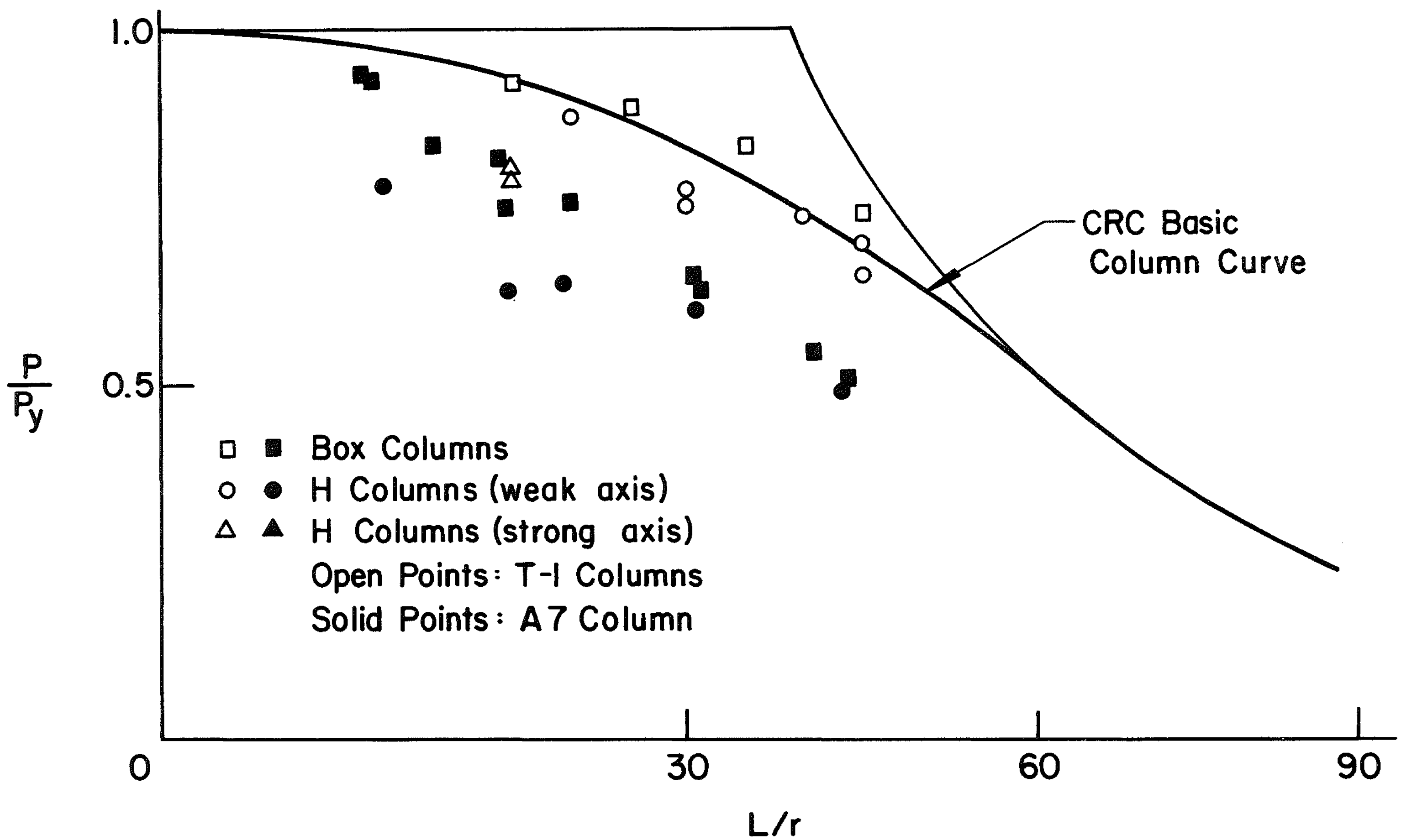


Fig. 22 Column Test Results

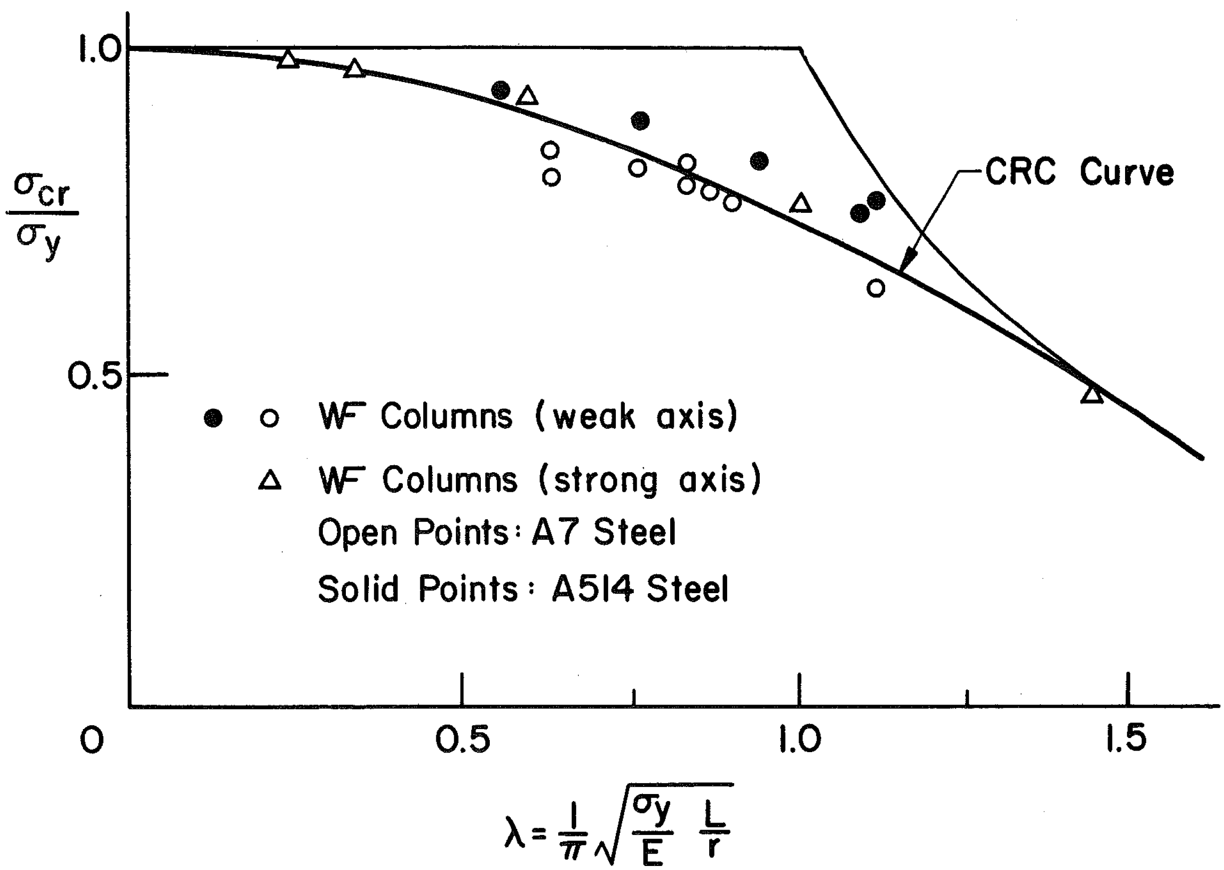


Fig. 23 The Strength of Rolled Columns of A514 Steel

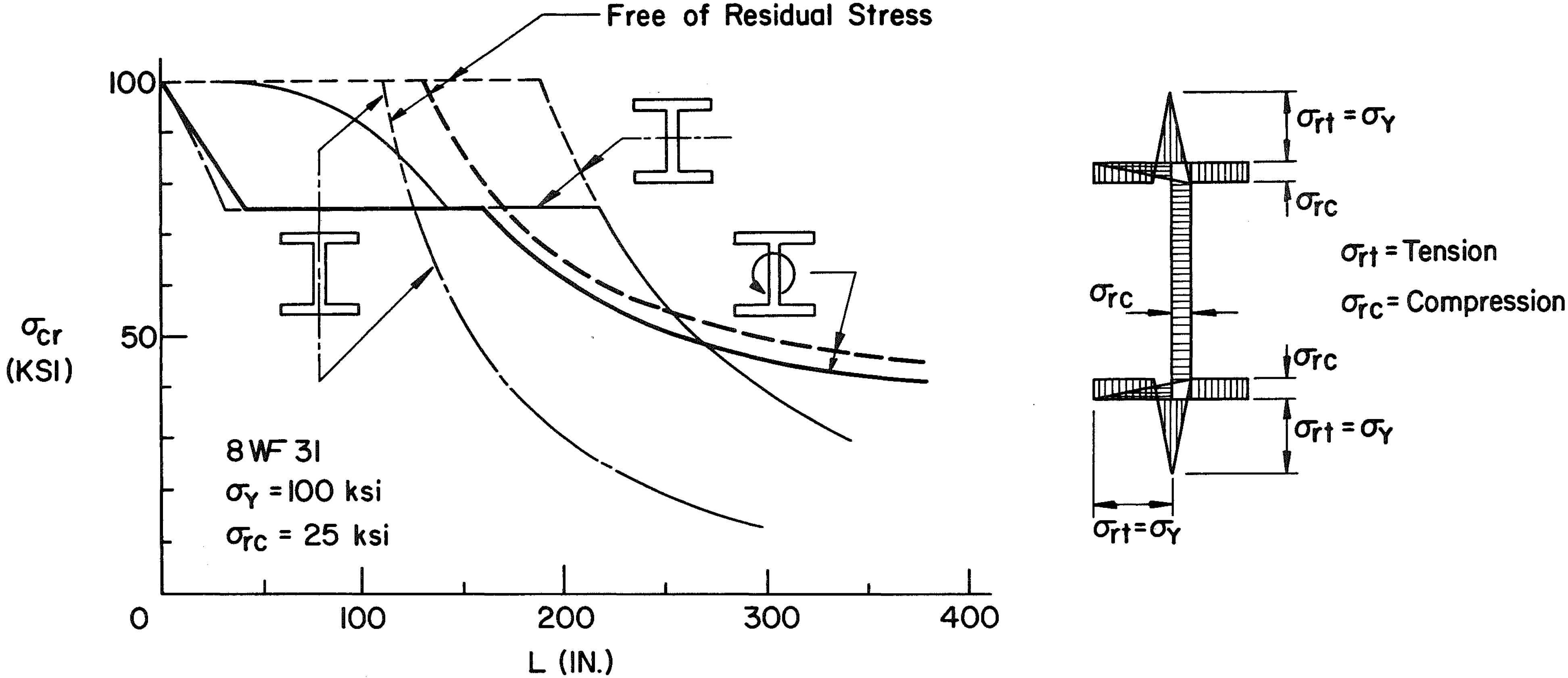


Fig. 24 Column Curves of Various Buckling Modes

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