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LEHIGH UNIVERSITY INSTITUTE OF RESEARCH

Hot-Rolled Shapes

THE COLUMN STRENGTH OF HOT-ROLLED TUBULAR SHAPES -- AN EXPERIMENTAL EVALUATION

by
Fiorello R. Estuar
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Fritz Engineering Laboratory Report No. 296.1

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ABSTRACT

A study of the column strength of rolled tubular shapes (square and rectangular) of ASTM A36 steel is presented in this report. Material property tests, residual stress measurements, stub column tests, and pinned-end column tests are analyzed and the results are evaluated on the basis of their influence on the strength of the tubular column cross section. Particular attention is given to the magnitudes of residual stresses in the cross section and to the effect of initial out-of-straightness on column strength.

I INTRODUCTION

The purpose of this investigation is to study the column strength of rectangular hot-rolled hollow structural tubing of ASTM A36 steel. The shapes were manufactured from seamless round tubes except when the perimeter of the cross-section is less than 14 inches, in which case the shapes were manufactured from tubing having a continuous longitudinal butt weld.

In this study a full column test program conducted for the purpose of evaluating the column strength of rolled tubular shapes is presented. Comparisons are made with tests on rolled wide-flange shapes and welded built-up columns. Comparison is also made with the CRC Basic Column Curve which is the basis for the column design criteria most commonly used in building design -- the AISC Formula.

II. SPECIMENS

The specimens for this series of tests consisted of various sizes of hot-rolled tubing of square and rectangular cross section. The sizes of the square tubes varied from 3-1/2" x 3-1/2" to a maximum of 10" x 10",and the rectangular tube was 6" x 4" in size. A summary of the schedule of specimens is given in Table 1.

A complete series of tests on a manufactured column section consists of a tensile coupon test, residual stress measurements, a stub column test, and a pinned-end column test. In this program, a completely correlated study was made on pieces AA, CC, DD, EE, and GG. These cross sections are representative of the shapes in production at the time of the investigation. Only tensile coupon tests and residual stress measurements were made on pieces BB and FF.

No special specifications were set forth in the manufacture of these specimens. The pieces were in their "as-rolled" condition. The only stipulation imposed was that the manufactured piece be as straight as possible and should not be mechanically straightened. All the specimens received were acceptable under these conditions.

Most of the work done in cutting the specimen was made at the Fritz Laboratory machine shop under the direct supervision of the project staff. The pieces were cut into four types of specimens as shown in Fig. 1.

Tensile test specimens were cut from the cross section in sets of four as shown in Fig. 2. The coupons were cut according to the ASTM standards for rectangular tensile coupons having a gage length of 8 inches[1].

The method of "sectioning" was used in measuring the residual stresses[2]. Gage holes 10 inches apart were laid out on an 11 inch long test section as shown in Fig. 3. The layout shown was used for the 10" x 10" x 1/2" tube section. For sections of other size tubes the width of the strips were varied; for example, 1/4" wide strips were used for the 3-1/2" x 3-1/2" sections.

To assure that the original residual stresses are undisturbed before the initial readings with the Whittemore gage are made, any preliminary cut made to reduce the length of the test piece to facilitate handling must be at least d distance away from the gage holes (d = the maximum dimension of the cross section). The layout is illustrated in Fig. 1.

After the initial readings are made, the 11 inch test piece was cut from the manufactured piece and further sectioned into strips to release the residual strains. The difference in length of a strip before and after cutting is a measure of the residual stress in the strip prior to sectioning.

Ordinarily for plate thicknesses of less than 1/2 inch, no appreciable difference between the residual stresses measured on the outside and inside surfaces can be observed. However, measurements on the 3-1/2" x 3-1/2" x 5/16" cross section indicated a marked difference in strains sufficient to cause the residual stress strips to bend considerably. Thus, it was necessary to measure the residual stress on both surfaces of all sections except for piece BB which was of thin material (5/32").

The method of measuring residual stresses on both surfaces of a box section is described in Ref. 3. The test piece is laid out as discussed earlier and the gage holes are drilled and the gage length measured with the Whittemore gage. The first cutting operation involves splitting the section into two angles as shown in Fig. 4. Additional gage holes are drilled on the inside surfaces, corresponding to strip widths on the outside surface. Initial readings on the gage lines on the inside surfaces are made. The pieces are then cut into 11 inch residual stress strips, after which final readings are made.

Stub column specimens were prepared according to a stub column test procedure standardized at Fritz Laboratory[4]. Each stub column was chosen such that the length is within the following limits:

(1) 2 d + 10" (or 3 d) minimum

(2) 20 r_y (or 5 d) maximum

where d = depth of cross section (the maximum width of a side of the tube)

r_y = radius of gyration about the weak axis

These limits are set forth to:

(1) Assure that the original residual stresses are contained in the 10 inch gage length, and

(2) Prevent lateral buckling, thus allowing the stub column to be stressed beyond its yield point.

In choosing the specimen for pinned-end column testing, the straightest portion of the tube was selected. A visual inspection of the test piece was made to make sure that it is in good condition, that is, no cold bending marks , knicks, or any defects that might influence the results of the test. The column specimen was prepared in accordance with the standard procedure used in the laboratory[3,5].

III. EXPERIMENTAL INVESTIGATION

The experimental study of the behavior of a column consists of tensile coupon tests, residual stress measurements, a stub column test, and a pinned-end column test.

The above series of tests can be correlated with each other as shown in Fig. 5. From a tensile coupon test, the stress-strain relationship of the material is known and can usually be represented by an elastic-perfectly-plastic relationship for carbon and low-alloy hot-rolled steels, as shown in Fig. 5a. The residual stress distribution, Fig. 5b, is determined from measurements. Also plotted in Fig. 5b is the result of the stub column test. The effect of residual stresses is shown in the difference between the results of the coupon test (dashed curve) and the stub column test. Figure 5c shows the tangent modulus and is obtained from Fig. 5b by measuring the value of the tangent to the curve of Fig. 5b. Finally, a column curve (Fig. 5d) is derived from a function of E_t.[6] Experimental values of column strength may be plotted with this theoretical column curve for comparison.

1. Tensile Coupon Tests

A total of 88 coupons were tested; the results of the tests on the tensile coupons are summarized in Table 2. The value of the static yield stress ranged from 34.6 ksi to 46.1 ksi with an overall average value of 38.4 ksi. The ASTM Designation A36 specifies a minimum yield point of 36.0 ksi.

The static yield stress (σ_{ys}) is the stress at zero strain rate.[7] The static yield stress corresponds to the yield values in buildings and static structures; its value is independent of machine and human influences. The yield point is the yield value at a finite strain rate, and hence the static yield stress values are lower than the yield point values.

2. Residual Stress Measurements

The results of the residual stress measurement are shown in Figs. 6a to 10a. The values are predominantly within the range of zero to plus or minus 5 ksi. All values shown in the figures are averages of inside and outside measurements and are referred to the outside face of the cross section (bold line). These magnitudes of residual stresses are of the same order as that found in rolled plates before welding.[8]

As mentioned earlier, the residual stresses on the inside face and the outside face differ from each other. A typical result of measurements on both faces is plotted in Fig. 11. It can be observed that the residual stresses at the outside face were compressive, ranging from about 6 ski to 21 ksi, with an average of 13 ksi.

3. Stub Column Tests

The general procedure used in performing a stub column test is described in detail in Refs. 3 and 4. The result of a stub column test is a stress-strain curve for the cross section which shows the effect of residual stresses. The results of tests on stub columns for pieces AA, CC, DD, EE, EEE, and GG are shown in Table 3 and in Figs. 6b to 10b. Comparison of these results with the static yield stress values given in Table 2 shows good agreement.

4. Pinned-End Column Test

A total of 10 pinned-end columns were tested. The slenderness ratio of the columns varied from 30 to 100, with column lengths varying from 6 ft. to 29 ft. The results of the pinned-end column tests are summarized in Table 4. The experimental load-deflection curves for each of the column specimens are given in Figs. 6d to 10d together with the initial out-of-straightness of each column specimen (Fig. 6c to 10c).

IV. EVALUATION OF TEST RESULTS

Probably, the most significant finding in this investigation is the low values of the residual stresses observed in the specimens. These values are of the magnitudes found in hot-rolled plates of A7 steel and have practically insignificant influence on column strength.

Further verification of the absence of any appreciable amount of residual stress is observed from the results of the stub column tests. All these test results show a common characteristic -- the proportional limit load is very close to the yield load of the cross section. Since the difference between the yield load and the proportional limit load is a measure of the maximum compressive residual stress in the cross section, these stub column test results indicate that only a small amount of residual stress was present. Thus, for purposes of theoretical analysis, it is reasonable to assume that the effect of residual stress is negligible.

A comparison of the column test results given in Table 4 and results of tests on the rolled WF shapes, welded box shapes, and the Basic Column Curve of the Column Research Council is shown in Fig. 12. The results of the column tests on the rolled tubular shapes show that, for the range of slenderness ratios and sizes of the specimens tested, the rolled tubular shape exhibits better column characteristics than the corresponding welded box shape and rolled WF shape. Comparison with the CRC Basic Column Curve shows that the column strength given by the CRC curve closely approximates the strength of the rolled tubular shapes. In most cases, the column strength predicted by the CRC curve is conservative.

The proper evaluation of the column strength of a rolled tubular shape is one based on a theoretical analysis using an assumption of no residual stress and taking into account the initial out-of-straightness. Such a theoretical analysis is presented in Ref. 9 which deals with the effect of initial deformation on the column strength of rolled WF shapes and of rolled tubular shapes. Reference 9 shows that for columns with no residual stress (or with negligible residual stress, as is the case with rolled tubular shapes) the reduction of column strength at the medium range of slenderness ratios (30 to 100) is due to the initial out-of-straightness. The results of the column tests and theoretical analysis are shown in Fig. 13. The theoretical results consider the measured out-of-straightness for each column. In this manner the strength of each column specimen may be critically examined in the light of the effect of initial out-of-straightness on its strength.

A reasonably good agreement is observed between the experimental values and the theoretical values. Except for columns C4 and C8, the percent differences in the two values are well within 6%. The percent differences for columns C4, and C8 are 17% and 12% respectively. No obvious explanation can be given for these differences, although a discrepancy between the actual and assumed shape in the initial out-of-straightness may account for this.

Observing that the column specimens exhibited elastic behavior at loads almost up to the point of instability, the Southwell plot for determining the value of the effective initial out-of-straightness may be used.(10) The plots are shown in Fig. 14 for columns C4 and C8. In this plot, the effective initial out-of-straightness is given by the intercept of the lines with the δ axis. Thus, for column C4, e = 0.036" ($\frac{e}{b}$ = 0.009) and for C8, e = 0.02" ($\frac{e}{b}$ = 0.002). Using these values of initial out-of-straightness the corresponding theoretical ultimate loads ~~are~~ P/P_y = 0.90 for column C4 and P/P_y = 0.97 for column C8, resulting in differences with experimental results of 20% and 5% respectively. Thus, the Southwell plot studies do not give any conclusive results. However, an indication of the probable source of discrepancy is given.

V. SUMMARY AND CONCLUSIONS

A study of the column strength of ASTM A36 rolled tubular shapes of square and rectangular section is presented. The column test program included the study of material properties, residual stresses, and pinned-end column strength. A total of ten columns were tested with slenderness ratios varying from 30 to 100. Particular attention was given to the magnitudes of residual stresses present in the shapes and to the effect of initial out-of-straightness on column strength.

Comparisons were made with results of tests on rolled WF columns and on welded built-up columns. Further comparisons were made with the basic column curve given by the Column Research Council.

Based on the findings of this study, the following conclusions may be made:

(1) The residual stresses found in rolled tubular shapes are of irregular and random pattern. The magnitudes of these residual stresses are practically negligible and have insignificant influence on column strength. (Figs. 6a through 10a, Figs. 11, 12)

(2) Initial out-of-straightness is the governing factor causing the deviation of the column strength of rolled tubular shapes from the ideal Euler curve - yield load criterion. (Fig. 13)

(3) The effective out-of-straightness of columns with a well-defined elastic behavior may be predicted with reasonable accuracy by using the Southwell Plot. (Fig. 14)

(4) Due to the negligible effect of the very small residual stresses found in the rolled tubular shapes, such shapes exhibit better column strength than rolled WF shapes and welded built-up columns of similar sizes. (Fig. 12)

(5) The CRC Curve gives a conservative prediction of the column strength of rolled tubular shapes. The test points were generally above the curve and exceeded the value predicted by the CRC curve. (Fig. 12)

VI ACKNOWLEDGEMENTS

This paper summarizes an investigation into the strength of hot-rolled tubular columns of ASTM A36 steel. The investigation was conducted at Fritz Engineering Laboratory in the Department of Civil Engineering of Lehigh University in Bethlehem, Pennsylvania. The National Tube Division of the United States Steel Corporation sponsored the research.

Column Research Council Task Group 1 under the chairmanship of John A. Gilligan provided valuable guidance. Roland R. Graham reviewed this paper and made a number of excellent suggestions which were incorporated. Sincere appreciation is due C. K. Yu for his assistance during the course of the investigation and the preparation of this paper.

VII. NOMENCLATURE

d	depth of the cross section
e	initial out-of-straightness of the column at midheight
e/b	ratio of the out-of-straightness at midheight to the width of the cross section in the direction of bending
L	pinned-end column length
P	load on the column
P_y	yield load of the column
r	radius of gyration of the cross section
σ	stress
σ_{ys}	static yield stress level, the average yield stress at zero strain rate

Table 1 Schedule of Specimens

Piece Desig.	Cross Section	Length	Col. No.	L/r	Specimens
AA	3-1/2 x 3-1/2 x 5/16	36' 4"	1 2	80 100	8' 6" column 10' 8" column coupons (4 sets) residual stress (2 sets) stub column
BB	3-1/2 x 3-1/2 x 5/32	36' 3"			coupons (2 sets) residual stress
CC	4 x 4 x 3/16	39' 5"	3 4	68 90	8' 8" column 11' 7" column coupons (2 sets) residual stress stub column
DD	6 x 6 x 1/4	39' 5"	5 6	32 51	6' 2" column 9' 10" column coupons (4 sets) residual stress stub column
EE	10 x 10 x 1/2	42' 0" (two)	7 8	60 90	19' 0" column 28' 6" column coupons (4 sets) residual stress (3 sets) stub column
FF	10 x 10 x 1/4	42' 0"			coupons (2 sets) residual stress
GG	6 x 4 x 1/4	36' 6"	9 10	50 80	6' 7" column 10' 7" column coupons (4 sets) residual stress stub column

Table 2 Coupon Test Results

Piece Design.	Coupon No.	Static Yield Stress (ksi)	Average (ksi)	Tensile Strength (ksi)	Average (ksi)	Modulus of Elasticity	Average
AA	E1	37.3	(35.6)	70.1	(70.5)	31.0	(29.25)
	E2	35.3		68.7		29.6	
	E3	35.6		70.4		30.0	
	E4	37.1		74.1		25.4	
	F1	35.0		68.3		26.9	
	F2	34.9		69.4		31.9	
	F3	35.8		70.2		29.7	
	F4	37.0		73.4		32.3	
	G1	34.6		68.4		28.7	
	G2	34.8		68.5		27.0	
	G3	35.0		70.5		30.5	
	G4	36.8		73.2		27.7	
	H1	34.8		70.1		28.9	
	H2	34.8		68.9		29.8	
	H3	34.5		70.1		29.2	
	H4	36.4		74.2		29.4	
BB	C1	36.2	(36.1)	69.0	(70.3)	29.6	(29.55)
	C2	35.0		68.7		27.9	
	C3	36.4		70.4		28.9	
	C4	38.6		75.4		32.7	
	D1	35.9		68.5		27.3	
	D2	35.0		69.0		28.3	
	D3	37.1		70.5		31.3	
	D4	34.6		71.1		30.4	
CC	G1	44.6	(44.6)	67.6	(67.5)	26.5	(29.6)
	G2	43.5		67.3		27.8	
	G3	42.8		66.6		31.6	
	G4	44.2		67.6		29.7	
	H1	46.1		67.5		27.9	
	H2	43.0		67.7		28.7	
	H3	42.3		67.3		30.5	
	H4	45.0		68.2		34.3	
DD	I1	38.4	(38.4)	64.6	(63.9)	29.6	(29.4)
	I2	39.7		64.2		28.7	
	I3	39.2		65.6		33.2	
	I4	39.2		63.3		29.2	
	J1	38.3		65.3		30.2	
	J2	38.7		63.5		-	
	J3	38.4		64.5		29.3	
	J4	38.1		63.8		28.3	
	K1	37.5		64.1		-	
	K2	39.1		63.5		29.2	
	K3	38.4		63.7		28.8	
	K4	38.4		64.0		30.0	
	M1	37.2		62.8		29.7	
	M2	38.6		63.4		27.5	
	M3	37.9		62.6		27.3	
	M4	37.9		63.0		30.4	

Table 2 Coupon Test Results (Cont'd)

Piece Design,	Coupon No.	Static Yield Stress (ksi)	Average (ksi)	Tensile Strength (ksi)	Average (ksi)	Modulus of Elasticity	Average
EE	E1	36.7	(38.2)	64.8	(66.2)	29.2	(29.0)
	E2	37.7		68.1		27.8	
	E3	38.0		65.7		28.6	
	E4	38.2		65.1		27.2	
	F1	38.0		66.1		30.0	
	F2	39.1		66.2		30.1	
	F3	39.1		66.9		20.2	
	F4	39.1		66.4		30.5	
EEE	E1	36.8	(38.0)	64.3	(64.0)	26.8	(29.9)
	E2	38.5		64.4		29.3	
	E3	37.0		63.0		30.5	
	E4	38.9		63.9		30.7	
	G1	37.0		64.0		31.1	
	G2	39.1		64.6		29.6	
	G3	37.6		64.2		29.4	
	G4	39.2		63.9		31.9	
GG	A1	35.8	(38.1)	56.2	(62.4)	30.1	(29.7)
	A2	37.3		62.2		30.1	
	A3	35.6		62.5		35.7	
	A4	37.3		61.8		31.3	
	G1	39.4		60.9		27.0	
	G2	41.4		65.6		28.9	
	G3	35.8		62.0		26.1	
	G4	39.0		63.8		31.6	
	H1	36.9		59.0		26.7	
	H2	37.7		62.7		26.9	
	H3	37.3		62.9		30.9	
	H4	38.6		63.3		30.1	
	K1	38.0		63.1		29.0	
	K2	38.8		63.5		30.3	
	K3	40.4		64.7		31.1	
	K4	39.6		64.0		28.4	

Table 3 Stub Column Test Results

Piece	Cross Section	Column Nos.	Proportional Limit (kips)	Yield Load (kips)	Area (in^2)	Yield Stress (ksi)
AA	3-1/2 x 3-1/2 x 5/16	C1 C2	115	140	3.85	36.4
CC	4 x 4 x 3/16	C3 C4	130	144	3.21	44.9
DD	6 x 6 x 1/4	C5 C6	200	237	5.80	40.9
EE	10 x 10 x 1/2	C7	740	755	19.80	38.2
EEE	10 x 10 x 1/2	C8	750	769	19.88	38.5
GG	6 x 4 x 1/4	C9 C10	170	185	4.35	42.5

Table 4 Results of Column Tests

Column No.	Cross Section	L/r	e/b	(P/Py) Exptl.	(P/Py) Theo.	(P/Py) CRC	(P/Py) Euler	$\left(\frac{\text{Theo.-Exptl.}}{\text{Theo.}}\right)100\%$
1	3-1/2 x 3-1/2 x 5/16	80	0.034	0.80	0.81	0.81	Yield	1.2%
2		100	0.046	0.67	0.70	0.71	0.87	4.3%
3	4 x 4 x 3/16	67.6	0.020	0.87	0.91	0.86	Yield	4.4%
4		90	0.002	0.75	0.90	0.75	0.98	16.7%
5	6 x 6 x 1/4	32	0.002	0.94	1.00	0.97	Yield	6.0%
6		51	0.002	0.95	1.00	0.92	Yield	5.0%
7	10 x 10 x 1/2	60	0.002	1.00	1.00	0.89	Yield	0
8		90	0.022	0.92	0.82	0.75	0.98	12.2%
9	6 x 4 x 1/4	50	0	0.99	1.00	1.93	Yield	1.0%
10		80	0.012	0.94	0.92	0.81	Yield	2.1%

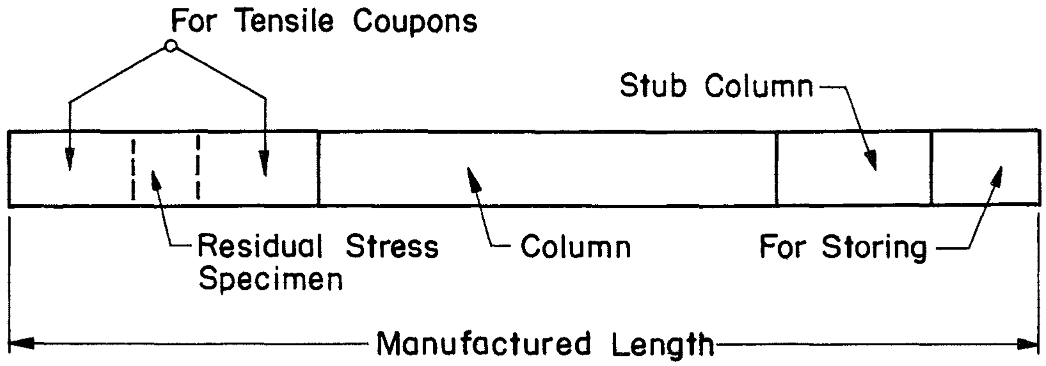

Fig. 1 LAYOUT OF TEST SPECIMENS

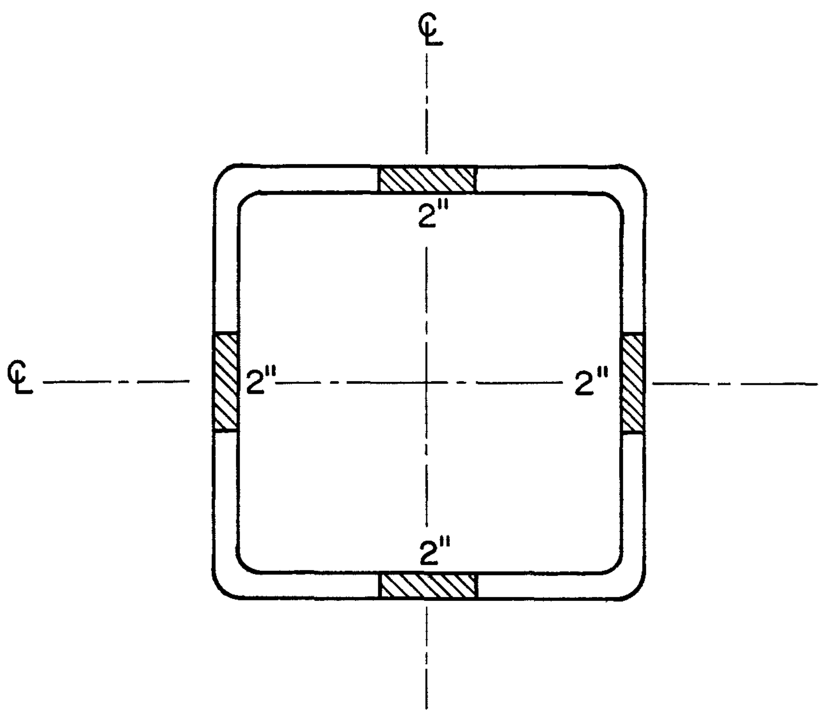

Fig. 2 LAYOUT OF TEST COUPONS

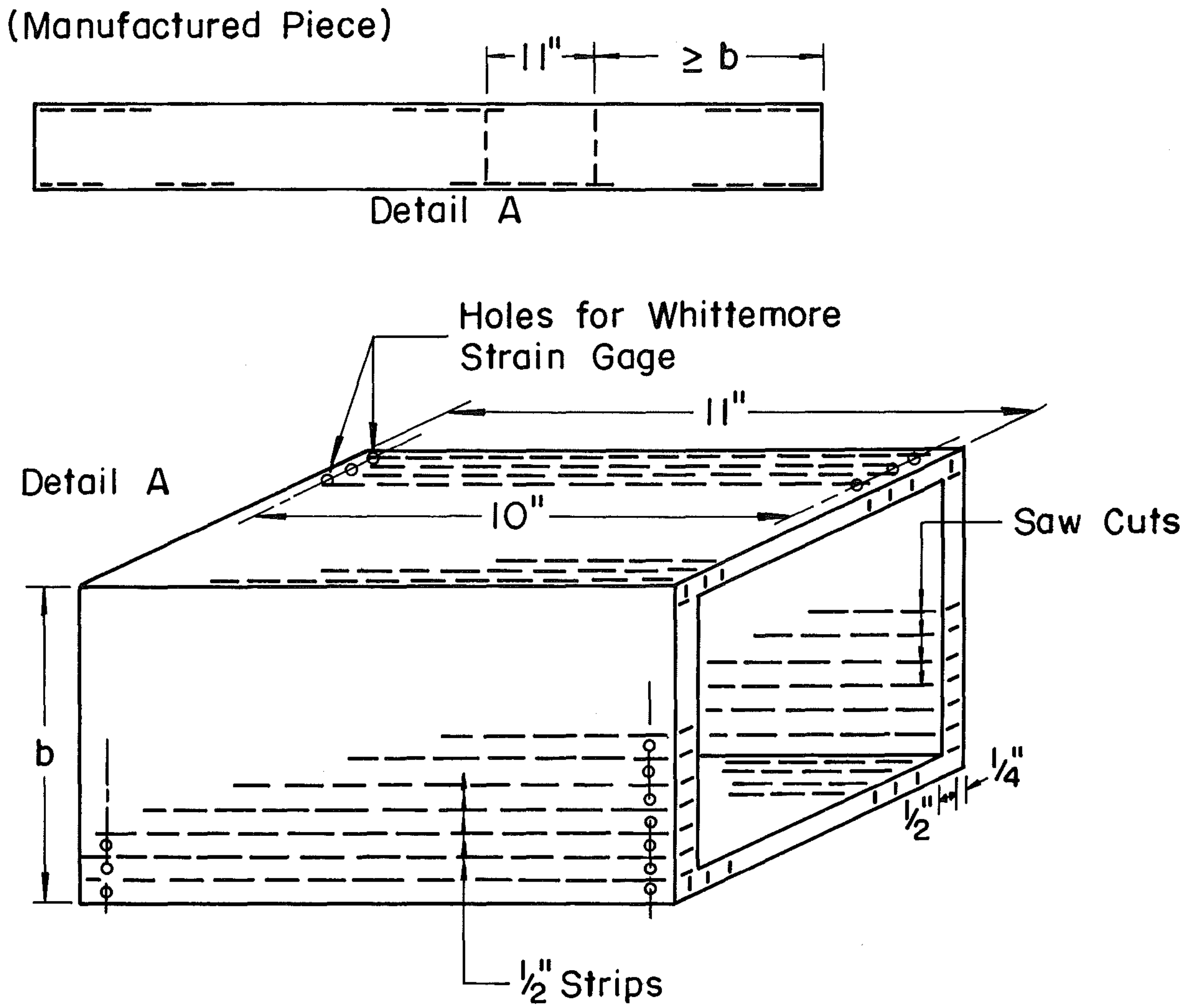

Fig. 3 MEASUREMENT OF RESIDUAL STRESS

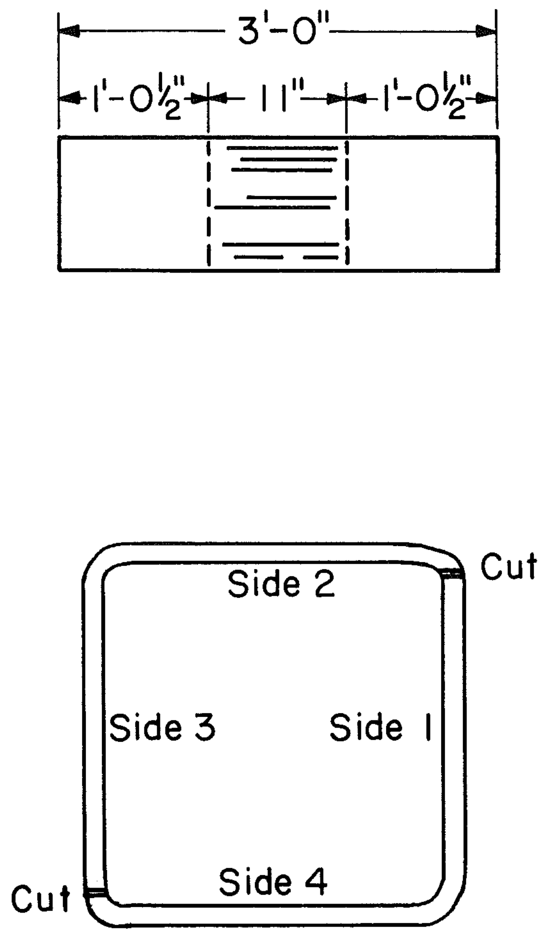

Fig. 4 INSIDE MEASUREMENT OF RESIDUAL STRESS

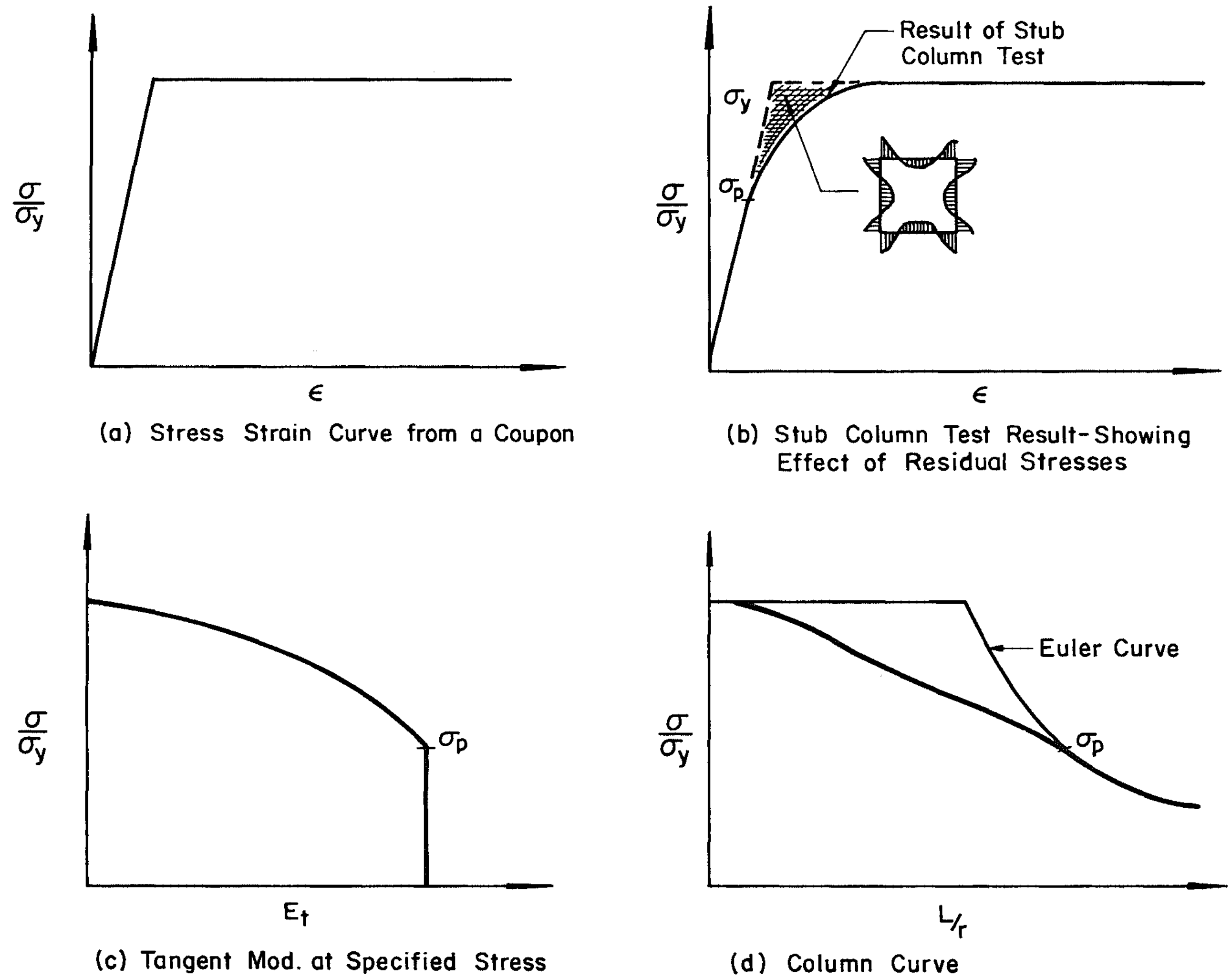

Fig. 5 CORRELATION OF COLUMN TEST SERIES

FIGS. 6 to 10   TEST DATA

(a) RESIDUAL STRESS DISTRIBUTION
(Note: Stresses are referred to the heavy outside line)

(b) STUB COLUMN TEST RESULT

(b) INITIAL DEFORMED SHAPE

(d) PINNED-END COLUMN TEST RESULT

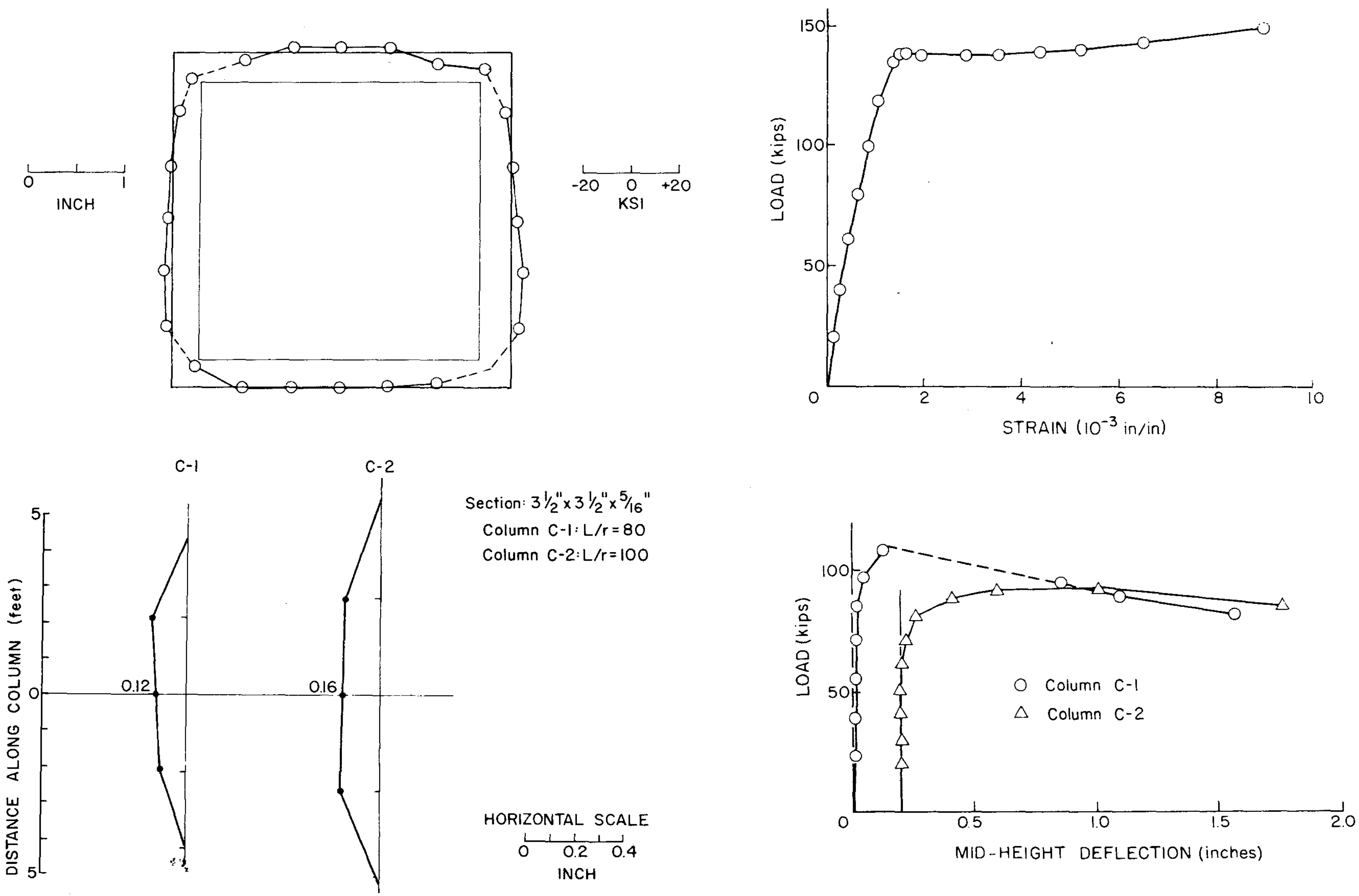

Fig. 6 TEST DATA FOR COLUMNS C1 AND C2

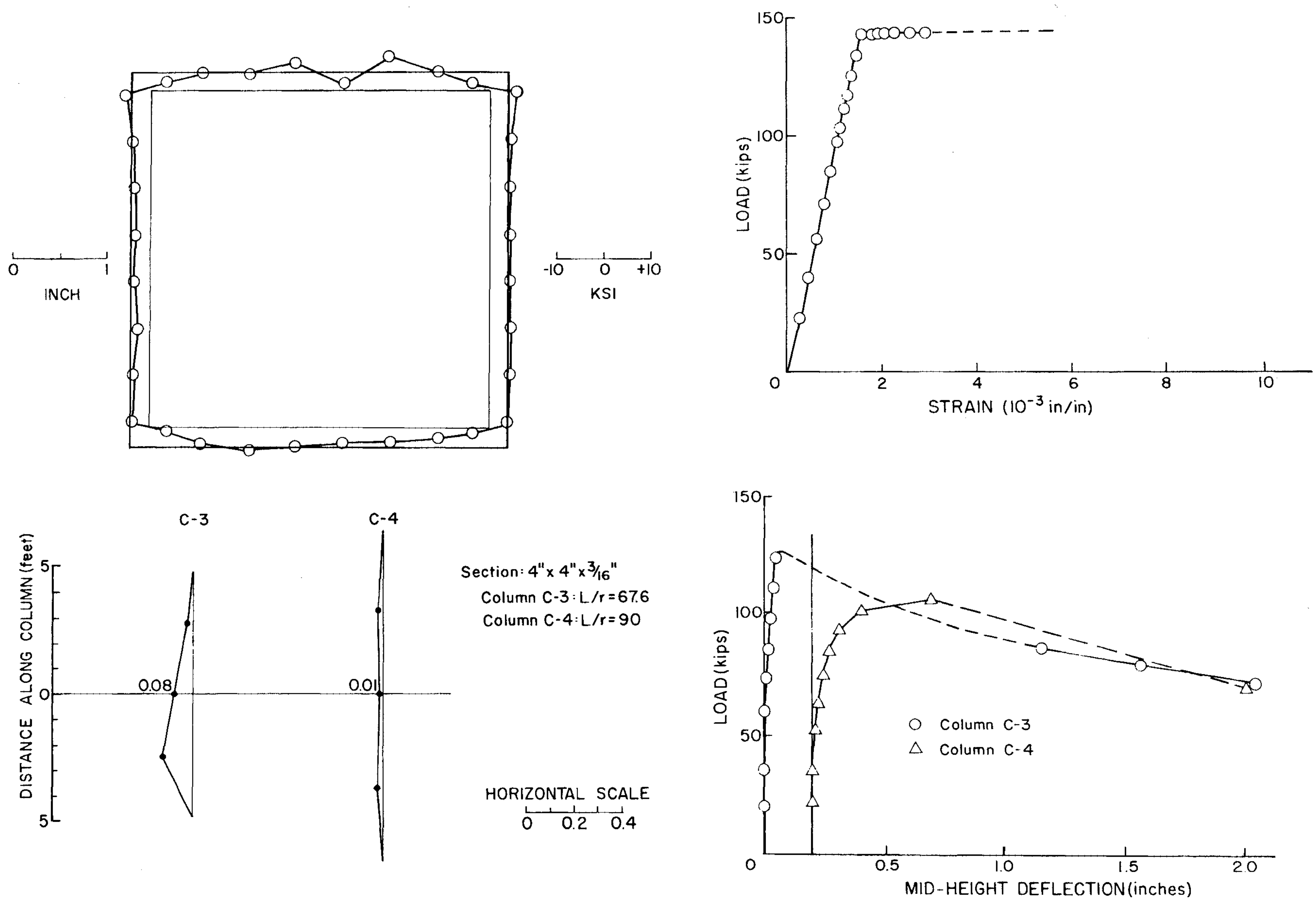

Fig. 7 TEST DATA FOR COLUMNS C3 AND C4

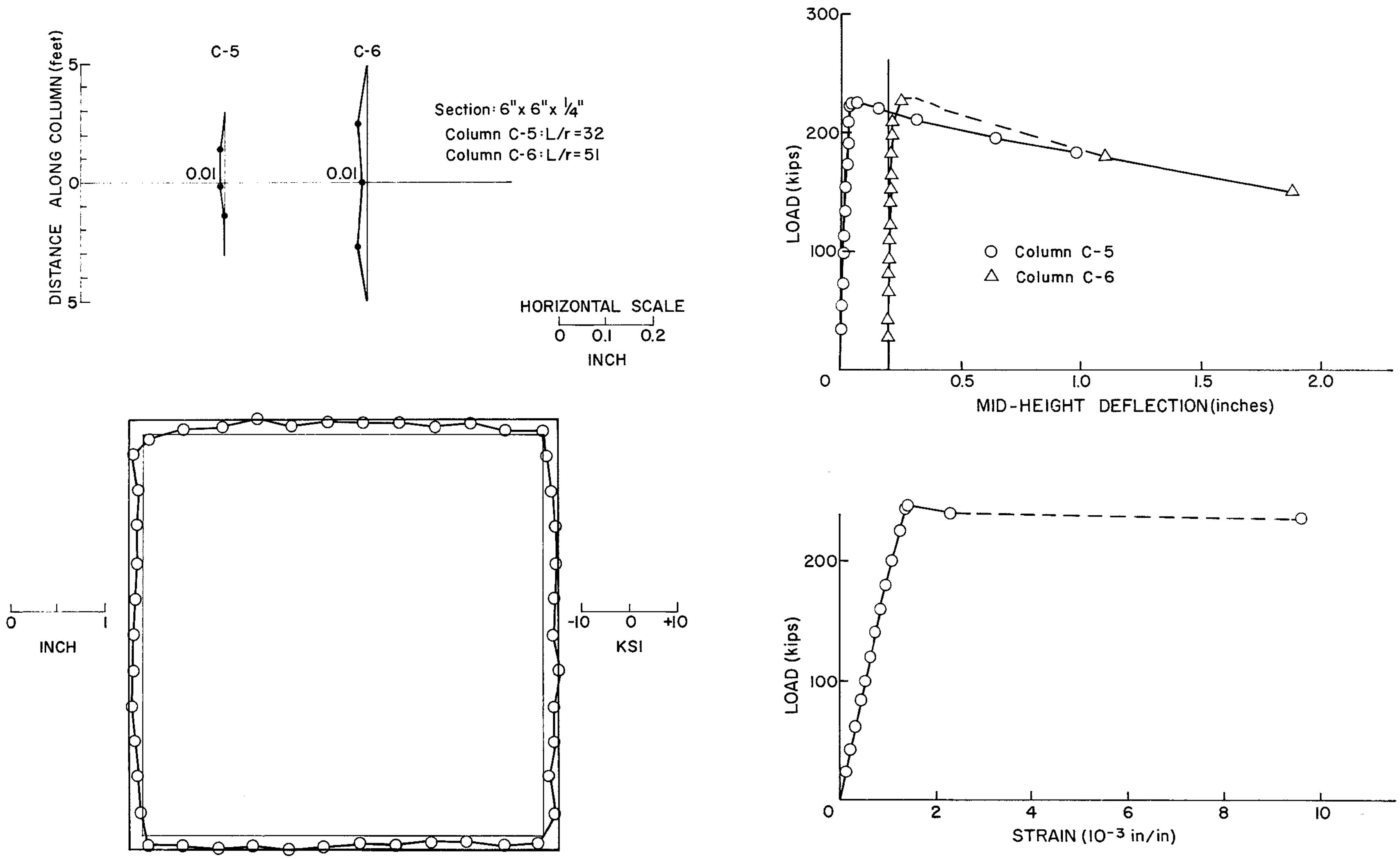

Fig. 8 TEST DATA FOR COLUMNS C5 AND C6

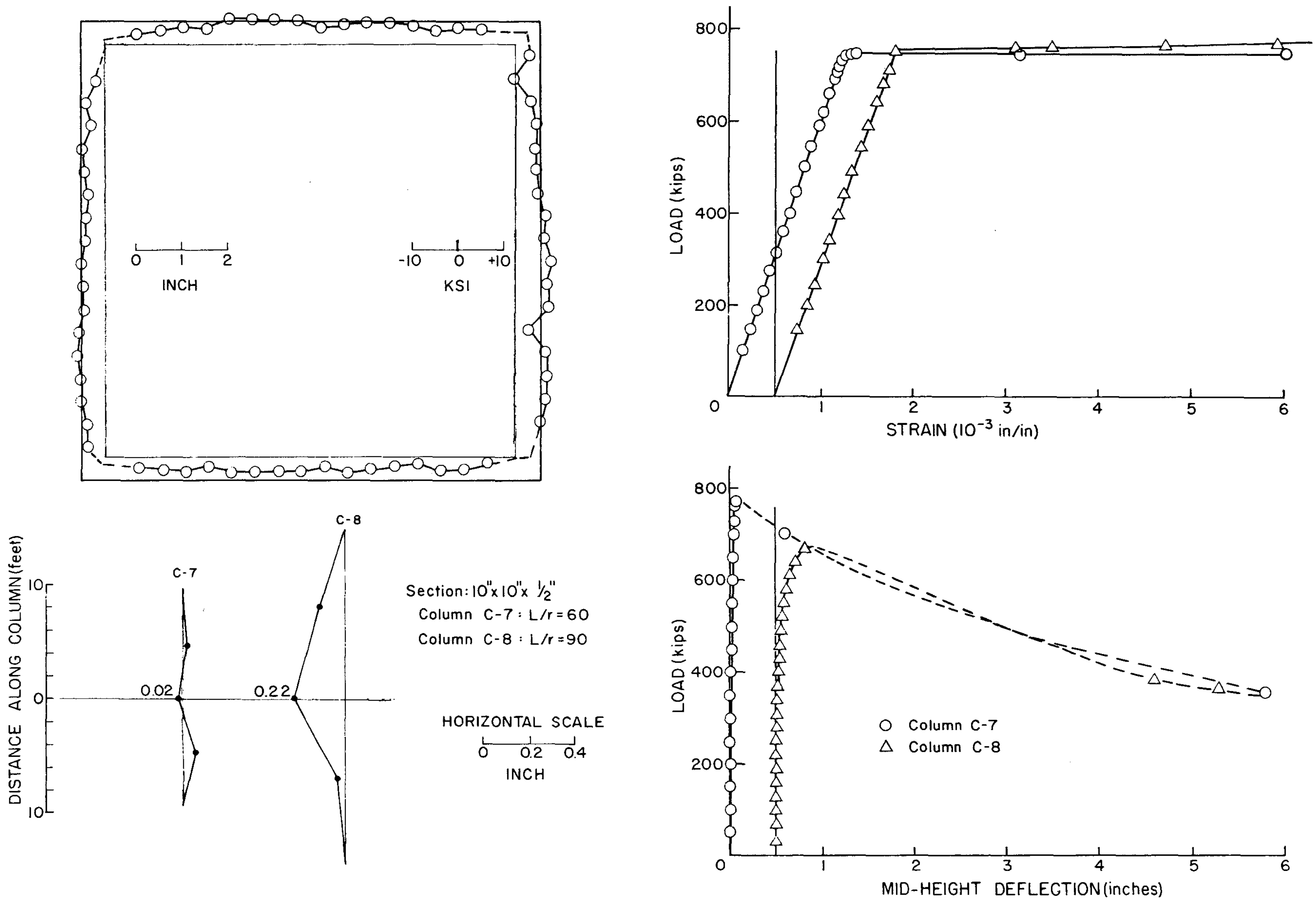

Fig. 9 TEST DATA FOR COLUMNS C7 AND C8

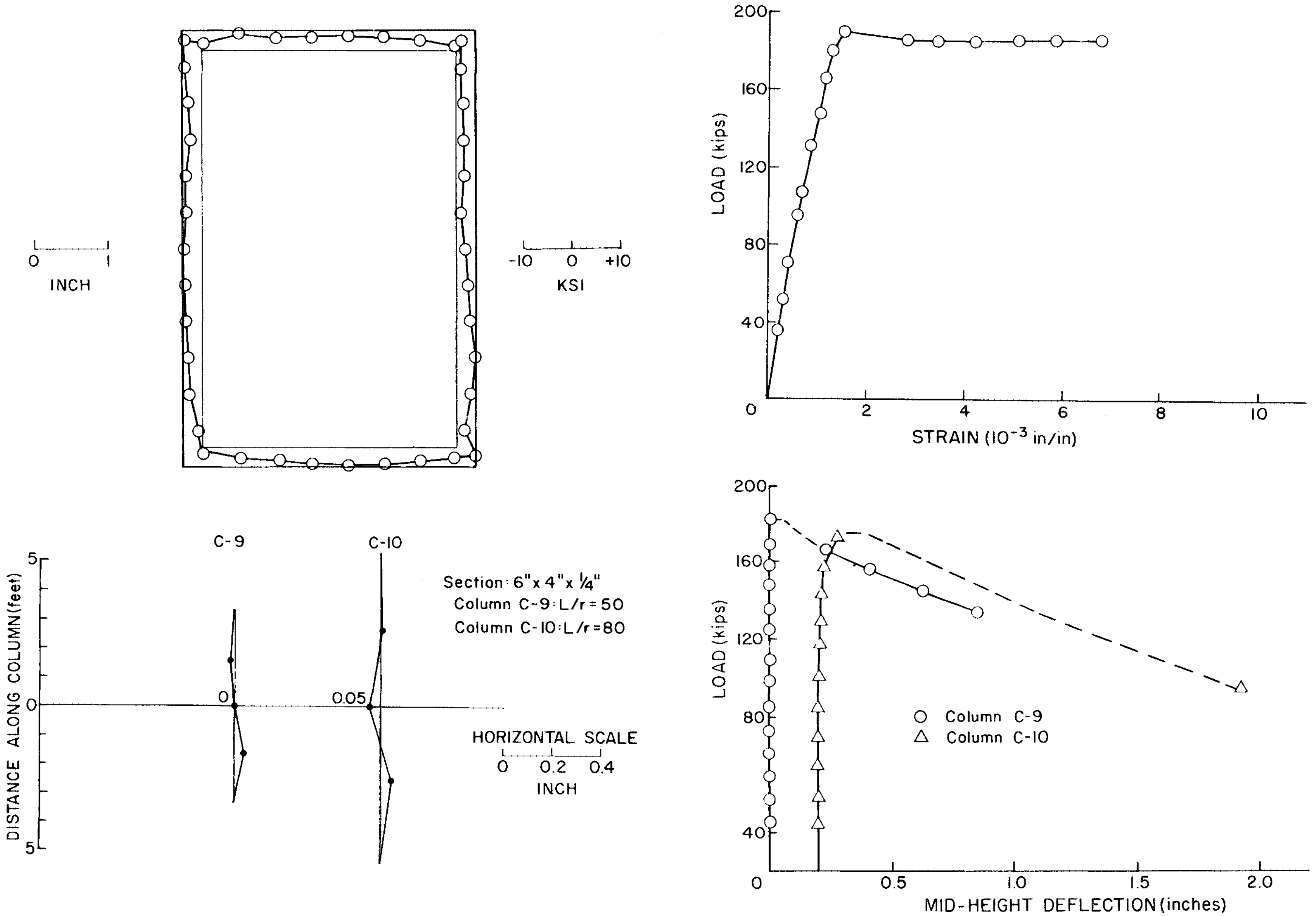

Fig. 10 TEST DATA FOR COLUMNS C9 AND C10

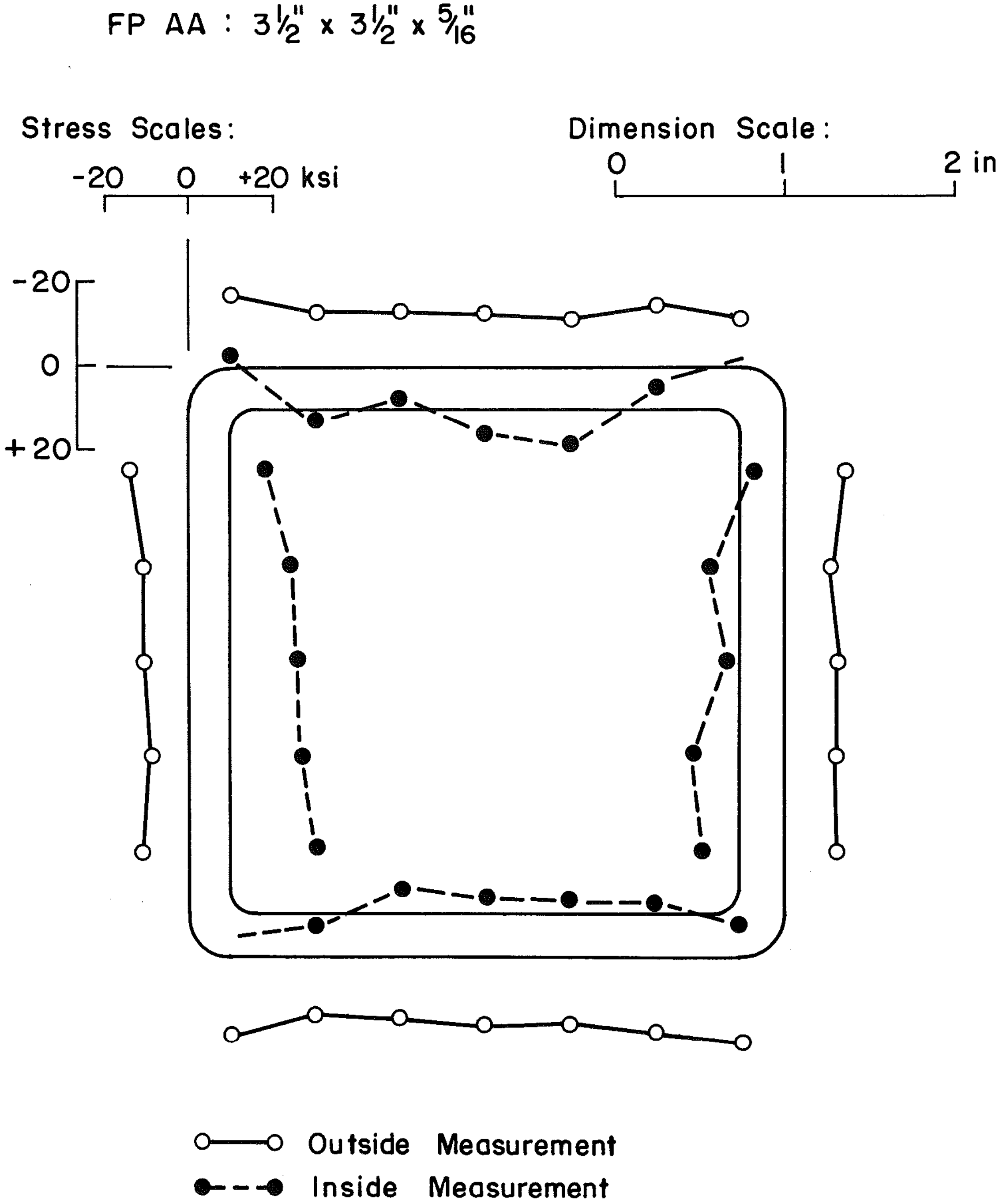

Fig. 11 INSIDE AND OUTSIDE RESIDUAL STRESSES

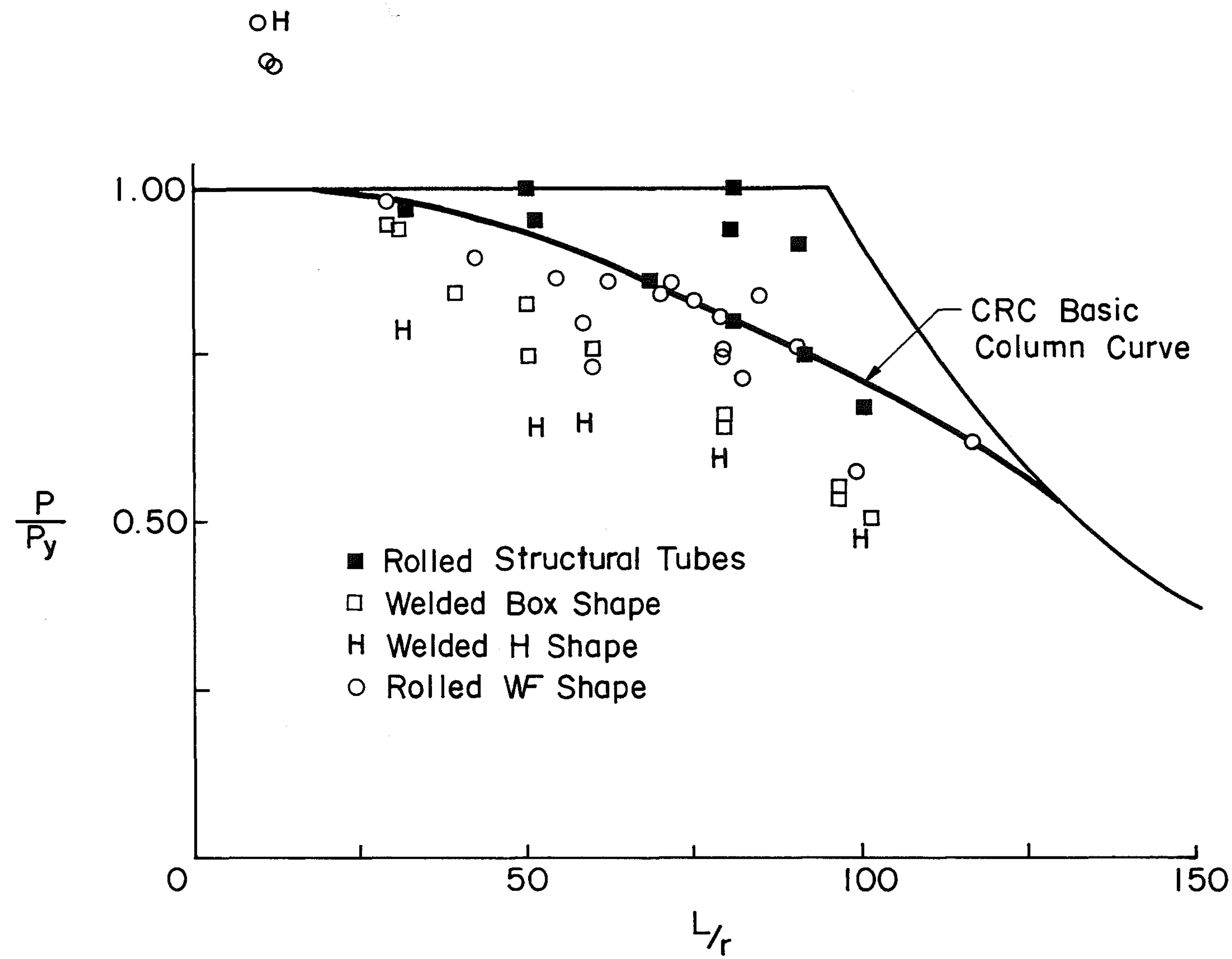

Fig. 12 COMPARISON OF ROLLED BOX SHAPE WITH OTHER SHAPES

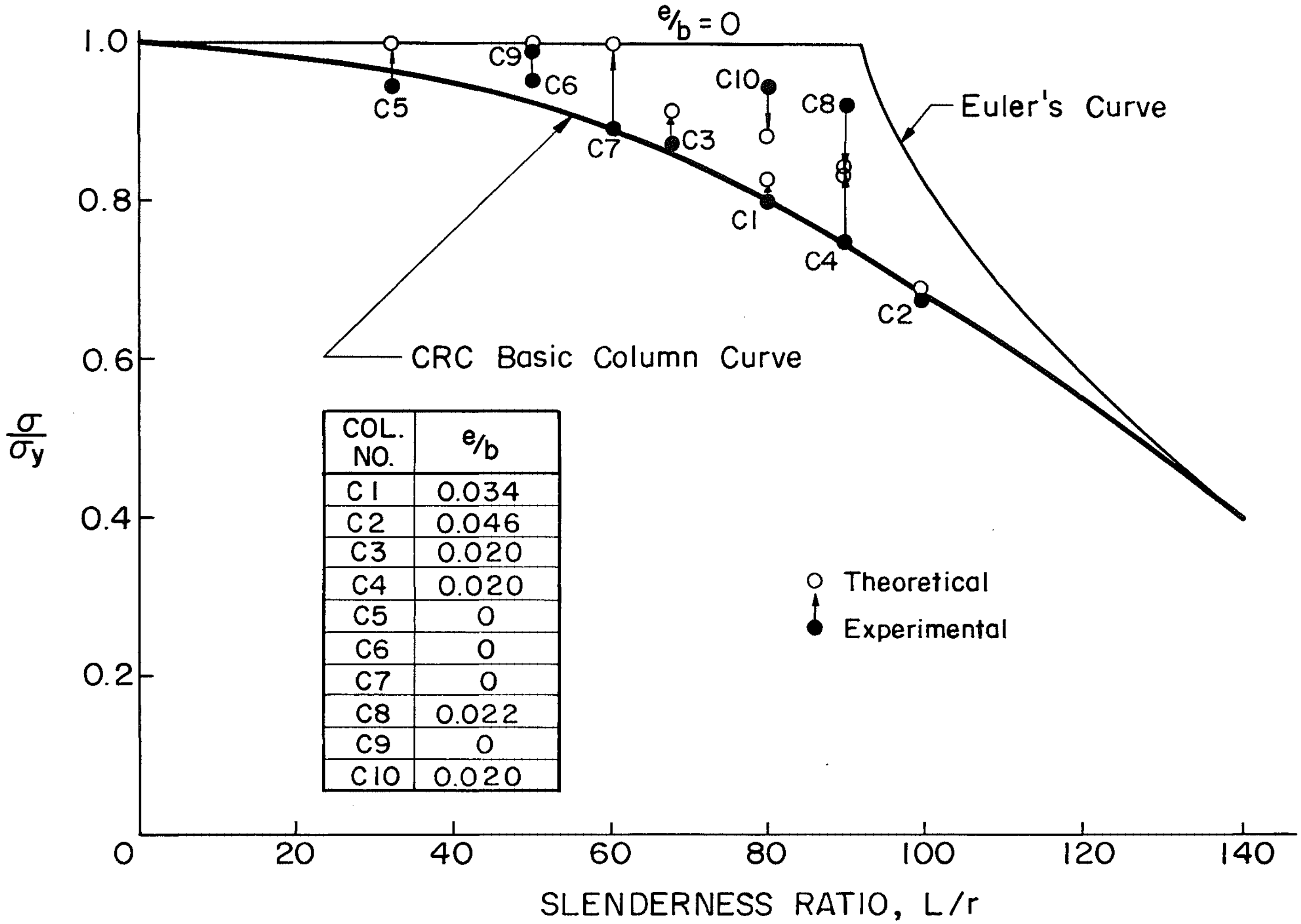

Fig. 13 COMPARISON OF EXPERIMENTAL RESULTS WITH THEORY

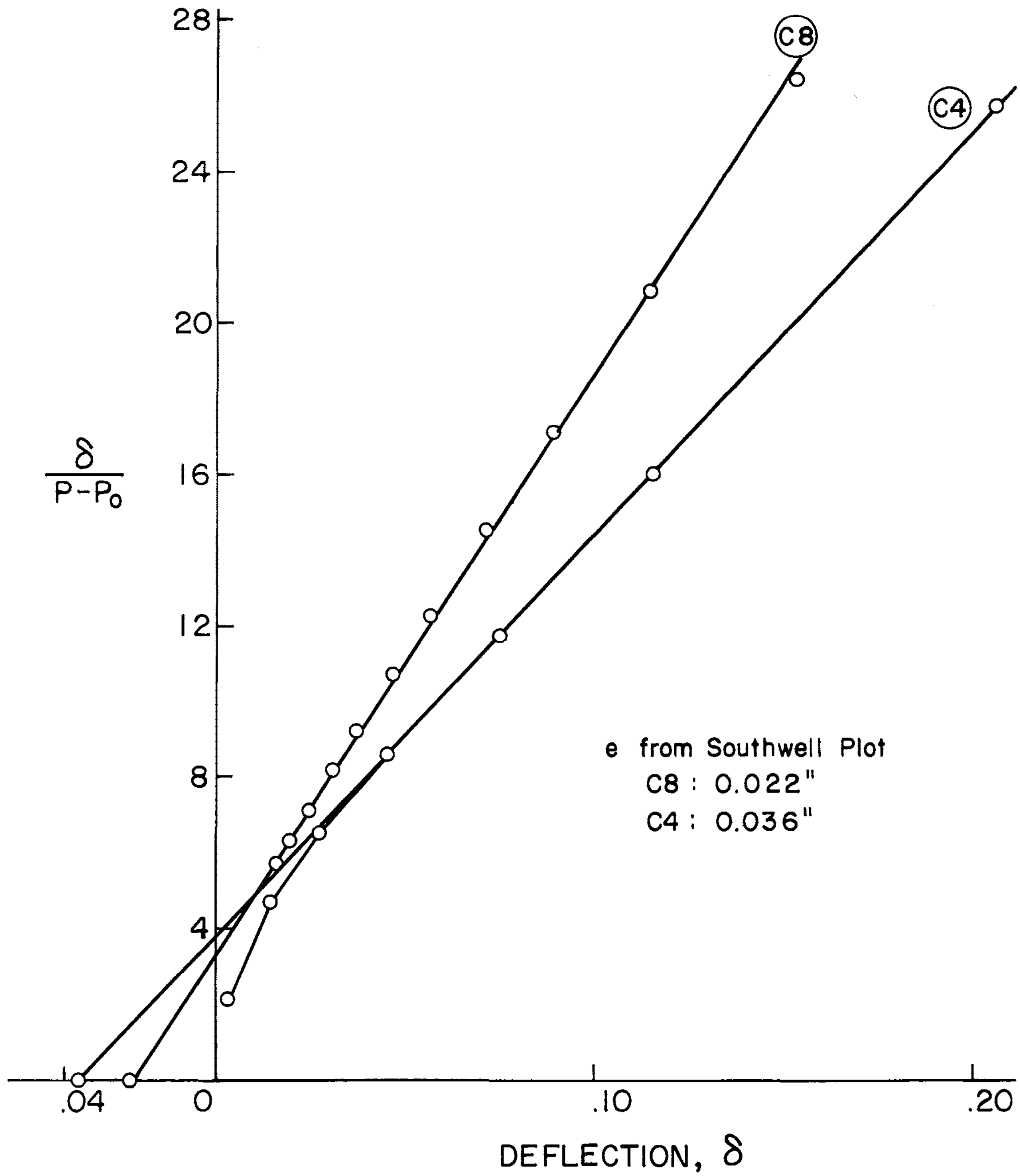

Fig. 14 MODIFIED SOUTHWELL PLOT FOR C4 AND C8

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