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LEHIGH UNIVERSITY INSTITUTE OF RESEARCH

Welded and Rolled T-1 Columns

A PILOT STUDY ON THE STRENGTH OF 5Ni-Cr-Mo-V STEEL COLUMNS

by
C. K. Yu
Lambert Tall

Fritz Engineering Laboratory Report 290-12

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

A PILOT STUDY ON THE STRENGTH OF 5Ni-Cr-Mo-V STEEL COLUMNS

by

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and

Lambert Tall

This work has been carried out as part of an investigation sponsored by the United States Steel Corporation.

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ABSTRACT

This report presents the results of the experimental investigation of the mechanical properties and strength of columns made of high-toughness alloy steel (5Ni-Cr-Mo-V steel) with a yield strength of about 140 ksi.

One column of 19'5" length was tested in the "flat-end" condition. Coupon tests, residual stress measurements and a stub column test also were conducted.

These tests were part of an overall study of the residual stresses in, and the column strength of, welded built-up and rolled heat-treated A514 steel columns. The present investigation on 5Ni-Cr-Mo-V steel extended the previous work on A514 steel columns. It was found that column strength can be predicted by using the tangent modulus concept.

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1. INTRODUCTION

Due to the increasing demands for higher stresses in, and larger sizes of structures such as long-span bridges, heavy-walled pressure vessels and hydrospace and space vehicles, the development and the use of weldable quenched and tempered constructional steels has been greatly accelerated. 5Ni-Cr-Mo-V steel with a yield strength of about 140 ksi shows the good weldability, toughness, and strength needed to fulfill these purposes.(1),(2),(3)

Although a great deal of research has been conducted on the investigation of metallurgical and welding characteristics of 5Ni-Cr-Mo-V steel by U. S. Steel under NAVSEC Contract NObs 88540,(1),(2),(3) this report is limited to the study of a rolled heat-treated wide flange section, and in particular, to its column strength and mechanical properties.

This pilot investigation included studies of:

1. The stress-strain relationship under a constant strain rate accepted by ASTM Standards in the elastic range, and under a zero strain rate in the inelastic range.
2. The patterns and magnitude of residual stress distribution in a rolled heat-treated wide flange section.
3. The effect of residual stress on the strength of columns.

4. Column behavior and theoretical predictions of strength.

Information from this study will indicate the possibility of using this steel for columns and beams in tall buildings.

2. DESCRIPTION OF TESTS

2.1 Test Material and Specimens

One piece of the rolled heat-treated 10WF112 section of approximately 30 ft. length was furnished by U. S. Steel Corp.* The member was austenitized by heating to 1500°F for 2 hours, and water quenched to ambient temperature. Then, it was tempered by heating to 1050°F for 2 hours, and water quenched.

The chemical composition (in per cent) is:

Carbon	0.08
Manganese	0.77
Phosphorus	0.007
Sulfur	0.012
Silicon	0.28
Nickel	4.92
Chromium	0.54
Molybdenum	0.51
Vanadium	0.07
Aluminum	0.012

Because of the very high strength of 5Ni-Cr-Mo-V steel and the comparatively larger thickness of this 10WF112 section, the ultimate load for a pinned-end column of medium slenderness ratio was greater than the maximum capacity of the pinned-end test fixture available in Fritz Laboratory. Therefore, the column was treated in the flat-ended condition.

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*The material was from an experimental heat produced during the development of Hy-130(T) steel on NAVSEC Contract NObs 88540

The detail of layout of specimens and geometric properties of the section are shown in Fig. 1. In Table 1 an outline of the test program is given. A complete set of experiments were performed, consisting of a test of the full-size column, a stub column test, seven standard tension coupon tests and ten compression coupon tests. Residual stress distribution was measured at two positions along the column in order to obtain a general pattern of the residual stress distribution representative throughout the whole length.

The coupon tests and stub column test were conducted first to determine the mechanical properties of the steel. Based on this information, the theoretical failure load of the column was computed and then the column test conducted.

2.2 Residual Stress Measurements

The residual stress distribution is one of the main factors influencing the strength of a column. Residual stresses are formed due to plastic deformations, due to cooling after rolling or welding, or to fabrication operations such as heat treatment or cold straightening. The mechanism by which residual stresses are formed has been studied extensively.(4)

The residual stresses were determined by the "method of sectioning".(4) Two sections, one located approximately 1'6" from one end, and the other approximately 3'0" from the other end, were used for residual stress measurements. The magnitude and distribution of residual stresses are shown in Figs. 2 and 3.

Residual stresses were measured over the whole surface at an interval of 1 inch between the adjacent points. It can be seen from Fig. 2 that the magnitude of residual stresses on top and bottom at any point are not identical. The deviation is more pronounced in the flanges with their comparatively large thickness of 1 ¼ in. The average residual stresses across the section is shown in Fig. 3.

The pattern of residual stress distribution is similar to those of previous investigations of rolled heat-treated A514 steel shapes,(5) with compressive stress on the flange tips and web center portion, and tensile stress at the junction of flange and web. The magnitude of residual stresses in this steel is slightly larger than those of A514 steel shapes. However, the residual stress magnitudes are less than 7% of the yield stress. Therefore, it was expected that the effect of residual stresses on the column strength is insignificant.

2.3 Mechanical Property Tests

Mechanical property tests include both tension and compression coupon tests. The reason for conducting both of these tests was to determine if the compressive and tensile properties for the steel are identical. For conventional carbon steels the information obtained from both tests are nearly identical; this was not the case for this steel.

Tension Coupon Tests

Three tension coupons, one from the web and two from the flanges, were cut from the member. Then, each flange coupon was sliced into three thinner coupons to fit the capacity of testing machine. The width of the coupons, according to ASTM standard for tension test specimens, is 1 ½", with a 2" gage length for the web coupon and 8" gage length for all the flange coupons. Dimensions of coupon specimens and test results are given in Table 2.

Figure 4 shows a typical stress-strain relationship for the steel. The sharp kink points, determined by stopping the test machine completely for about ten minutes, give "static" values (the value measured at a zero strain rate).(6) By connecting these points, as shown by the dotted line, a stress-strain relationship independent of the influence of strain rate, is obtained. The basic difference between this steel and carbon steels is that the stress-strain relationship can not be represented by the straight-line elastic-plastic assumption. Instead, after the elastic range, the slope of the stress-strain curve is continually decreasing with increasing stress. The Ramberg-Osgood representation(7) of the stress-strain curve gives a good approximation.

The Ramberg-Osgood representation is

$$\epsilon = \frac{\sigma}{E} + K\left(\frac{\sigma}{E}\right)^{n}, \qquad (2.1)$$

where E, σ and ϵ are the modulus of elasticity, the stress and the strain, respectively and K and n are constants depend on the material properties.

Using a curve fitting method(7) and a non-dimensional form, the stress-strain curve can be represented by the following equation

$$e = s + \frac{3}{7} s^n \qquad \begin{array}{l} n = 20 \text{ when } s \leq 1 \\ n = 65 \text{ when } s \geq 1 \end{array} \qquad (2.2)$$

where $e = \frac{\varepsilon E}{\sigma_1}$, $s = \frac{\sigma}{\sigma_1}$, and σ_1 is the secant yield strength, equal to the ordinate of the intersection with the stress-strain curve of a line through the origin having a slope equation to 0.7E. It is usually chosen in a way that makes σ_1 equal to σ_y (0.2% offset).

Compression Coupon Tests

Ten compression coupons were tested to determine the mechanical properties of the steel in compression and to compare the data with that obtained from tensile coupon tests. The dimensions of the compression coupons and test results are listed in Table 3. SR-4 gages were attached to each side of the rectangular coupon and the average value of the strain was used for the stress-strain relationship. The details of the instrumentation for a compression coupon test is shown in Fig. 5.

The test results of compression coupon tests show that the modulus of elasticity and yield stress are larger than those obtained from tension coupon tests. There appears to be no explanation for these differences, although it is expected to be metallurgical in nature.

Figure 6 shows a typical stress vs. strain curve for the compression coupon test. Due to the limitation of machine capacity the curve could not be obtained for strains much in excess of the yield strain; however, the curve is sufficient to determine the general type of stress vs. strain relationship and to furnish data relevant to the mechanical properties of the steel. In Fig. 6, comparison between the experimental results and the Ramberg-Osgood curve (Eq. 2.2) shows a good agreement. Since Eq. 2.2 is obtained from the tension coupon tests, it may be concluced that the same Ramberg-Osgood curve in non-dimensional form can be used to represent the stress vs. strain relationship for both compression and tension coupon tests, although the static yield stress and modulus of elasticity obtained from one test differ from those from the other.

From the test data, the important mechanical properties of this steel are

	σ_y static yield stress (ksi)	E* modulus of elasticity (ksi)
Tension Coupon test	130	28.4×10^3
Compression coupon test	140	29.6×10^3

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*The values of E should be regarded as indicative only, since they were measured directly from the antographically recorded curve.

2.4 Stub Column Test

A stub column test was performed in order to obtain the average stress-strain curve for the complete cross-section; this curve includes the effect of the residual stress. The length of a stub column should be sufficiently long to retain the original magnitude of residual stresses and short enough to prevent any premature failure from occurring before the yield load of the section is obtained.(8) For this 10WF112 section, a length of 3'4" was selected.

The average stress-strain curve obtained from the stub column test is given in Fig. 7. Using the same Ramberg-Osgood representation, with $n = 19$ when $s \leq 1$, and $n = 65$ $s \geq 1$, a good approximation to the test results is obtained. Figure 8 also shows a comparison between the actual test points and the Ramberg-Osgood curve.

The Ramberg-Osgood equations obtained from tension coupon tests, compression coupon tests and from the stub column test are nearly identical, except that of the stub column has a slightly smaller value of n for $s \leq 1$. Because the stress-strain curve obtained from mechanical property tests (both tension and compression) is very close to that of the stub-column tests, it is expected that the effect of residual stresses on the strength of columns is insignificant.

2.5 Column Test

One column of 19'5" length was tested. The ends of the column were machined flat and then welded to a 2 ½" thick base plate. Due to the limitation of the capacity of the available end fixtures, the column was tested in the flat-end condition. For a perfectly straight column without residual stresses, tested in the fixed-end condition, the effective length of the column is one-half that of the pinned-end column, that is, the effective length factor K is 0.5. In the flat-end condition, the ends were not fully fixed and the testing machine structure is not completely rigid; in addition, the column itself was not perfectly straight. The effective length factor of a flat-end column can be assumed as 0.55 to 0.6. The actual effective length of the column was measured between points of inflection by the SR-4 strain gages, attached along the column as shown in Fig. 8.

The initial out-of-straightness of the column was measured before performing the test, as shown in Fig. 9. The maximum e/b was 0.0086, where e is the measured maximum out-of-straightness and b is the width of the flanges.

The column was tested in a 5,000,000 lb. hydraulic testing machine. Alignment was performed by adjusting the tapered disc furnished by the testing machine at the top of the column and by moving the whole column. The maximum load used for alignment was less than the load which would yield the section. In this test, a maximum alignment load of 1,500 kips was used.

The column failed by bending about the weak axis. The ultimate load was 3,320 kips or 0.726 P_y. Figure 10 shows the load vs. mid-height deflection curve.

The curvature at each different location along the column was measured by the four SR-4 gages at the four corners. The curvature at any position was computed by the equation

$$\phi = \frac{(\epsilon_3 + \epsilon_4) - (\epsilon_1 + \epsilon_2)}{2d} \tag{2.3}$$

where ϕ is the curvature, ϵ_3, ϵ_4 the strain readings on concave side, and ϵ_1, ϵ_2 the strain readings on the convex side.

Figure 11 shows the plot of curvature along the length. It is noted that the points of inflection, that is, zero curvature points, are not fixed but rather change with load. Thus the effective length of the column is not a constant but a function of applied load. This might be due partly to the initial out-of-straightness and partly to the fact that the rigidity of the testing machine varies with the applied load. Table 4 shows the effective length and effective length factor of the column at different loading. The effective length factor K ranges from 0.56 to 0.64 with a average value of 0.61 and 0.58 at the ultimate load.

From Fig. 10, it can be seen that the lateral deflections begin at a load approximately one-half of the ultimate load and that no point of bifurcation could be observed. This is because the column was not initially perfectly straight. Figure 12 shows the overall deflected shape of the column throughout the duration of the test. It also shows that the points of inflection were changing with the load.

3. THEORETICAL INVESTIGATION

3.1 Introduction

Since the publication of Shanley's papers(9),(10) the tangent modulus load has been recognized as the smallest value of the axial load at which bifurcation of equilibrium can occur, and has therefore been considered as the design criterion for a centrally loaded column, although the actual ultimate load of a perfectly straight column should be always slightly higher than the tangent modulus load.(11) Because of the effects of the inevitable initial out-of-straightness of the columns, it was found that the ultimate load usually is close to the tangent modulus load if the initial out-of-straightness is small.

In this study, the tangent modulus load concept was adopted for the determination of the column strength. However, several usual assumptions are made in the theoretical analysis, as follows:

1. Plane sections remain plane.
2. Stress-strain relationship in any "fiber" of the column are the same as under uniform strain.
3. Column is initially perfectly straight.
4. Residual stress magnitude and distribution are the same at every cross section of the column.

3.2 Column Strength

The Ramberg-Osgood type curve, which is used to represent the stress-strain relationship of this "5Ni-Cr-Mo-V" steel, is not perfectly elastic-plastic in nature; thus, it will be very difficult to find an explicit analaytical solution for most practically used shapes with the consideration of the residual stress effect. A numerical analysis by using a digital computer is necessary.

From the conditions of equilibrium of internal and external forces, the governing equations obtained are(12)

$$\int_A E_t \; y \; dA = 0 \tag{3.1}$$

and

$$\frac{d^2v}{dx^2} \int_A E_t \; y^2 \; dA + pv = 0 \tag{3.2}$$

where
y, distance of a point on the section from the neutral axis
x, coordinate along the length of the column
P, axial force
v, deflection in the direction of y

Equation 3.1 gives the location of the neutral axis. For a symmetric section, this axis coincides with the principal axis of the section. The critical load P_{cr} is obtained from equation 3.2 as

$$P_{cr} = \pi^2 \frac{\int_A E_t y^2 dA}{L^2} \tag{3.3}$$

where L is the length of the column. If the notation $(EI)_m$, modified flexural stiffness, is introduced,

$$(EI)_m = \int_A E_t \, y^2 \, dA \tag{3.4}$$

Then,

$$P_{cr} = \frac{\pi^2 (EI)_m}{L^2} \tag{3.5}$$

Here, $(EI)_m$ depends on the residual stress distribution across the section, and the magnitude of applied force and stress-strain relationship of the material. It will not be generally practical to calculate P_{cr} directly. Instead, the equivalent length L is solved. Steps for numerical computation are as follows;

1. divide the section into a sufficient number of finite area meshes.
2. record the residual strain at each point (assuming residual stresses distributed on each mesh are uniform and same as that at the center point of the mesh).
3. apply uniform strain on the column. The total strain at a point is equal to the residual strain plus applied uniform longitudinal strain.
4. from the stress-strain curve, locate the corresponding stress and tangent modulus for each mesh.
5. sum up the internal axial forces on all the meshes $P = \int_A \sigma \, dA$ and compute modified flexural stiffness $(EI)_m$ from Eq. 3.4.

6. Compute equivalent column length for the calculated P_{cr} and $(EI)_m$

$$L = \pi \sqrt{\frac{(EI)_m}{P_{cr}}}$$

7. increase the applied uniform longitudinal strain and repeat step 1 to step 6 until the whole column strength curve is obtained.

3.3 Results and Evaluation

Figure 13 shows the theoretical column curves obtained from the computation procedure described in Section 3.2. Compare the curve without the consideration of residual stress effect to those considering the effect of residual stresses; it shows that their difference are indeed small. This is because the residual stress in this rolled "5Ni-Cr-Mo-V" steel shape are relatively small with respect to the yield stress of the material. This confirms the previous predictions obtained from actual residual stress measurements and stub column test that the influence of residual stresses on the strength of this column is insignificant.

The Column Research Council column strength curve ("CRC Curve") is also plotted in Fig. 13. It is close to the theoretically calculated tangent modulus load curves of this column, thus it is expected that the same design philosophy may be applied to the design of rolled "5Ni-Cr-Mo-V" steel columns although the material properties of this steel and residual stress distribution in this shape are different from those of the rolled A7 shapes from which the CRC curve was derived.

The experimentally observed load is compared with the theoretically computed tangent modulus load, bent about the weak axis. It was found by using the effective slenderness ratio $KL/r = 50.5$ (or $K = 0.58$ at ultimate load) that the test ultimate load 3320 kips shows a good agreement with the predicted load, 3430 kips (or $0.75\ P_y$) see Fig. 13. The small discrepancy is due probably to the effect of initial out-of-straightness.

4. SUMMARY

A study of the column strength of a rolled 5Ni-Cr-Mo-V steel wide flange section is presented. The test program consisted of the study of mechanical properties, residual stresses and column strength.

Based on the experimental study, the following conclusions may be made:

1) Tension coupon tests show that the 5Ni-Cr-Mo-V steel column studied had a static yield stress σ_y (0.2% offset) = 130 ksi and modulus of elasticity E = 28.4 x 10^3 ksi; and compression coupon tests show σ_y = 140 ksi and E = 29.6 x 10^3 kis (Tables 2 and 3). No explanation is available as to why the results from compression coupon tests are higher than those of tension coupon tests.

2) The pattern of residual stress distribution is similar to those of previous investigations of rolled heat-treated A514 steel shapes. However, the magnitude of residual stresses are slightly larger than those of A514 steel shapes with a maximum compressive residual stress about 10 ksi on the flange tips (Figs. 2 and 3).

3) The stress-strain curve is of a non-linear type, and the Ramberg-Osgood curve gives a good representation by assuming $n = 20$ when $s \leq 1$ and $n = 65$ when $s \geq 1$ (Fig. 6).

4) The theoretical tangent modulus load shows good agreement with the test ultimate load if the effective length of the column at ultimate load can be accurately determined. In the case when the actual effective length can not be detected, the assumption of K equal to 0.6 (average effective length factor) gives a good prediction of strength for flat end columns.

5. ACKNOWLEDGEMENTS

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The United States Steel Corporation sponsored the study, and appreciation is due to Charles G. Schilling of that corporation who provided much information and gave many valuable comments. Column Research Council Task Group 1 under the chairmanship of John A. Gilligan provided valuable guidance. K. Okuto assisted in the tests. Appreciation is due also to authors' colleagues who assisted in various parts of the study.

6. NOMENCLATURE

b	width of the flanges
E	modulus of elasticity
E_t	tangent modulus
e	$\epsilon E/\sigma_1$, measured maximum out-of-straightness
K, n	constants in Ramberg-Osgood representation
L/r	slenderness ratio
P	axial force
s	σ/σ_1
v	deflection
x	coordinate along the length of the column
y	distance of a point on the section to the neutral axis
ϵ	strain
σ	stress
σ_1	secant yield stress
σ_{cr}	buckling (critical) stress
σ_y	static yield stress

7. TABLES AND FIGURES

TABLE 1. OUTLINE OF TEST PROGRAM

	Length	Number of Tests
Column Test	19' 5"	1
Stub Column Test	3' 4"	1
Residual Stress Measurement	11"	2
Tension Coupon Test	1' 8"	7
Compression Coupon Test	2"	10

TABLE 2. TENSION COUPON TEST RESULTS

Shape	Piece	Coupon No.	Width (in.)	Thickness (in.)	Modulus of Elasticity E(10^3ksi)	Static yield stress σ_y(ksi) (0.2% offset)	Ultimate Stress σ_u	Reduction of Area (%)	Gage Length (in.)	Elongation in Gage Lgth. (%)	Testing Machine
10WF112	HY-1 (flange coupon)	HY-1A	1.502	0.253	28.1	131.5	142.8	34.2	8	9.0	120^k mech. testing machine
		HY-1B	1.503	0.499	28.2	134.5	146.7	50.5	8	12.8	
		HY-1C	1.503	0.254	28.5	130.0	141.7	41.9	8	9.5	
	HY-2 (web coupon)	HY-2	1.501	0.787	28.5	130.0	143.7	52.2	2	--	300^k hydrau. test. machine
	HY-3 (flange coupon)	HY-3A	1.502	0.378	28.6	130.0	141.6	39.4	8	12.6	120^k mech. test. machine
		HY-3B	1.504	0.252	28.5	130.0	141.8	52.2	8	10.1	
		HY-3C	1.505	0.375	28.2	130.0	142.2	42.2	8	12.1	

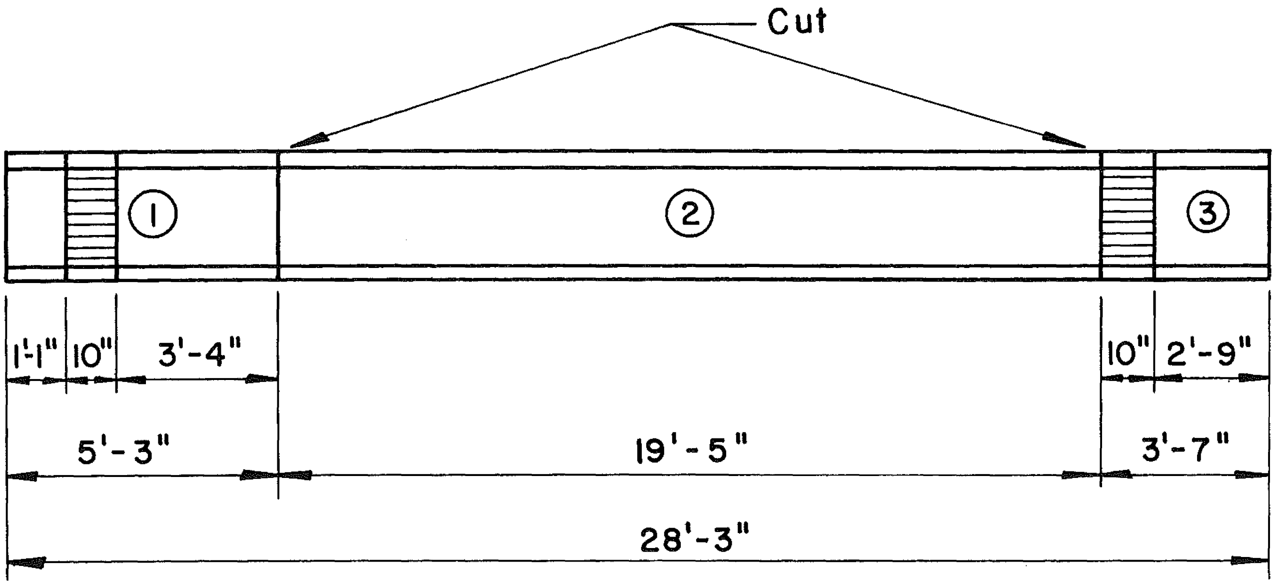
TABLE 3. COMPRESSION COUPON TEST RESULTS*

No.	Width (in)	Thickness (in)	Area (in^2)	Static Yield Stress (ksi) (0.2% offset)	Modulus of Elasticity (10^3ksi)
19	0.750	0.751	0.564	141	29.8
15	0.754	0.751	0.565	142	29.8
6	0.650	1.225	0.795	143	29.6
2	0.653	1.225	0.800	143	29.6
29	0.650	1.225	0.795	142	29.5
A-2	0.652	1.225	0.800	141	29.8
A-29	0.650	1.220	0.794	143	29.6
A-6	0.651	1.225	0.797	141	29.8
A-19	0.752	0.753	0.566	142	29.4
A-15	0.751	0.755	0.567	141	29.3

*All compression coupons are 2 in. in length

TABLE 4. EFFECTIVE LENGTH FACTORS DURING LOADING

Load No.	Load (kips)	Effective Slenderness Ratio KL/r	Effective Length Factor K
8	2700	55.5	0.64
9	3000	54.5	0.63
10	3080	56.0	0.64
11	3140	56.0	0.64
13	3230	54.1	0.62
14	3260	53.3	0.61
15	3280	54.5	0.63
16	3310	53.7	0.62
17	3320	50.5	0.58
18	3300	48.8	0.56
19	3050	49.2	0.56



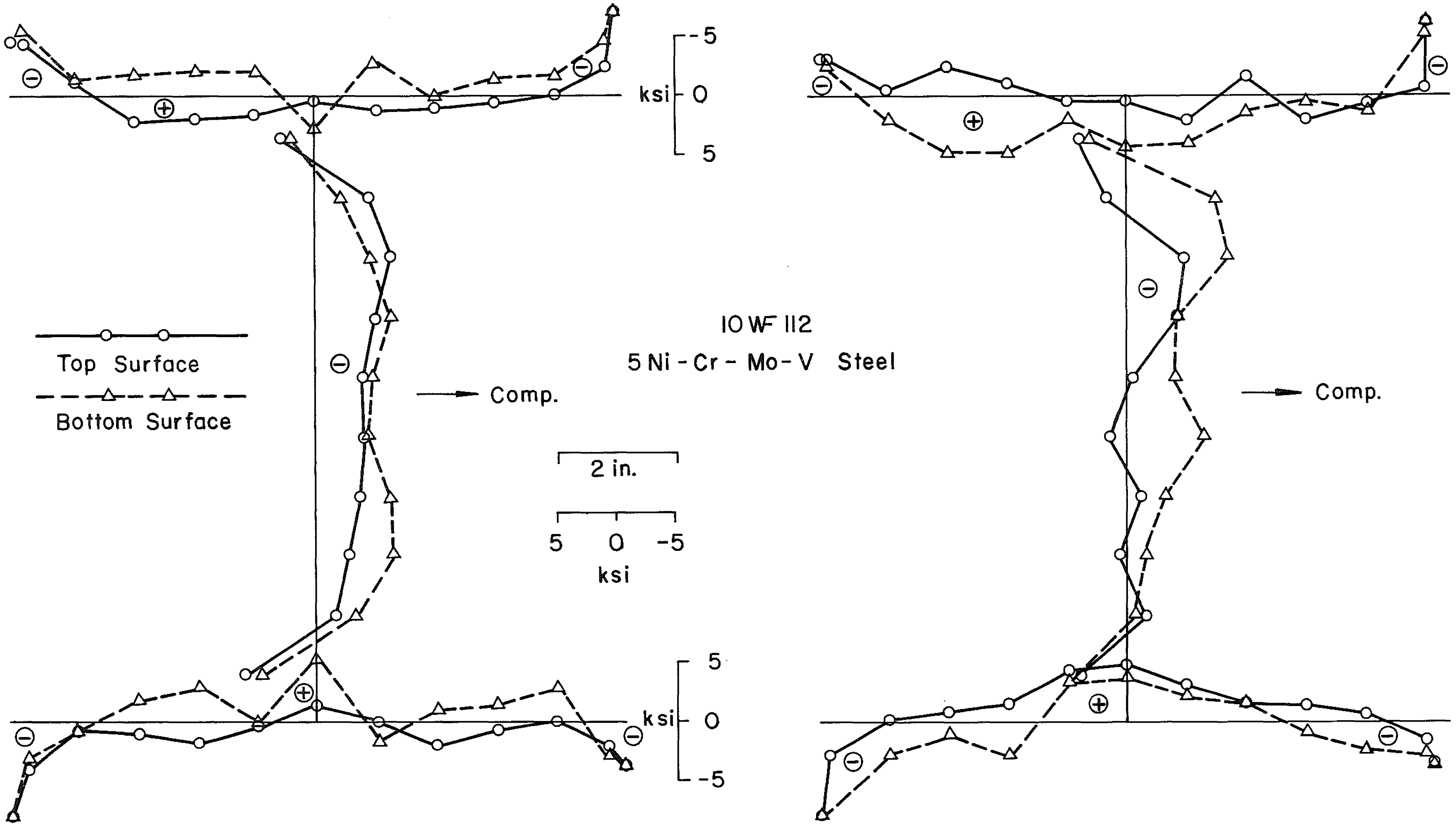
Piece:

① Residual stress measurement, compression coupons and stub column test.

② Column test.

③ Residual stress measurement and tension coupons.

Fig. 1 Layout of a Delivered Piece



Measurement No. 1

Measurement No. 2

Fig. 2 Residual Stress Distribution

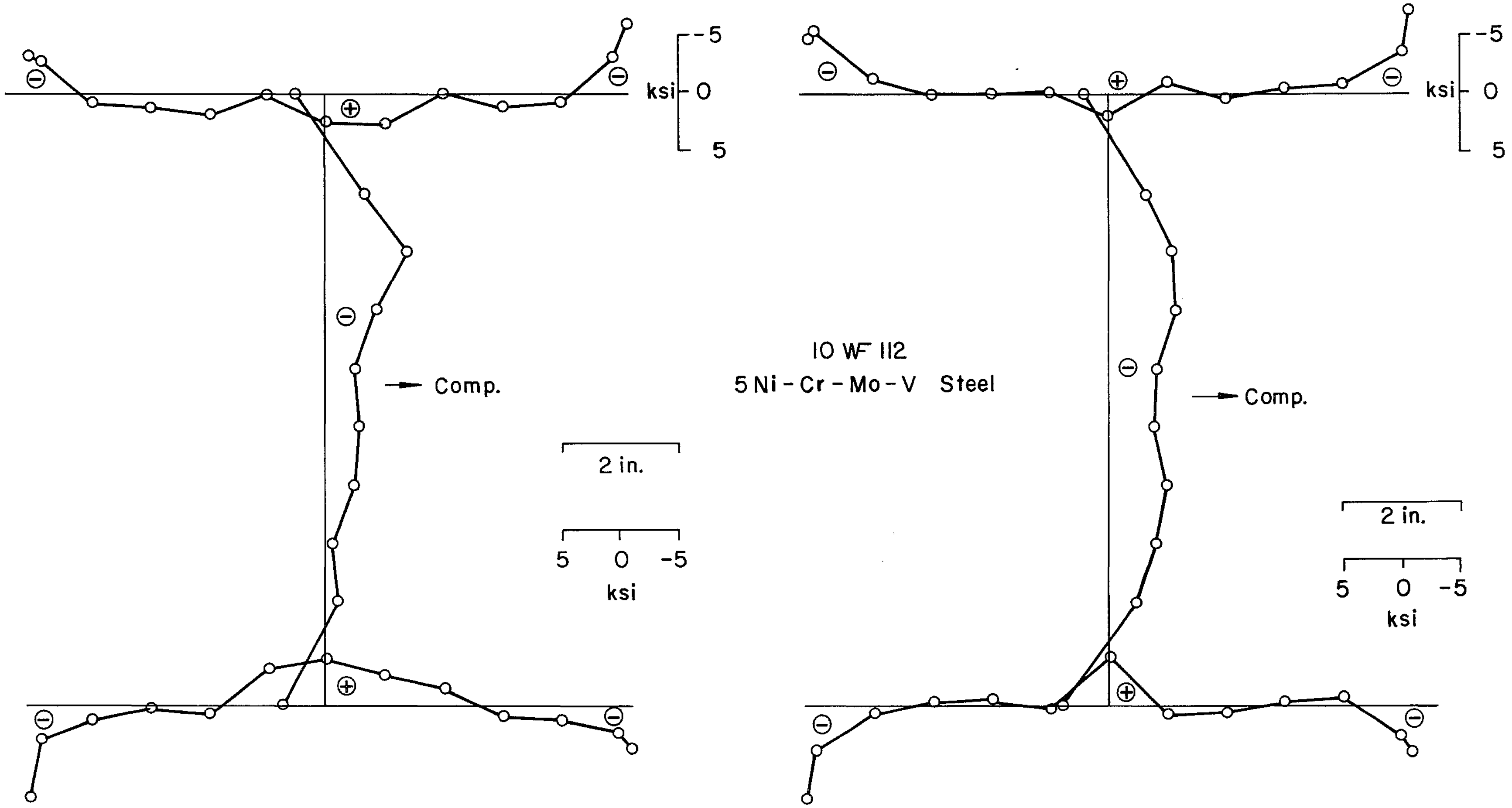


Fig. 3 Residual Stress Distribution (Average)

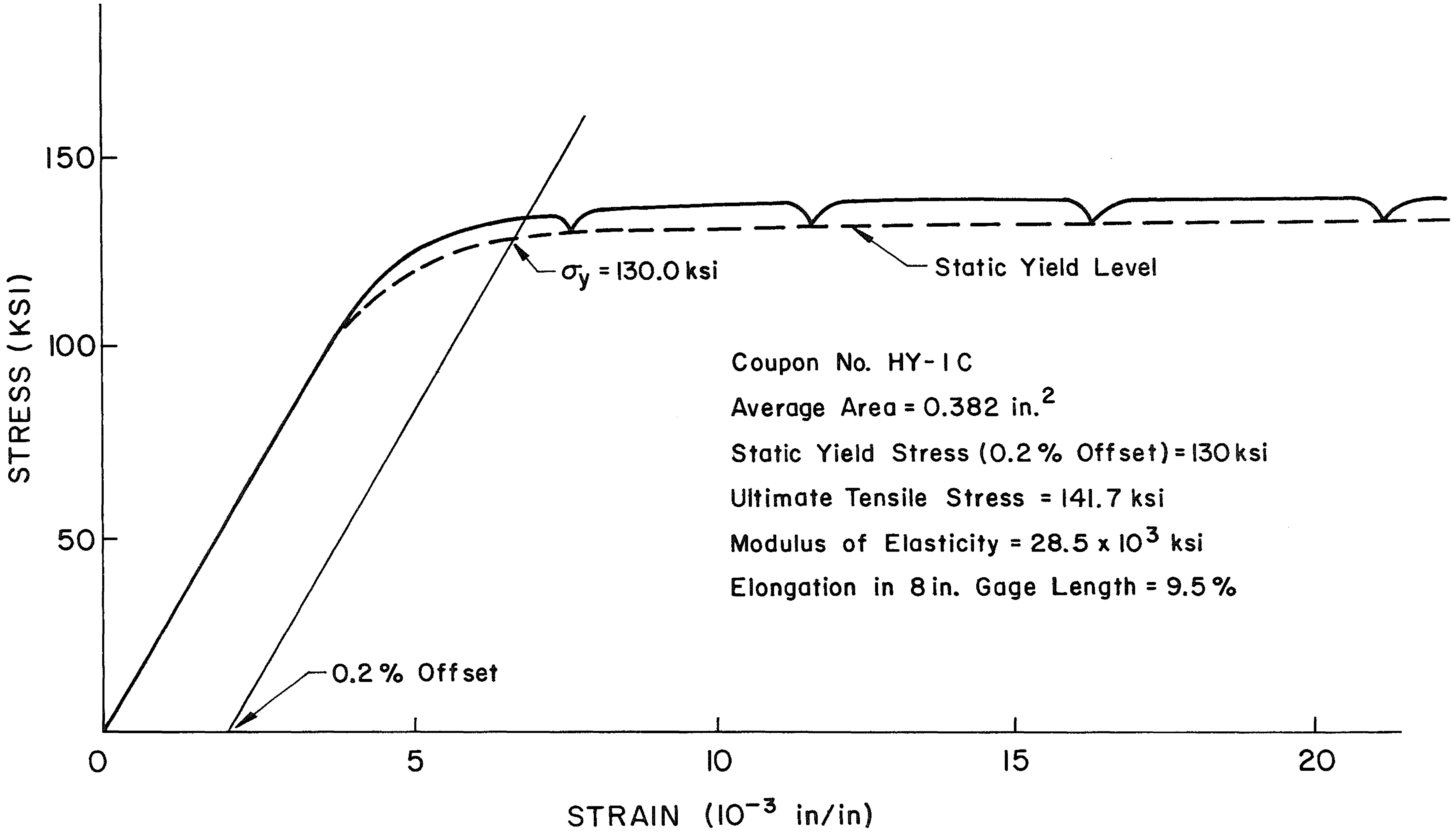


Fig. 4 Typical Stress Strain Curve for a Tension Coupon

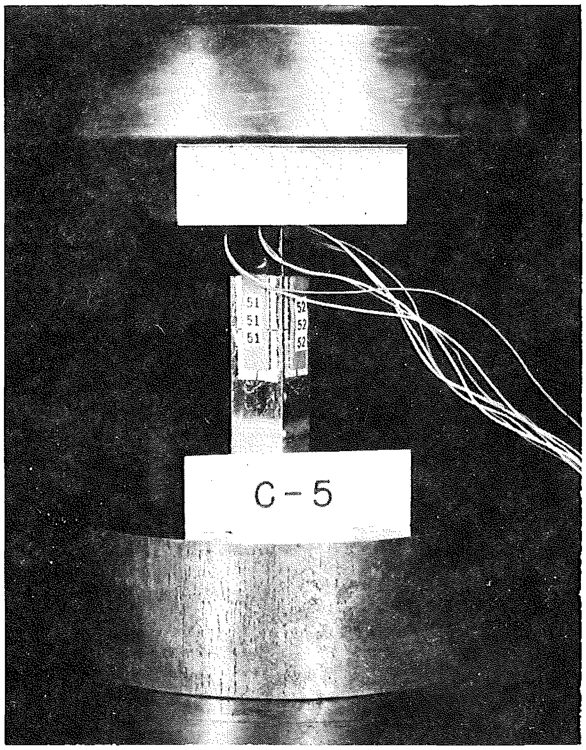


Fig. 5 Instrumentation for a Compression Coupon Test

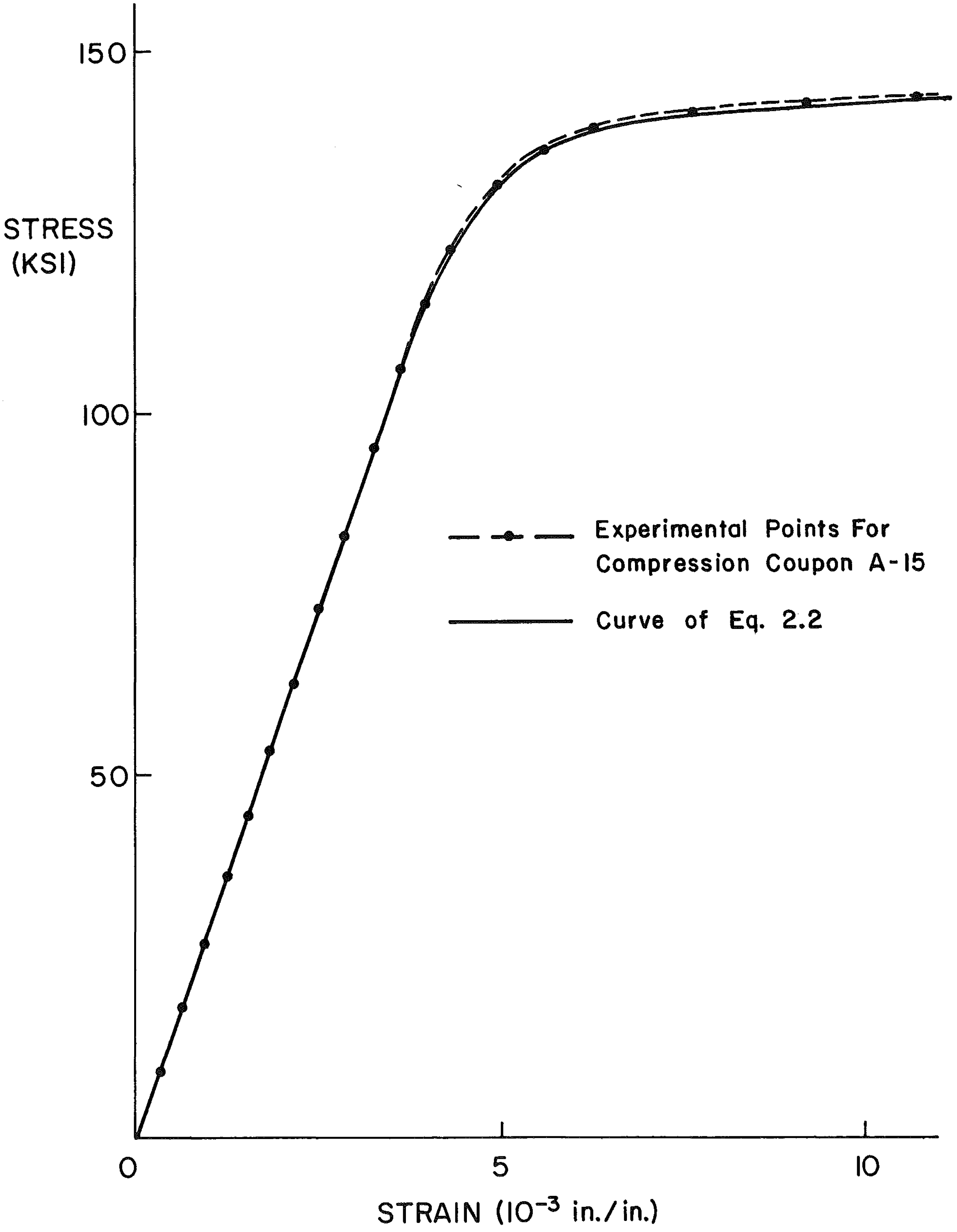


Fig. 6 Typical Stress-Strain Curve for a Compression Coupon Test

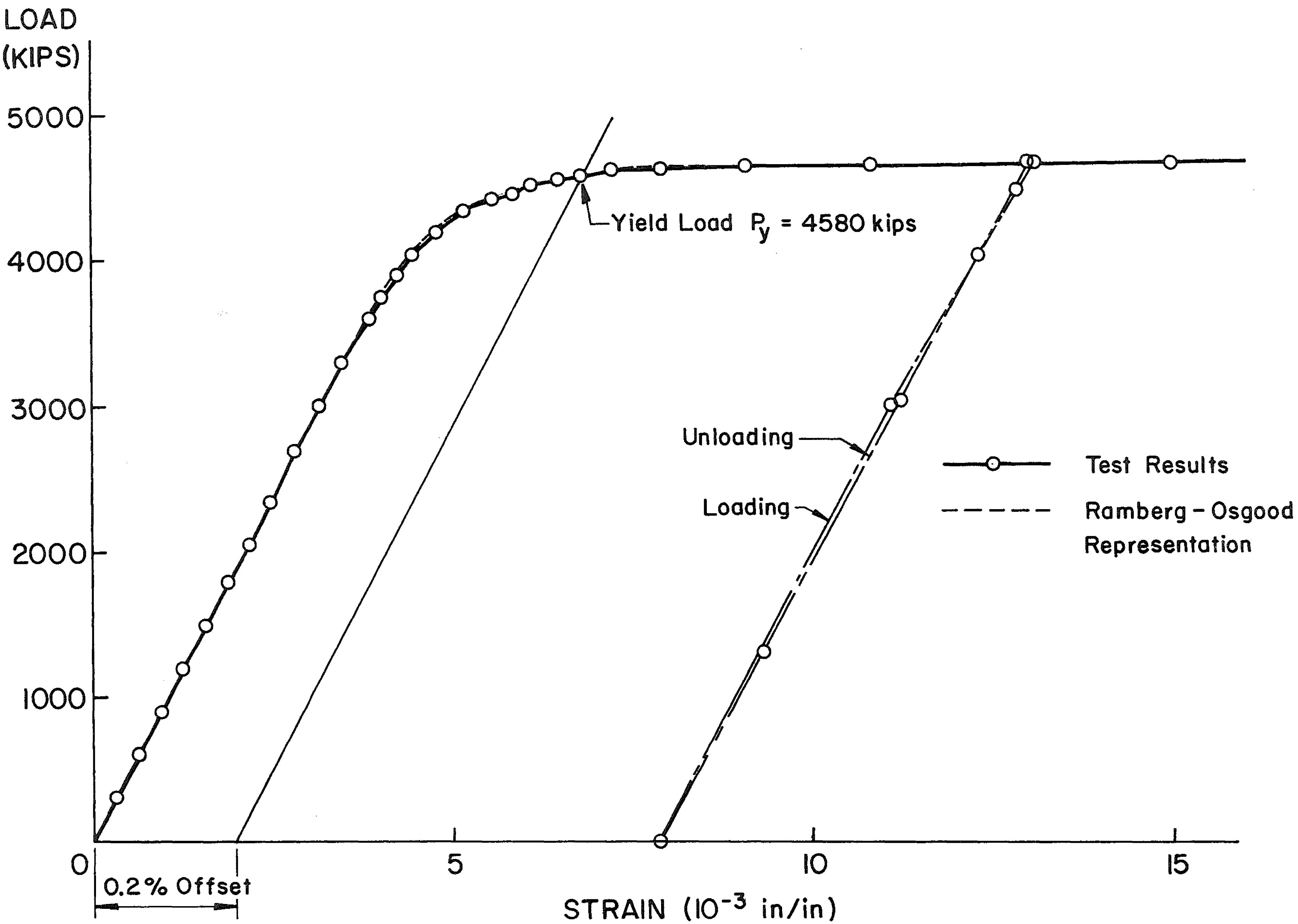


Fig. 7 Load-Strain Curve for a Stub Column Test

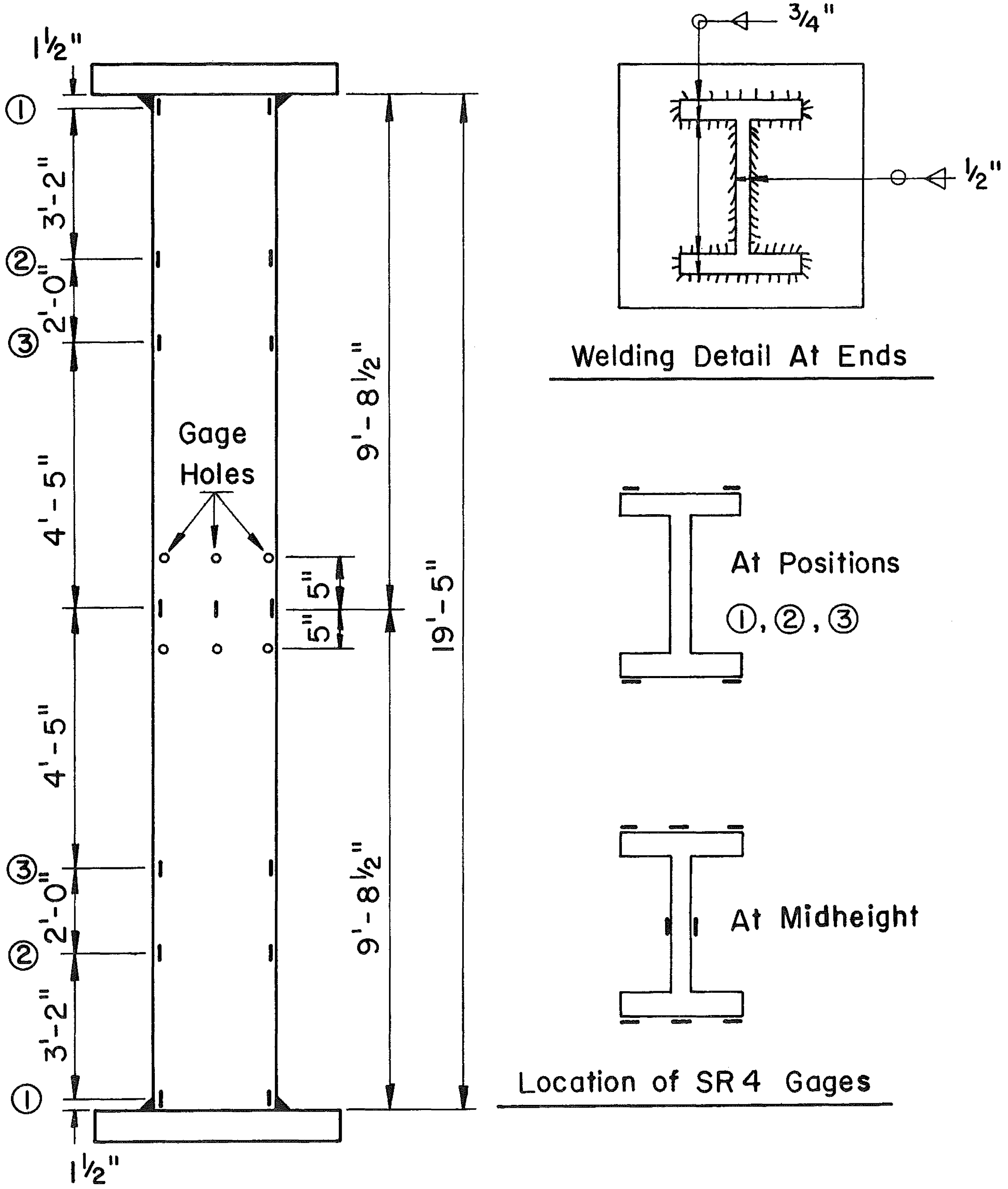


Fig. 8 Detail of the Column Test Specimen

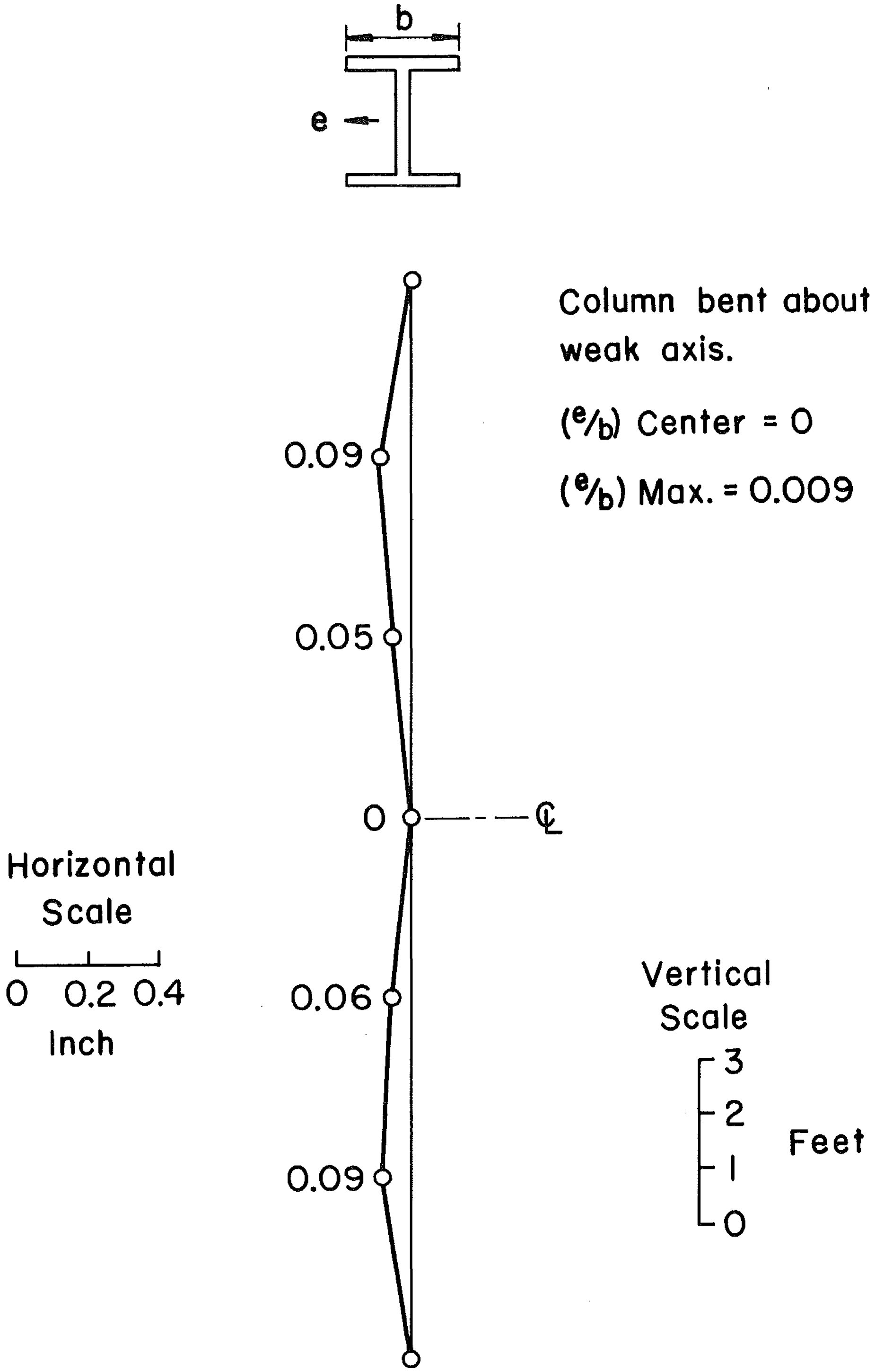


Fig. 9 Initial Out-of-Straightness of the Test Column

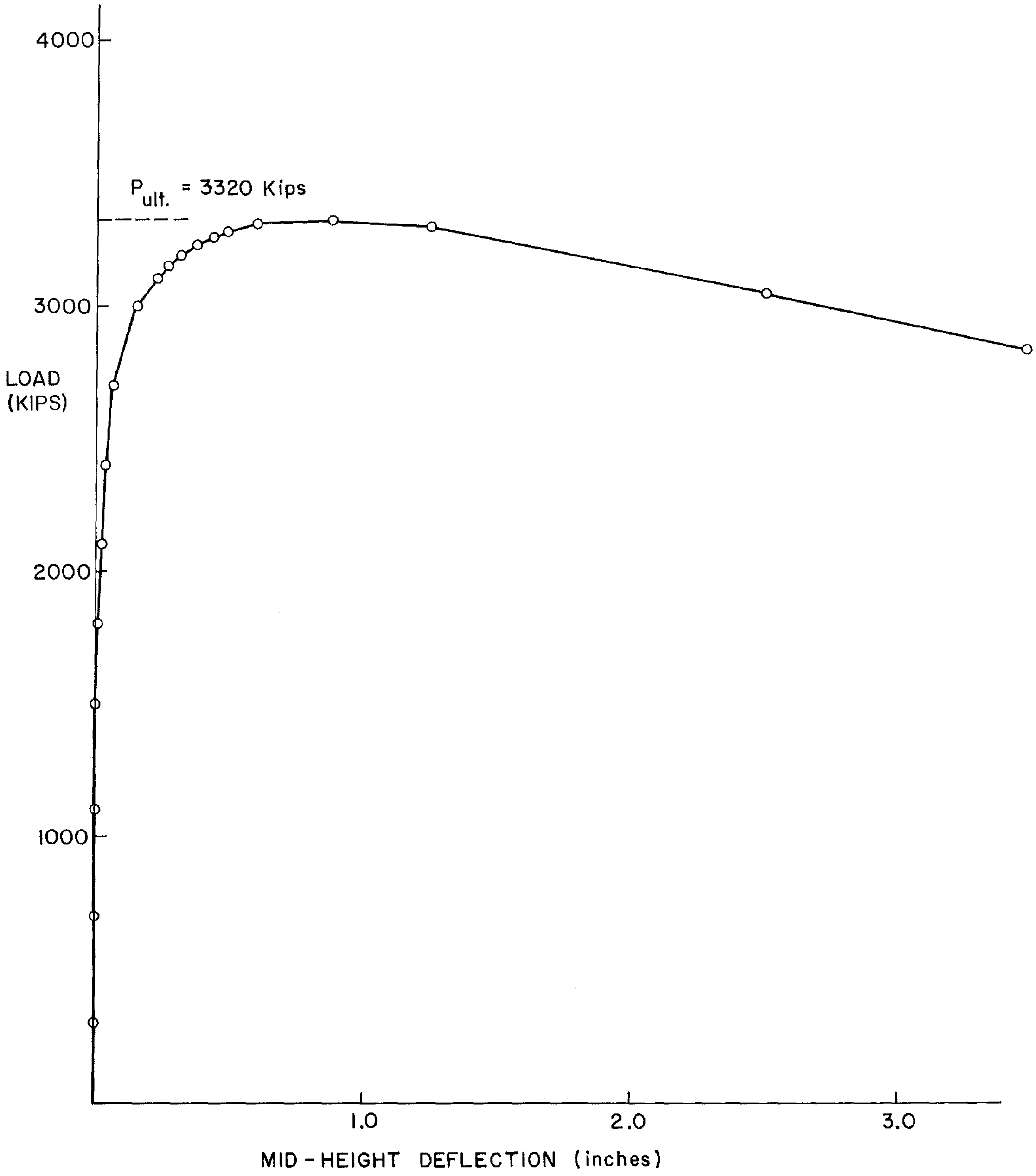


Fig. 10 Load Deflection Curve for Column Test

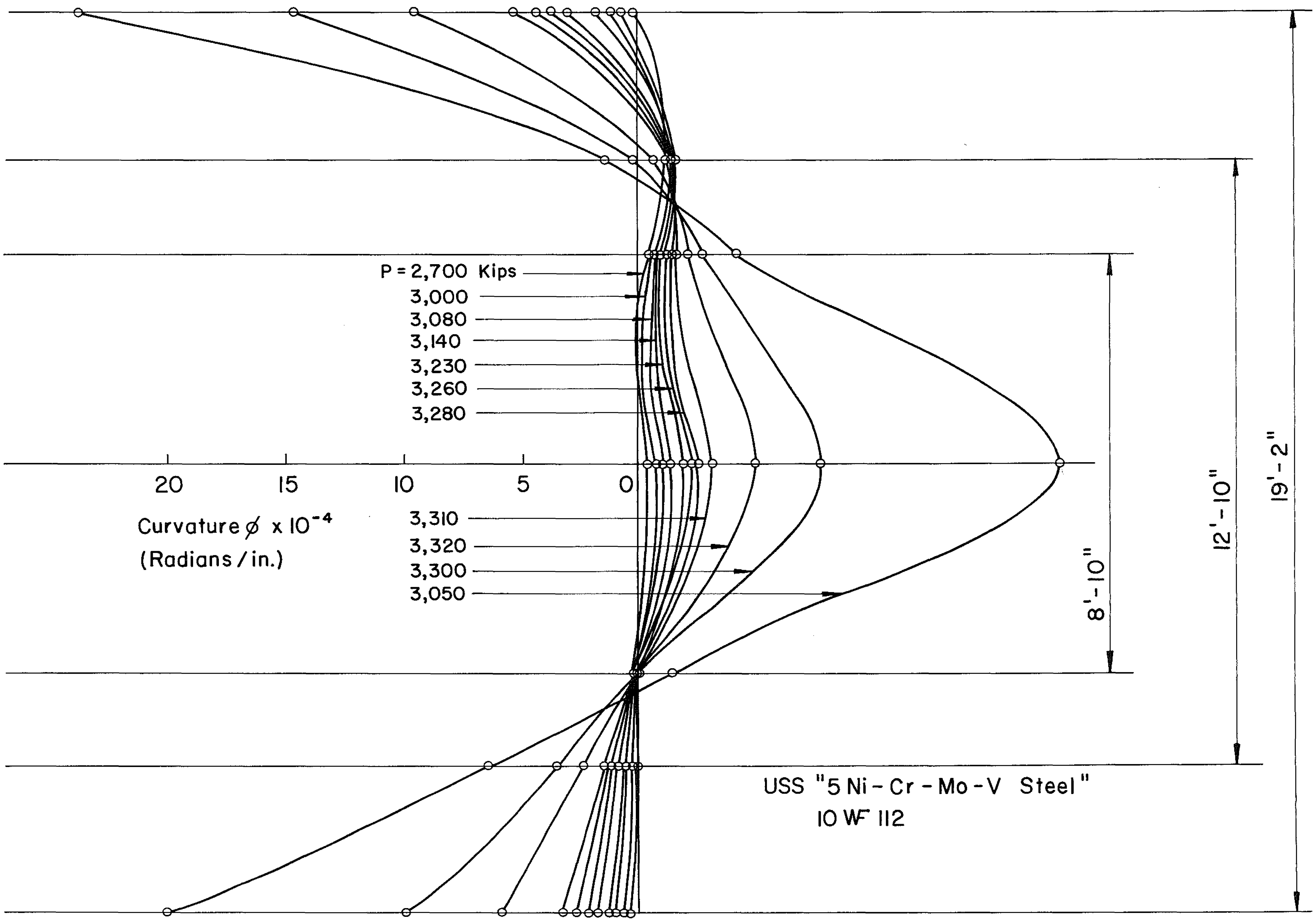


Fig. 11 Curvature Curves

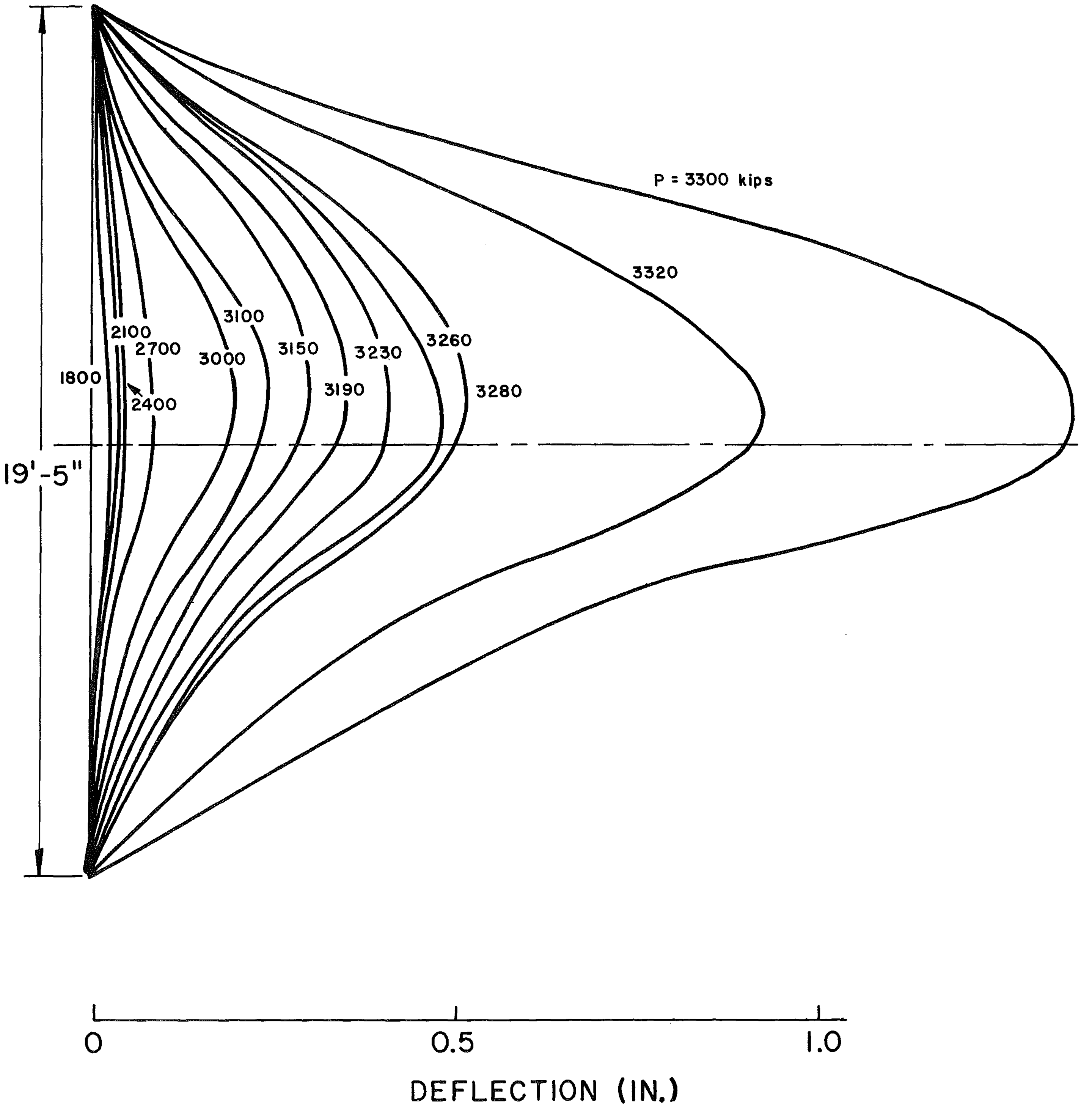


Fig. 12 Deflections Along the Column During Test

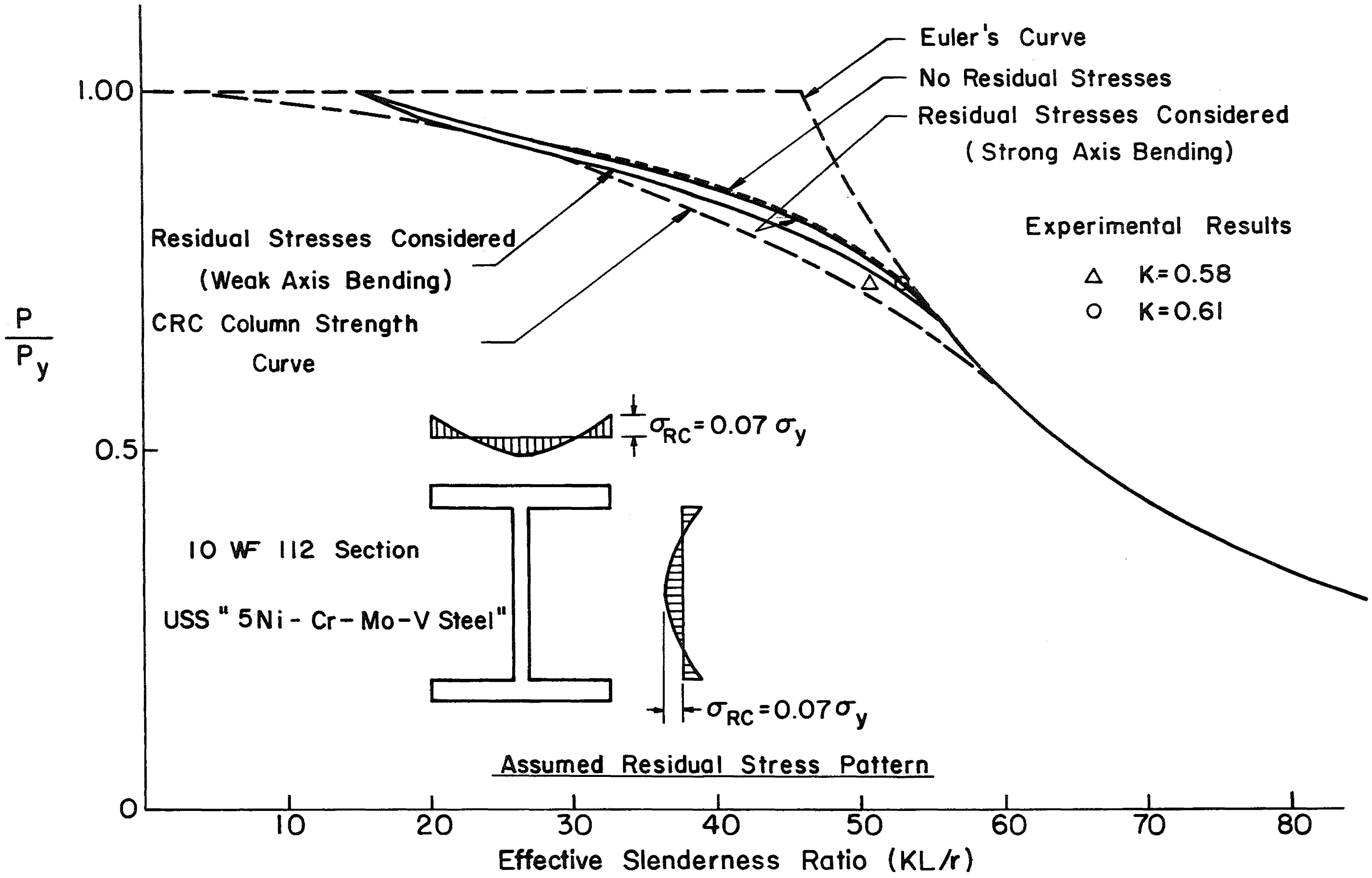


Fig. 13 Column Strength Curves

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