Lehigh University
Lehigh Preserve

Fritz Laboratory Reports

Civil and Environmental Engineering

1965

Residual stresses in rolled beat. Treated T-1 shapes, July 1965, Reprint No. (67-3)

E. Odar

F. Nishino

L. Tall

LEHIGH UNIVERSITY INSTITUTE OF RESEARCH

LEHIGH UNIVERSITY
Centennial Anniversary 1965-66

Welded and Rolled T-1 Columns

RESIDUAL STRESSES IN ROLLED HEAT-TREATED T-1 SHAPES

by

Enver Odar
Fumio Nishino
Lambert Tall

Fritz Engineering Laboratory Report No. 290.5

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

RESIDUAL STRESSES IN ROLLED HEAT-TREATED T-1 SHAPES

by

Enver Odar

Fumio Nishino

Lambert Tall

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

Fritz Engineering Laboratory

Department of Civil Engineering

Lehigh University

Bethlehem, Pennsylvania

September 1965

Fritz Engineering Laboratory Report No. 290.5

TABLES OF CONTENTS

ABSTRACT

This report presents the results obtained from an experimental investigation of residual stresses in rolled heat-treated "T-1" steel shapes. "T-1" steel meets the requirements of ASTM Designation A514.

Residual stresses present in medium-size sections were measured and the results obtained were compared with the results for similar shapes of other steels. The knowledge of residual stress in the cross section makes it possible to predict the strength of the compression members made of steel.

Results obtained showed that the geometry was the most important factor for the formation of residual stress. The heat treatment after rolling appears to have reduced the magnitude of the observed residual stresses; the maximum value of compressive residual stress did not exceed 10 ksi. Since the value of compressive residual stress constitutes only a small fraction of the yield strength, the effect of the residual stress on the load carrying capacity of the compression members made of heat treated T-1 steel shapes may be expected to be negligible.

1. INTRODUCTION

A research project on "Welded Built-Up and Rolled Heat-Treated T-1 Columns"* has been in progress at Fritz Engineering Laboratory, Lehigh University. Experimental investigation of residual stress present in members made of T-1 steel is the first and basic phase of this project. The study of residual stresses was carried out in three separate parts; residual stresses in welded T-1 steel plates, residual stresses in welded built-up shapes, and residual stresses in rolled heat-treated shapes. This report is concerned with the residual stresses present in rolled heat-treated T-1 steel shapes.

Purpose and Scope

It has long been known that an axially loaded steel column does not behave in accordance with the simple Euler formula for the buckling load. As soon as yielding occurs in a section of a column due to compressive residual stresses in those regions, the Euler buckling formula is no longer valid[1,2]. The buckling load may be determined from the tangent modulus load taking into account the effect of the residual stresses[1,2,3]. The knowledge of the magnitude and distribution of residual stress in the section is essential for the determination of the strength of steel columns[3].

* "T-1" steel is a high strength structural alloy steel produced by the United States Steel Corporation; it meets the requirements of ASTM A514 and/or A517 steel.

Influencing Factors

The residual stresses in rolled shapes are generally produced during cooling from rolling or from other processing and fabrication procedures, such as heat-treatment, cambering and cold-straightening after rolling. Residual stresses are the stresses present in the shape at ambient temperature before the application of any external load.

All the shapes in this study were rolled heat-treated shapes made of T-1 steel. The heat-treating procedure was standard for all rolled shapes. All shapes were water quenched from 1650^{o}F and then tempered at temperatures ranging from 1150-1200^{o}F, (except 12WF36 which was tempered at 1200-1250^{o}F), and then air cooled.

The plastic deformations during cooling are dependent on many factors, such as the rate of cooling, the material properties, the temperature distribution, and the most important one being the size and geometry of the shape. Generally, the portions of a section which cool rapidly are first under residual tension and the portions which cool slower are initially under compression. During this process, yielding may occur in tension or compression, or both, and the resulting non-elastic deformations determine the magnitude and distribution of the residual stress[4,5]. Thus, in wide flange shapes the flange tips and the center of the web, which cool more rapidly, will exhibit compressive residual stress, and the flange center and web ends, which cool slower, will exhibit tensile residual stresses[4,6].

The heat treatment after rolling that is used in producing T-1 steel shapes apparently reduces the residual stresses; however, the general pattern of the resulting residual stress is the same as that observed in hot rolled sections which have not been heat treated. In this study an attempt was made to avoid, for the purpose of residual stress measurements, those parts affected by cold working.

Previous Studies

A rather extensive study was carried out in Fritz Laboratory on residual stresses in rolled shapes. The test results are available for a wide range of shapes of ASTM A7, ASTM A242, and ASTM A441 steels. Refs. 2, 4 and 7 give the results for A7 steel shapes, Ref. 8 presents the results for A242 steel shapes, and Ref. 9. gives the results for A441 steel shapes. Also, Ref. 4 presents a theoretical prediction for cooling and cold working residual stresses in wide-flange beams. For one particular shape, 8WF31, results are available for comparison for four different steels, A7, A242, A441, and T-1.[10]

2. DESCRIPTION OF TESTS

Residual Stress Measurements

Nine rolled and heat treated T-1 steel shapes varying from light-weight shapes to medium-weight shapes were included in this study; their weights ranged from 17 to 120 pounds per foot. Representative shapes were chosen so that the results obtained would enable the prediction of the residual stresses in other wide flange shapes in this medium-size range. Table I gives the shapes tested and Table II shows their dimensions. The shapes were delivered in long sections varying in length from 10' to 40', and a layout was then made for residual stress measurements, stub column tests and coupons. Fig. 1 shows the layout of a typical section. An attempt was made to select parts for residual stress measurements free of yield lines due to cold-straightening; cold-straightening usually is needed to meet the required tolerances as to straightness. However, it was not known before testing whether the sections investigated has been cold-straightened because the minimal amount of scale on the heat treated shapes precluded seeing the yield lines. The results obtained, by their symmetry and magnitude, would indicate this after cutting. The variation of residual stress along the length of the section was studied for most of the sections by taking the measurements at more than one section, and for the shapes that were delivered in two, 10-foot lengths, one set of measurements were taken from each shape, to determine the difference in residual stress in shapes having the same geometry but cut from different pieces.

The residual strains were measured by a 1/10,000" Whittemore gage over a 10" gage length on a series of holes previously laid out. The spacing of the gage holes was arranged in such a way as to give more readings in regions of stress variation than in regions of constant stress. The readings were taken on both faces of the flanges and web for all shapes. Reference 11 has a detailed explanation of residual stress measurements and Fig. 2 gives a typical layout for holes and for sectioning.

Mechanical Property Tests

To secure the mechanical properties, tensile coupon tests were included in the study. Table III gives the coupons included in the study, and Fig. 3 shows the locations from which the coupons were cut. All the coupons were standard ASTM[12] flat coupons, as shown in Fig. 3, cut from flanges, and the webs of the shapes.

Stub Column Tests

Stub columns of 8WF31 and 12WF120 shapes were tested to obtain an average stress-strain curve which would show the effect of the residual stress on the compressive properties of the section as a whole and also would verify the results obtained by direct measurement of the residual stresses[2]. The lengths of the stub columns were determined by a specified procedure, and the testing set up and the procedure followed was as indicated in Ref. 13. Figure 4 shows the stub column tested.

3. TEST RESULTS AND DISCUSSIONS

Residual Stress Measurements

The experimental results obtained from this study are shown in Figs. 5 through 7, and are presented also in tabular form in Table IV. The solid lines with circles are the results obtained from measurements of the top face and the dotted lines with triangles are the bottom face measurements.

Residual stresses in almost all shapes confirm that the slowest cooled parts are in tension and the fastest cooled parts are in compression. The compressive residual stresses were at the flange tips and over most the web. The portion of the flange under the compressive residual stress varied for different flange sizes. For light shapes such as 8WF17, 8WF31, 10WF25, and 16BL26 with relatively small flanges, the compressive residual stress was over most of the flange portions (Figures 5 and 7b), and for the shapes with heavier flanges like 12WF36, 12WF45, and 12WF120, most of the flange was left with tensile residual stress and the compressive residual stresses were only at the flange tips (Figs. 6b, 6c and 7a). In general the pattern of residual stress was similar in all shapes and was as shown on Figs. 8 and 9, where the resulting patterns are the average values of top and bottom face readings. The results obtained show that the sections measured were apparently free from cold bending.

The variation of residual stress through the thickness was relatively small in all sections measured (Figs. 5 through 7); even the 12WF120 shape, with flanges thicker than one inch, showed this.

The results obtained from this study showed that the maximum value of compressive residual stress was less than 10 ksi for all shapes investigated. The average of compressive residual stress at the flange tips was about 3 ksi for shapes with flanges less than 1/2" in thickness (Figs. 5 and 6a) and about 4 to 5 ksi for shapes with flange thicknesses more than 1/2" (Figs. 6b, 6c and 7). The maximum compressive residual stress in the web was small also, not exceeding 5 ksi. The average for the first group of shapes was about 1 to 2 ksi and slightly higher for heavier shapes, where the average was 2 to 3 ksi. The tensile residual stresses in the flange center and web ends did not exceed 5 ksi; the average for all shapes was about 2 to 3 ksi for the flange center and for the web ends (Figs. 5 through 7).

The patterns of the residual stress were approximated best by smooth curves, with smooth transitions from tensile to compressive residual stresses.

Generally, the residual stresses formed in rolled heat-treated T-1 steel shapes investigated were very small. They constituted only a small fraction of the yield strength so that their effect on the load carrying capacity of the rolled heat-treated T-1 steel column may be expected to be negligible.

Mechanical Property Tests

Some of the results obtained from the coupon tests conducted are presented in Table V. Figure 10 shows a typical load-strain relationship for a coupon taken from the flange of 8WF31. The static yield stress*obtained from the tests was about 110 ksi.

Stub Column Test Results

The average load-strain relationship obtained from the stub column test of 12WF120 is shown in Fig. 11. The effect of residual stress in the cross section on the load-strain relationship is to lower the proportional limit, and to cause the load-strain diagram to be non-linear beyond that point and up to the yield stress level[2]. The load-strain relationship obtained from stub column tests affected by residual stresses normally would present a lower proportional limit compared to the one obtained from a tension coupon free of residual stresses. As seen from Fig. 11, the load-strain relationship is linear up to 90% of the yield load which, for a 12WF120, was about 3500 kips. The proportional limit was 90% of the yield stress, suggesting that the residual stresses were small and their effect on the cross section relatively insignificant. This fact confirmed low residual stresses obtained from direct measurement.

* Definitions are given in Section 7.

4. COMPARISON WITH THE RESULTS OF OTHER STEELS

The pattern of distribution of residual stress in T-1 steel rolled heat-treated shapes is generally the same as observed for rolled shapes of other steels. No direct comparison is possible among the shapes of this study and of the studies of other steels for most of the shapes, because different geometries were studied. However, results for the 8WF31 shape are available for ASTM A7, A242, and A441 steels for comparison. Figure 10 shows the results obtained for these different steels.(10) The pattern of the residual stress distribution is similar especially in the flange, which has the greatest effect on the strength of the columns. The difference in magnitude is most pronounced for the T-1 steel shape as compared to the other three shapes. The magnitude of residual stress in the T-1 steel shape is between one third to one half of that observed in shapes made of other steels. The heat-treatment after hot-rolling probably is the explanation for this lower magnitude of residual stress, and therefore, it may be regarded as characteristic of T-1 steel shapes.* Thus, it is expected that the effect of residual stress on the buckling strength of compression members of rolled heat-treated T 1 steel shapes will not be as significant as it is for members of structural carbon steel because the compressive residual stresses in T-1 steel constitute a very small fraction of the yield strength, whereas in other steels, especially A7 and A36 steels, it is an important factor.

---

* Thus it may be expected that the results of other heat-treated constructional alloy shapes will be the same; preliminary studies on one shape of an experimental 140 ksi shape have shown this.

The stub column test of 12WF120 showed a linear relationship for as high as 90% of yield load; the load-strain relationship as obtained for stub columns of A7 steel starts to deviate at about 60 to 70% of the yield load[14], showing partial yielding of the cross section, which in turn shows the importance of residual stress in the behavior of columns of A7 steel.

5. SUMMARY AND CONCLUSIONS

A summary of the results obtained from an experimental study into the magnitude and distribution of residual stresses in rolled heat-treated T-1 steel shapes is presented in this section. The shapes were tested in the rolled and heat-treated condition and in sections varying from 8WF17 to 12WF120 in weight.

1. The maximum compressive residual stress observed was less than 10 ksi, an average ranging between 3 to 5 ksi for flange thicknesses of 1/2" and more respectively. (Section 3, Figs. 5 through 7) (Average for the A7 steel was about 9 to 10 ksi).
2. Geometry is the most important factor in the formation of residual stress. The shapes with narrower flanges had residual stress higher in magnitude than those with wider flanges (Figs. 5 through 7).
3. Tensile residual stresses in the shapes were less than 5 ksi (Section 3, Figs. 5 through 7). (It was about 5 to 6 ksi for A7 steel).
4. The residual stress pattern is approximately parabolic with smooth transitions from tensile to compressive residual stresses (Section 3, Figs. 5 through 7).

5. Residual stresses in heat-treated T-1 steel shapes were lower than the residual stresses in other previously tested steels with lower yield strengths probably because of the tempering treatment. (Section 4, Fig. 12).
6. The linear relationship of load-strain up to 90% of the yield load obtained in stub column tests confirms the conclusion above (Section 3, Fig. 11).
7. Because the residual stress constitutes only a small fraction of the yield strength, the load-carrying capacity, of medium-size rolled heat-treated T-1 steel columns should not be affected significantly by this presence.

6. ACKNOWLEDGEMENTS

This study has been carried out as part of the research project on "Welded Built-Up and Rolled Heat-Treated T-1 Steel Columns" being conducted at Fritz Engineering Laboratory, Department of Civil Engineering, Lehigh University in Bethlehem, Pennsylvania.

The project is sponsored by the United States Steel Corporation. Charles G. Schilling of that corporation made many valuable comments, both in the course of the program, and in the preparation of this report. Task Group 1 of the Column Research Council of the Engineering Foundation acted in an advisory capacity under the chairmanship of John A. Gilligan. The assistance of Ching-Kuo Yu during the study is acknowledged.

7. DEFINITION OF TERMS

Residual Stress

Residual stresses are stresses formed as a result of permanent deformations of certain fibers during fabrication or cooling processes.

Yield Point

The yield point is the first stress in a material less than the maximum attainable stress, at which an increase in strain occurs without an increase in stress[12].

Yield Strength

The yield strength is the stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain. The deviation is expressed in terms of strain[12].

Yield Stress Level

The yield stress level is the average stress during yielding in the plastic range. It remains fairly constant for structural steel, provided the strain rate remains constant.

Static Yield Stress Level

The static yield stress level is the average stress during yielding in the plastic range, with zero strain rate.

Stub Column

A stub column is a short compression-test specimen, sufficiently long for use in measuring the stress-strain relationship for the complete cross-section, but short enough to avoid buckling as a column in the elastic and plastic ranges.

8. TABLES AND FIGURES

TABLE 1 SHAPES INCLUDED IN THE INVESTIGATION

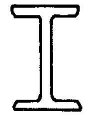
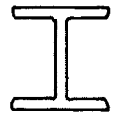
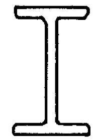
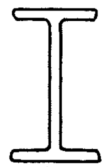
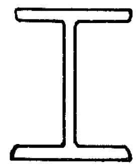
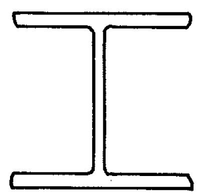
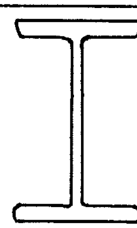
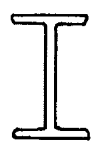
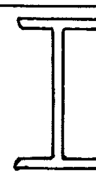
TEST NO.	SHAPE		DELIVERED LENGTHS
T-R-A	8WF17		2 x 10'
T-R-B	8WF31		1 x 40'
T-R-C	10WF25		1 x 10'
T-R-D	12WF36		2 x 13'
T-R-E	12WF45		2 x 15'
T-R-F	12WF120		3 x 36'
T-R-H	16WF64		2 x 15'
T-R-J	CB-102-33		2 x 11'
T-R-K	CBL-16-26		2 x 10'

TABLE II. DIMENSIONS OF THE SHAPES TESTED

	Flange		Web	
	Width	Thickness	Height	Thickness
8WF17	5.250	0.308	8.00	0.230
8WF31	8.00	0.433	8.00	0.288
10WF25	5.762	0.430	10.0	0.252
12WF36	6.56	0.540	12.24	0.305
12WF45	8.042	0.576	12.06	0.336
12WF120	12.32	1.106	13.12	0.71
16WF64	8.50	0.715	16.0	0.443
16BL26	5.50	0.345	15.65	0.250
10WF33	7.96	0.433	9.75	0.292

TABLE III. COUPONS TESTED

Test No.	Shape	Coupon No.	Place Taken
T-R-A	8WF17	T-R-A-1	F
		T-R-A-2	F
		T-R-A-3	W
		T-R-B-1	F
		T-R-B-2	W
		T-R-B-3	F
T-R-B	8WF31	T-R-B-4	F
		T-R-B-5	W
		T-R-B-6	F
		T-R-C-1	F
T-R-C	10WF25	T-R-C-2	F
		T-R-C-3	W
		T-R-D-1	F
T-R-D	12WF36	T-R-D-2	F
		T-R-D-3	W
		T-R-E-1	F
T-R-E	12WF45	T-R-E-2	F
		T-R-E-3	W
		T-R-F-1	F
		T-R-F-2	W
T-R-F	12WF120	T-R-F-3	F
		T-R-F-4	F
		T-R-F-5	W
		T-R-F-6	F
		T-R-H-1	F
T-R-H	16WF64	T-R-H-2	F
		T-R-H-3	W

F - flange
W - Web

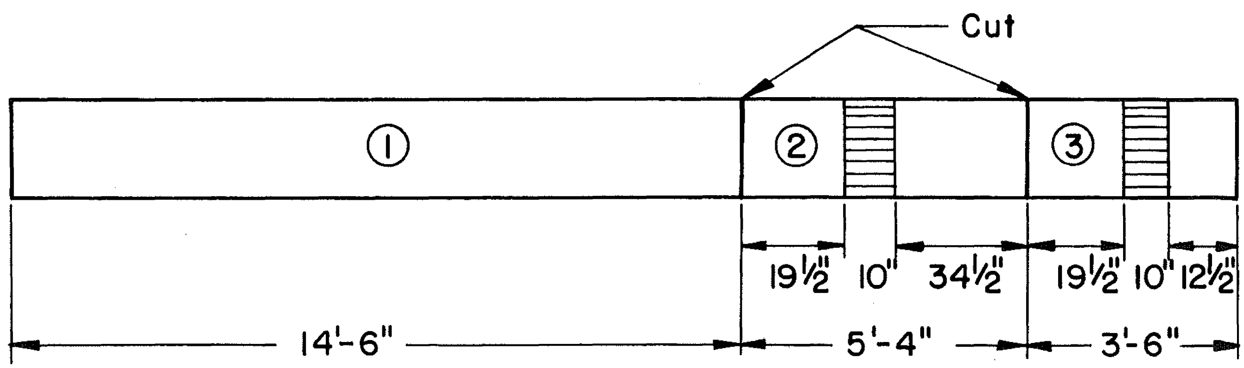
TABLE IV. RESIDUAL STRESSES MEASURED IN ROLLED SHAPES

Test No.	Shape	Residual Stresses in ksi						
		Flange Edge*			Web Center			
		Top Face	Bottom Face	Average	Flange Center	Top Face	Bottom Face	Aver.
T-R-1-A	8WF17	-1.0	-4.5	-2.75	+1.5	-2.5	-1.5	-2.0
T-R-1-B	"	-1.0	-4.0	-2.5	+2.5	-1.5	-2.0	-1.75
T-R-2-A	8WF31	-3.0	-1.50	-2.25	+2.0	-2.5	-3.0	-2.75
T-R-2-B	"	-3.0	-3.5	-3.25	+2.0	-1.5	-2.0	-1.75
T-R-3-A	10WF25	-3.5	-3.0	-3.25	+2.25	0	+1.5	+0.75
T-R-3-B	"	-3.0	-2.5	-2.75	-0.5	+1.0	+1.5	+1.25
T-R-4-A	12WF36	-4.0	-3.4	-3.70	+2.0	-3.0	-3.0	-3.0
T-R-4-B	"	-4.0	-4.0	-4.0	+2.5	-3.5	-3.5	-3.5
T-R-5-A	12WF45	-4.75	-4.5	-4.65	+2.0	-3.0	-2.5	-2.75
T-R-5-B	"	-5.25	-6.5	-5.80	+3.0	-4.5	-4.5	-4.5
T-R-6-A	12WF120	-5.70	-5.0	-5.35	+3.20	-3.0	-1.5	-2.25
T-R-6-B	"	-8.1	-4.5	-6.3	+2.6	-3.5	-2.5	-3.0
T-R-7-A	16WF64	-4.27	-3.11	-3.75	+2.3	-1.0	+1	0
T-R-7-B	"	-4.50	-2.10	-3.30	+2.0	-1.0	-0.5	-0.75
T-R-8	CB-102-33	-1.72	-2.21	-2.0	+1.0	+0.2	+0.5	+0.35
T-R-9	CBL-16-26	-2.50	-1.72	-2.11	+2.0	-3.0	+1.0	-1.0

* Average of four flange tips
\+ Tensile residual stress
\- Compressive residual stress

TABLE V. COUPON TEST RESULTS

Coupon No.	Place Taken	Area (in^2)	Static Yield Stress σ_y (ksi)	Tensile Stress σ_{UL} (ksi)
T-R-B-1	FLANGE	0.628	115.0	121.7
T-R-B-2	WEB	0.4150	111.0	121.5
T-R-B-3	FLANGE	0.6350	113.9	126.2
T-R-B-4	FLANGE	0.6130	113.3	122.3
T-R-B-5	WEB	0.4202	110.4	119.8
T-R-B-6	FLANGE	0.6340	112.2	123.5
T-R-D-1	FLANGE	0.8362	105.7	118.6
T-R-D-2	FLANGE	0.8403	112.6	125.4
T-R-D-3	WEB	0.4743	110.8	123.2



Piece:

(1) Store

(2) Residual stress measurement, tension coupons, stub column test.

(3) Residual stress, tension coupons.

Note: The holes for residual stress measurements to be drilled after cutting.

Fig. 1 Layout of a Delivered Piece

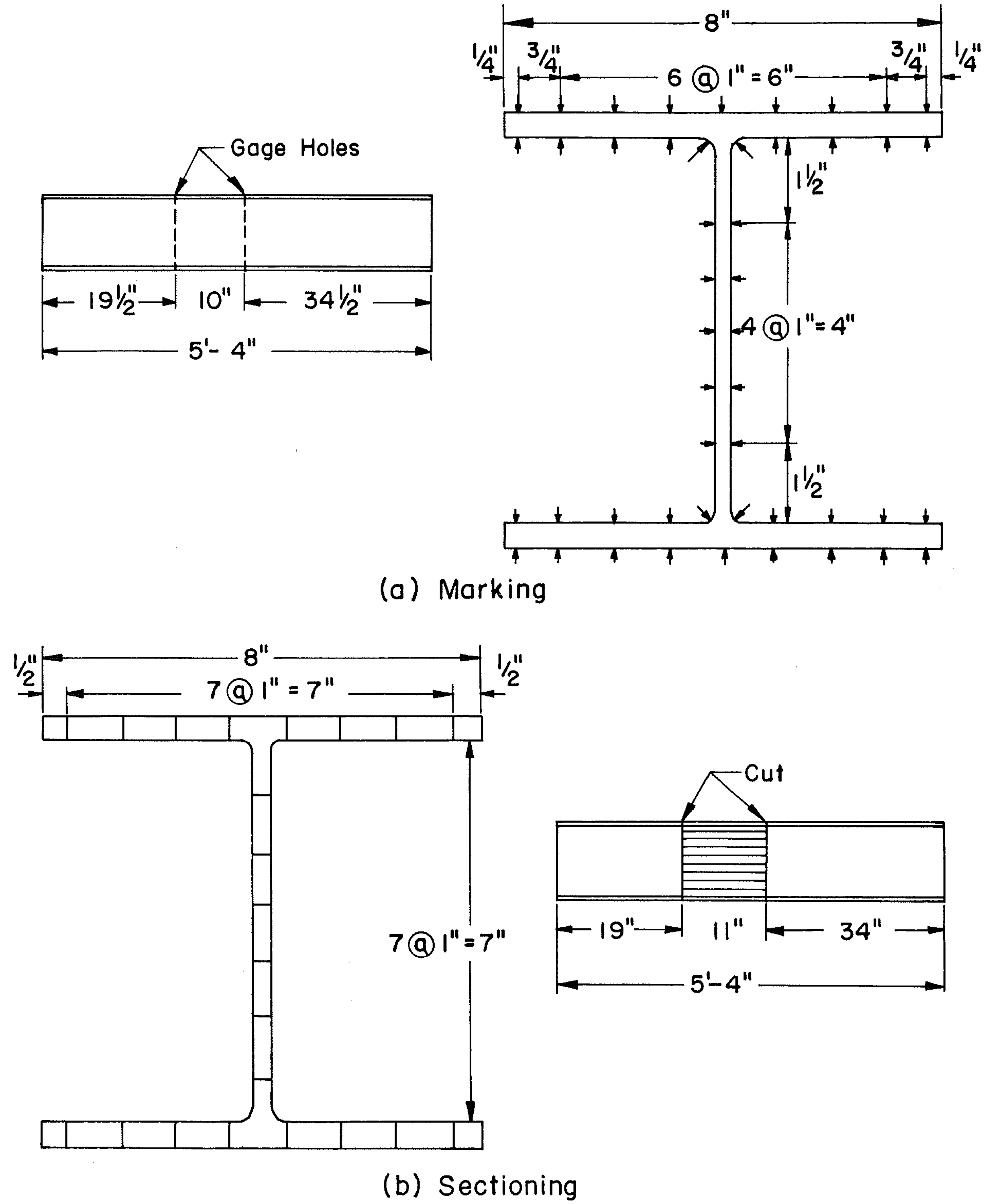


Fig. 2 Detail of Gage Holes and Sectioning for Residual Stress Measurement

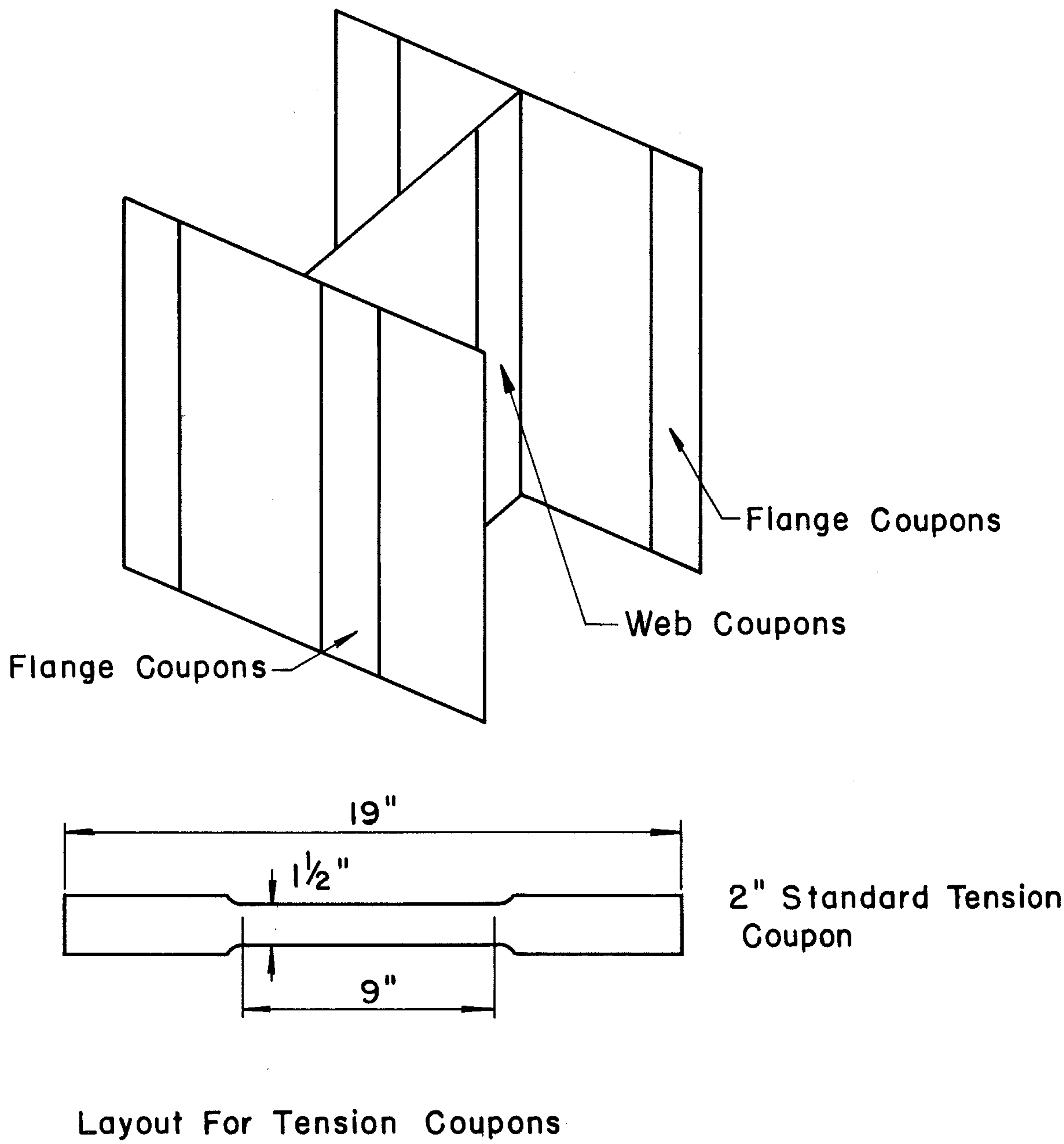


Fig. 3 Layout for Tension Coupons

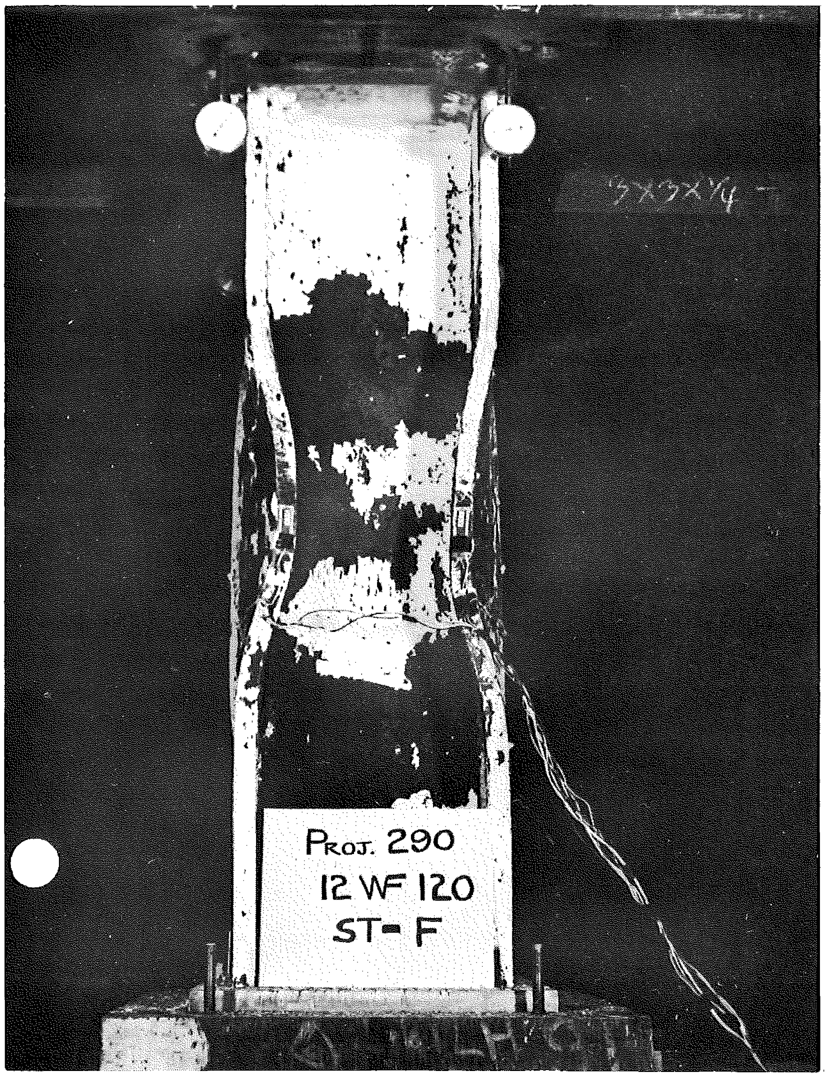


Fig. 4 Stub Column Test

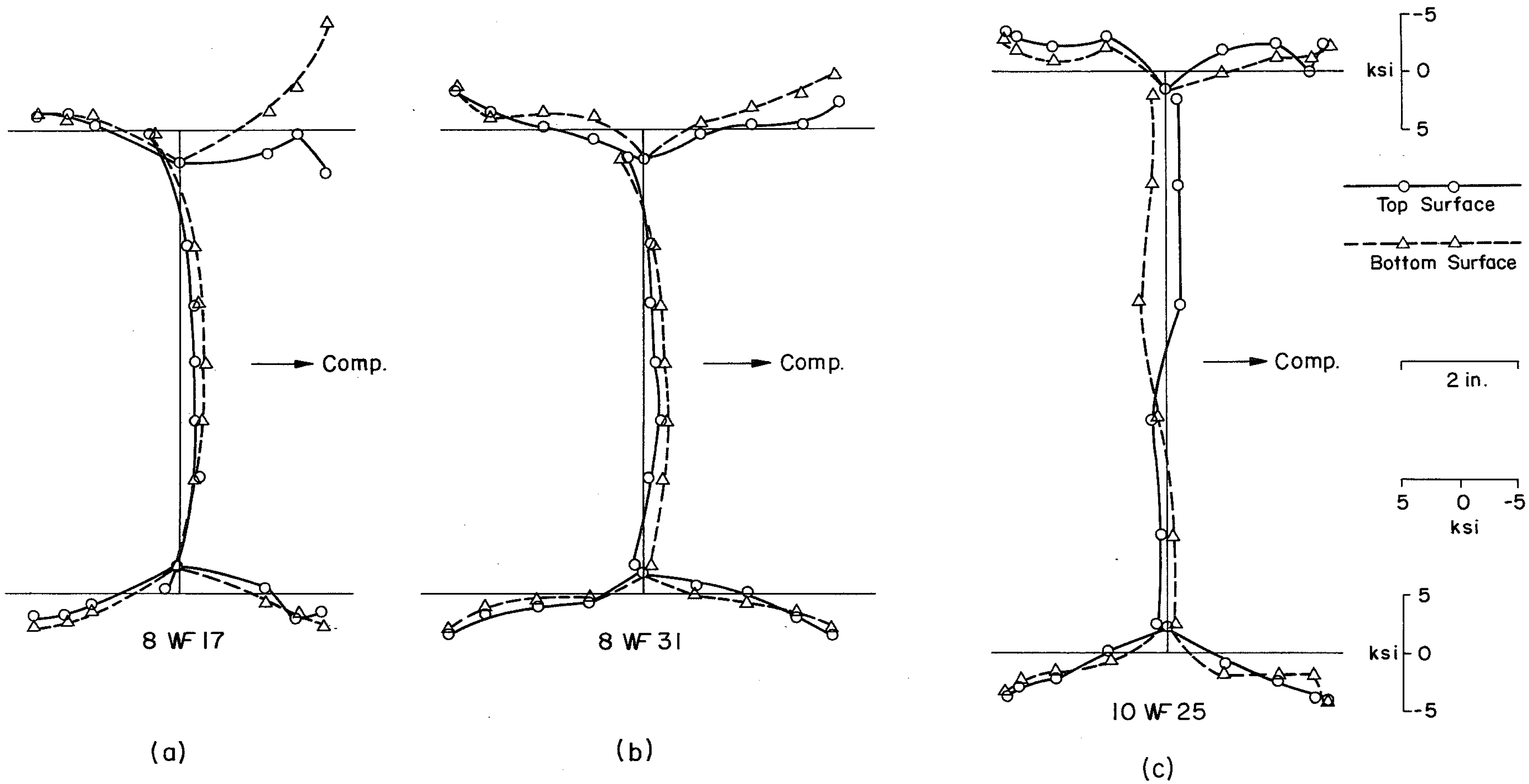


Fig. 5 Measured Residual Stresses

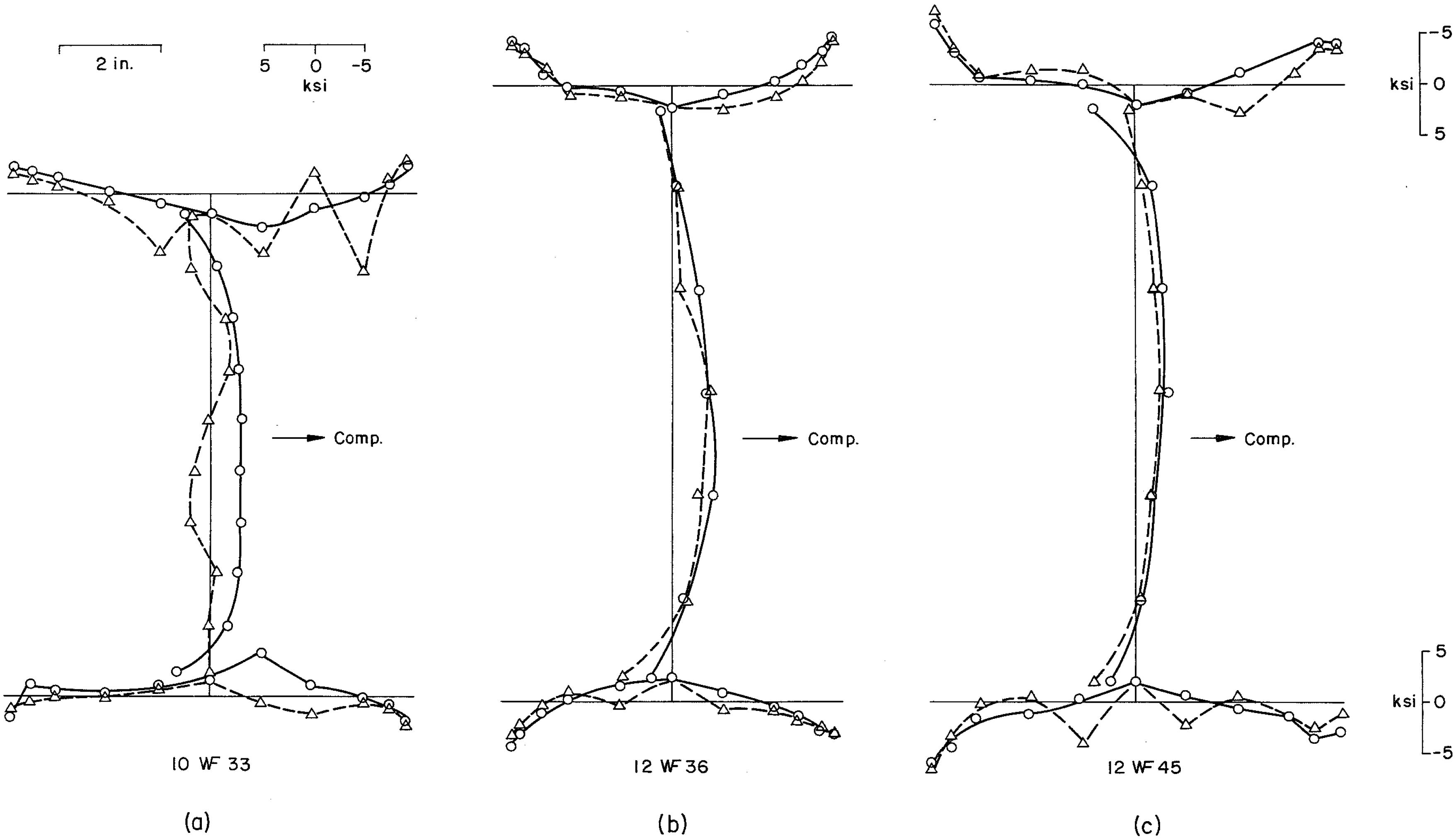


Fig. 6 Measured Residual Stresses

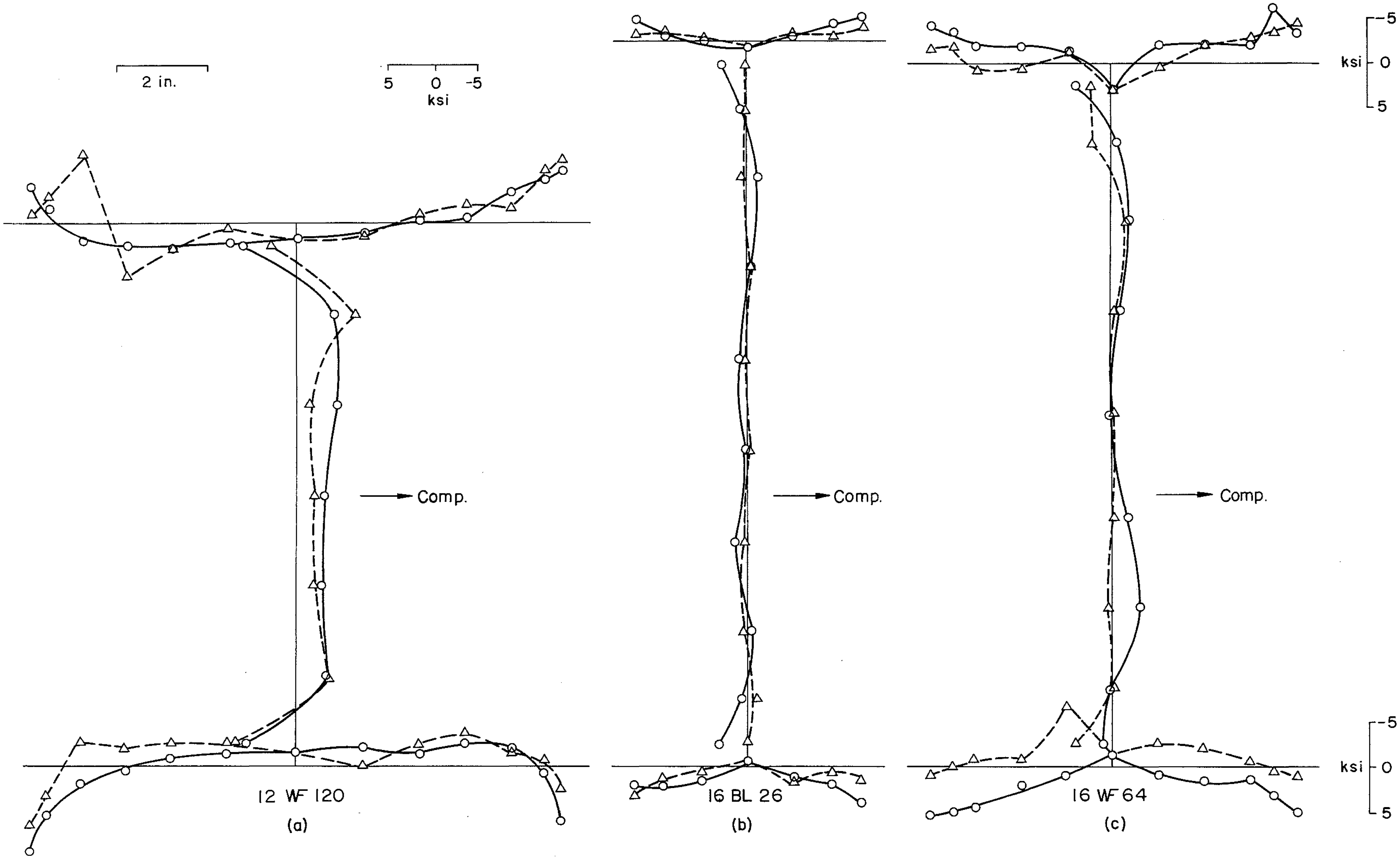


Fig. 7 Measured Residual Stresses

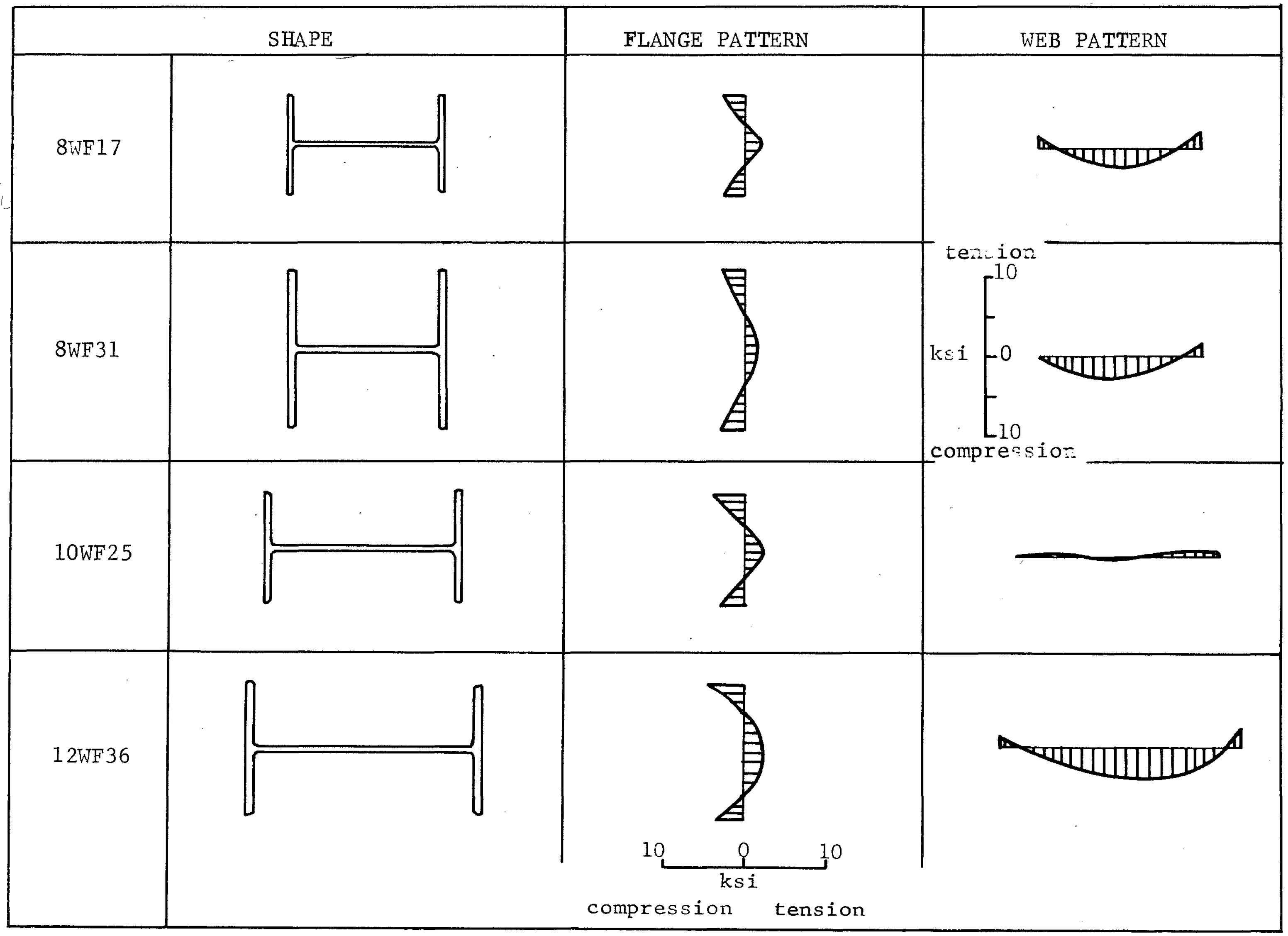


Fig. 8 Residual Stress Patterns in Rolled Heat-treated T-1 Steel Shapes

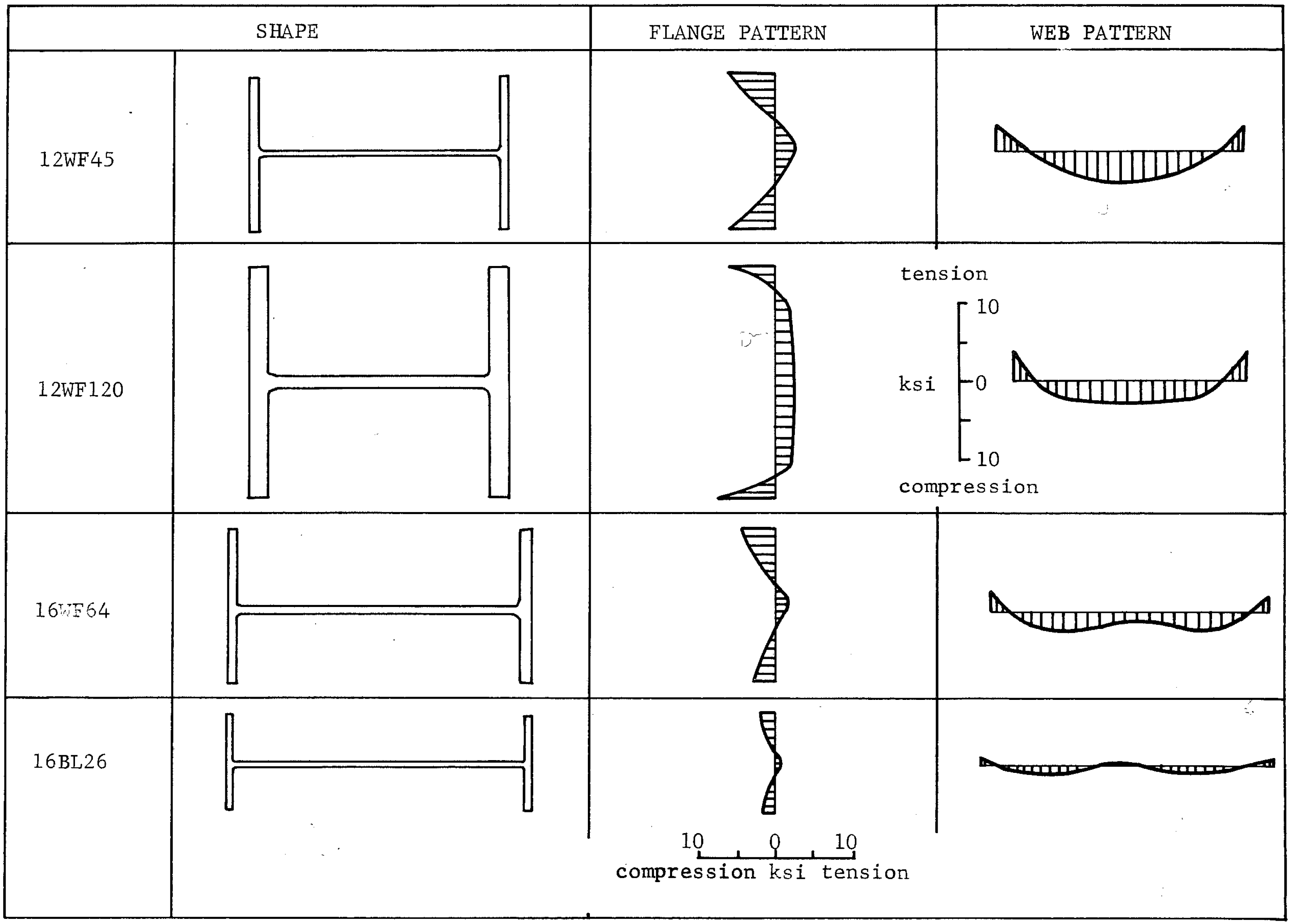


Fig. 9 Residual Stress Patterns in Rolled Heat-Treated T-1 Steel Shapes

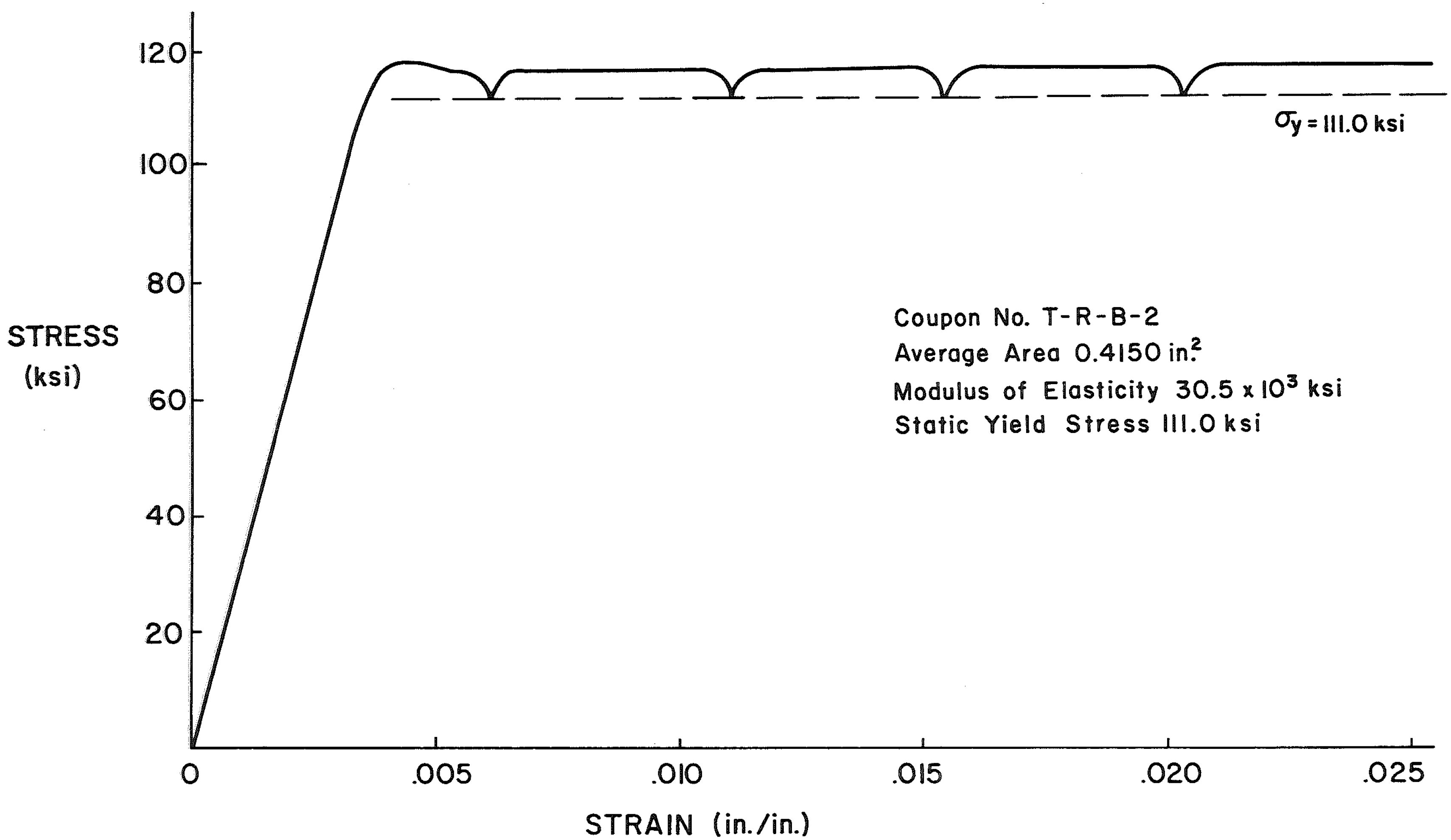


Fig. 10 Typical Stress-Strain Relationship of a Tension Coupon

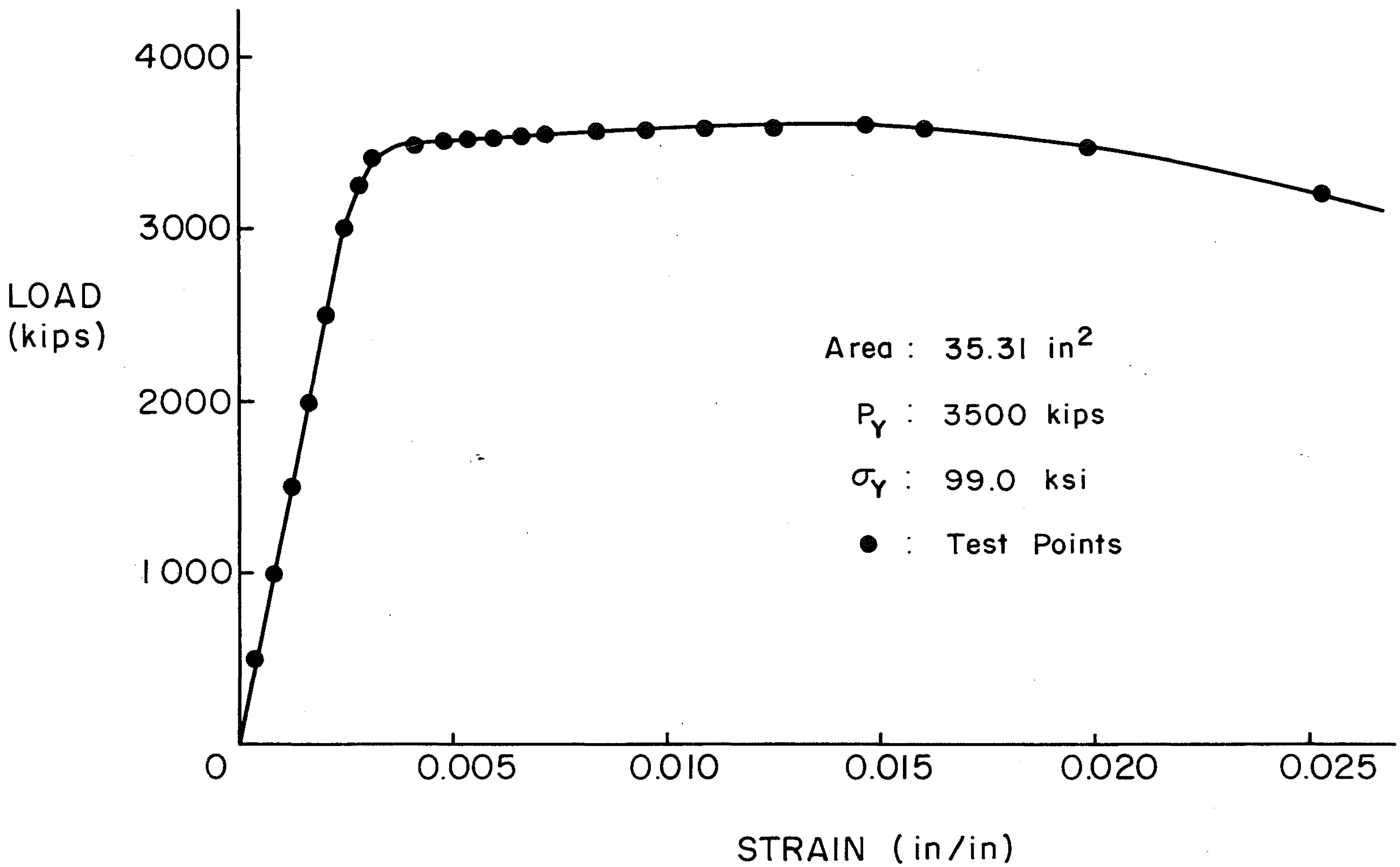


Fig. 11 Stub Column Tests Results on 12WF120

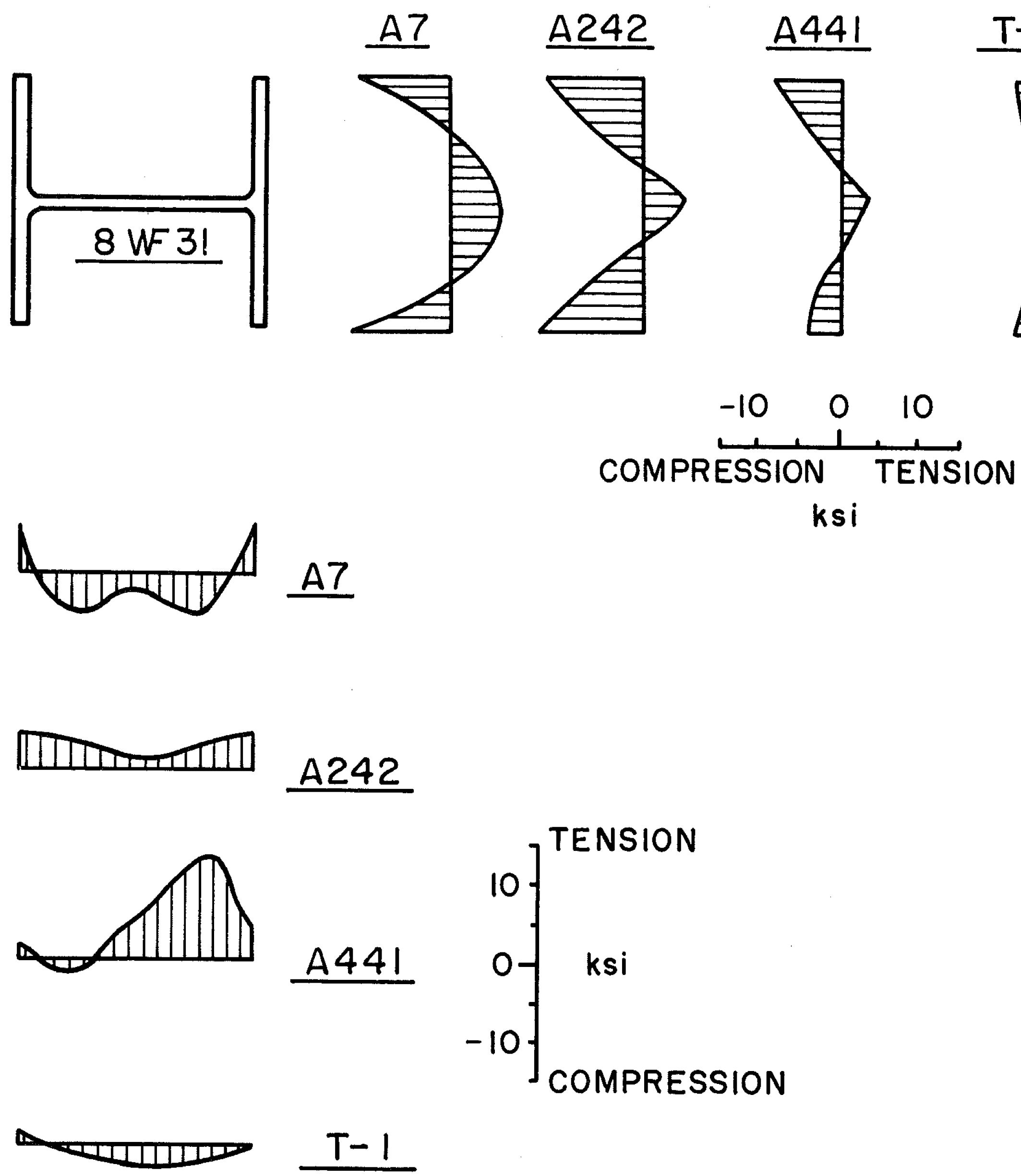


Fig. 12 Comparison With Results Obtained From Other Tests

9. REFERENCES

1. Yang, C. H., Beedle, L. S. and Johnston, B. G.
RESIDUAL STRESS AND THE YIELD STRENGTH OF STEEL BEAMS, The Welding Journal, Research Supplement, Vol. 31, April, 1952

2. Beedle, L. S., and Tall, L.
BASIC COLUMN STRENGTH, ASCE Proc. Paper 2555, Vol. 86, ST7, July, 1960

3. Ketter, R. L.
THE INFLUENCE OF RESIDUAL STRESSES ON THE STRENGTH OF STRUCTURAL MEMBERS, Welding Research Council Bulletin No. 44, 1958

4. Huber, A.
THE INFLUENCE OF RESIDUAL STRESS ON THE INSTABILITY OF COLUMNS, Ph.D. Dissertation, Lehigh University, 1956

5. Tall, L.
RESIDUAL STRESSES IN WELDED PLATES -- A THEORETICAL STUDY, Welding Journal, Vol. 43, January, 1964

6. Huber, A. and Beedle, L. S.
RESIDUAL STRESS AND COMPRESSIVE STRENGTH OF STEEL, The Welding Journal, 33 (12), p. 589-s, December, 1954

7. Yuzuru, Fujita
THE MAGNITUDE AND DISTRIBUTION OF RESIDUAL STRESS, Fritz Laboratory Report No. 220A.20, Lehigh University, May, 1956

8. Feder, D. K., and Lee, G. C.
RESIDUAL STRESSES IN HIGH STRENGTH STEEL, Fritz Laboratory Report 269.2, Lehigh University, April, 1959

9. Adams, P. F., Lay, M. G., and Galambos, T. V.
EXPERIMENTS ON HIGH-STRENGTH STEEL MEMBERS, Fritz Laboratory Report No. 297.8, July 1964

10. Tall, L.
RECENT DEVELOPMENTS IN THE STUDY OF COLUMN BEHAVIOR, Journal, Institution of Engineers, Australia, Vol. 36 December, 1964

11. Nagaraja Rao, N. R., and Tall, L.
RESIDUAL STRESSES IN WELDED PLATES, The Welding Journal, Vol. 40, October, 1961

12. ASTM Specifications No. 370-557

13. Tall, L.
STUB COLUMN TEST PROCEDURE, Fritz Laboratory Report No. 220A.36, February, 1961, Also, IIW Document X-282-61, Oslo, July, 1962

14. NagarajaRao, N. R. and Tall, L.
COLUMNS REINFORCED UNDER LOAD, The Welding Journal, Vol. 42, April 1963