1968

Stub column and residual stress measurement (a572, Grade 65), May 1968

R. Scheid

Recommended Citation

Scheid, R., "Stub column and residual stress measurement (a572, Grade 65), May 1968" (1968). *Fritz Laboratory Reports.* Paper 372.
http://preserve.lehigh.edu/engr-civil-environmental-fritz-lab-reports/372

LEHIGH UNIVERSITY INSTITUTE OF RESEARCH

Plastic Design In A572 (Grade 65) Steel

STUB COLUMN TEST AND RESIDUAL STRESS MEASUREMENT (A572, GRADE 65)

by
Roger A. Scheid

Fritz Engineering Laboratory Report No. 343.3

Plastic Design in A572 (Grade 65) Steel

Stub Column Test and Residual Stress Measurement (A572, Grade 65)

by

Roger A. Scheid

Fritz Engineering Laboratory
Department of Civil Engineering
Lehigh University
Bethlehem, Pennsylvania
May, 1968

Fritz Engineering Laboratory Report No. 343.3

TABLE OF CONTENTS

ABSTRACT

This study forms part of Project No. 343 - Plastic Design in A572 (Grade 65) Steel, sponsored by the American Institute of Steel Construction. This portion of the project was aided also by a National Science Foundation Undergraduate Research Participation grant. The object of the overall study is to determine whether the plastic design criteria for structural carbon steel can be extended to the high strength steel, A572 in particular. This report is concerned with a stub column test, a set of residual stress measurements, and theoretical predictions based upon them.

The maximum compressive residual stress measured in a 16WF71 section was found to be 16.8 ksi, which is higher than that found in A7 or A36 steels. However, the column strength shows less sensitivity to this higher value than do the lower strength steels.

Although the local buckling was premature according to the theory, there was unusually large post-buckling deformation capacity.

1. INTRODUCTION

A number of studies have been made of the determination of residual stresses and their influence on column strength. These studies have also given the mechanical properties in ASTM A7 and A36 steels. It is the purpose of this report to present the residual stress pattern due to both cooling and rotarizing, and to give the compressive properties of a 16WF71 shape of ASTM A572 (Grade 65) steel. These results will be compared with previously obtained data on other steels.

The test program was divided into two parts: (a) a stub column test, and (b) the measurement of the residual stresses by the method of sectioning. Theoretical studies included an analysis of column strength based on the measured residual stresses and assumed residual stress patterns. The influence of local buckling was also observed and compared to other tests.

The study reported in this paper is related to a larger program, Project No. 343, whose objective is to determine whether or not the plastic design criteria developed for lower grade steels can be applied also to the higher strength material.

2. SHAPE CHARACTERISTICS

A 16WF71 section was used in both the stub column test and the residual stress measurements. The measured geometrical dimensions and mechanical properties of the section are given in Tables 1 and 2 below. Both the flange thickness and the web thickness are average values determined from several sets of micrometer measurements. The cross sectional area was determined by weighing a known length.

Table 1: Dimensions of 16WF71 Rolled Shape

	Handbook	Measured	Maximum value for E_{st}=500ksi
Flange width, b	8.54 in.	8.58 in.	---
Flange thickness, t	.795 in.	.80 in.	---
b/t	10.75	10.72	10.8
Web thickness, w	.486 in.	.50 in.	---
d/w	33.25	32.50	30.6
Cross sectional area, A	20.86 sq.in.	21.35 sq.in.	---

It is seen that the measured dimensions of the shape agree with handbook values within about 2%. The measured values were used in the subsequent calculations.

The mechanical properties were determined by standard tension tests using flat specimens. The mechanical properties, summarized in Table 2, are the subject of a separate report.(1) Using the information obtained from the flange, the strain-hardening strain ϵ_{st} averages at 12.0 x 10^{-3}in/in, or about six times the elastic limit value. A typical stress-strain curve obtained with autographic records is shown in Fig. 1.(1)

The average strain-hardening modulus E_{st} for the two flange specimens is 679. A value that is slightly lower than observed in earlier tests of A36 and A441 steels.

Table 2: Mechanical Properties of 16WF71 Rolled Shape (65 Grade)

Test Specimen	Location	Mill Test Yield Point, in ksi	Static Yield σ_{ys}, in ksi	Strain-hardening Strain, ε_{st}, in in/in x 10^{-3}	Strain-hardening Modulus, E_{st}, in ksi
4.13.1W	Web	72.9	62.6	18.0	590
4.13.2W	Web	72.9	61.0	--	--
4.13.3F	Flange	--	62.2	12.0	688
4.13.4F	Flange	--	63.7	11.9	670
Stub column		--	63.5	--	245
Weighted average of flange and web		--	62.7	--	--

3. STUB COLUMN BEHAVIOR

A stub column 34 inches long was tested following the standard stub column test procedure.(2) However, the determination of a 34 inch length was not obtained without some defficulties. The standard stub column test procedure requires a minimum length of 42.25 inches (2d+10) and a maximum of 38.6 inches ($20r_y$).(2) The first requirement is established in order not to disturb the residual stresses, and the second to prevent the member from buckling as a column. However, this resulted in a contradiction with a minimum length greater than the maximum. Therefore, the criterion was re-examined for the particular test specimen.

Using the Modified Euler formula for the strain-hardening range,

$$\sigma_y = \frac{\pi^2 E_{st}}{(L/r_y)^2} \qquad (1)$$

and with trial value of E_{st} = 500 ksi and σ_y = 65.0 ksi, L/r_y equal to 8.73 was obtained. With r_y = 1.93 in. and the fixed end condition (which doubles the effective length) a stub column of 34 inches would be satisfactory.

The instrumentation used is shown in Fig. 2. Four 1/1000 inch dial gages, placed at the corners of the specimen, were used for alignment. Four SR-4 strain gages mounted on the outside flange tips at midheight, and two 1/10,000 inch dial gages mounted on two box frames with a gage length of ten inches were used for measuring the deformation. This, too, was in accordance with the standard stub column test procedure.(2)

Results of the test are as follows: (Details of the procedures followed for the calculations can be found in Ref. 2).

E,	Young's modulus	29.6×10^3 ksi
σ_p,	Proportional limit	53.0 ksi
σ_{ys},	Static yield	63.5 ksi

Figures 3 and 4 show the relationship between stress and strain of the stub column. (In these figures only selected points are plotted.) The proportional limit of 53.0 ksi and a static yield of 63.5 ksi results in an apparent compressive residual stress of 10.5 ksi, which does not correspond very well with the 16.8 ksi from the measured residual stress. The proportional limit of 53.0 ksi, determined from the stress-strain curve, agrees very well with the value observed when yield lines on the flanges were first noticed (52.5 ksi). Since the stub column was only 34 inches long and not the required 42.25 inches which is required not to disturb the residual stresses, the reduced value of 10.5 ksi is possible. However, this does not seem to explain such a large difference.

In the plastic range a test point was recorded after a ten-minute waiting period, or until there was no further movement of the cross-heads. The static yield level of the stub column was then determined as the average value in that portion of the plastic range between load no. 42 and when buckling was first observed (Load No. 48). A somewhat lower value would be obtained if the full yield range had been used in the average.

The static yield of 63.5 ksi of the whole cross-sectional area agrees fairly well with the tension test results which gave an average web value of 61.8 ksi, a flange value of 63.0 ksi and a weighted value of 62.7 ksi. This is within about 1% of the stub column value, as would be expected, considering that the tension specimens were taken from the same heat, ingot, and piece as the stub column.

In Fig. 5 and 6 (both taken at Load No. 38) the flanges have completely yielded, and the web has begun to yield. Load numbers are shown on Figs. 3 and 4 for comparison. In Fig. 7 (Load No. 45) the web also has completely yielded, and the section has moved from an elastic-plastic state to a totally plastic state. As the strain was increased the flanges began to wrinkle slightly as shown in Figs. 8 and 9 (Load No. 56), and continued to do so until the test was stopped at Load No. 65 (Figs. 10 and 11). Load 65 corresponds to an average strain of 55 x 10^{-3} in/in.

Fig. 4 shows that the stub column apparently began to strain harden at a strain of 13.7 x 10^{-3} in/in, even though significant flange buckling had cocurred prior to this. The corresponding value of ϵ_{st} in the flange coupons was 12.0 x10^{-3} in/in (see Table 2), which represents fairly good agreement. The value of E_{st} computed from the stub column curve was 245 ksi, a value considerably less than the value obtained from the tension specimens. Undoubtedly this was affected by the prior local buckling.

4. RESIDUAL STRESS

Residual stresses are stresses that are formed in the steel due to plastic deformation.(3) These plastic deformations in rolled shapes are caused by differential cooling or they occur as a result of fabrication operations (for example, by gagging, rotarizing, riveting, shearing, or welding).

Since some parts of a rolled section cool more rapidly than others, the slower cooling parts usually are left in a state of residual tension and the faster cooling parts (for instance, the flange tips) in compression.

A measurement of the residual stresses by the method of sectioning was made on the 16WF71 shape. A complete sectioning was performed with the cuts being made every ½ inch on the web and flange. The initial and final readings, made with a Whittemore strain gage, were made on both sides of the web and flanges, following the procedure set forth in Ref. 3. The results of these measurements are shown in Fig. 12. This residual stress pattern is a combination of the effects of cooling and of rotary straightening. By examination of the yield lines of the shape, Fig. 12, and of the measured residual stress pattern, it appears that the shape had been rotarized.

The maximum compressive residual stress for this shape was 18.8 ksi on the outside of the lower flange (using the orientation of Fig. 12). The inside stress at the same location was 14.8 ksi, a maximum for the inside of the flanges. This results in an average of 16.8 ksi at this location. From here to the flange tip, the compressive residual stress decreases and finally enters the positive region, as would be expected from the straightening process.

The top flange had a maximum compressive stress of 12.0 ksi. The upper and lower flange patterns are quite different and are very unsymmetrical. Comparing the two, it seems as though the bottom one was bent more than the top, and especially the right side of the bottom flange.

The similarities between the stress pattern of this rotarized shape and the cold-bent A7 steel in Fig. 13 can be seen, with the cold bent flange tip going into tension.(4)

Comparison between the maximum and minimum stresses of the 16WF71 can be made with the maximum and minimum values of cooling alone for A36 shapes in Fig. 14.(4) Even though the shape had been rotarized, the maximum and minimum stresses should be of the same order of magnitude as the cooling residual stresses.(4) The increase in yield strength from 36 ksi to 65 ksi seems to have increased the residual stresses. However, this cannot be certain with such limited tests with rotarized sections. The residual stresses measured in a 12B19 shape of A572 (grade 65) steel showed a similar pattern to those found in structural carbon steel but with a lower maximum residual stress.(5)

5. COLUMN STRENGTH

From the actual measured residual stress pattern (Fig. 12), an assumed symmetrical pattern was developed as shown in Fig. 15. Using this assumed pattern, a tangent modulus column curve was calculated according to the procedure given in Ref. 4, the resulting curve is shown in Fig. 16. The nearly uniform compressive stress on the flanges makes the column curve very "flat" with a nearly "vertical" jump, similar to a modified Euler curve, after the flanges have completely yielded.

Because of the fairly uniform compressive stress in the web, a straight line approximation also was made (Fig. 17) and its column curve, calculated by computer, is shown in Fig. 18. This straight line approximation and the curved symmetrical pattern show very good correlation.

Except for a small region at L/r about 30, Fig. 18 shows that the higher strength material has relatively less sensitivity to residual stress effects than is the case for A36 steel.

Neither calculation takes into account the lack of symmetry in the residual stress distribution shown in Fig. 12. Such a calculation would have to be carried out on an "ultimate strength" basis, and this is beyond the scope of the present report.

The results of analysis of column strength based on direct application of tangent-modulus theory to the average stress-strain curve measured in the stub column test is shown in Fig. 19.(4) Throughout the entire transition range it reflects a higher column strength than that based on measured residual stress, the latter representing a more precise solution to the problem.

6. LOCAL BUCKLING

Local flange buckling was measured with a 1/10,000 inch dial gage between the flange tips on one side of the stub column (see inset, Fig. 2). These measurements were made every 3 inches the entire length of the specimen except for the top 7 inches and the bottom 6 inches. The local deformations were measured only on one side, since the buckling is likely to be symmetrical.

The graph of the local buckling deformations is shown in Fig. 20. It is a plot of the maximum flange deflection observed at any point along the entire length of the stub column vs. the average strain, a procedure followed in Ref. 6. The critical strain, indicated by the arrow, is defined as the average strain at which deflection of the flange starts to increase more rapidly than initially. This critical strain is found by the intersection of the tangents drawn along the straight section of the curve.(6)

The graph of Fig. 20 shows the critical strain of the flanges to be 7×10^{-3} in/in strain, which is just before the strain when flange buckling was noted visually at Load No. 49. From observation the web began to buckle first at a strain of 7.3×10^{-3} in/in, with the flanges following at 7.9×10^{-3} in/in, as shown in Fig. 3. This sequence of buckling is consistent with the degree to which the geometry of the shape met the flange and web requirements (Table 2).

The critical b/t ratio at which it is possible for a fully yielded section to start to buckle is given by (7)

$$b/t = 2\sqrt{\frac{1}{\sigma_y}\left\{G_{st} + 0.381\ E_{st}\ (\frac{w}{t})^2\ \sqrt{\frac{A_F}{A_W}}\right\}} \qquad (2)$$

$$G_{st} = \frac{E}{1 + \nu + \frac{E}{4E_{st}}} \qquad (3)$$

where ν = .3

E = Young's Modulus

E_{st} = Strain hardening Modulus

w = Web thickness

t = Flange thickness

σ_y = Static yield

A_F = Area of flange

A_W = Area of web

Using the values obtained for the A572 (Grade 65) material and shape, the required values are $b/t \leq 10.8$ and $d/w \leq 30.6$. The proportions for the 16WF71 were very close to these requirements (see Table 2).

According to the theory if the actual b/t value is less than this critical value, local buckling will not begin until after the strain-hardening strain is reached.(7) Since the actual b/t ratio is less than the critical value in the 16WF71 shape, local buckling should follow the theory (i.e. buckling should not occur prior to ϵ_{st}). From past experiments it also has been observed that local buckling will not start until the average strain across the flanges is equal to the strain-hardening strain ϵ_{st}.(8) Referring to Table 2 in Section 2, SHAPE CHARACTERISTICS, ϵ_{st} is seen to range from 11.9×10^{-3} in/in to 18.0×10^{-3} in/in. However, Figs. 3 and 4 show that the local buckling did not begin at the strain-hardening strain, but began at approximately 7.5×10^{-3} in/in, which is far below the predicted value. The flange and web buckled nearly simultaneously. At present there is no way to account for this premature local buckling.

It is very interesting, however, that after the section did buckle, it exhibited unusually high post-buckling strength. From a yield load of approximately 1350 kips, the load had dropped only to 1100 kips (a loss of 19%), at 55.0×10^{-3} in/in strain, a value equal to 20 times the yield strain ϵ_y and 7 times the strain when local buckling was first observed. This is a greater postbuckling strength than observed in any prior tests.

Although the postbuckling deformation was considerable, the strain-hardening modulus of the stub column was very low, $E_{st} = 190$. At the onset of strain-hardening the load had dropped to 61.6 ksi, due to local buckling, but at a strain of 21.6×10^{-3} in/in the load had risen only to 63.1 ksi. After this the load began to drop at a slow rate, giving considerable additional postbuckling deformation (Fig. 4).

7. SUMMARY

The following summarizes the results of this study of stub column strength, residual stress distribution, and local buckling behavior of an ASTM A572, grade 65, 16WF71 steel member.

1. The measured geometrical properties and handbook values were in good agreement (within 1%).

2. The static yield level determined by tension tests of web material (61.8 ksi) was 16% lower than that obtained in the mill report (72.9 ksi) which is fairly consistent with prior observations.

3. The compressive static yield level of the stub column was 63.5 ksi, compared to the weighted average of 62.7 ksi from the tension tests (slightly over 1% difference).

4. The measured residual stresses and the observation of mill scale showed that the shape had been rotarized. The maximum compressive residual stress of 16.8 ksi is high compared to that found in A36 steel.

5. Column strength analysis shows that this higher strength material has relatively less sensitivity to residual stress effects than is the case for A36 steel. This is consistent with other observations.

6. The maximum compressive residual stress of 16.8 ksi from measurement does not agree very well with the value 10.5 ksi deduced from the stub column test.

7. According to theory the flange width-thickness ratio required to prevent buckling prior to strain hardening is 10.8. for E_{st} = 500 ksi. (This is a conservative value of E_{st} compared to those found in the tension tests, Table 2) The ratio for the test member was 10.7. However, local buckling occurred at a strain of about half the expected value.

8. Although local buckling occurred at a strain considerably less than would be predicted by the theory (7.5×10^{-3} in/in compared to 12.0×10^{-3} in/in), there was unusually large post-buckling deformation capacity. At a strain of 55.0×10^{-3} in/in, the load had dropped only to 1,100 kips from approximately 1,350 kips, a loss of but 19%. This is greater post-buckling deformation than observed in any previous tests of A7, A36, or A441 stub columns. It is the major difference observed thus far in the study of A572, grade 65 steel.

9. Although the tension tests using flat specimens resulted in values of the strain-hardening modulus E_{st} of 590 ksi for the web and 688 and 670 ksi for the flange of the 16WF71 shape, the stub column showed a lower value (245 ksi). This may well have been affected by the prior local buckling.

10. The results obtained in this test suggest that even though buckling occurred prior to strain-hardening, the width-thickness proportions predicted by the theory will be satisfied for stub columns through reliance on post-buckling strength.

The same thing may not be true when the shape is used as a beam. Local buckling, in that case, could trigger lateral failure. Other tests are being performed to give information on this aspect of the problem

8. ACKNOWLEDGEMENTS

This study was made during the summer of 1967 at the Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania, with the aid of a National Science Foundation Undergraduate Research Participation grant in the Civil Engineering Department for the period. The study is one of the parts of a project investigating the plastic design criteria in high strength steel, sponsored by the American Institute of Steel Construction.

Much help and encouragement was received from Dr. Lynn S. Beedle and Dr. Lambert Tall in conducting the research and preparing the report. Mr. S. N. S. Iyengar and Mr. C. K. Yu gave assistance in setting up the necessary tests. Acknowledgement is due also to Mr. Geoffrey Kroll, Mr. David Miller and Mr. Suresh Desai for their aid in carrying out the tests.

Mrs. Flo Ann Gera typed the report.

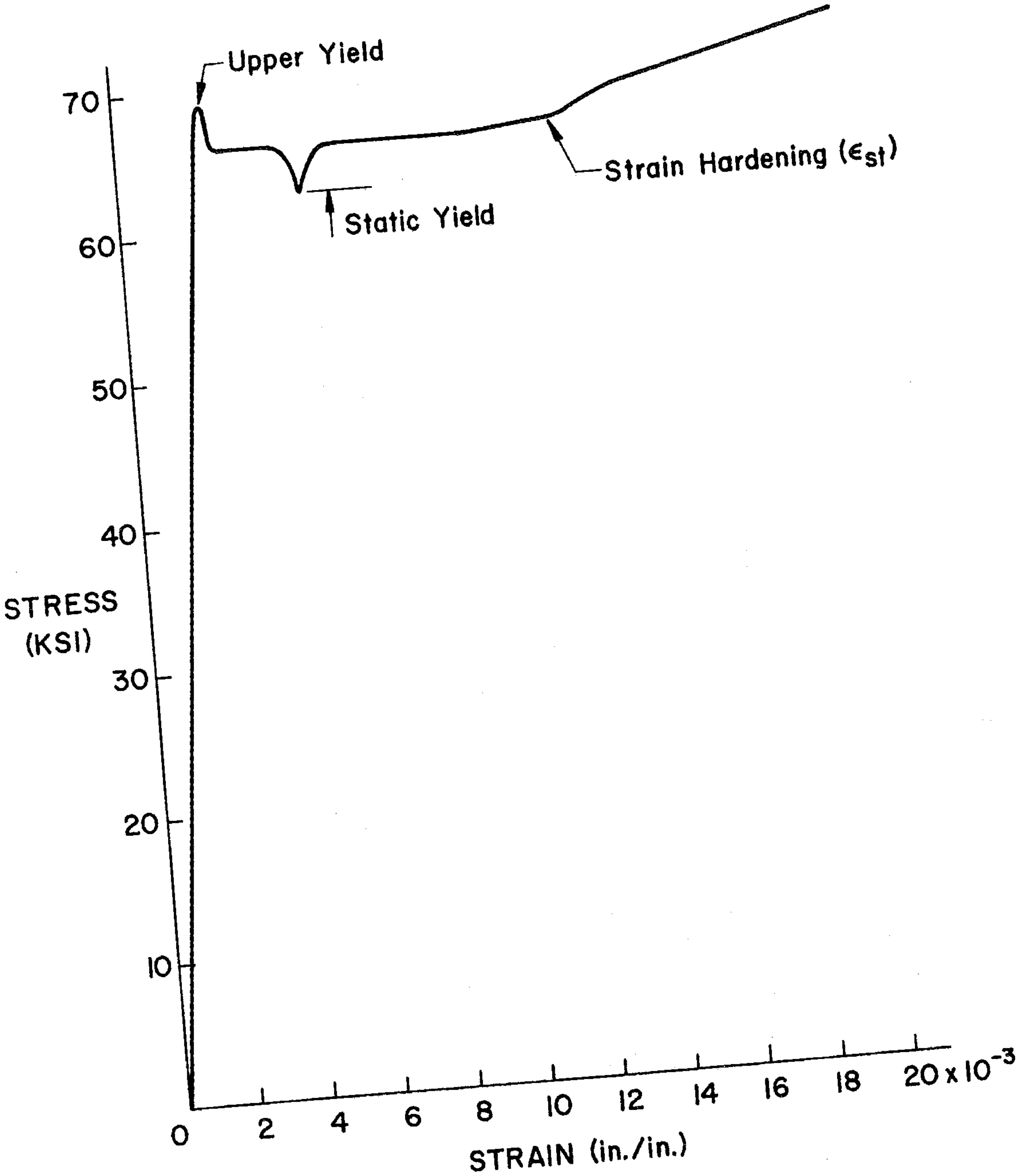

FIG.1 TYPICAL STRESS-STRAIN CURVE FOR A572 (Grade 65) STEEL

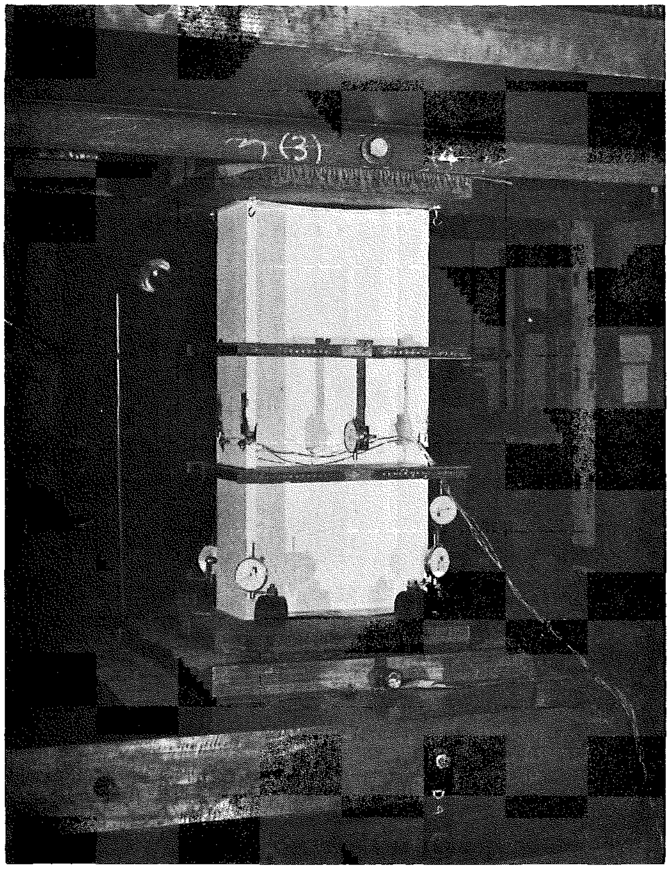

FIG. 2 STUB COLUMN INSTRUMENTATION

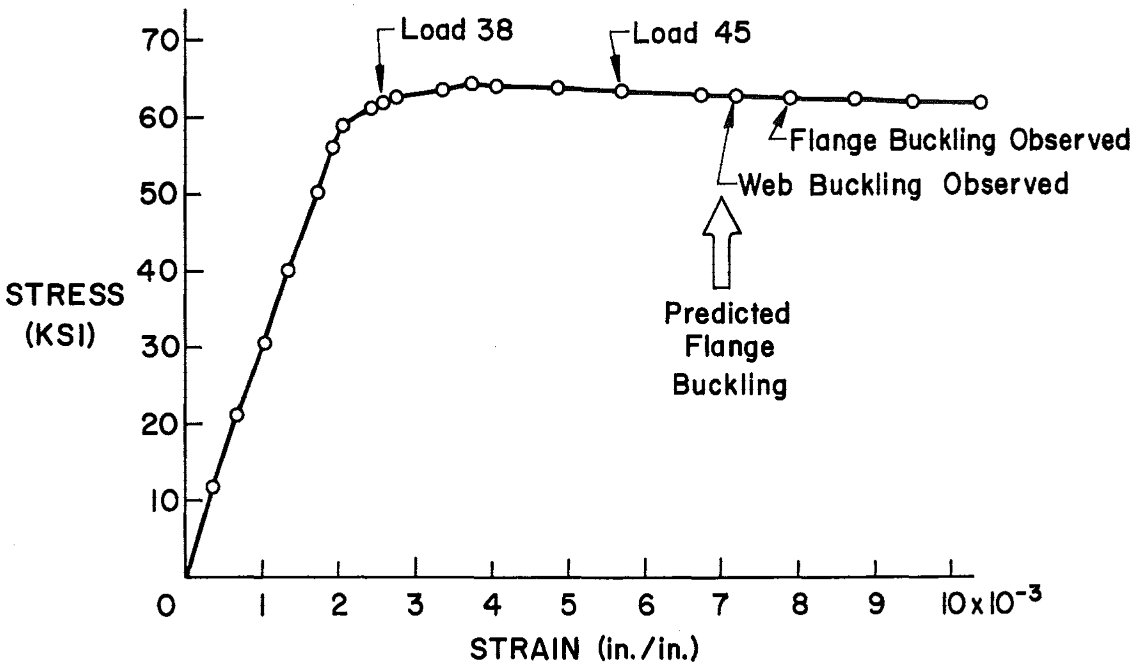

FIG. 3 STUB COLUMN STRESS-STRAIN CURVE (First Portion)

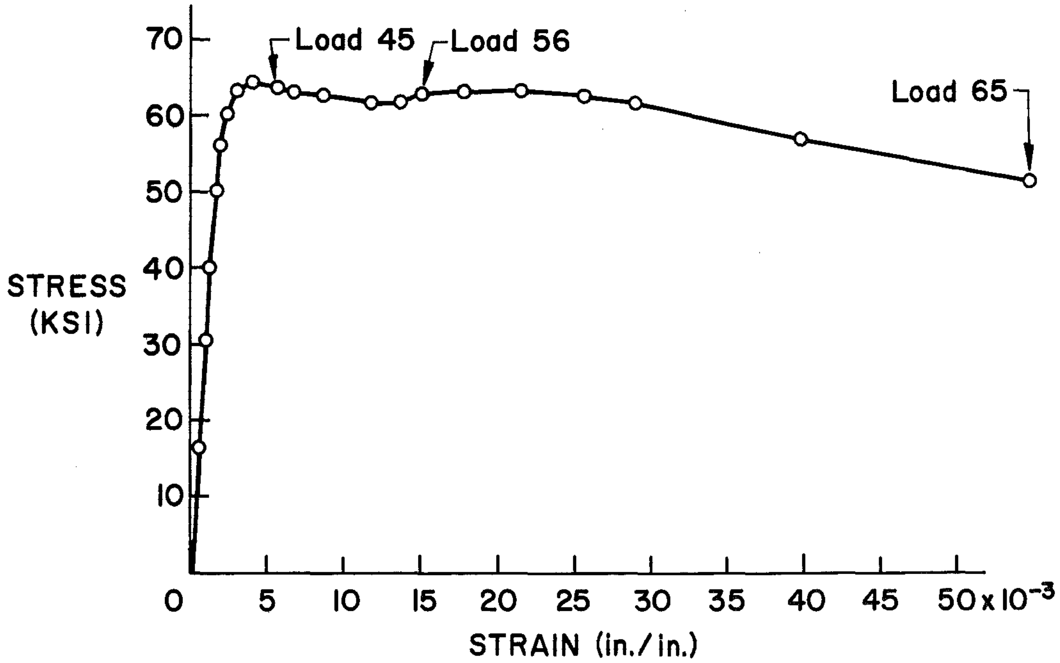

FIG. 4 COMPLETE STUB COLUMN STRESS-STRAIN CURVE

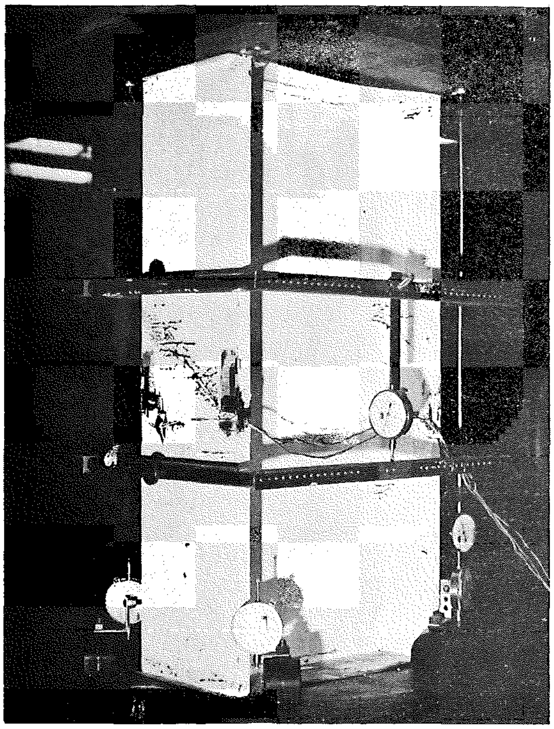

FIG. 5 YIELDED FLANGE

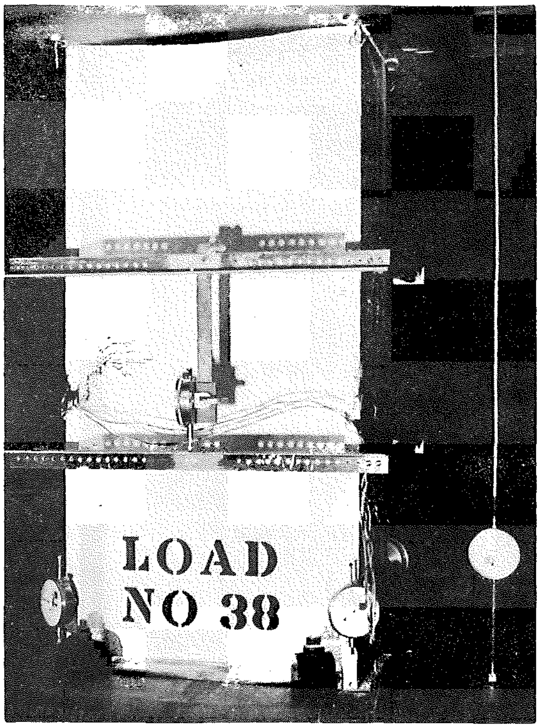

FIG. 6 INITIAL WEB YIELDING

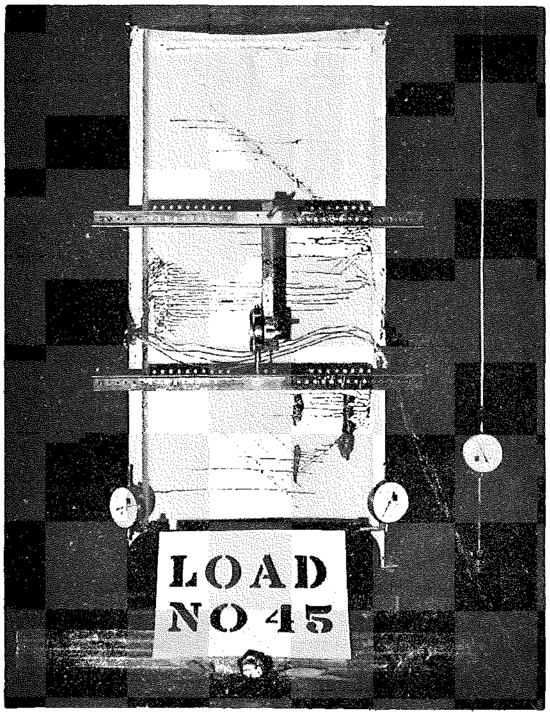

FIG. 7 YIELDED WEB

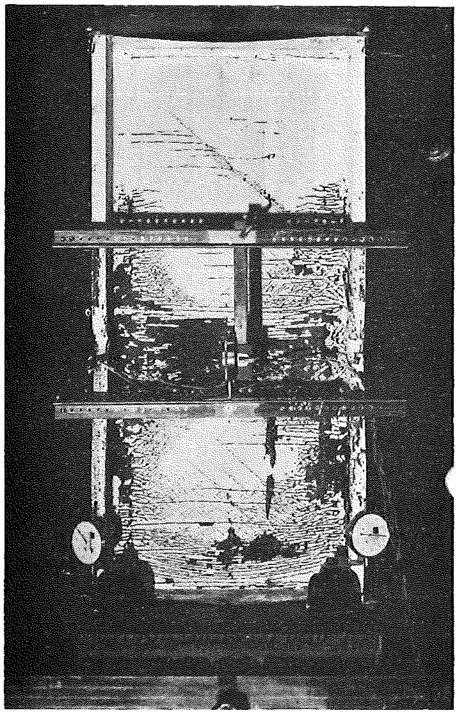

FIG. 8 FLANGE WRINKLING
(WEST SIDE)

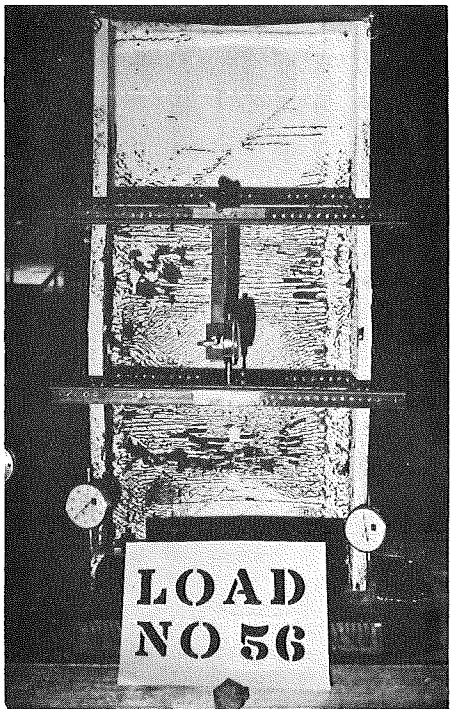

FIG. 9 FLANGE WRINKLING
(EAST SIDE)

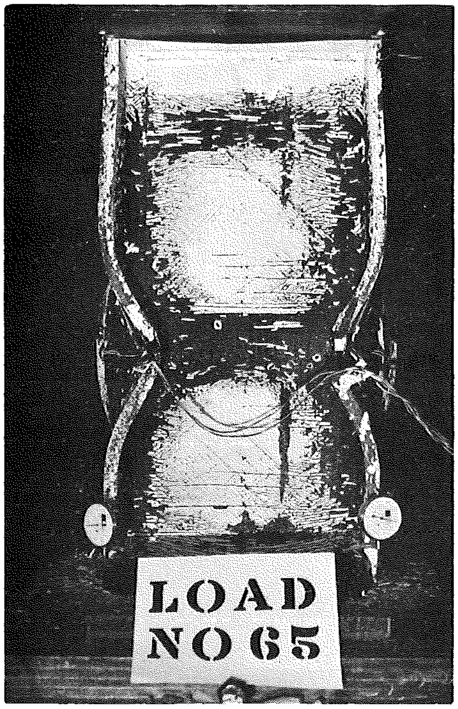

FIG. 10 STUB COLUMN AFTER TEST

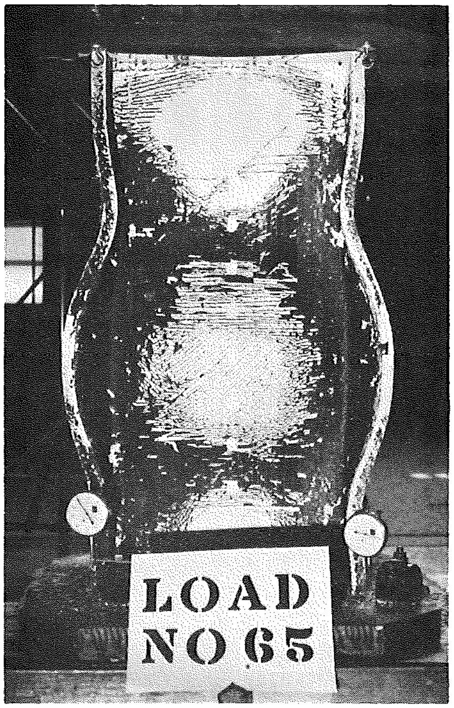

FIG. 11 STUB COLUMN AFTER TEST

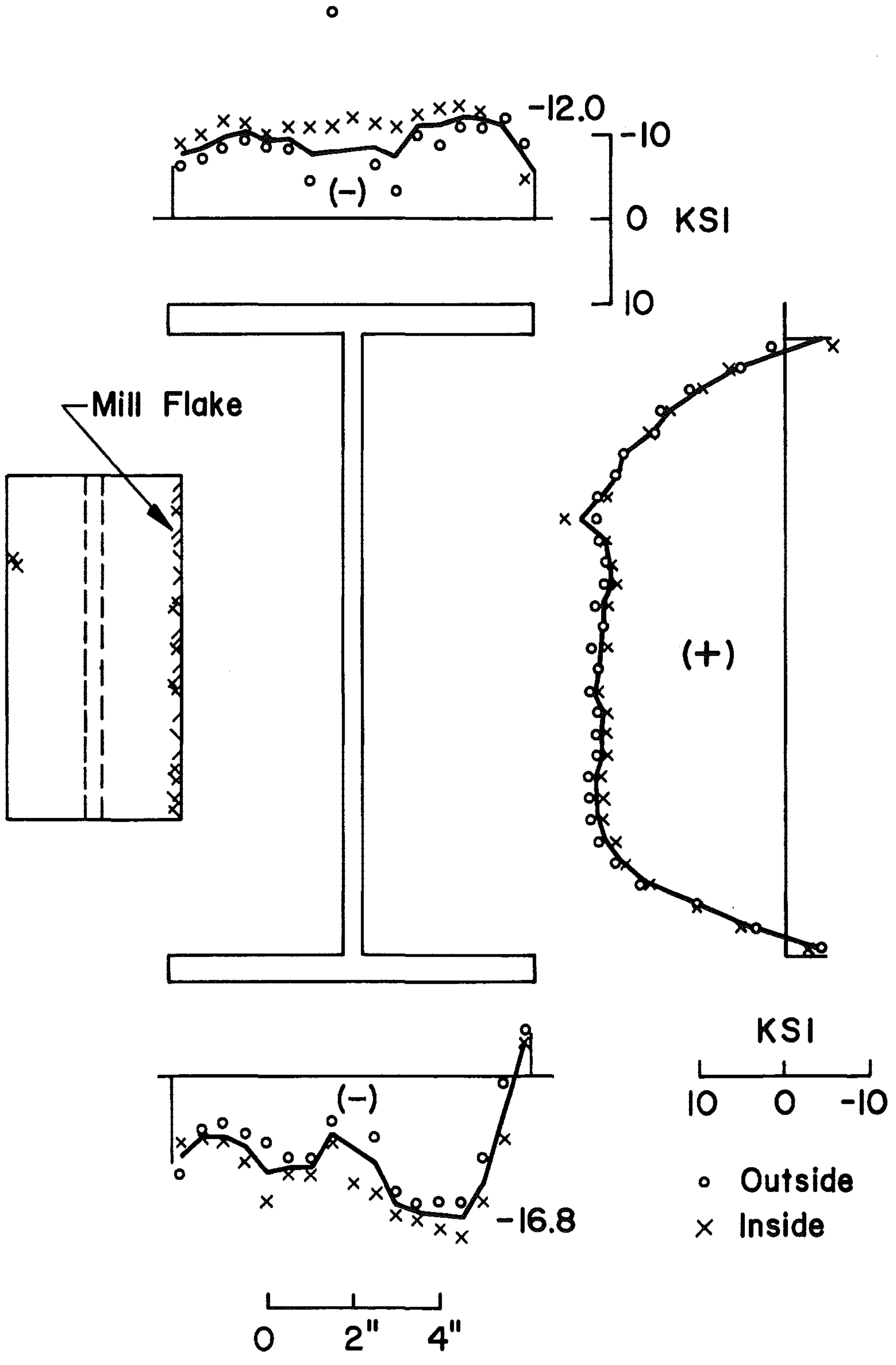

FIG. 12 MEASURED RESIDUAL STRESS PATTERN FOR 16W71

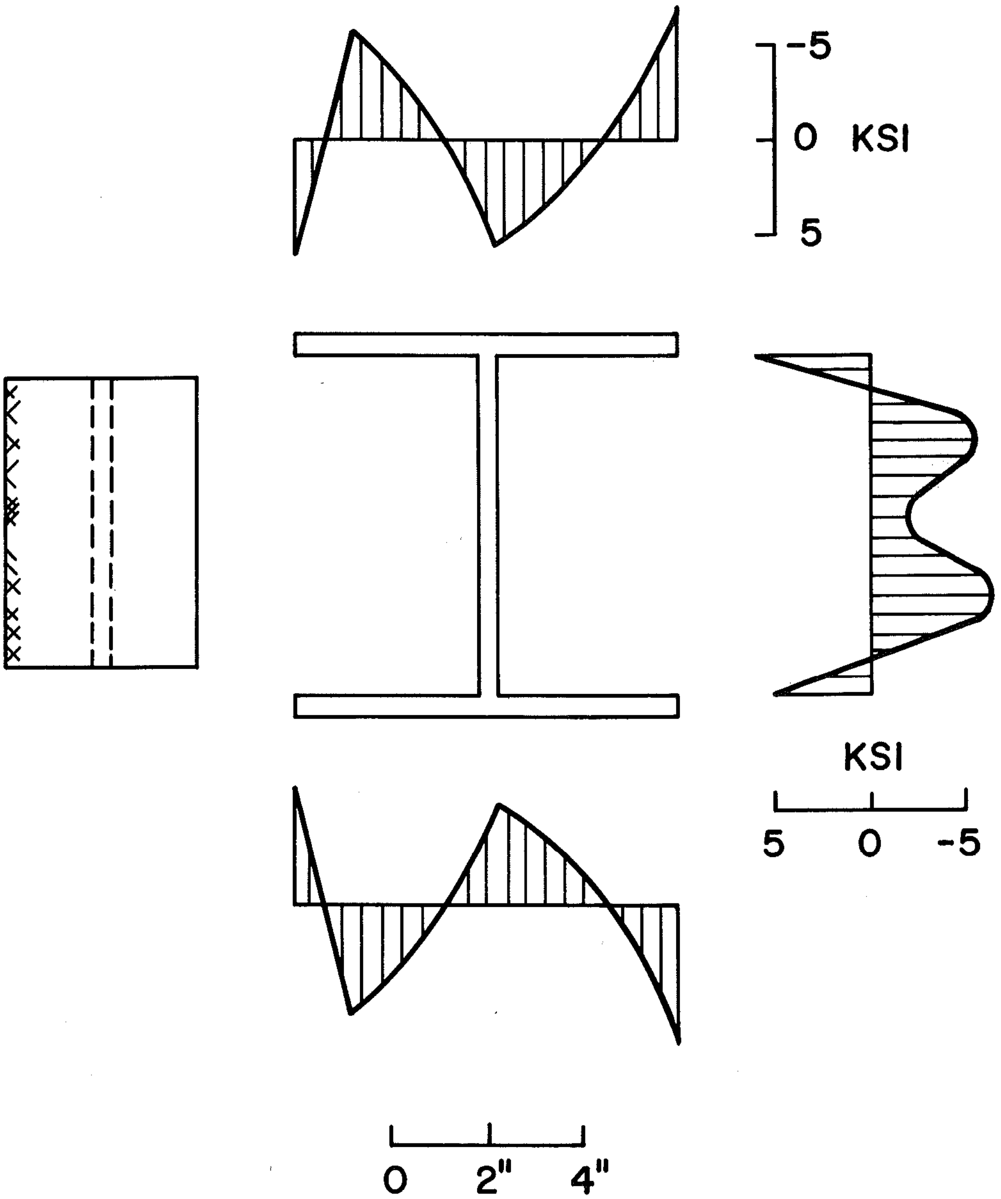

FIG. 13 COLD BENDING RESIDUAL STRESS PATTERN IN 8W31 (A7)

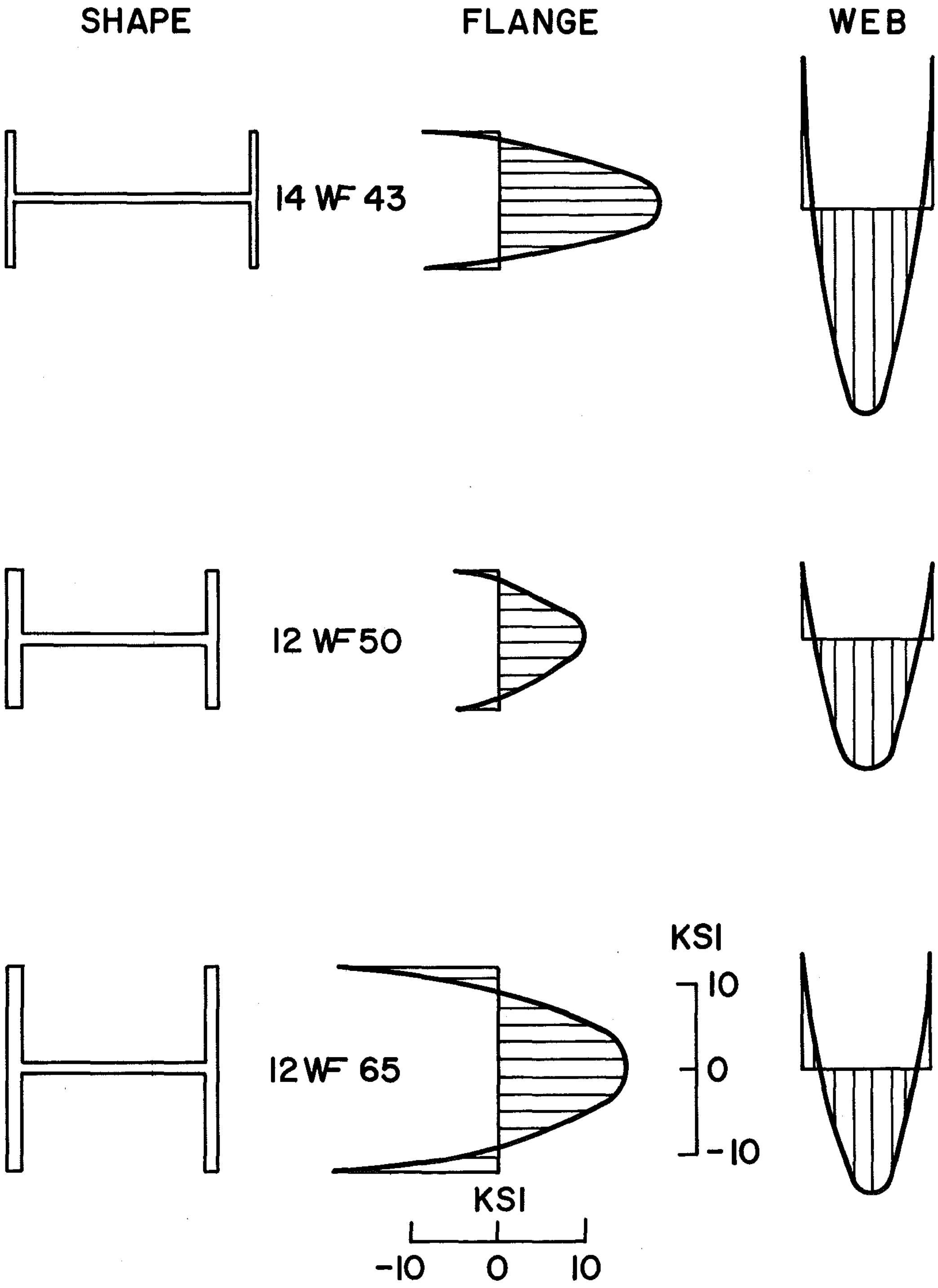

FIG. 14 COOLING RESIDUAL STRESS PATTERNS (A36)

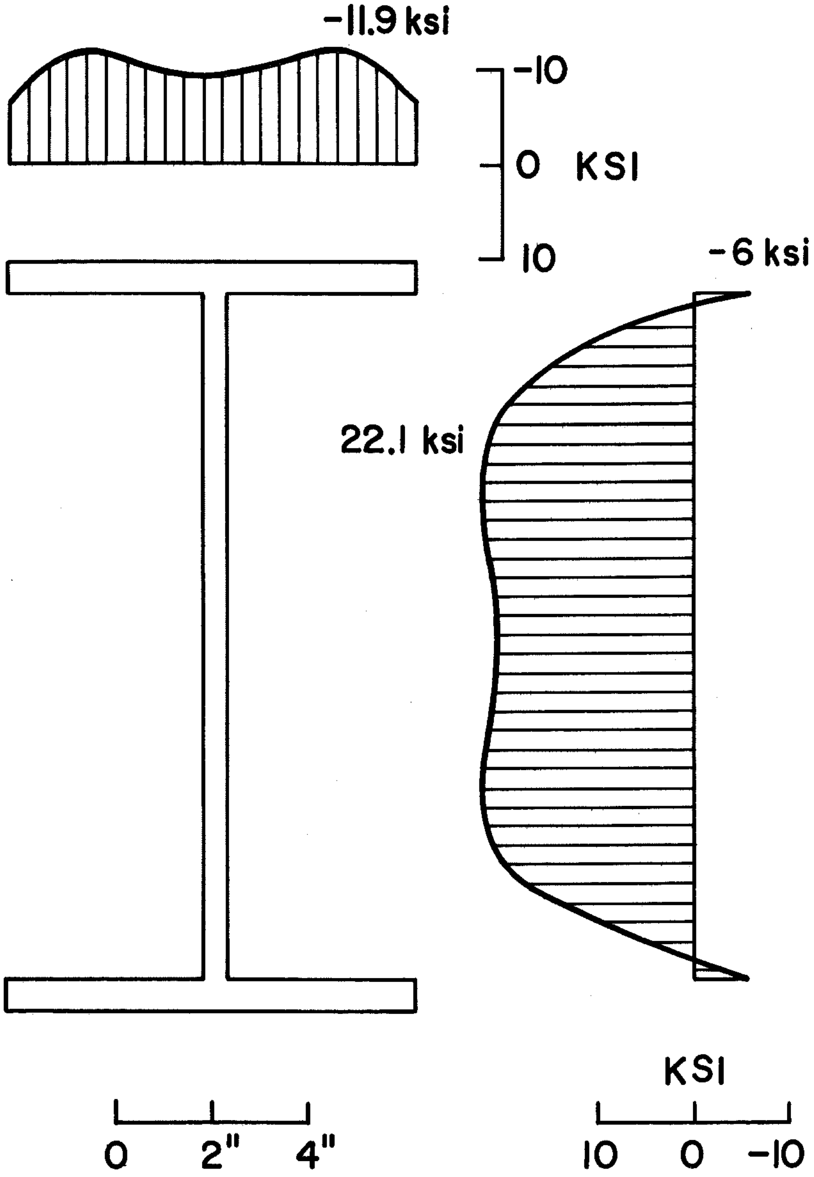

FIG. 15 ASSUMED RESIDUAL STRESS PATTERN FOR 16W71

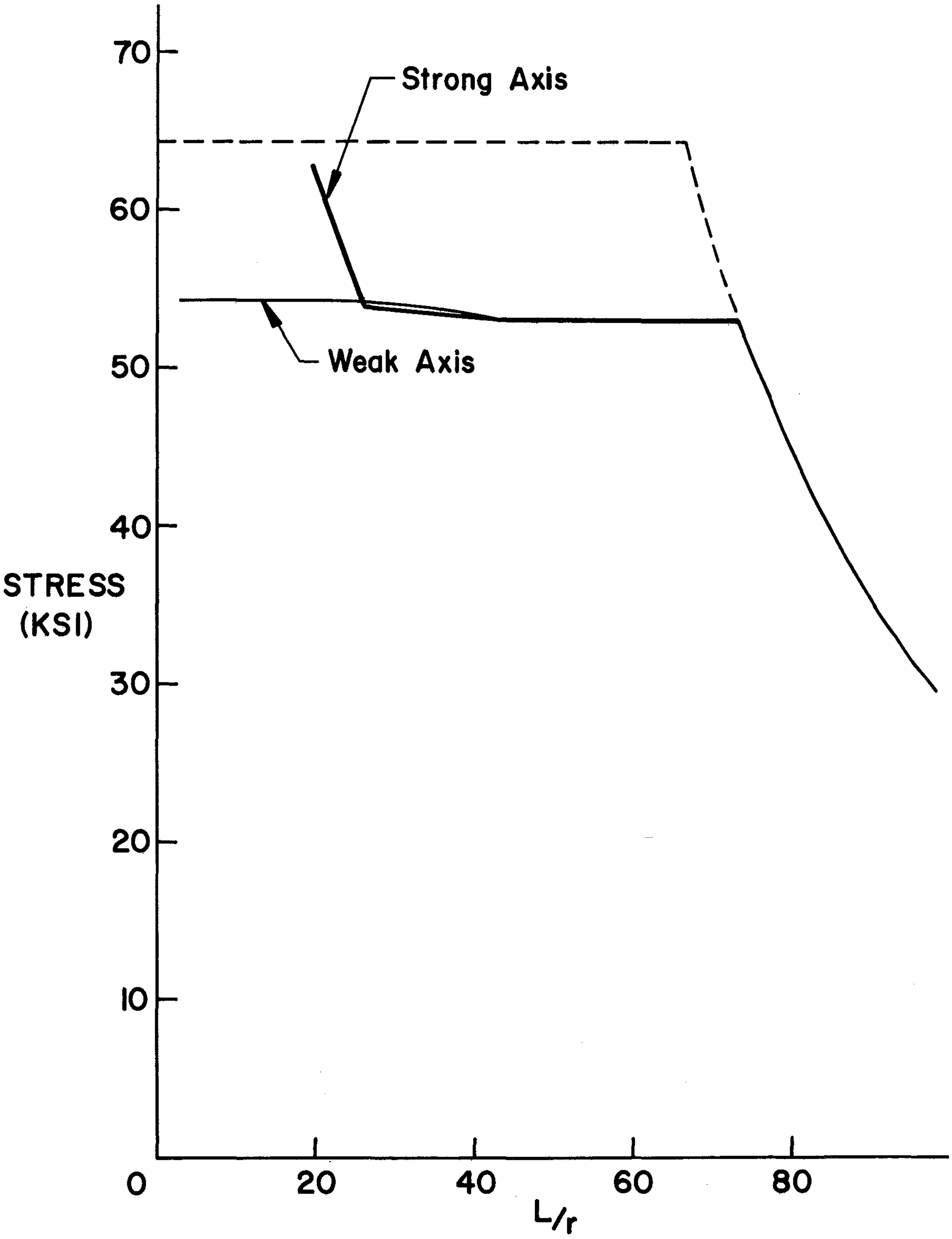

FIG. 16 COLUMN CURVE FOR ASSUMED RESIDUAL STRESS PATTERN

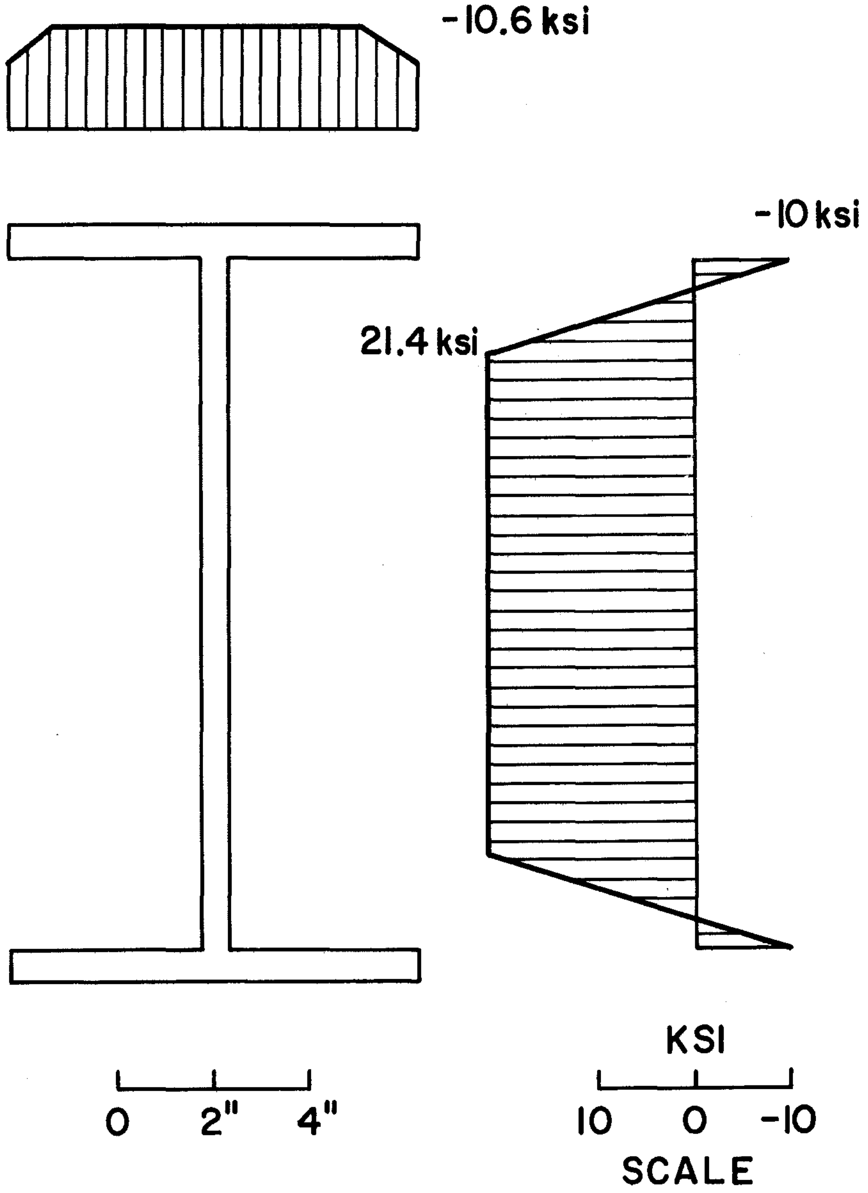

FIG. 17 ASSUMED STRAIGHT LINE RESIDUAL STRESS PATTERN FOR 16W71

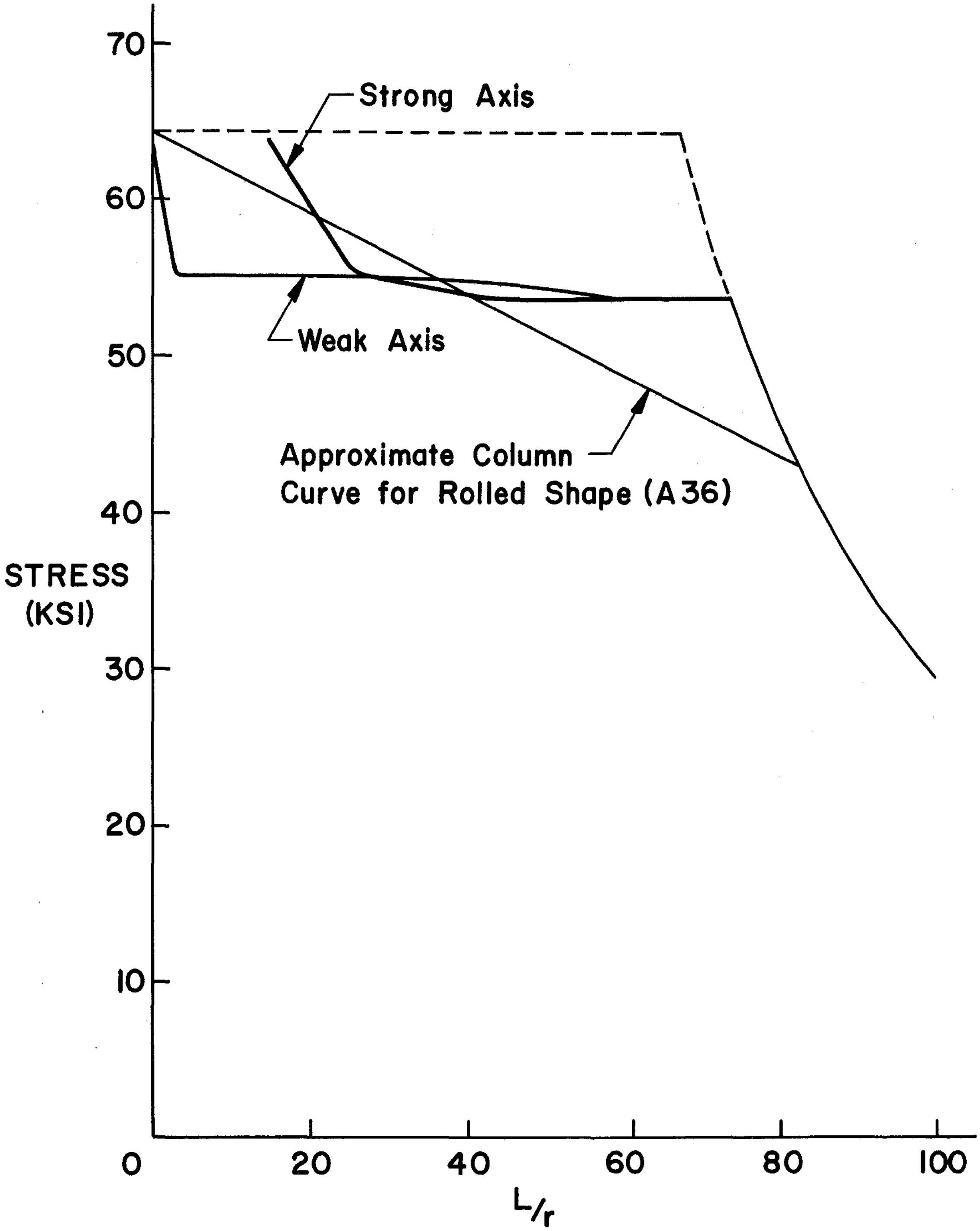

FIG. 18 COLUMN CURVE FOR STRAIGHT LINE RESIDUAL STRESS PATTERN

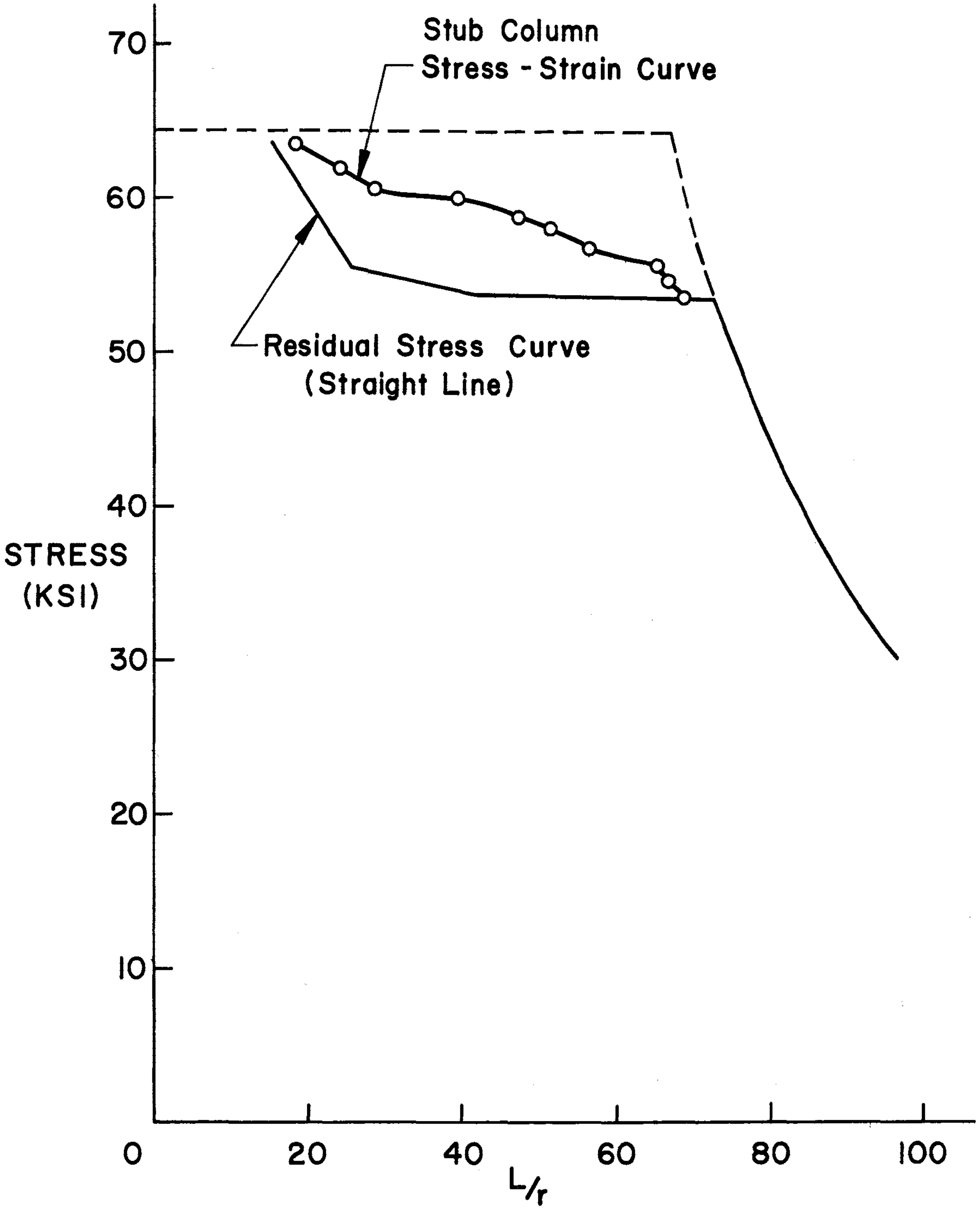

FIG. 19 TANGENT MODULUS CURVE FROM STRESS-STRAIN CURVE

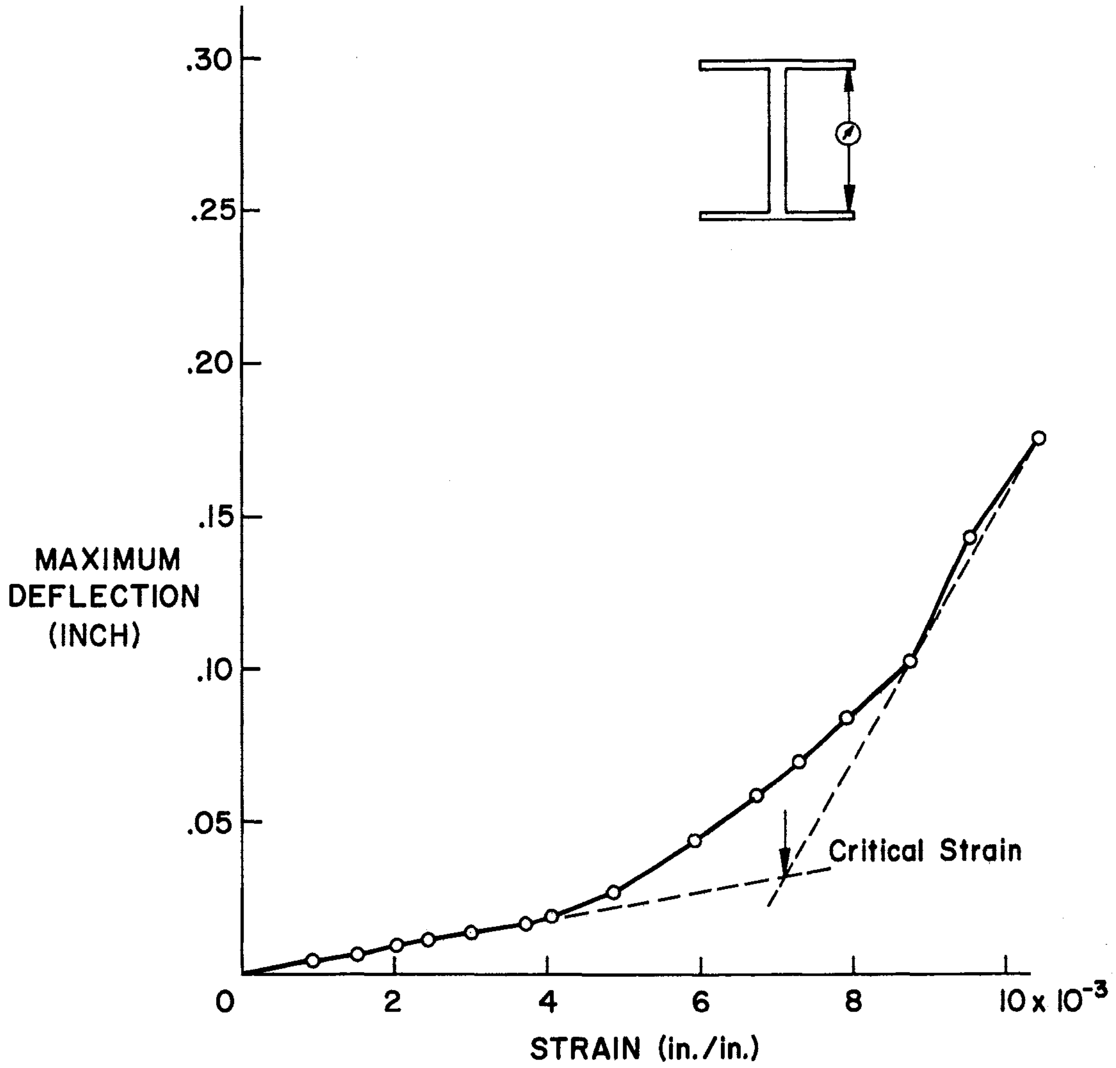

FIG. 20 LOCAL BUCKLING OF 16W71

10. REFERENCES

1. Desai, S.
MECHANICAL PROPERTIES OF ASTM A572 GRADE 65 STEEL, Fritz Engineering Laboratory Report No. 343.2 (In preparation)

2. Johnston, B. G.
COLUMN RESEARCH COUNCIL GUIDE TO DESIGN CRITERIA FOR METAL COMPRESSION MEMBERS, Second Edition, John Wiley & Sons, Inc. New York 1966

3. Huber, A. W. and Beedle, L. S.
RESIDUAL STRESS AND THE COMPRESSIVE STRENGTH OF STEEL, The Welding Journal, 33, p. 589-s, December 1954

4. Beedle, L. S. and Tall, L.
BASIC COLUMN STRENGTH, Proc. ASCE, 86(ST7), p. 139, July 1960

5. Marquez, E. S.
RESIDUAL STRESS MEASUREMENTS ON 12B19 SHAPE (A572), Fritz Engineering Laboratory Report No. 343.1 (In preparation)

6. Haaijer, G. and Thurlimann, B.
INELASTIC BUCKLING IN STEEL, Trans. ASCE, 125(I), p. 308, 1960

7. Lay, M. G.
FLANGE LOCAL BUCKLING IN WIDE FLANGE SHAPES, Proc. ASCE, 9(ST6), December 1965

8. Driscoll, G. C., Jr., et al
PLASTIC DESIGN OF MULTI-STORY FRAMES (Lecture Notes) Lehigh University, Department of Civil Engineering, Summer 1965