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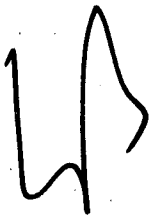
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Kyoto, Japan

P U B L I C   S E S S I O N

THE STRENGTH OF WELDED A514 STEEL STRUCTURAL COMPONENTS

by

Lambert Tall

December, 1968

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PUBLIC   SESSION

THE STRENGTH OF WELDED A514 STEEL STRUCTURAL COMPONENTS

(La Résistance des Elements de Structures

en Acier Soudé A514)

by

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Synopsis

This paper summarizes some aspects of a major research project into the strength of welded structural components of A514 steel, a high strength constructional alloy steel with a minimum yield stress of 100 ksi (70 kp/mm^2).

The mechanical properties of the steel were determined, and residual stress measurements were made for a wide variety of sizes of flame-cut welded plates and shapes. Full size tests were made of plate and column buckling, and of beam-column behavior, and the results were correlated with theoretical predictions, and, in some cases, with the behavior of their rolled counterparts.

Cet article résume quelques aspects d'un important project de recherche sur la résistance des éléments d'ossatures en acier soudé A514, qui est un acier allié de construction à haute résistance avec une limite d'élasticité minimum de 70 kp/mm^2.

Les propriétés mécaniques de cet acier sont déterminés, et des mesures de contraintes résiduelles furent faites pour un grand nombre de différent profils reconstitués, et de plaques oxycoupées et soudées. Des essais de plaques, de flambement, et de poutres en sollicitation composeé, ont été expérimentés sur des spécimens de grandeur nature, et les résultats on été corroborés avec les prédictions théoriques, et, pour quelques cas, avec le comportement des profils laminés de même dimension.

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1. INTRODUCTION

With the continued modern developments in steel making, a new low-carbon, quenched and tempered constructional alloy steel was introduced some 15 years ago. This was "T-1" steel; it meets the requirements of ASTM A514/517 introduced in 1966. These steels have exceptional strength and toughness, combined with good weldability.

This report is a very brief summary presenting the highlights of a major research project undertaken to determine the strength and characteristics of A514 steel structural components, information which could be used in the preparation of design recommendations. The study included the determination of mechanical properties, the residual stress distribution in rolled and welded plates and shapes, and the determination of the strength of columns and beam-columns, and the effect of local buckling. Particular attention was paid to welded structural components. Theoretical predictions were checked with experimental results. The details of the study are given in Reference 1, and in the other papers referred to throughout this report.

2. MECHANICAL PROPERTIES

A514/517 steel is a low-carbon, constructional alloy steel which is water quenched from 1650/1750 ^{o}F (910/970 ^{o}C) and tempered at 1100/1275 ^{o}F (610/700 ^{o}C).[2] It is furnished with a minimum yield strength of 100 ksi (70 kp/mm^2), and a tensile strength in the range of 115 to 135 ksi (80 to 95 kp/mm^2) for plate thicknesses between 3/16 " to 2.1/2 " (5 to 65 mm.) inclusive. [2]

A number of preliminary tests were performed on the material prior to the testing of structural components; these were tension and compression specimen tests, residual stress measurements, and stub column tests.

The average of 58 tension specimen tests resulted in a static yield stress [3] σ_{ys}, of 112 ksi (78.5 kp/mm^2), at the 2% offset. The proportional limit, σ_p/σ_{ys}, is 0.82; the tensile strength, σ_u, is 123 ksi (86.2 kp/mm^2); the reduction in area is 48%, and the elongation in an 8" (200 mm.) gage length is 11%. The results of tension and compression tests were essentially the same.

A typical stress-strain relationship curve obtained from a tension specimen test is shown in Fig. 1, and is compared with the stress-strain curve of a structural carbon steel , (a mild steel), ASTM A36. While the stress-strain relationship of A36 steel may be represented by a pair of straight lines, that is, by an elastic-plastic relationship, A514 steel has a non-linear stress-strain relationship, and there is no yield plateau. A mathematical expression was developed to represent the stress-strain relationship of A514 steel -- it consists of an initial straight line to represent the elastic part, a curve at the knee, and a second straight line beginning at the onset of strain-hardening. This mathematical expression defines the actual relationship, a necessary prerequisite to the computation of the strength of structural members. The shape of the stress-strain relationship has a marked influence on the strength of compression members.

The stub column tests [4] are compression tests on short lengths of the complete section of a shape. The stub column test furnishes an average stress-strain curve for the complete cross section taking into account the effects of residual stress; such a curve may be used to prepare the tangent modulus column curve. [5]

3. RESIDUAL STRESSES

Residual stresses have been studied extensively for many years. However, it was only in the past decade and a half that it was realized that

residual stresses are a major influence in the strength of compression members.[6,7,8] It has been shown that they are the cause of the transition curve in the column curve and the plate buckling curve, and that variation in their magnitude and distribution exerts comparatively great influence on column strength and on the strength of plates in compression.

Residual stresses are formed in a structural member as a result of plastic deformations; these stresses exist in the cross section even before the application of an external load. These plastic deformations may be due to cooling after hot-rolling or welding, or due to fabrication operations such as cold-bending or cambering.

Residual stresses due to cooling after welding generally are of much higher magnitudes than those due to cooling after rolling. [8,9] This is due to the very high temperature gradient near the source of heat input. It is these very large magnitudes of residual stress in welded shapes that cause their compression members to exhibit low strengths when compared to those of similar rolled shapes, for the small to medium sizes. [8,10]

Since A514 is a quenched and tempered steel, it may be expected that the heat treatment will affect the residual stress distribution. Indeed, the tempering has an effect similar to annealing -- the residual stresses which may have existed from cooling after rolling, are reduced substantially in the heat treatment, as seen in Fig. 2. [11] For the small to medium size rolled shapes, the magnitude of compressive residual stresses generally vary between 3 and 5 ksi, which is about one third of that for similar shapes of mild steel. [6,8] A comparison of the magnitude of compressive residual stress to the yield point of the material, gives approximately 5% for A514 steel, and about 40% for A36 steel.

Welded A514 structural shapes are built up from component plates which are normally prepared to size by flame-cutting. Figure 3a shows the

residual stress distribution in such a typical plate. Flame-cutting involves the melting of base metal, and so is a source of heat very similar in nature to that of welding; this is the reason for the magnitudes of the tensile residual stress at the cut edge. A weld or a flame-cut edge will always exhibit a tensile residual stress equal in magnitude to the yield point of the weld metal, or parent metal, respectively.[12]

Figure 3b shows the same flame-cut plate, with a center V-weld. The magnitude of tensile residual stress at the weld is equal to the yield point of the weld metal, which, in this case, was made with an electrode of lower strength than A514 steel.[13] The introduction of tensile stresses due to the additional heat source requires an equilibrium change to the residual stress distribution, an increase in the magnitude of the compressive residual stresses, and a decrease in the magnitude of the tensile stresses at the flame-cut edge. Therefore, for wide plates, the change in distribution due to the weld is comparatively small.[13]

The residual stress distribution in two welded A514 shapes are shown in Fig. 4. Similar observations may be made as for the welded plates -- in particular, the wider the plate, the smaller the magnitude of residual stress at positions away from the weld. The study showed that welded A514 shapes contain residual stresses only slightly larger in magnitude than those in welded shapes built up from mild steel plates. [14]

A comparison of the residual stresses in a welded A514 H-shape and in its component welded plates is shown in Fig. 5. The distributions are similar. It was concluded that the residual stress distribution in a welded shape may be predicted from those in the separate component welded plates.[14]

4. COLUMN STRENGTH

The strength of columns of a practical length corresponds to the condition of inelastic buckling, that is, buckling where part of the cross section has yielded. [8] It is the tangent modulus load [15,16] which defines the buckling strength of an initially perfectly straight column; this load is almost never observed in tests, since columns are usually not initially straight. The ultimate load of a column, on the other hand, is the load which is usually obtained from experiments. For an initially straight column, it is a load in excess of the tangent modulus load, but less than the reduced modulus load; it may vary considerably for practical columns, depending on the magnitude of the initial out-of-straightness of the column. Generally, test results will tend to approximate the tangent modulus load.

It was mentioned above that residual stresses reduce column strength. This is brought about by certain portions of the cross section reaching the yield level early, due to the presence of compressive residual stresses; the effective moment of inertia of the cross section is reduced, lowering the load-carrying capacity of the compression member.

For A514 steel, the magnitude of the compressive residual stress is very small when compared to the yield point -- thus, it may be expected that column strength is proportionately high. This is exactly what happens and is shown in Figs. 6a and 6b for rolled and welded columns, respectively; in both cases, the A514 steel (σ_y = 100 ksi or 70 kp/mm^2 , nominal) is compared with mild steel (A7 steel, σ_y = 33 ksi, or 23 kp/mm^2, nominal.) Figure 6 shows test results only -- the CRC curve is included for reference, it is the basis of the AISC design curve [17] used for all steels and fabrication procedures. This curve was based on the tangent modulus load and test results obtained for small rolled shapes of mild steel (A7 steel.) It was the first design curve to include the effects of residual stress directly.

The strength of the A514 columns were predicted by the tangent modulus concept, assuming both the idealized elastic plastic $\sigma - \varepsilon$ curve, and also the actual inelastic $\sigma - \varepsilon$ curve. [5] This is illustrated in Fig. 7 for weak axis buckling of an 8WF31 rolled shape, for residual stress distributions applicable for both A514 steel and for A7 steel; test results are also presented for this steel. Figure 7 indicates that column strengths may be predicted with a reasonable accuracy.

Both theoretical and experimental studies [5,18,19] have shown that, for A514 steel, rolled WF columns are stronger than welded H-columns, and that welded box-columns and rolled WF columns exhibit similar strengths. Also, A514 steel columns are much stronger than their mild steel counterparts. These findings reflect the influence of the small magnitude of the residual stresses in A514 steel. Although welding introduces relatively high magnitudes of tensile stresses, the compressive stresses are increased only slightly, (Fig. 4), so that, even for welded shapes, the proportion of the compressive residual stress to the yield stress is comparatively low for A514 steel; in addition, the tensile values of residual stress at the flange tips due to the flame-cut edge create a favorable condition, one where the flange tips remain elastic during loading. Welded box shapes similarly exhibit relatively high column strength due to the high values of tension at the welded corners.

5. BEAM - COLUMNS

Beam-columns, structural members with significant amounts of both bending and compression, have been investigated for many decades. More recently, the use of the concept of column deflection curves has been introduced [20] and has proven useful in consideration of the behavior of the beam-column in a subassemblage or in a multi-story frame.

All the previous investigations were limited to materials with an elastic-perfectly-plastic stress-strain curve, as well as being restricted to small cross sections of mild steel with residual stresses corresponding to rolled shapes. It had also been assumed that no reversal of the strain of plastified sections is allowed during the entire loading history, and that the reversal of curvatures after the ultimate load (the "unloading effect") is neglected.

This investigation [5,21] considered the behavior of both rolled and welded beam-columns of A514 steel. Both the non-linearity of the stress-strain curve, and the appropriate residual stress distribution were used, and the effect of strain reversal and unloading of moments were included. Numerical solutions were compared with full-scale test results, and also with analytical solutions obtained by extrapolation from results of rolled mild steel shapes.

Test results are compared with theoretical predictions for the ultimate strength of an A514 beam-column in Fig. 8; both a rolled shape (8WF40), and a welded shape (11H71) are considered. Figure 9 presents an interaction curve for the same shapes, and includes the solution extrapolated from mild steel analysis.

This study [5,21] showed that the extrapolation procedure provides an approximate , although conservative, estimate of the strength of A514 beam-columns, when compared to the direct integration procedures used. Comparison between theory and tests showed that, not only the ultimate strength, but also the complete history of a beam-column behavior can be predicted; this is critical, since the unloading part of the M-θ diagram is needed for the computation of the strength of subassemblages and of multi-story frames.[15,20] The strain reversal effect is pronounced for the nonlinear stress-strain curve of A514 steel; the unloading effect, however, becomes pronounced only on

the latter part of the unloading M-θ curve.

6. LOCAL BUCKLING

The efficient design of a column requires a cross section with comparatively thin plates, and thus, local buckling may increase in significance as steels of higher yield point are used. Consideration must be given to the stability of plate elements so that the most economical cross section can be designed. These points are significant for A514 steel.

Residual stresses play an important role in the buckling of plates as compression members -- and, unlike columns, residual stresses affect the elastic buckling of plates.[22] This study presented, for the first time, solutions to the elastic-plastic and plastic buckling of plates with residual stresses.[22,23,24] The study was complemented by experimental verifications, using square box shapes.[25,26]

The study of this investigation included the analysis of plate elements and the analyses of plate assemblies. Several combinations of edge conditions were considered: free, simply-supported, and fixed, with the loading edge in each case simply-supported. These results are useful in estimating the overall buckling strength of the cross section.

Figure 10 presents some typical results of both the analysis and the experiments.[22,25] The analysis presents the bifurcation curves for a plate, simply-supported on all edges, and containing a residual stress distribution which very closely approximates that in a plate welded at the unloaded edges. For the analysis, the simplified assumption of an idealized, elastic-perfectly-plastic stress-strain curve was made. In this case, the plate is one side of a square box, welded at each corner. The test results are for both A7 steel and for A514 steel. The compressive residual stress, σ_{rc},

defines the plate buckling curve for the elastic -plastic and elastic

buckling conditions, and values of $\sigma_{rc}/\sigma_y = 1/8$ corresponds approximately to

A514 steel, and values = 3/8 corresponds approximately to A7 steel. On a non-

dimensional basis, A514 steel exhibits a higher plate-buckling strength than

does A7 steel, due entirely to the relative magnitudes of compressive residual

stress. Considerable post-buckling strength is exhibited for elastic buckling.

The buckling load of welded plates correlated well with the total strain theory

for elastic-plastic buckling; the incremental theory predicted high critical

values.

Figure 10 shows also that it is possible for a plate to buckle

with no external load. This phenomenon was explained for the first time in this

study [22,23]; it is necessary only for a particular magnitude and distribution

of residual stress to exist for a particular b/t ratio. It has been observed

that some relatively thin plates buckle upon welding.

It is also seen from Fig. 10 that a critical value of width-

thickness ratio exists, such that plates with a b/t ratio less than this value

can sustain the full yielding load. It was shown that the 1963 AISC Specification

requirements [17] for critical width-thickness ratios can be extended directly to

the A514 steel shapes, both rolled and welded.

The initiation of local buckling did not reduce the strength of

the beam-columns tested. [5,21] If further study confirms this, then the use

of beam-columns could be extended beyond the local buckling point.

7. S U M M A R Y

Some of the conclusions of this investigation were:

1. The stress-strain relationship of A514 steel is different from that of

mild steel -- there is no yield plateau. The relationship was defined

mathematically in order to be used in theoretical predictions. The shape
of this relationship has a marked influence on the strength of compression
members.

2. The distribution of residual stress in welded A514 steel plates and shapes
   is similar to that for mild steel. But, the magnitude of the compressive
   residual stresses is small when compared to the yield stress; thus, the
   effect of these stresses on structural strength is much smaller than for
   mild steel.

3. Residual stresses in rolled, heat-treated A514 shapes are very small in
   magnitude, generally less than 5 ksi, and thus exhibit relatively high
   column strength.

4. The prediction of the strength of A514 steel columns from the tangent
   modulus concept correlated well with test results.

5. The buckling load of welded plates correlated well with the total strain
   theory for elastic-plastic buckling; the incremental theory predicted
   high critical values.

6. The results of the beam-column tests agreed well with the theoretical
   analysis which took into account the non-linearity of the steel in
   developing the moment-curvature-thrust relationships and the interaction
   curves.

7. The strength and behavior of A514 steel welded plates and shapes should not
   be extrapolated from that of mild steel, since the difference of yield point,
   mechanical properties, and residual stresses, are significant.

        The findings of this study were used in the preparation of the
new (1969) revision of the design specifications of the American Institute
of Steel Construction.

8. ACKNOWLEDGEMENTS

9. NOMENCLATURE

b/t	width/thickness ratio of plate
CRC	Column Research Council
E	Young's Modulus
H	symbol denoting welded H-shape
L/r	slenderness ratio of column
M	moment acting on end of beam-column
M_{max}	moment corresponding to ultimate load on beam-column
M_p	plastic moment
M_{pc}	plastic moment modified by axial load
P	axial load on column
P_y	axial load to cause complete plastification of column cross section
WF	symbol denoting wide-flange rolled H-shape
ε	strain
θ	angular rotation at end of beam-column
λ	symbol denoting a non-dimensional slenderness ratio
σ	stress
σ_{cr}	critical stress, buckling stress, stress at bifurcation
σ_p	stress at proportional limit
σ_{rc}	residual compressive stress
σ_{rt}	residual tensile stress
σ_u	stress at ultimate load
σ_y	yield stress
σ_{ys}	static yield stress, corresponding to a zero strain rate in the plastic range.

10. REFERENCES

1. C. K. Yu and L. Tall
   WELDED AND ROLLED A514 STEEL COLUMNS - A SUMMARY REPORT
   Fritz Laboratory Report No. 290.16, December 1968. To be published
   in the Welding Journal.

2. U. S. Steel Corporation
   T-1 CONSTRUCTIONAL ALLOY STEEL
   Publication Number ADUSS ol-1205, 1966

3. N. R. NagarajaRao, M. Lohrmann, and L. Tall
   EFFECT OF STRAIN RATE ON THE YIELD STRESS ON STRUCTURAL STEEL
   ASTM Journ. of Materials, Vol.1, No. 1, March 1966

4. L. Tall
   STUB COLUMN TEST PROCEDURE
   Fritz Laboratory Report No. 220A.36, February 1961.
   Revisions by IIW Working Group (H. Louis, M. Marincek, and L. Tall),
   IIW Class C Standard Document, July 1962.
   Appendix C, CRC Guide, 2nd Ed., B.G. Johnston Editor, Wiley, 1966.

5. C.K. Yu
   INELASTIC COLUMNS WITH RESIDUAL STRESSES
   PhD Dissertation, Lehigh University, 1968. University Microfilms, Inc.,
   Ann Arbor, Michigan.

6. A. W. Huber and L. S. Beedle
   RESIDUAL STRESS AND THE COMPRESSIVE STRENGTH OF STEEL
   Weld. Journ., Vol. 33, December 1954

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

8. L. Tall
   RECENT DEVELOPMENTS IN THE STUDY OF COLUMN BEHAVIOR
   Journ., Inst. of Engrs., Australia, Vol. 36, December 1964

9. N. R. NagarajaRao, F.R. Estuar, and L. Tall
   RESIDUAL STRESSES IN WELDED SHAPES
   Weld. Journ., Vol. 43, July 1964

10. F. R. Estuar and L. Tall
    EXPERIMENTAL INVESTIGATION OF WELDED BUILT-UP COLUMNS
    Weld. Journ., Vol. 42, April 1963

11. E. Odar, F. Nishino, and L. Tall
    RESIDUAL STRESSES IN ROLLED HEAT-TREATED T-1 SHAPES
    W.R.C. Bull. No. 121, April 1967

12. L. Tall
    RESIDUAL STRESSES IN WELDED PLATES - A THEORETICAL STUDY
    Weld. Journ., Vol. 47, January 1964

13. E. Odar, F. Nishino, and L. Tall
    RESIDUAL STRESSES IN T-1 CONSTRUCTIONAL ALLOY STEEL PLATES
    W.R.C. Bull. No. 121, April 1967

14. E. Odar, F. Nishino, and L. Tall
    RESIDUAL STRESSES IN WELDED BUILT-UP T-1 SHAPES
    W.R.C. Bull. No. 121, April 1967

15. L. Tall, Editor-in-Chief
    STRUCTURAL STEEL DESIGN
    Ronald Press Co. 1964, New York

16. a. B.G. Johnston
       BUCKLING BEHAVIOR ABOVE TANGENT MODULUS LOAD
       Proc. ASCE, Vol. 87 (EM6), December 1961
    b. L. Tall and F.R. Estuar: Discussion to Ref. 16a, Proc. ASCE,
       Vol. 88 (EM5), October 1962

17 American Institute for Steel Construction
    SPECIFICATIONS FOR THE DESIGN, FABRICATION, AND ERECTION OF STRUCTURAL
    STEEL FOR BUILDINGS
    AISC, New York, 1961, 1963, and 1969

18. F. Nishino and L. Tall
    EXPERIMENTAL INVESTIGATION OF THE STRENGTH OF A514 STEEL COLUMNS
    Fritz Laboratory Report No. 290.9, in preparation; for publication in
    the Welding Journal.

19. F. Nishino and L. Tall
    NUMERICAL METHOD FOR COMPUTING COLUMN CURVES
    Fritz Engineering Laboratory No. 290.6, December 1966

20. G. C. Driscoll, et al.
    PLASTIC DESIGN OF MULTI-STORY FRAMES
    Summer Conference Notes, Lehigh University, 1965

21. C. K. Yu and L. Tall
    A514 STEEL BEAM-COLUMNS
    Fritz Laboratory Report No. 290.15, October 1968. To be published
    in ASCE.

22. Y. Ueda and L. Tall
    INELASTIC BUCKLING OF PLATES WITH RESIDUAL STRESSES
    IABSE Publications, Vol. 77, Zurich, December 1967

23. Y. Ueda
    ELASTIC, ELASTIC-PLASTIC, AND PLASTIC BUCKLING OF PLATES WITH RESIDUAL
    STRESSES
    PhD Dissertation, Lehigh University, 1962. University Microfilms, Inc.,
    Ann Arbor, Michigan

24. F. Nishino
    BUCKLING STRENGTH OF COLUMNS AND THEIR COMPONENT PLATES
    PhD Dissertation, Lehigh University, 1964. University Microfilms,
    Inc., Ann Arbor, Michigan.

25. F. Nishino, Y. Ueda, and L. Tall
    EXPERIMENTAL INVESTIGATION OF THE BUCKLING OF PLATES WITH RESIDUAL STRESSES
    ASTM STP No. 419, 1967

26. F. Nishino and L. Tall
    RESIDUAL STRESSES AND THE LOCAL BUCKLING STRENGTH OF STEEL COLUMNS
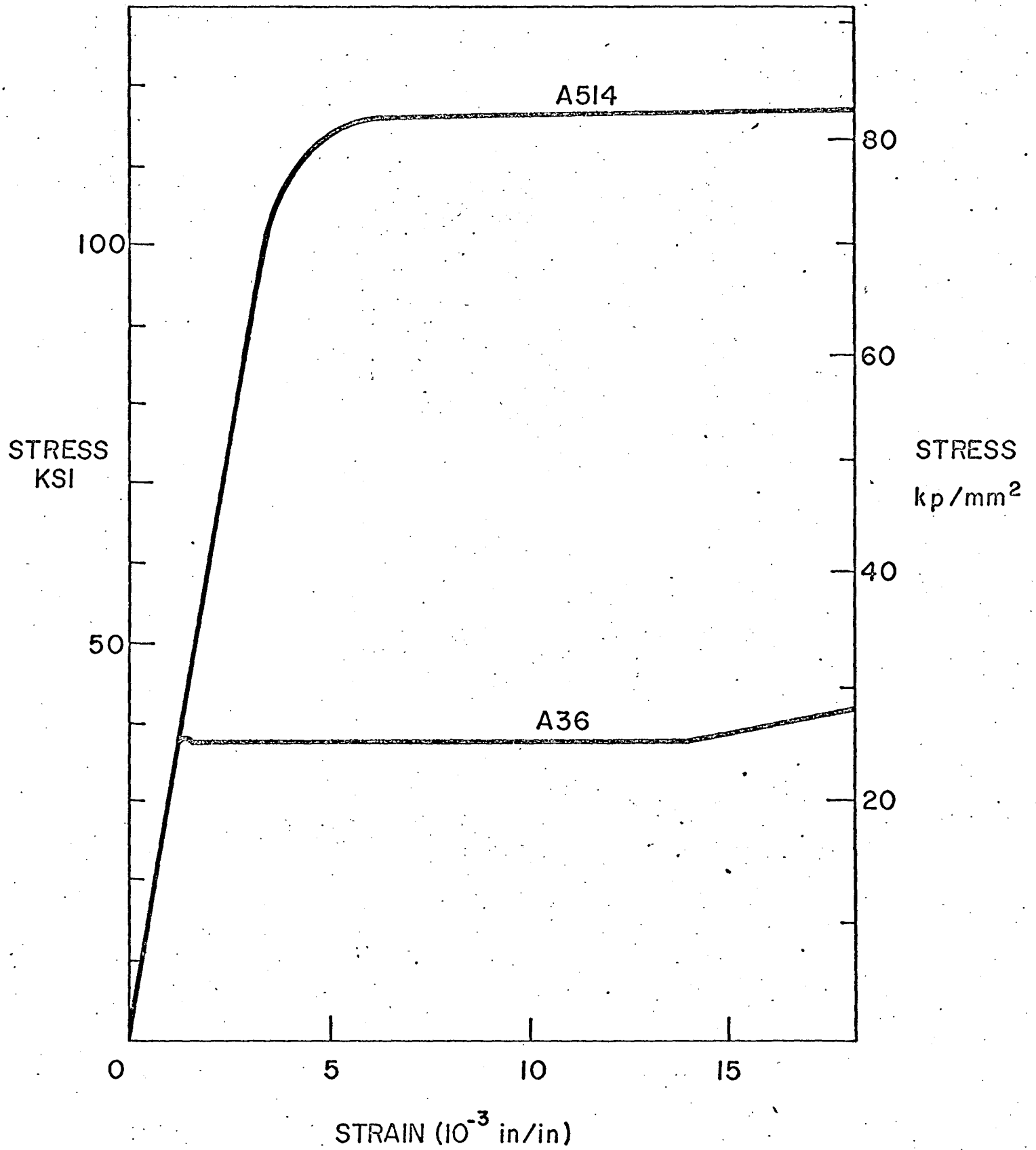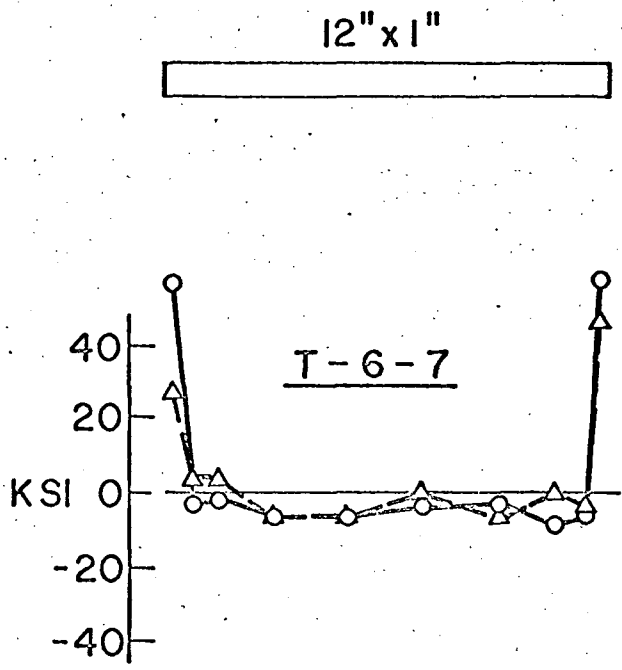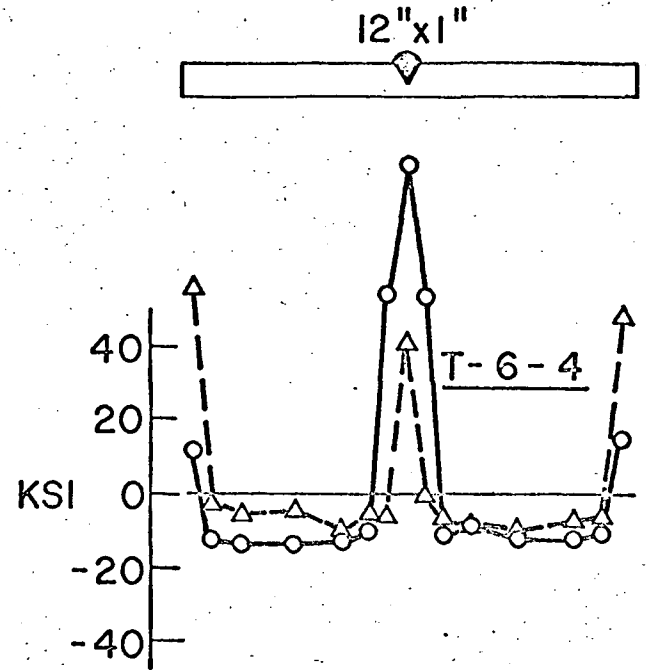   Fritz Laboratory Report No. 290.11, January 1967.

Fig. 1   TYPICAL STRESS-STRAIN RELATIONSHIP

Fig. 2   RESIDUAL STRESSES IN ROLLED HEAT-TREATED A514 STEEL SHAPES

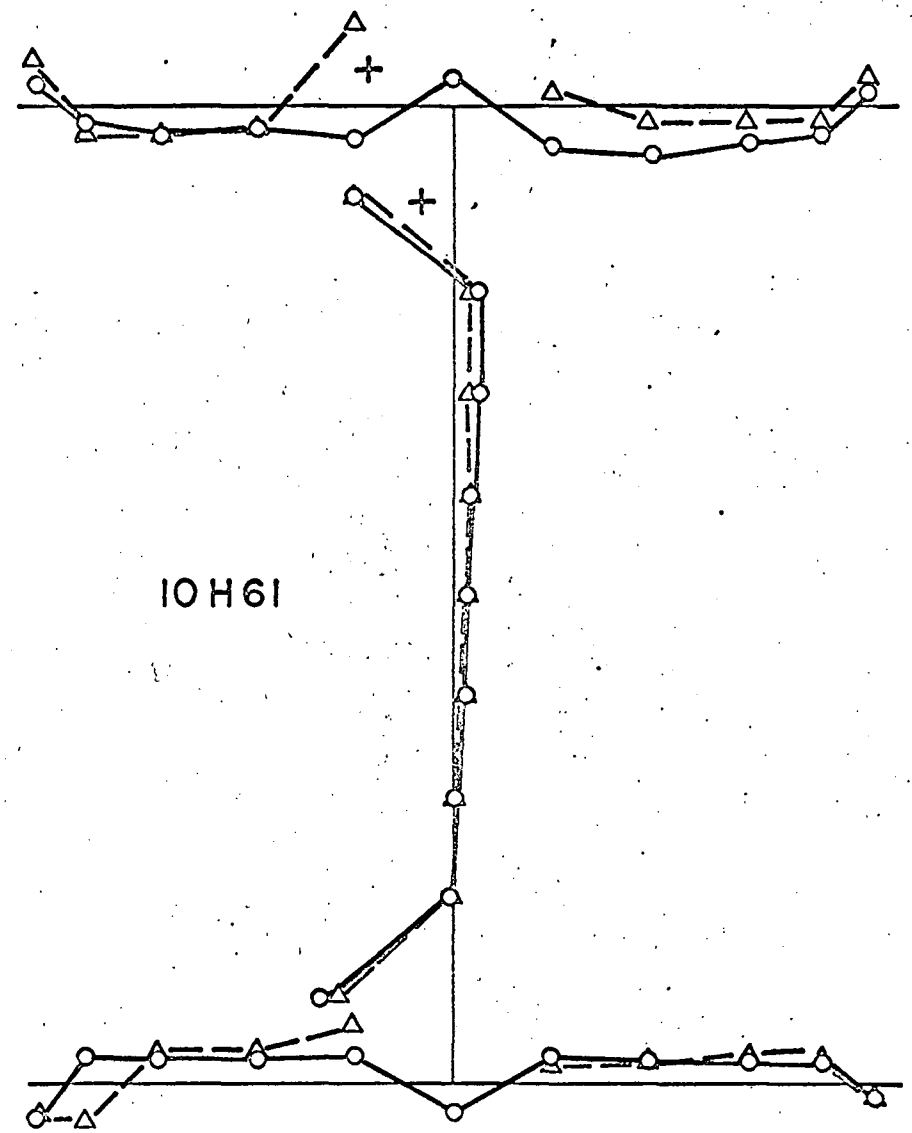Fig. 3   RESIDUAL STRESSES IN A514 PLATES

6 H 27

2 IN.

KSI
40   0   -40

10 H 61
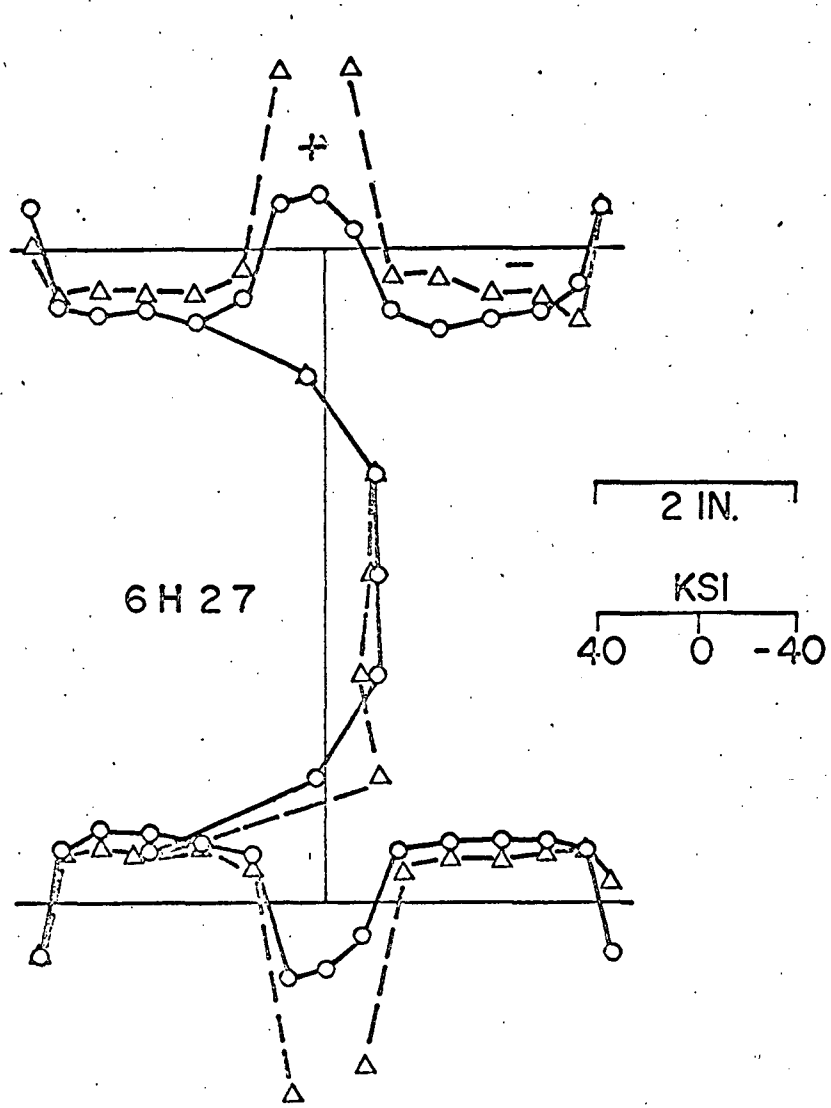
Fig. 4   RESIDUAL STRESSES IN WELDED A514 SHAPES

6H27
(Flame Cut)
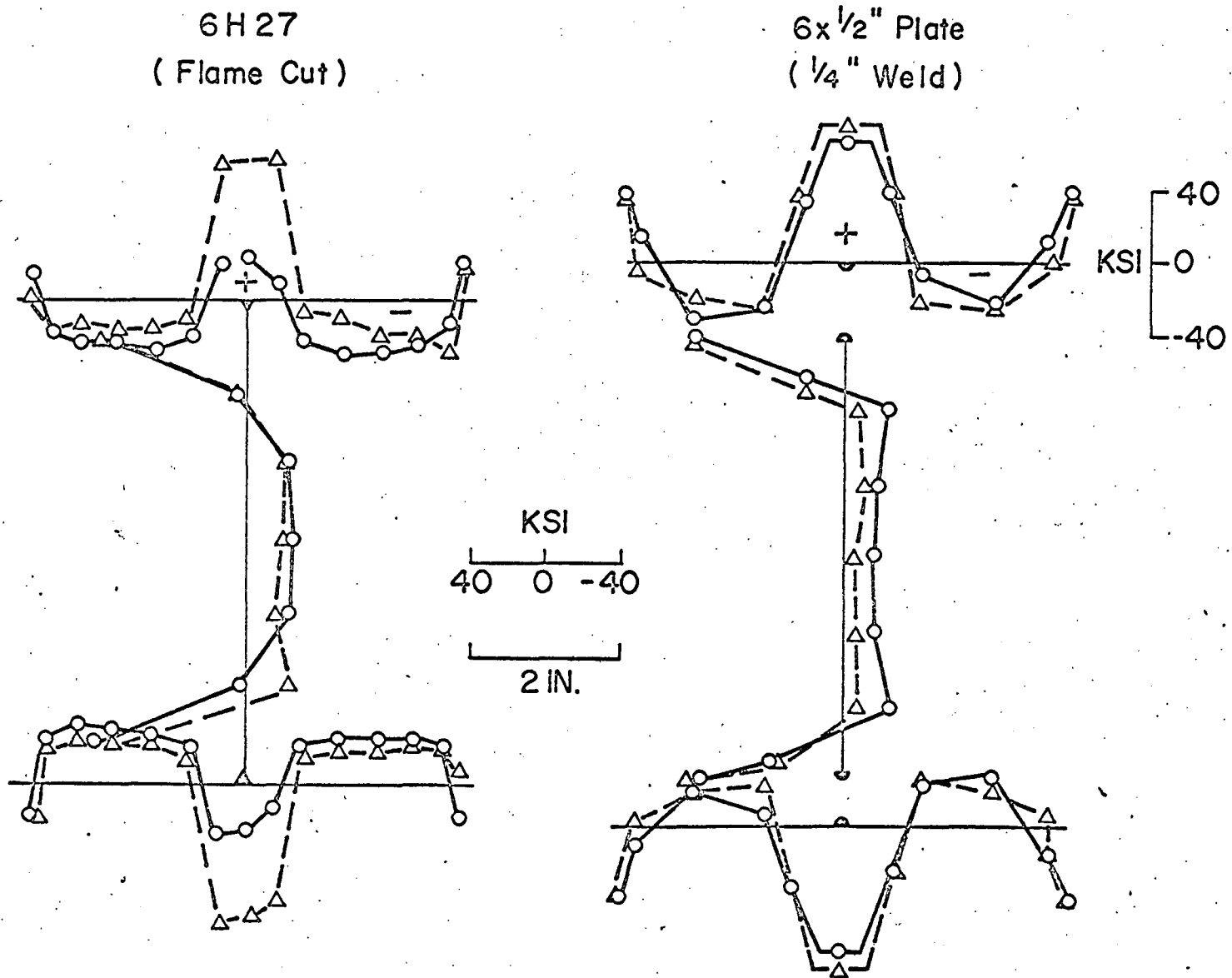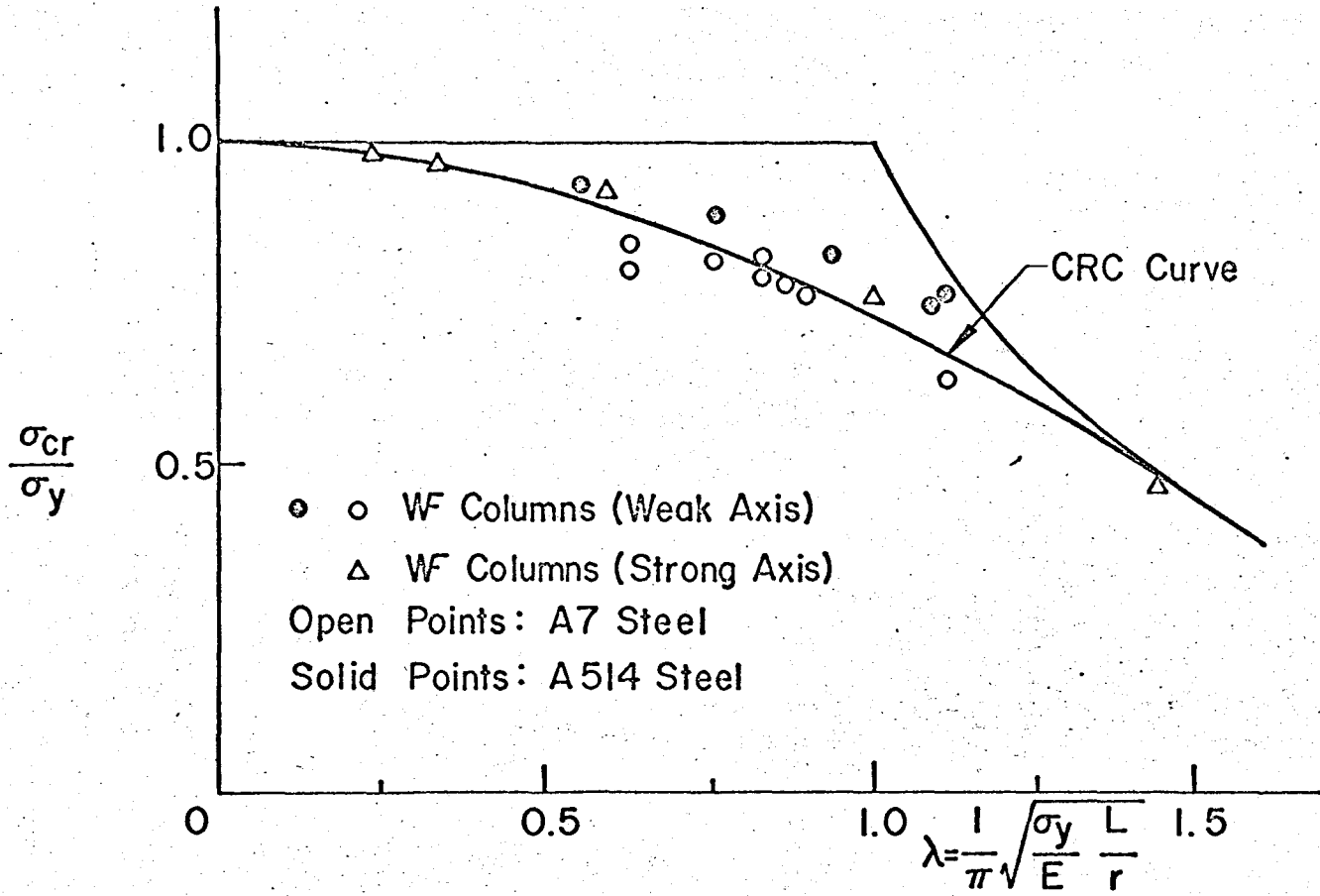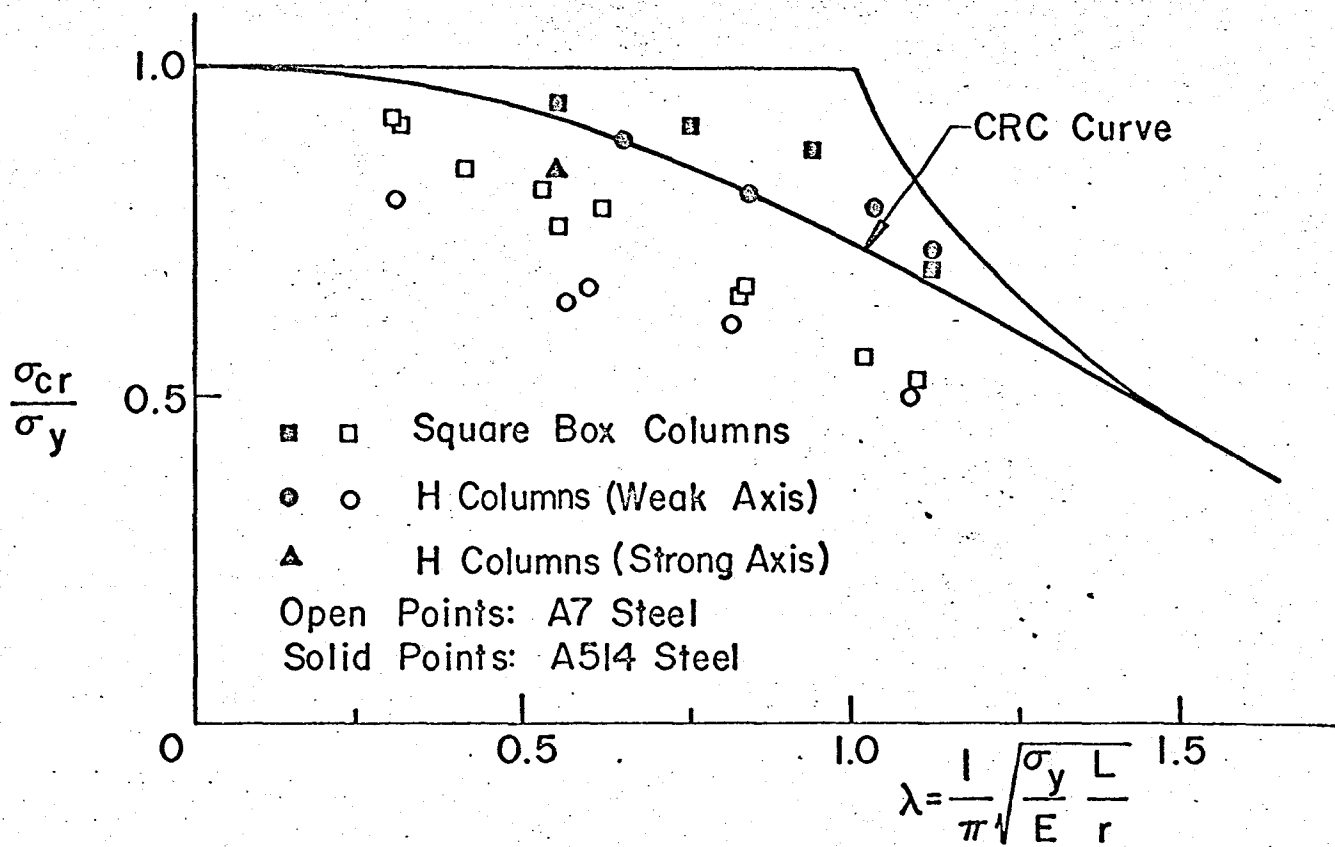
6x ½" Plate
(¼" Weld)

40
KSI — 0
-40

KSI
40 0 -40

2 IN.

Fig. 5   RESIDUAL STRESSES IN A514 STEEL SHAPE AND IN ITS COMPONENT WELDED PLATES

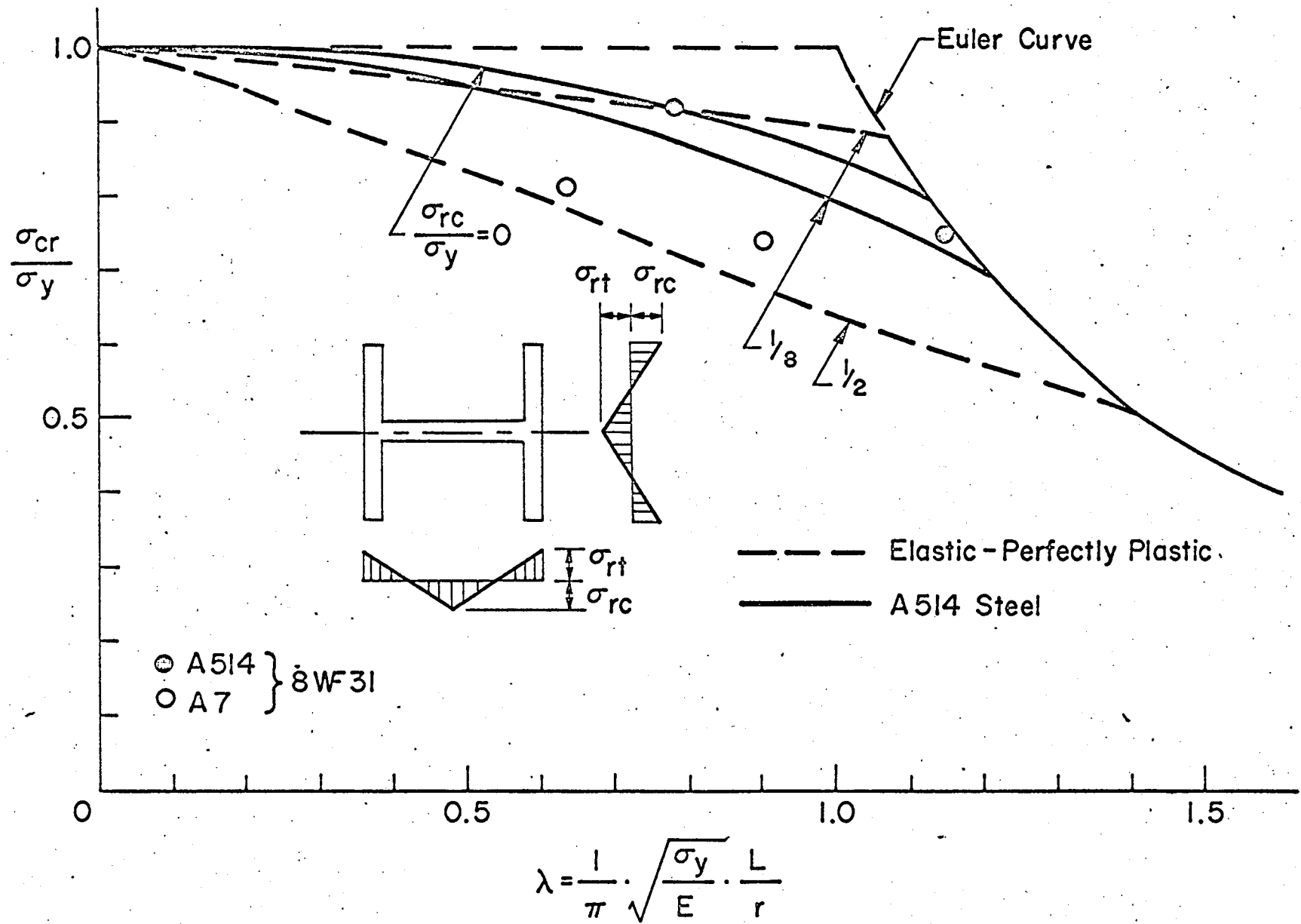(a) Rolled Columns

(b) Welded Columns

Fig. 6   THE STRENGTH OF A514 STEEL COLUMNS

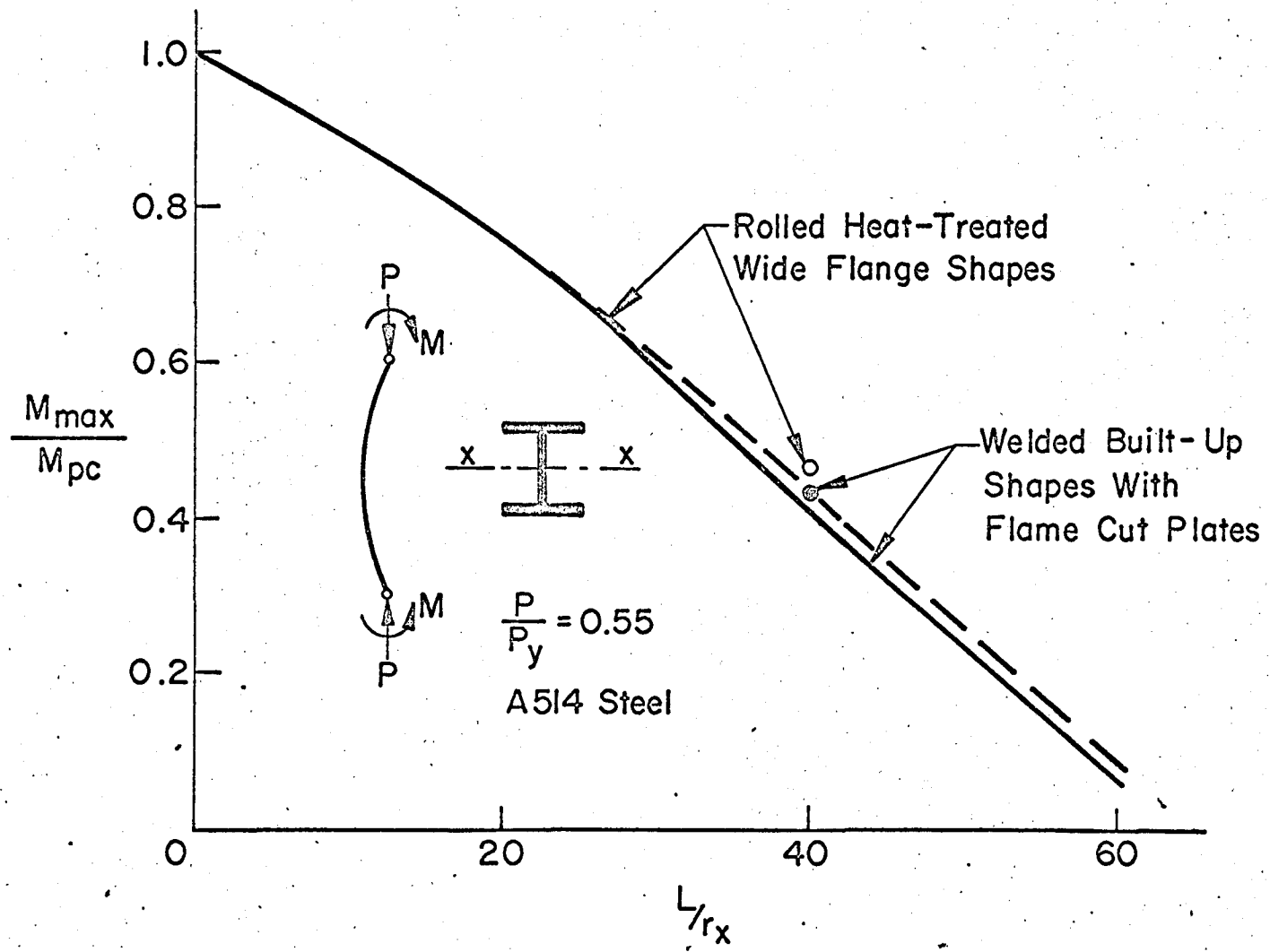Fig. 7   PREDICTION OF COLUMN STRENGTH BY TANGENT MODULUS LOAD

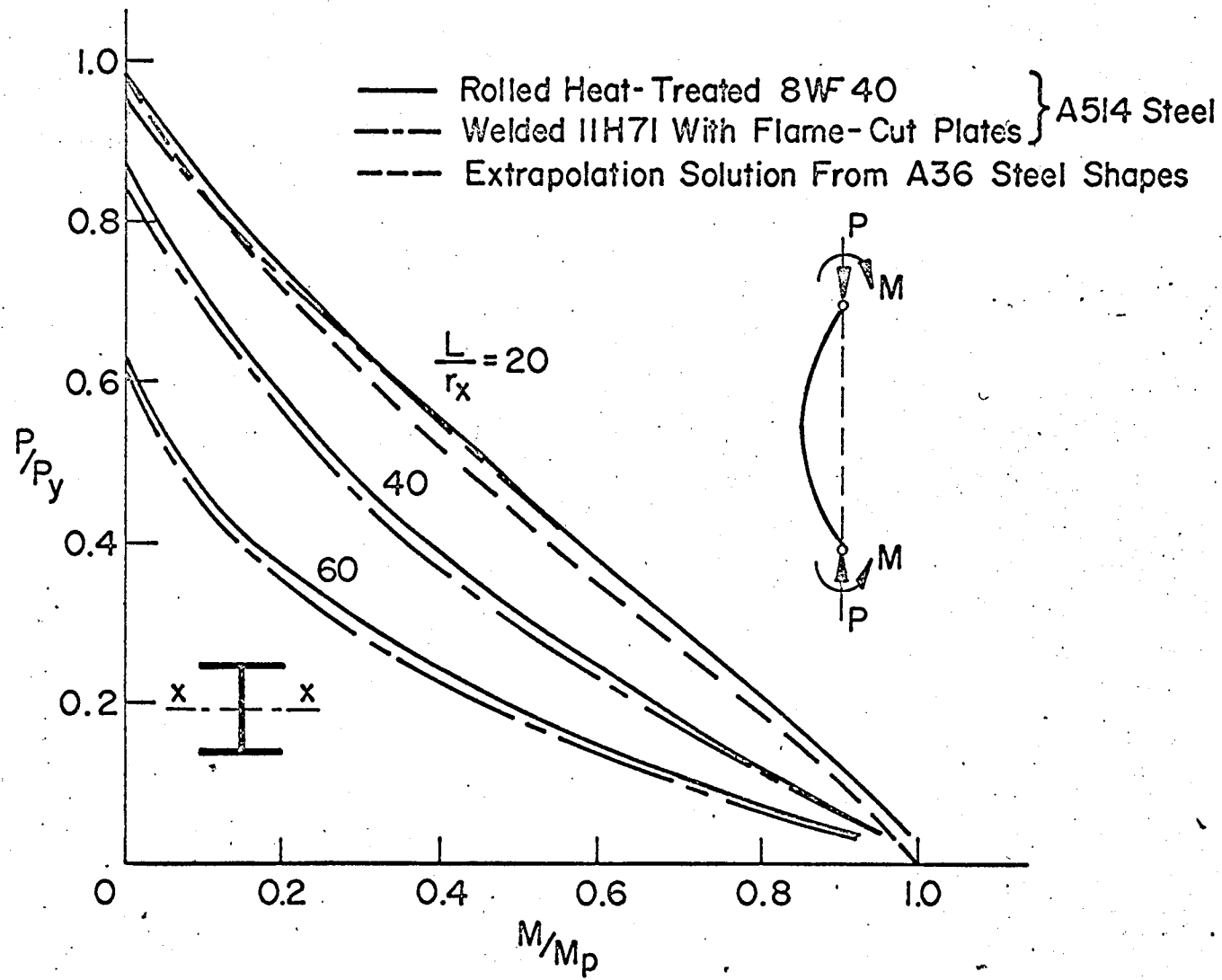Fig. 8 A514 BEAM-COLUMN STRENGTH
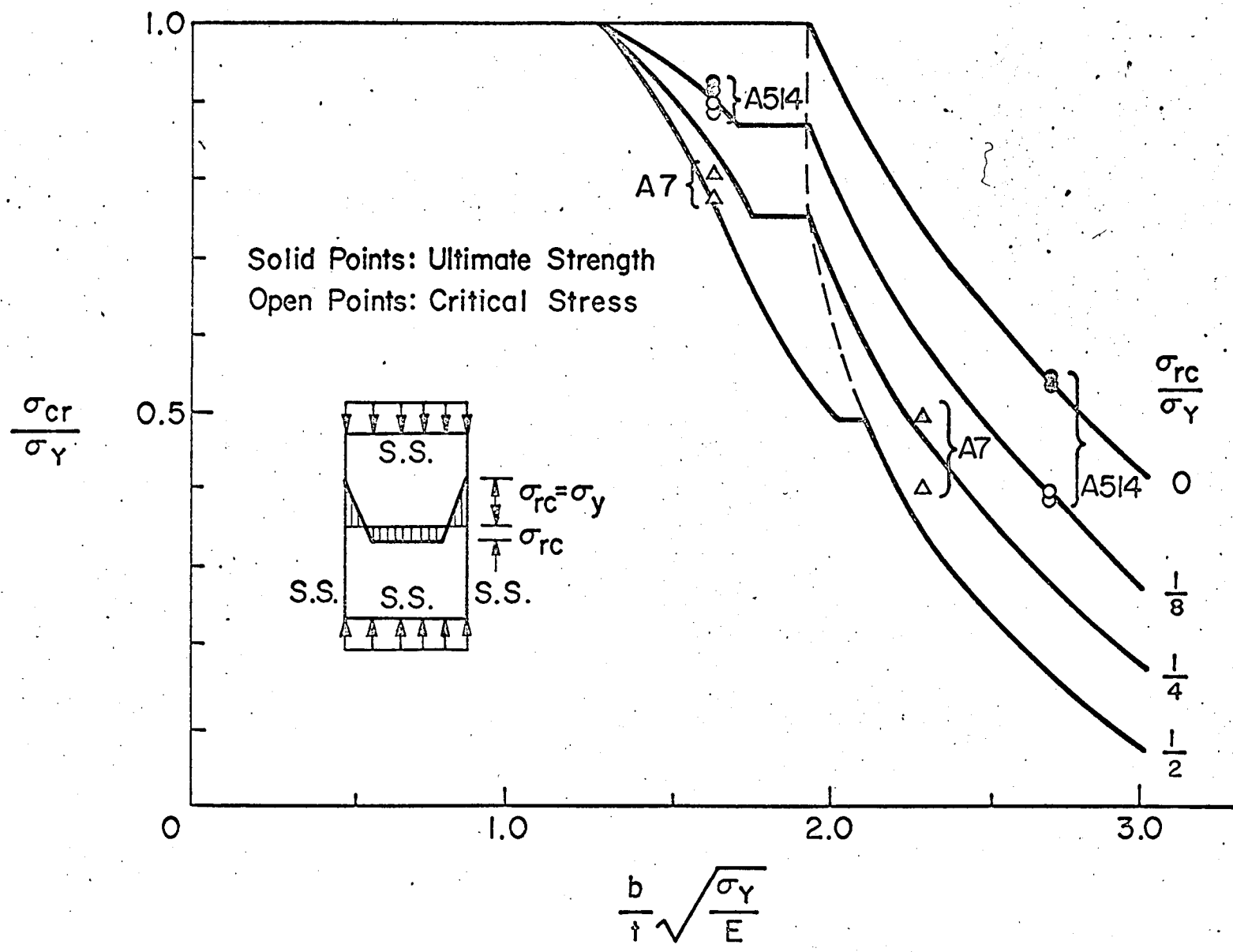
Fig. 9   INTERACTION CURVES FOR A514 BEAM-COLUMNS

Fig. 10   PLATE BUCKLING