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Residual stresses in a heavy rolled shape 14wf730, February 1970

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ON LOAN

Residual Stresses in Thick Welded Plates

RESIDUAL STRESSES IN A HEAVY ROLLED SHAPE 14WF730

by
Jacques Brozzetti
Goran A. Alpsten
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HEAVY ROLLED SHAPE

14WF730

by

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January 1970

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ABSTRACT

Increasingly heavy column shapes are being used in today's steel structures. Only little information is available on the behavior of such heavy sections under compressive loads. Within the framework of a research project, "Residual Stresses in Thick Welded Plates", a rolled shape specimen 14WF730, the biggest section presently rolled in the United States, was studied.

This report presents the results of an extensive investigation into the residual stresses in the 14WF730 shape considered. The study provides also information on mechanical properties of longitudinal tension test specimens taken across the flange thickness and the web thickness.

The results of the residual stress measurements and the tensile property tests were used to predict the strength of 14WF730 columns. The column strength was predicted by the tangent modulus load theory, taking into account a simplified distribution of the residual stresses determined in the measurements, and by the maximum ("ultimate") load concept, where initial geometrical imperfections and

the actual residual stresses were used in the prediction.
The next phase of this study will be an experimental
investigation of the strength of the column.

1.   <u>INTRODUCTION</u>

Almost twenty years ago, it was shown theoretically proved[1] and later experimentally verified[2] that residual stresses have a major influence on column strength. While many measurements have been made on light and medium-size rolled sections ,[3] very little information is available on residual stress and column strength of heavy rolled shapes. This report presents the residual stress measurements of heavy rolled shape 14WF730 made of ASTM A36 steel.

Residual stresses were measured by the sectioning method using a mechanical extensometer, and the variation of residual stress across the thickness was then determined by the slicing method as described in detail elsewhere.[4] The results obtained during these different steps of sectioning and slicing are given in the first part of this report.

Several tension test specimens were taken from various positions over the cross section to investigate the mechanical properties across the flange and the web of the 14WF730 specimen. Variations of the mechanical

properties as well as the characteristics of the stress-strain relationship are given.

Next, the prediction of column strength by the tangent modulus as well as the maximum strength concept is given and based upon the measured distribution and magnitude of residual stresses.

2.   SEQUENCE OF SECTIONING AND SLICING

The residual stress specimen of 16" length was cut from a 13'-9" long member, as shown in Fig. 1.   The specimen was located in the center part of the member in order to avoid geometrical end effects and the effect of the transverse flame cutting at the ends.

The dimensions of the cross section of the specimen are shown in Fig. 2, the member is manufactured of ASTM A36 steel.   Mechanical and chemical properties as given by the mill test report are shown in Table 1.

Longitudinal residual stresses, as measured at the surface of the specimen, and across the thickness of the flange and the web were investigated.   Only longitudinal residual stresses were measured because of their primary importance in determining the load carrying capacity of a column.   A sectioning procedure which allows the measuring of the longitudinal stresses around the surface of the specimen, and a slicing procedure which gives the variation of the longitudinal residual stresses across the thickness, have been used to determine the complete pattern and

magnitude of residual stresses. These methods are fully

described elsewhere,[4,5] and only the sawing steps adopted

for this investigation are reported. The next section will

give the results after each step of sawing operation.

2.1   Sectioning Operations

       Before any sawing operation, 68 small gage holes

were laid out around the specimen as shown in Fig. 2. The

longitudinal distance between two holes was measured with a

10 inch gage length mechanical extensometer of the Whittemore

type. Throughout the sectioning procedure, the strains

released were computed after the different steps of sawing.

       First, the residual stresses specimen was transversely

cut by cold-sawing, and the released strains in the 68 gage

hole readings were determined.

       Second, the section was longitudinally cut into

seven pieces, Fig. 32, and the released residual stresses in

the cross section were again computed. This step will be

referred to as "partial sectioning".

       In the third sawing operation, the complete

sectioning, the flanges and the web were divided into

smaller elements as given in Fig. 3b. Special attention
has been paid to dividing the function between the flange
and the web where a greater variation of residual stresses
could be expected. The complete sectioning as previously
described leads to a total number of 38 elements of
approximately 0.8 inch thickness for the flanges, and 13
elements of about 0.6 inch thickness for the web.

2.2 Slicing Operations

The variation of the longitudinal residual
stresses across the thickness of a strip is of great
importance. After complete sectioning, 22 new gage holes
were drilled on both sides of each flange strip and,
similarly 14 new gage holes on both sides of each web
strip were made. A total number of 509 gages holes were
made on the 14WF730 specimen studied.

After taking initial readings corresponding to
all gage holes, a partial slicing was made, as shown on
Fig. 3c, in order to establish a procedure for predicting
the variation of longitudinal stresses across the thickness
of the plate, without the need of a complete slicing. One
of the objectives was to determine a more relevant procedure,

in order to reduce the considerable amount of work needed in such investigation. It was intended to predict the variation of residual stresses through the thickness, from the data obtained after this partial slicing.

Finally the complete slicing was carried out according to Fig. 3d. This intensive series of measurements of residual stresses leads to a total number of 23,000 gage readings. The data were reduced with the help of a computer program.

3. RESULTS OF RESIDUAL STRESS MEASUREMENTS

The residual stress diagrams obtained from the released strains after each step in the sectioning and slicing techniques will be discussed. Figure 4 represents the magnitude and distribution of residual stresses for some parts of the flanges and web of the 14WF730 shape, after the first two transverse saw cuts of the residual stress specimen. The notations "near side" and "far side" mean results obtained for the surface which is located close to the diagram, and opposite to the diagram, respectively. The outer sides of the flange are in compression while the inner side is in both tension and compression, tension at the connection of the flange and web, and compression at the flange tips. Only tensile residual stresses exist in the web. The maximum compressive residaul stress is about 18 ksi at the flange tips and the stress at the flange-web connection is 12 ksi.

The results after the next step, partial sectioning, are shown in Fig. 5. The magnitude and distribution of residual stresses have not changed very much from the previous step. The discontinuities in the residual stress curves are mainly due to the partial sectioning.
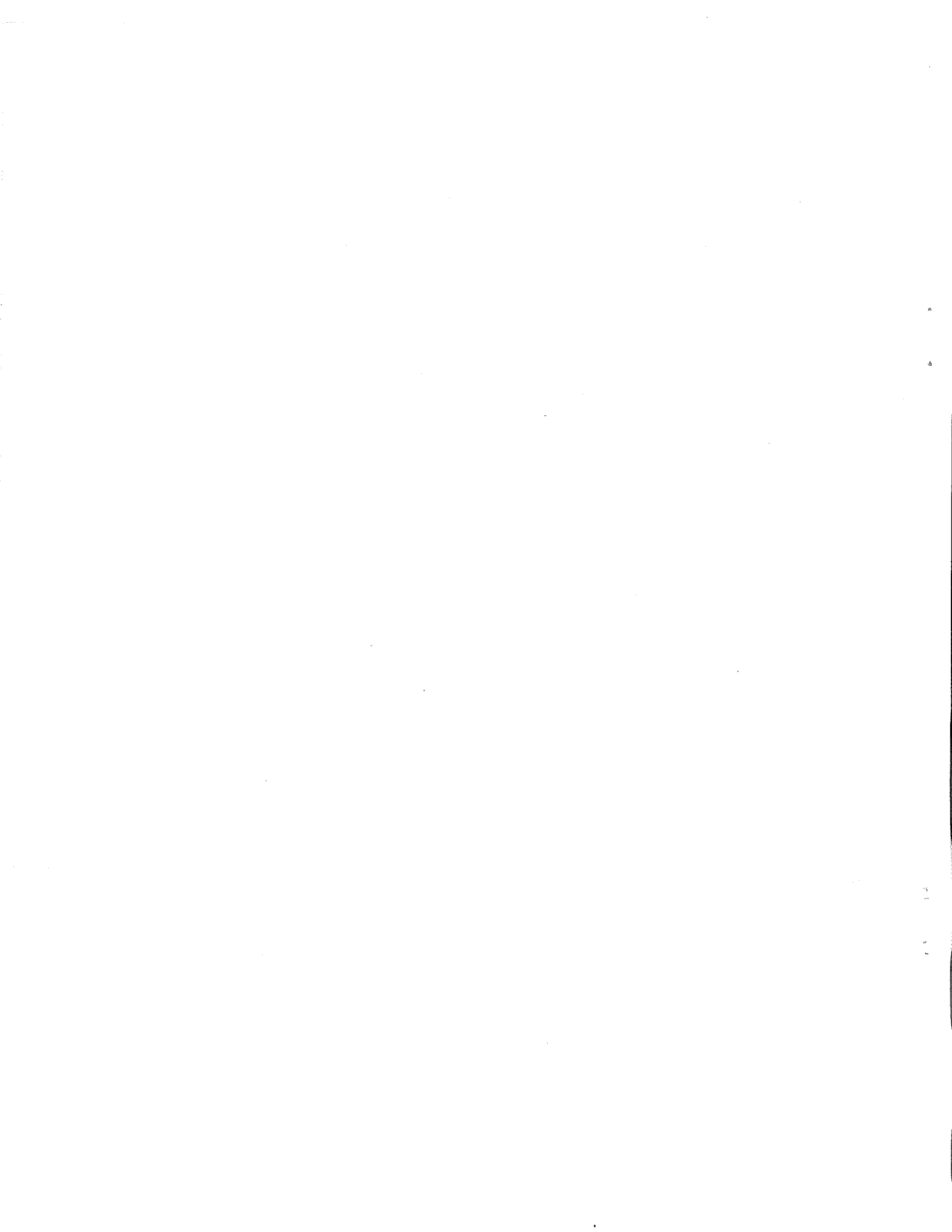
was noticed in the case of the milling process, where
machining stresses were introduced and measured in specimens
which were initially free of residual stresses by stress
relieving, [6] and in measurements carried out on thick
plates and heavy welded shapes. [7]

Some detailed results concerning the residual
stresses released by the slicing process, of four sectioned
strips, whose locations are shown in Fig. 9 are discussed
in the following. Two strips were studied from the left
part of the upper flange at a location where no irregularities
in the residual stress diagram could be noticed, and two
strips from the right part of the flange where some
discontinuities were observed.

The diagrams resulting from the partial and
complete slicing of these four strips are presented in
Figs. 10 and 11 for the left and right strip locations,
respectively. Several remarks may be noted from Fig. 10a
relative to the residual stress distribution and magnitude
after partial slicing of the strips from the left side.
From the linearity and the parallelism observed it may be
concluded that the assumption of the beam effect implied in
the sectioning and slicing techniques, is well satisfied.

The variation of residual stresses through the thickness
is shown in Fig. 10b. This variation varies usually
between plus and minus 4 ksi in the flanges. A slightly
greater variation of residual stresses was observed at the
flange tips. Generally, the maximum compressive stress
released by the slicing technique was found below the
rolled surface, as seen in Fig. 10b. A similar observation
was already pointed out in a particular study on the
residaul stresses induced by surface rolling.[6]

Figure 11 presents a different behavior as
compared with the previous figure. The irregularities
already seen in Fig. 7 are amplified by the slicing
procedure. This non-symmetrical residual stress
distribution is probably due to the cold straightening
process after the rolling which involves plastic deformations
of the material. Two principal kinds of residual stresses
are co-existing in the rolled section 14WF730 specimen
studied, that is, thermal and cold-bending residual
stresses. The 14WF730 shape normally is gagged in the
manufacturing procedure, that is, a load is applied to the
beam between two supports; this process is repeated. This
straightening practice used at the mill results in localized
residual stresses at certain locations, which are more
difficult to analyze.

4. TENSILE TEST RESULTS

When computing the load-carrying capacity of a column, several assumptions are made concerning the mechanical properties of the material. It is usual to consider that each fiber of the cross section behaves as an elastic-perfectly-plastic material, and it is also customary to assume that the yield strength of the material is constant over the cross section. However, it is important to know more closely the characteristics of the stress-strain relationship and the variation of the mechanical properties inside the member.

Several tension tests were made on longitudinal specimens taken at various locations through the flange and the web thickness. Figure 12a gives the location of the tension tests were performed on small size specimens as shown in Fig. 12b.

During this investigation, the rate of straining was kept identical for all specimens. In the elastic and plastic range, the speed of the cross-head of the machine was set at 0.025 ipm, and in the strain-hardening range it

was raised to 0.5 ipm. The results were compared in terms
of the static yield strength in order to eliminate the
strain rate factor upon the apparent yield strength.[8]

The results for flange specimens are summarized
in Table 2, and in Table 3 for the web specimens. No
significant variation can be noticed in the static yield
strength of the 18 flange specimens, for which the average
is 40.9 ksi and the sample standard deviation is 0.8 ksi.
The average of the static yield strength of the seven
web specimens, 41.3 ksi, is slightly higher, and the sample
standard deviation is equal to 3.3 ksi. The weighted
average according to the respective areas of the flanges
and the web of this rolled shape is 41 ksi. Thus, the
material fulfills the requirement of a minimum yield strengh
of 36 ksi given by the ASTM specifications.[9]

The strength of the longitudinal fibers of the
flanges and web of the 14WF730 shape may be regarded as
constant because no significant differences are revealed
by the results of the tensile tests. The average of the
static yield strength for the flange specimens and for the
web specimens differs only by one percent. Usually, greater
differences are found between material properties of the

flanges and web.[3]   In this case, the small difference
observed may be attributed to the fact that the cooling
rate of the web is not substantially higher than that
of the flange.

    Figure 13 gives two stress-strain curves as
autographically recorded for two tension test specimens
located in the center and at the surface of the components
of the shape.   The stress-strain curve of a specimen from
the surface of the rolled section does not have any plateau
and a definite onset of strain-hardening as opposed to those
of specimens taken from the interior of the section.   These
two different forms of stress-strain relationships were
observed for all tensile test specimens.   The different
form of the stress-strain curves for fibers located at the
interior and at the periphery of the cross section might
be regarded as a peculiar effect of the rolling process
which was noticed also in other investigations.[6,7]

5. EVALUATION OF THE COLUMN
STRENGTH OF THE 14WF730 SHAPE

The load-carrying column capacity of the 14WF730
rolled shape has been computed based upon two different
approaches, that is, the tangent modulus concept and the
maximum strength analysis.

First, predictions by the tangent modulus concept
are discussed, and the assumptions made are presented.
When performing this calculation, the cross section was
discretized into a number of finite area meshes as shown
in Fig. 14.

The magnitude and distribution of residual stress
as found experimentally could not satisfy the main hypothesis
of the tangent modulus concept, because of the non-
symmetrical distribution observed. The tangent modulus
concept applies only when the residual stress distribution
is symmetrical. As reported above in Sect. 3, a symmetrical
distribution was not observed for both diagrams, that is,
after sectioning (Fig. 6), and after complete slicing,
(Fig. 8). For predicting the tangent modulus load, two
residual stress distributions, mentioned above, were transformed

into a symmetrical distribution by averaging out the
experimental values found in the four quarters of the
cross section.

In addition to this simplification, the usual
assumptions were made, that the column is assumed perfectly
straight, that plane sections remain plane and that the
stress-strain relationship of all fibers is identical and
that it can be approximated by an elastic-perfectly plastic
behavior. This last assumption was not quite experimentally
observed, as was discussed above. The yield strength of the
material was chosen as 41 ksi, which is the average value
of the static yield strength obtained in tension tests
performed on 25 specimens.

Two sets of curves were obtained for both axes of
bending. These results are shown in Fig. 15 in a non-
dimensional diagram relating the load and the slenderness
ratio. A set of curves gives the tangent modulus load for
the distribution of residual stress when assuming a linear
distribution across the thickness, that is, as determined
after complete sectioning, and under the modification
discussed above. The two other curves, also relative to
both axes of bending indicate the tangent modulus load
when assuming the true distribution of residual stress as

given by the slicing procedure. In this last computation

a modified symmetrical distribution of residual stress was

also determined from the results of Fig. 8.

When analyzing the results of tangent modulus load,

it appears that the tangent modulus curves with respect to

the weak axis bending based upon complete sectioning data

and complete sectioning and slicing respectively, are almost

identical. The observed deviation is somewhat larger for

the column curves with respect to the strong axis bending.

This seems to indicate that, in spite of the relatively

great variation of residual stresses through the thickness,

the difference obtained in the tangent modulus loads for

weak axis bending when assuming a linear variation of

residual stresses across the thickness and the true

distribution is not of great importance. It should be

pointed out, however, that the previous approach was made

possible by transforming the non-symmetrical diagram of

residual stresses to a symmetrical one. The errors due to

this simplification were indicated by considering the second

approach which take into account the actual distribution of

residual stresses.

The load carrying capacity of the 14WF730 shape

was calculated by maximum strength analysis and according

to the following assumptions. The actual non-symmetrical
distribution of residual stresses as indicated in the Fig. 8
was taken into account in the computation, and the same
meshes of finite areas as represented in Fig. 14 was used.
An initial-out-of-straightness was assumed to be a sine
curve with a magnitude at the mid-height of the column
equal to $S_{init}/L = 0.001$. The maximum strength of this
section was obtained with respect to the weak axis bending.

The non-symmetrical residual stress distribution,
(right part in Fig. 8), was assumed to be located at the
convex side of the deflected column with respect to the
minor axis. This leads to a slightly lower maximum strength
as compared to the case where the cold-bending affected
part is chosen to be on the concave side of the initially
bent column.[11]

The results of the computation are given in
Fig. 16.[11] The maximum strength curve falls far below
the tangent modulus curves in Fig. 15. Two reasons explain
this significant difference. First, the maximum strength
of an initially curved column is, of course, always less
than the load-carrying capacity of the corresponding
straight column and may even be less than the tangent
modulus load (the bifurcation load of a straight column).[12]

Secondly, as enphasized previously, the maximum strength

analysis takes into account the actual residual stress

distribution, whereas the tangent modulus analysis was

based upon a simplified residual stress distribution where

the non-symmetry of the actual distribution was "averaged-

out".

Therefore, the use of the tangent modulus concept

for a column affected by a cold-bending process is not

directly applicable for the prediction of the load- carrying

capacity. Transforming the non-symmetrical distribution of

residual stress to a symmetrical one in order to satisfy the

basic conditions required by the tangent modulus load

analysis, leads to a higher column strength.

In the near future it is planned to carry out two

tests, a stub column test and a column test with respect to

the weak axis for an effective slenderness ratio of 40.

This will provide an experimental check of the theoretical

calculations.

6. SUMMARY AND CONCLUSIONS

The purpose of this study was to investigate experimentally the distribution and magnitude of residual stresses in a heavy rolled shape 14WF730 of ASTM A36 steel. The residual stresses were used to predict analytically the column strength of the 14WF730 shape. Two approaches were used in these predictions, the tangent modulus concept for an initially straight column, and the maximum strength, analysis, where an initial out-of-straightness of the column was assumed. This investigation into residual stresses and theoretical column strength will be correlated later with experimental results for a stub column test and a column test.

Prior to this experimental investigation, analytical computation of thermal residual stresses existing in the hot rolled 14WF730 shape after cooling was performed under several assumptions and boundary conditions.[13] Based upon the free-cooling and the forced heat-transfer conditions, the predictions had indicated a higher magnitude of residual stresses than those which were experimentally found and approaching the yield strength of the material

at the flange tips. When comparing these results, it has
to be kept in mind that the 14WF730 shape on which
residual stress measurements were carried out, was cold-
straightened after rolling. Therefore, this member was
not free of cold-bending effects, and two types of
residual stresses were coexisting, thermal stresses and
stresses due to the straightening process.

No significant variation of the yield point was
observed between tensile test specimens from the flanges
and from the web, the weighted average of the static yield
strength was 41 ksi, well above the specified minimum value
of 36 ksi for A36 steel. The stress-strain curves were of
two kinds, depending upon the location of the tension
specimen in the cross section. The stress-strain curve of
the specimens taken from the rolled surface did not have
any plateau and no definite onset of strain-hardening, as
was observed for the specimens sampled from the interior
of the cross section. Analogous results were obtained in
a series of tension tests on specimens taken from two
thick plates. [7]

The use of the tangent modulus load to predict
the strength of the straightened column specimen appears
to over-estimate the actual strength. This is probably

caused by the fact that the actual residual stress distribution
must be transformed into a symmetrical distribution. In this
transformation, the residual stresses are "averaged out" in
a way that may not represent the correct conditions. The
maximum strength analysis, which takes into account the
initial out-of-straightness and the effect of the non-
symmetrical residual stress distribution should be regarded
as the method which reproduces as closely as possible the
real mechanical behavior of the column.

7. ACKNOWLEDGEMENTS

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The investigation is being carried out under the sponsorship of the National Science Foundation and the Column Research Council. The technical guidance of Task Group 1 of the Column Research Council under the chairmanship of John A. Gilligan is gratefully acknowledged.

Some of the computations were made at the Royal Swedish Institute of Technology and the Stockholm Computing Center, and acknowledgements are due to them for the excellent cooperation.

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test specimens.   The assistance of Charles R. Nordquist in
the measurements on the 14WF730 shape is sincerely
appreciated.

Appreciation is also extended to John M. Gera
for preparing the drawings, and to Miss Joanne Mies for
typing the manuscript.

8.   <u>TABLES AND FIGURES</u>

TABLE 1   MILL REPORT OF MECHANICAL
          PROPERTIES AND CHEMICAL
               COMPOSITION

MECHANICAL PROPERTIES

Shape Designation	Yield Point (ksi)	Tensile Strength (ksi)	Elongation* (%)
14WF730	45.5	78.5	30.5

*The gage length was 2".

CHEMICAL COMPOSITION

Shape Designation	C %	Mn %	P %	S %	Si %
14WF730	.22	1.12	.013	.028	.23

TABLE 2   TENSION SPECIMEN TEST RESULTS
Flange of the 14WF730
ASTM A36 Steel

Tension* Specimen No.	Static Yield Strength (ksi) $\epsilon = 0.005$	Modulus of** Elasticity E (ksi)	Tensile Strength σ_u (ksi)	Reduction of Area (%)	Elongation in Gage Length*** (%)
1A	41.0	26500	72.1	56.9	28.2
1B	40.6	27000	75.3	55.4	26.5
1C	41.0	24200	74.7	54.4	27.3
1D	41.3	22000	75.1	51.5	24.1
1E	39.7	26800	74.6	53.1	28.0
1F	42.3	30600	75.4	53.0	20.9
2A	40.7	27700	76.2	59.9	26.5
2B	41.7	29200	74.4	46.3	26.4
2C	40.4	25300	74.5	51.6	23.4
2D	41.5	25500	77.3	49.5	24.0
2E	41.6	27300	73.0	51.6	27.1
2F	39.5	26500	74.0	50.9	26.9
3A	40.3	25800	73.5	47.9	27.3
3B	40.4	32100	74.8	53.2	21.5
3C	41.6	28200	75.8	53.1	28.1
3D	40.8	31800	76.3	50.8	26.7
3E	42.2	21500	76.2	50.1	29.0
3F	39.5	28600	73.7	47.1	28.4
Average	40.9	27000	74.8	52.0	26.1

*   The numbers used in this table refer to those identified
      in Fig. 12A.
**   The values of E should be regarded as indicative only since
      they were evaluated directly from the autographically recorded
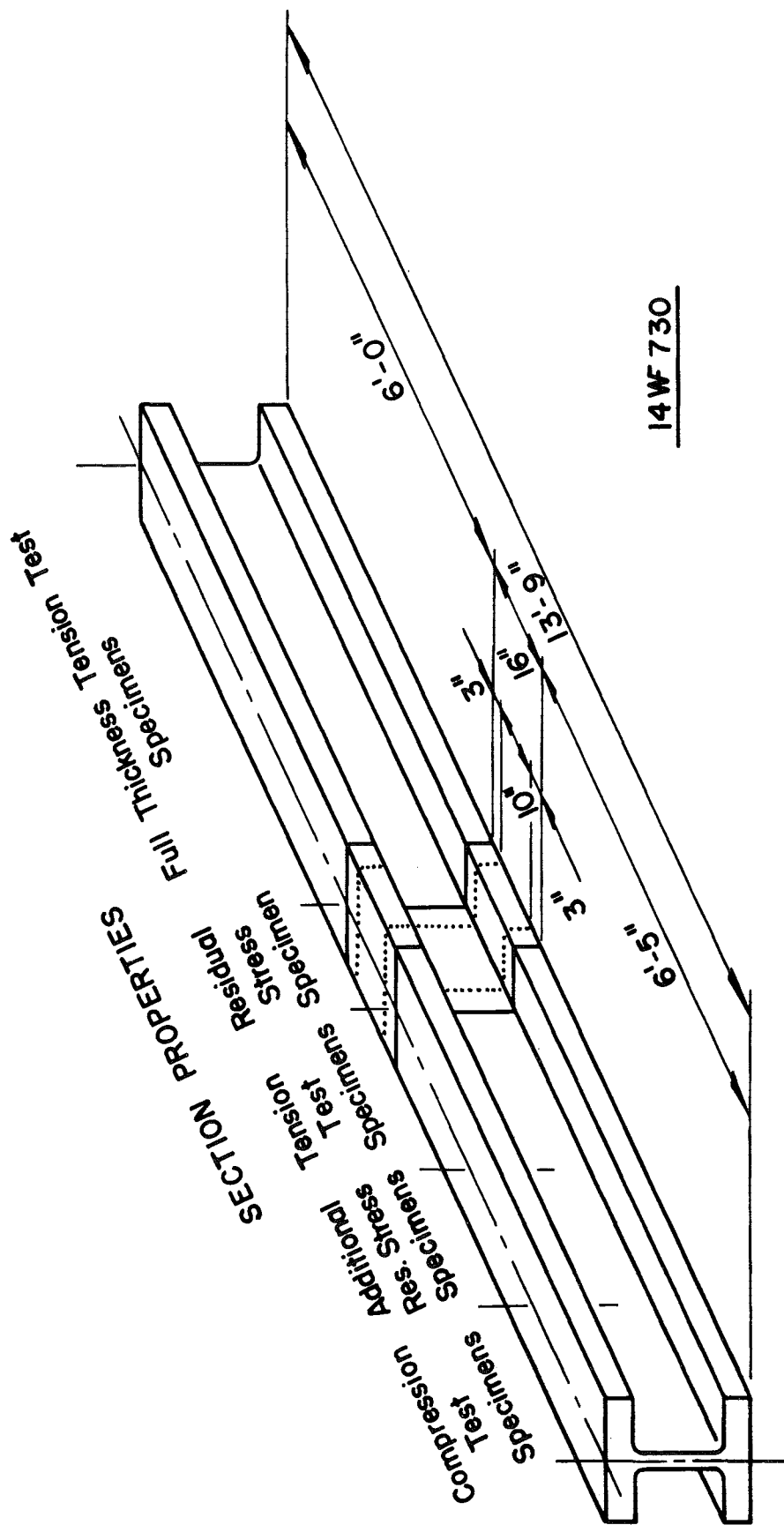   curve.
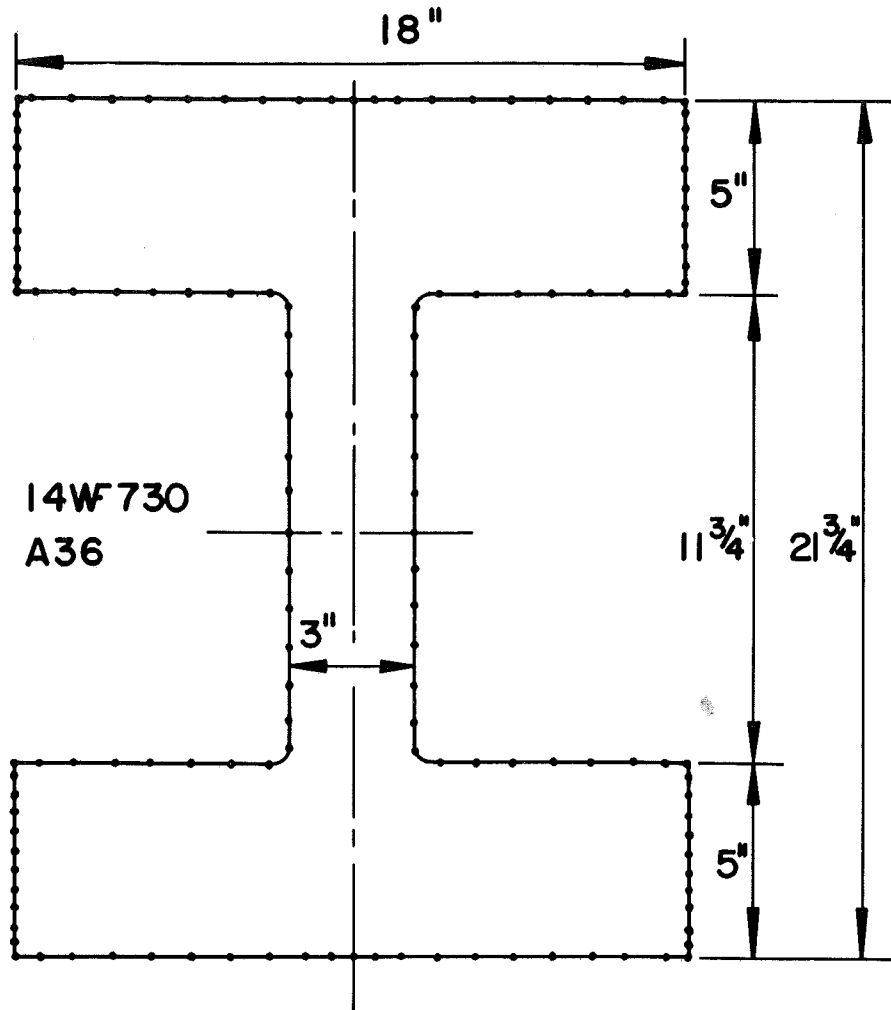***   The gage length was 2 inches.

TABLE 3   TENSION SPECIMEN TEST RESULTS
Web of the 14WF730
ASTM A36 Steel

Tension* Specimen No.	Static Yield Strength(ksi) $\epsilon = .005$	Modulus of** Elasticity E (ksi)	Tensile Strength σ_u (ksi)	Reduction of Area (%)	Elongation in Gage Length*** (%)
4A	39.4	34400	72.8	52.5	24.5
4B	44.5	23400	83.5	47.1	22.9
4C	39.3	26100	71.1	50.1	24.7
4D	36.3	36000	69.0	49.1	31.1
4E	45.7	38500	82.4	45.2	26.7
4F	41.2	33100	74.5	51.9	24.7
4G	42.9	28700	80.6	49.3	23.6
Average	41.3	31500	76.3	49.3	25.5

*   The numbers used in this table refer to those identified
      in Fig. 12A.
**   The values of E should be regarded as indicative only since
      they were evaluated directly from the autographically recorded
      curve.
***   The gage length was 2 inches.

SECTION PROPERTIES

Full Thickness Tension Test Specimens

Residual Stress Specimen

Tension Test Specimens

Additional Res. Stress Specimens

Compression Test Specimens

6'-0"

3'-6"

3"

6"

0'

3"

6'-5"

14 WF 730

Fig. 1   Layout of Test Specimens

Fig. 2   Dimensions of the Shape   Layout of Gage Holes
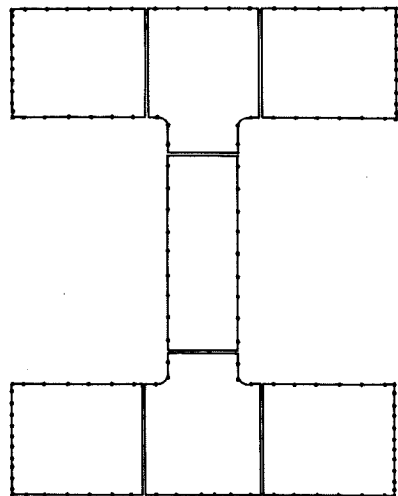
(a)
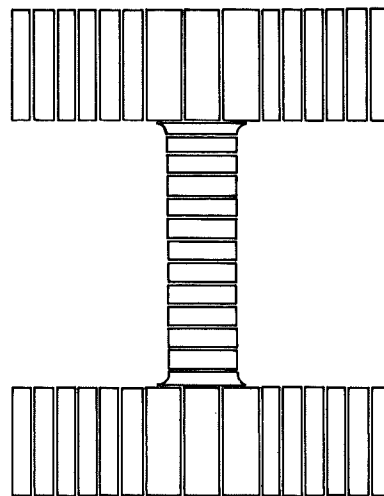
(b)
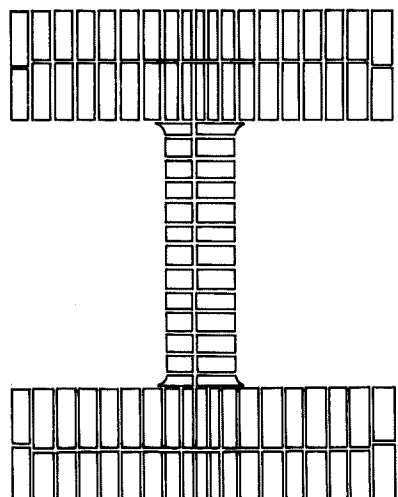
(c)
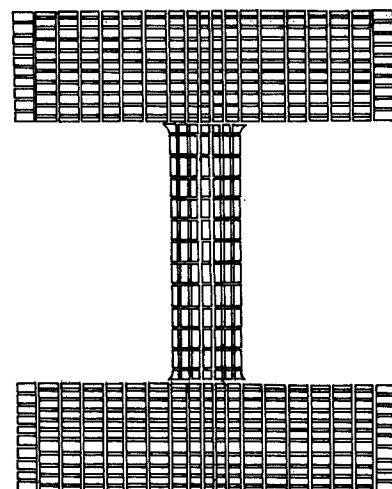
(d)

Fig. 3   Sectioning and Slicing Details
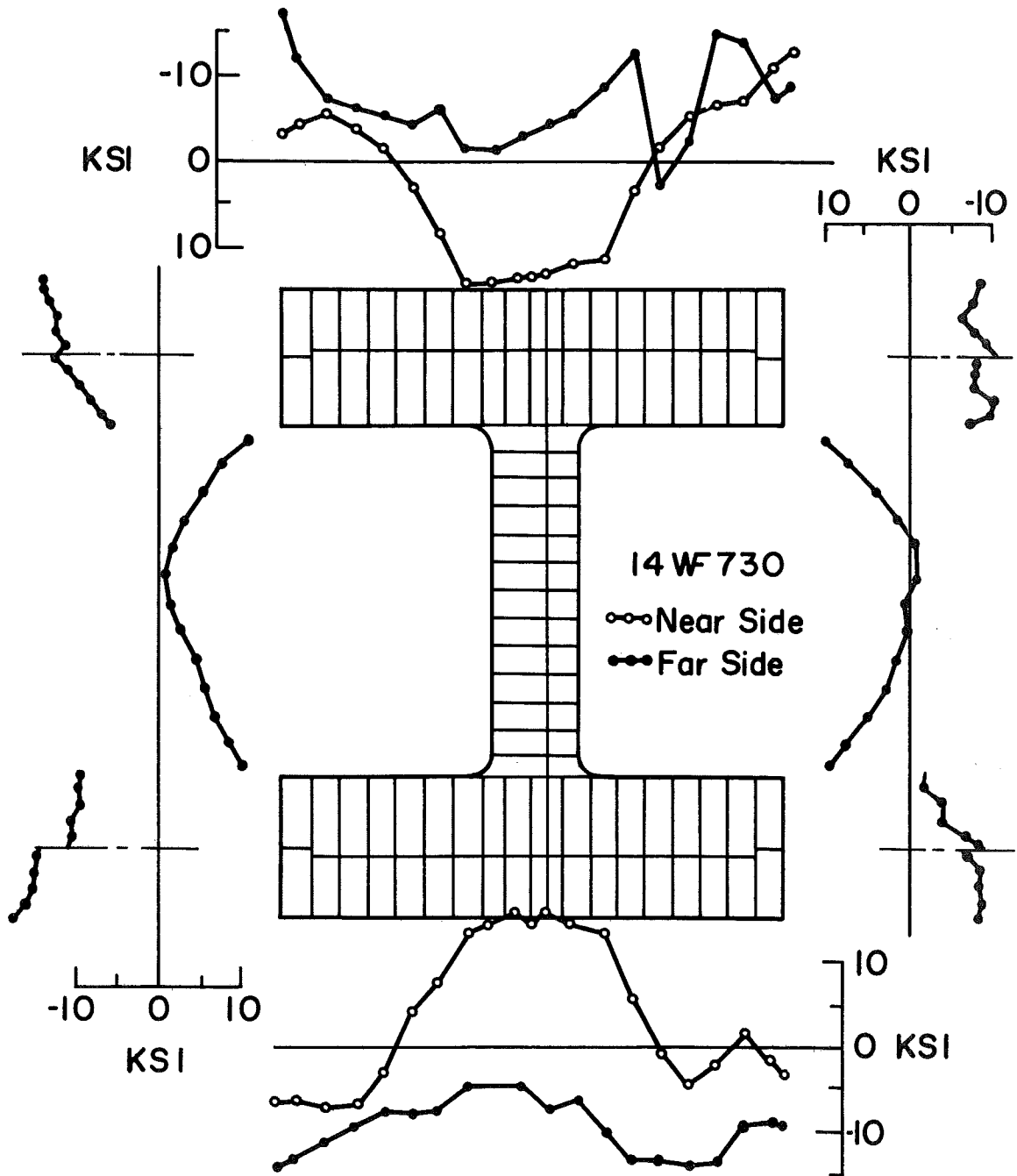
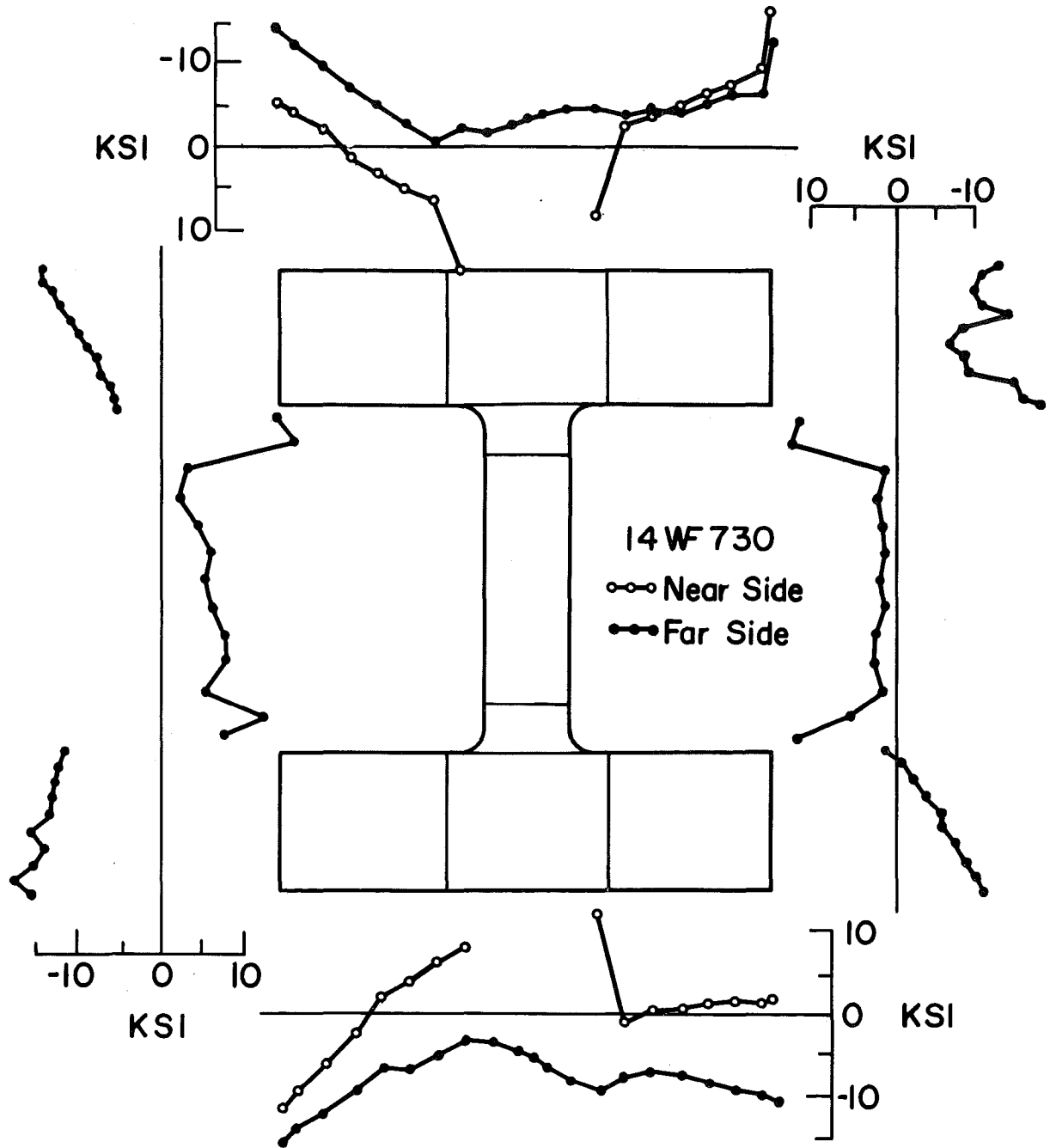Fig. 7   Residual Stresses after Partial Slicing

KSI

KSI

10   0   -10

14 WF 730
o—o Near Side
•—• Far Side

-10   0   10

KSI

10

0

-10

KSI

Fig. 5   Residual Stresses after Partial Sectioning
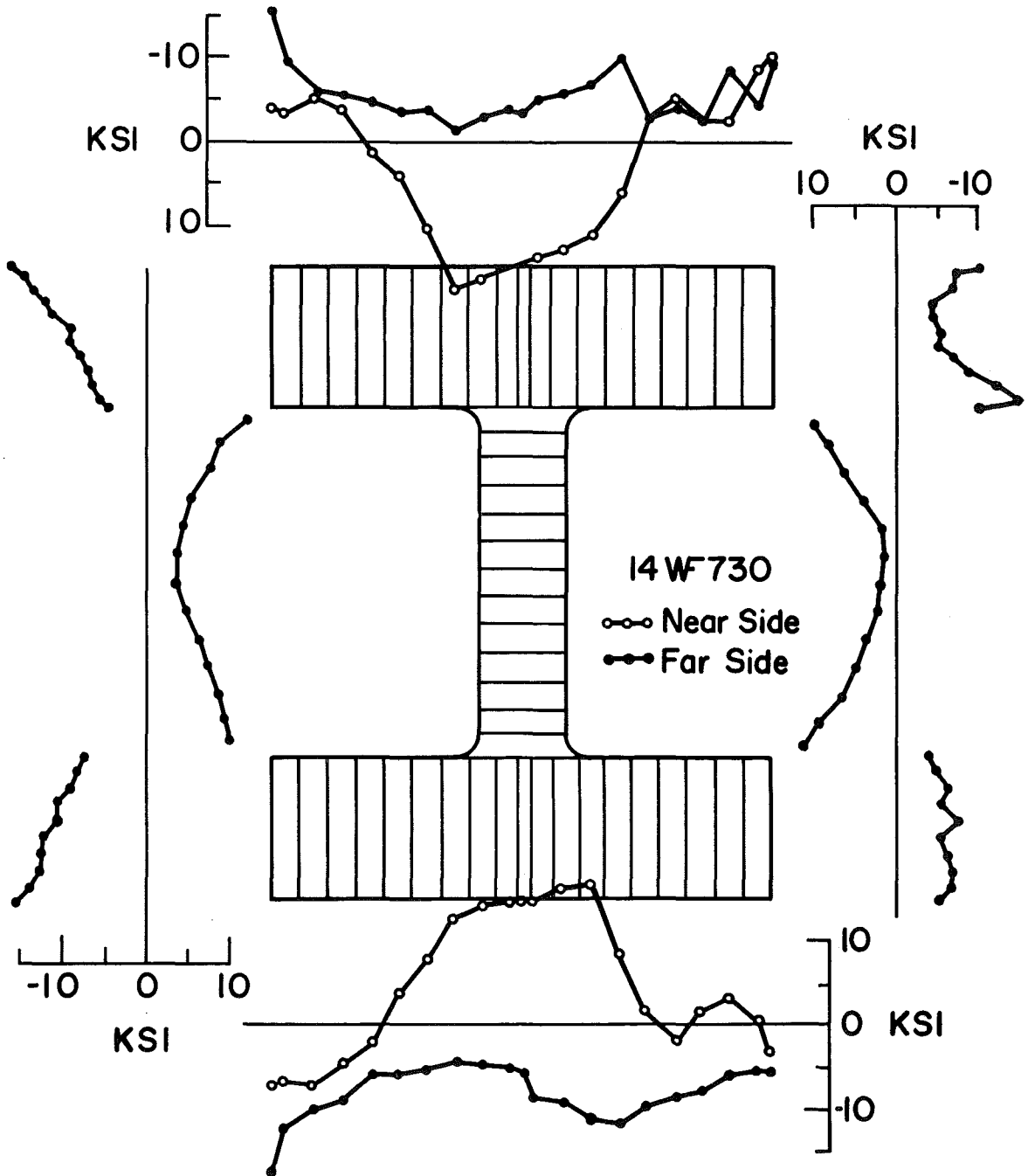
Fig. 6   Residaul Stresses after Complete Sectioning
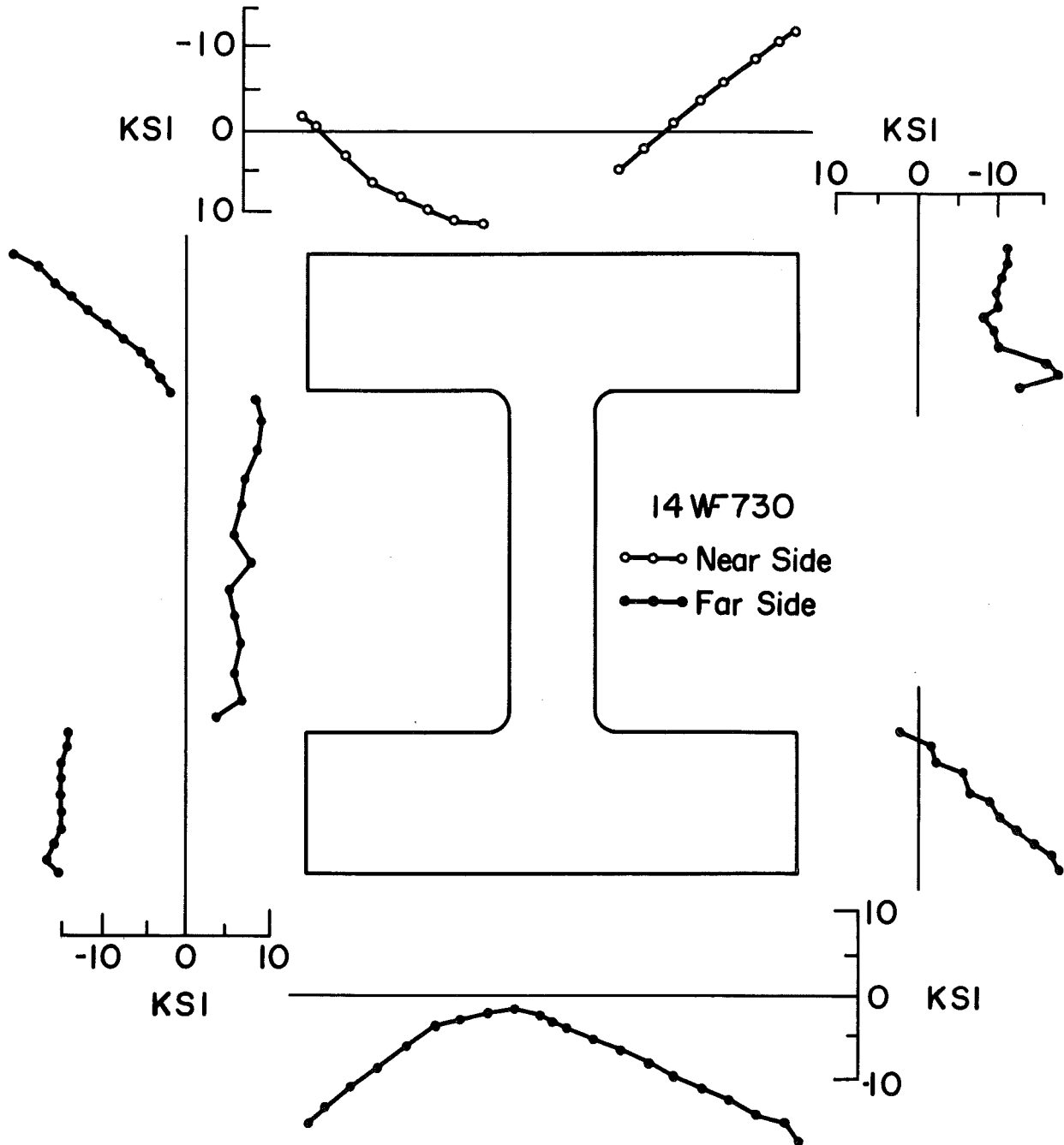
Fig. 4   Residual Stresses after Transverse Cutting
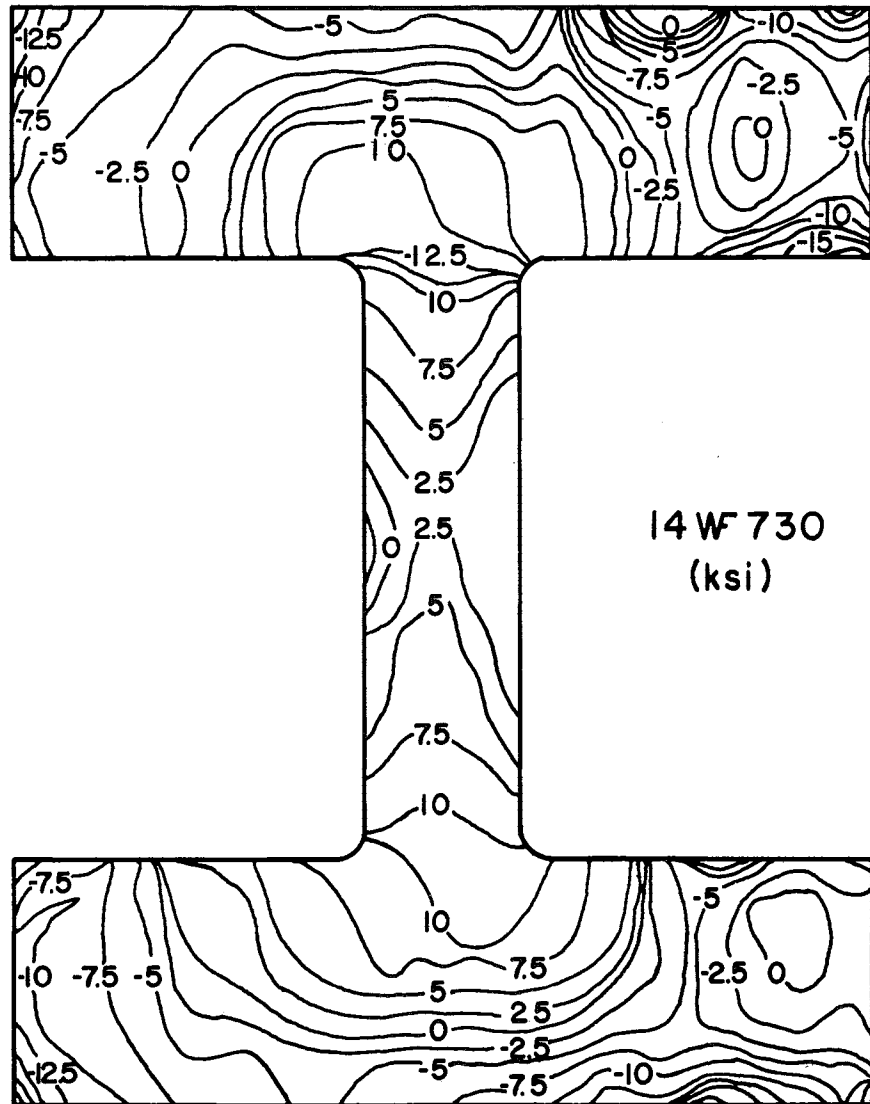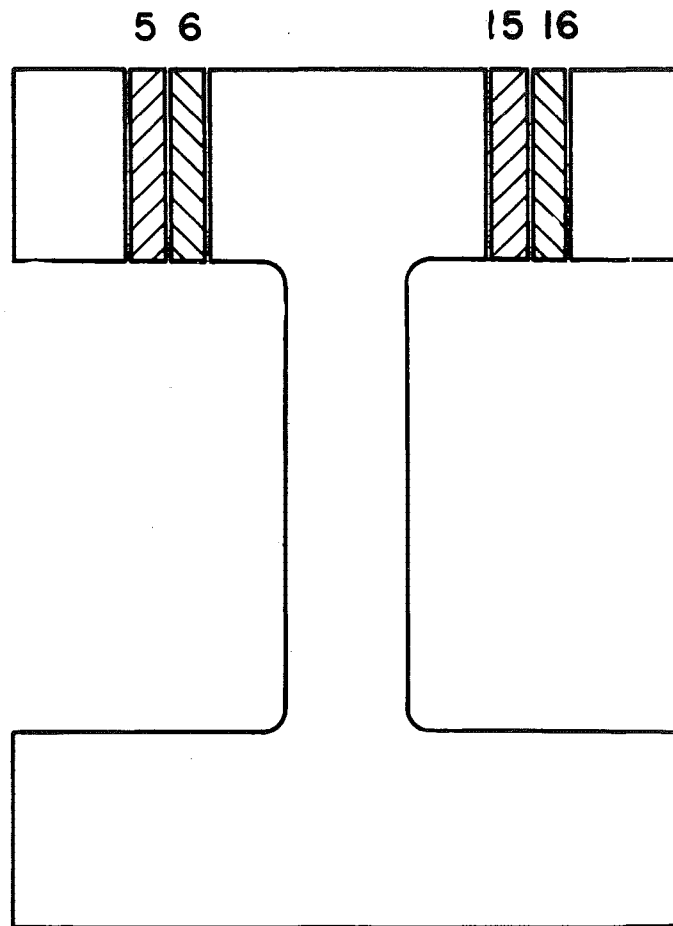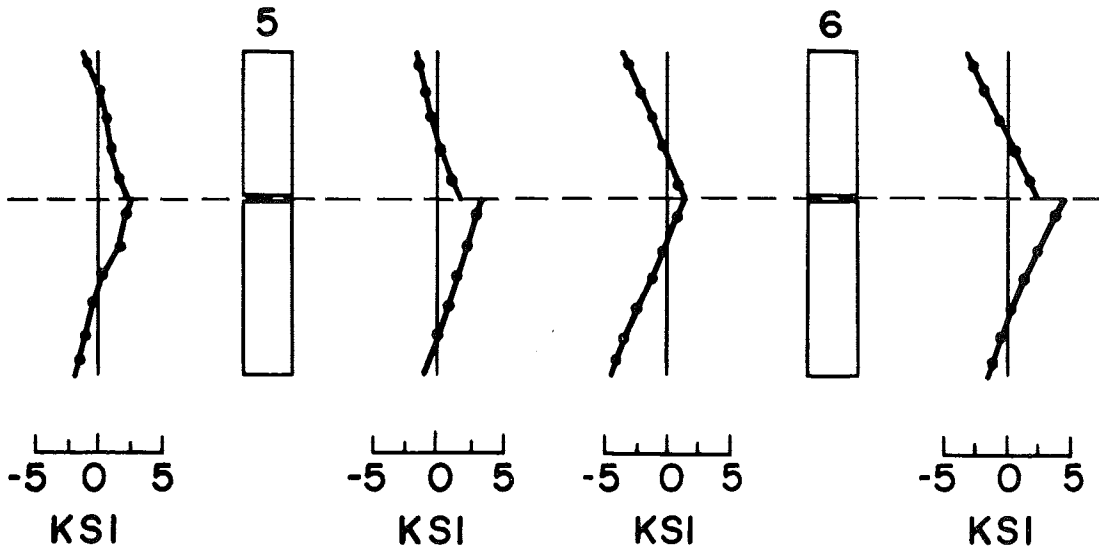
Fig. 8   Residual Stresses after Complete Slicing

Fig. 9   Location of Sample Strips in Flange

Partial Slicing

Complete Slicing

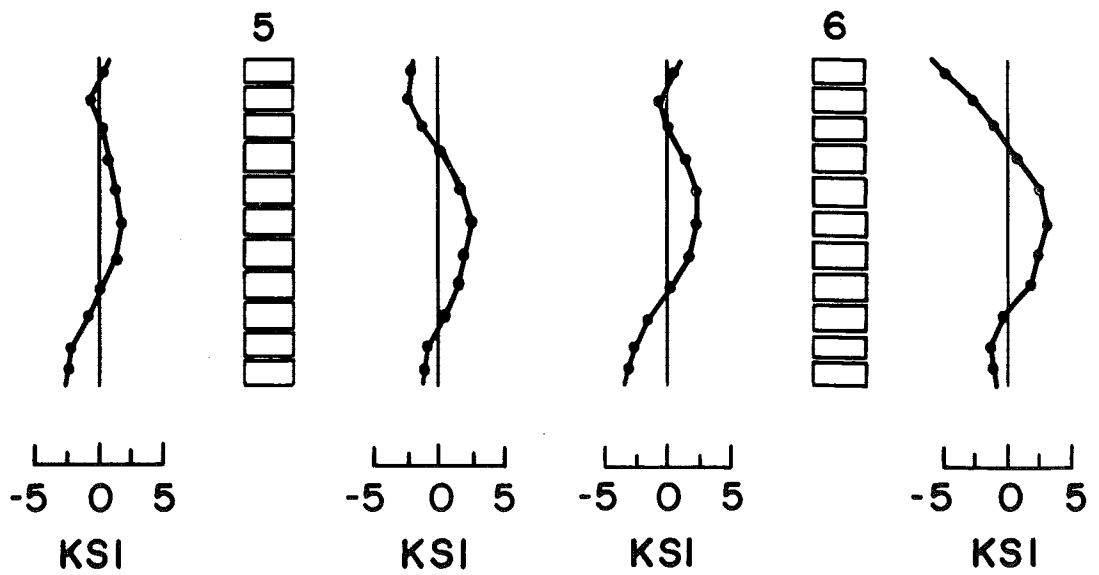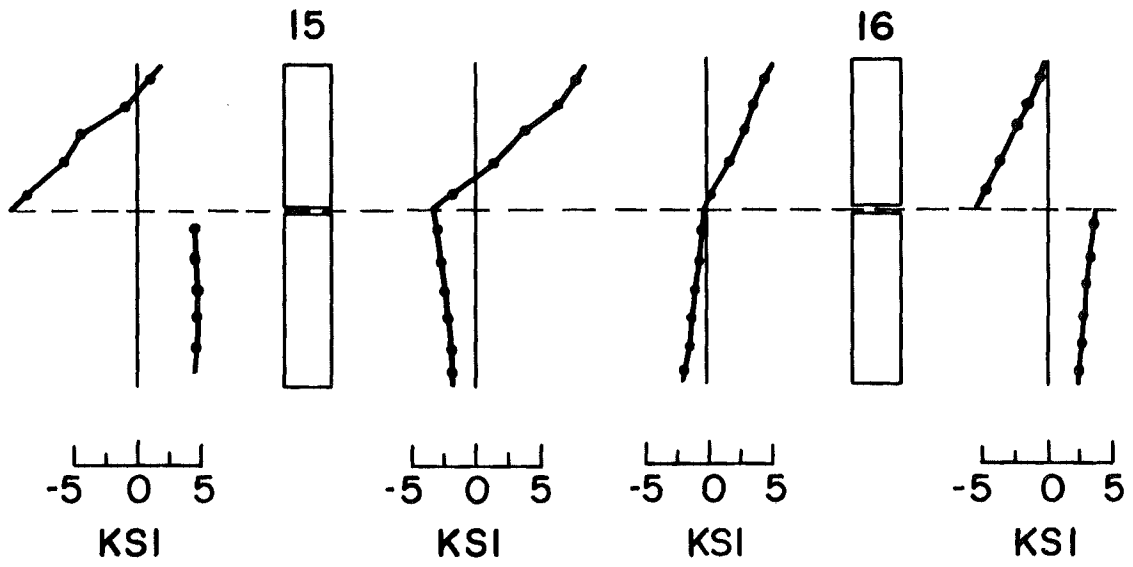Fig. 10   Residual Stresses Released by Slicing of Strips 5 and 6

Partial Slicing

15   16

-5 O 5   -5 O 5   -5 O 5   -5 O 5
KSI   KSI   KSI   KSI

Complete Slicing

15   16

-5 O 5   -5 O 5   -5 O 5   -5 O 5
KSI   KSI   KSI   KSI
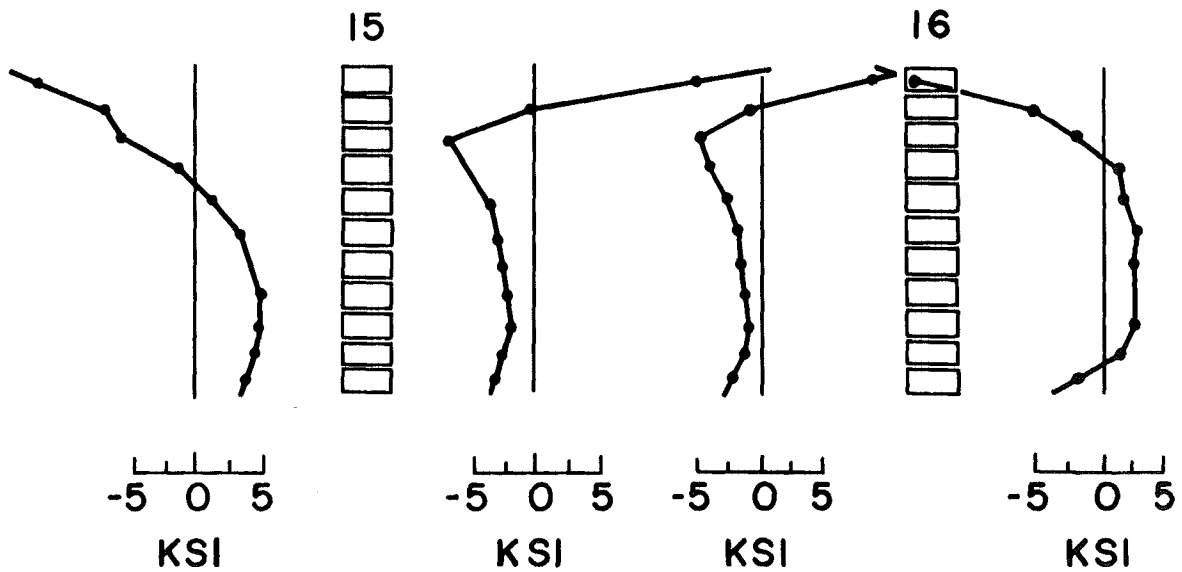
Fig. 11   Residual Stresses Released by Slicing of Strips 15 and 16
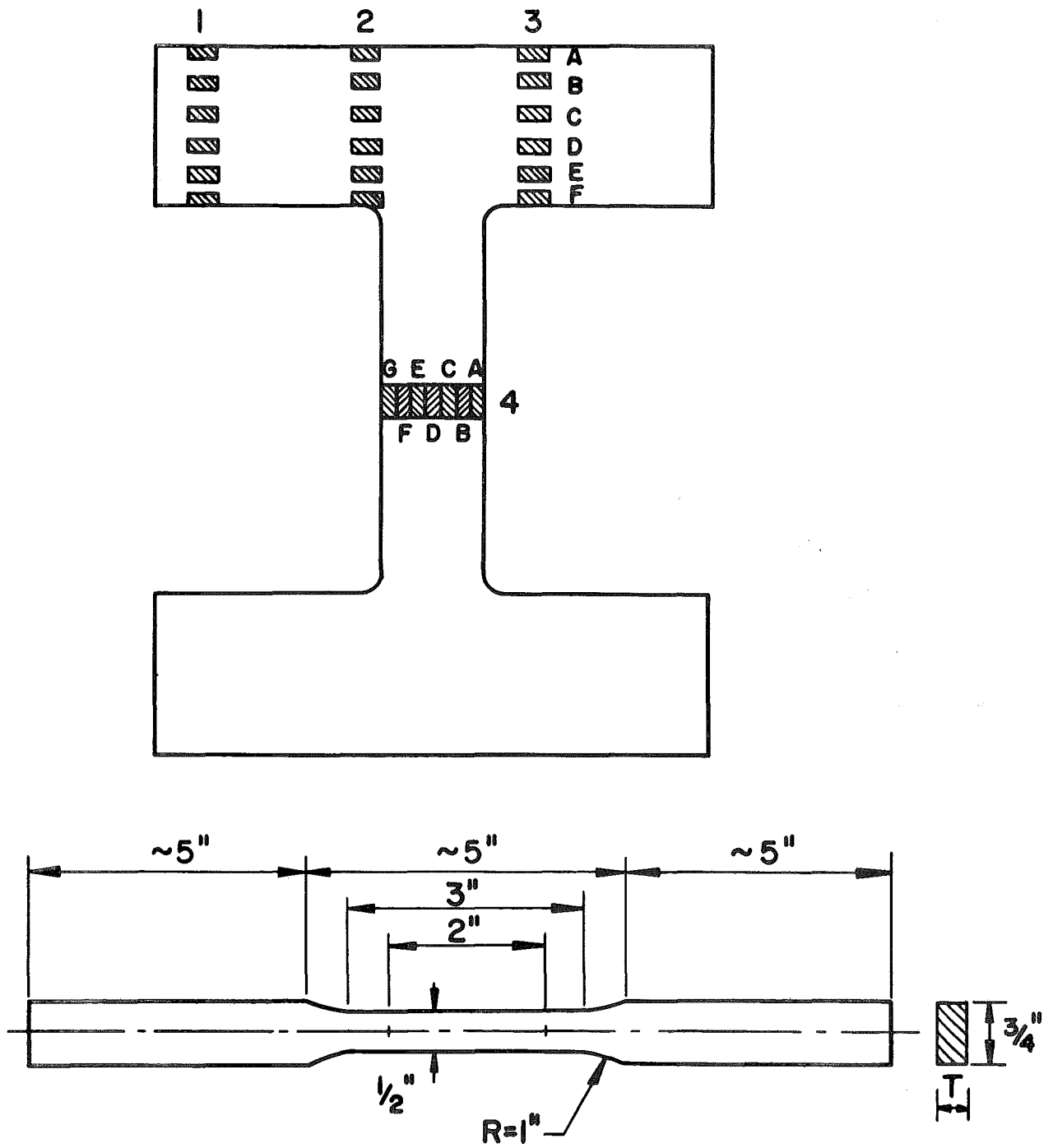
Fig. 12   Location of Tension Specimens Across the 14WF730
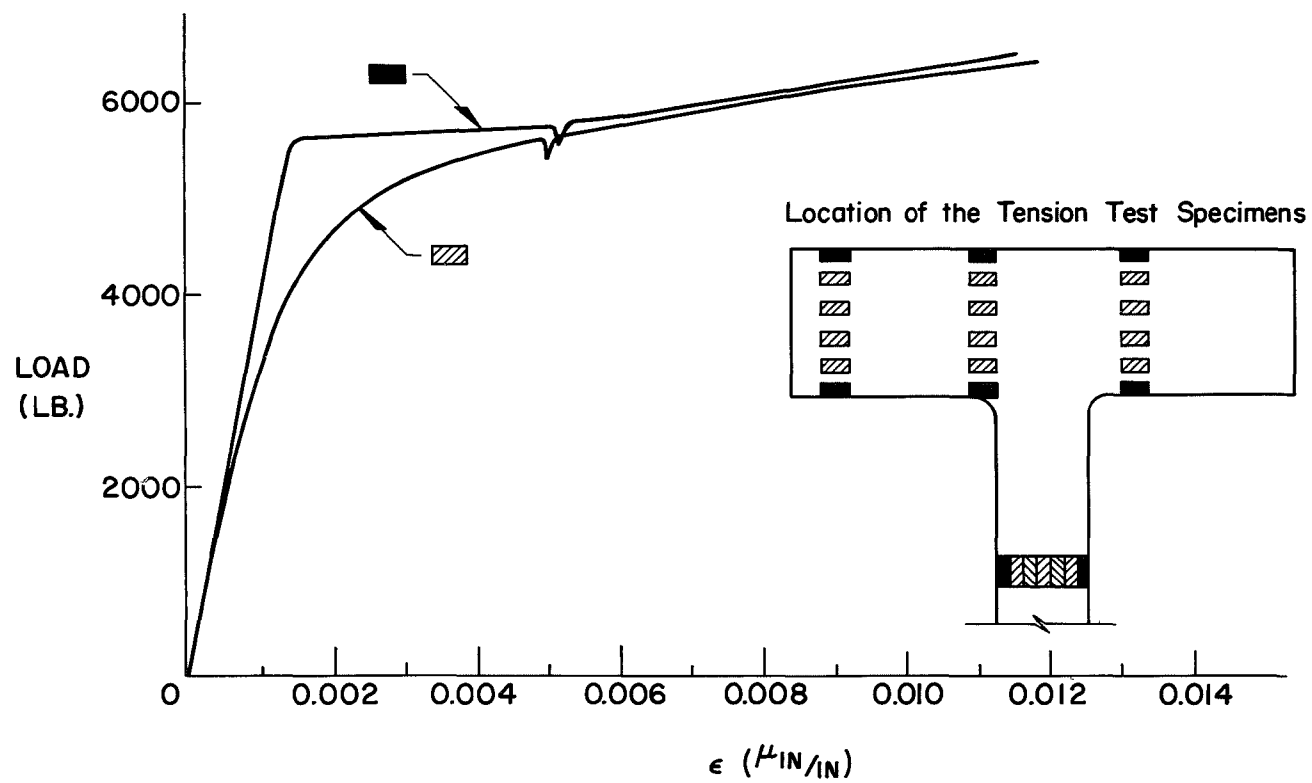   Cross Section

Fig. 13   Typical Stress-Strain Relationships
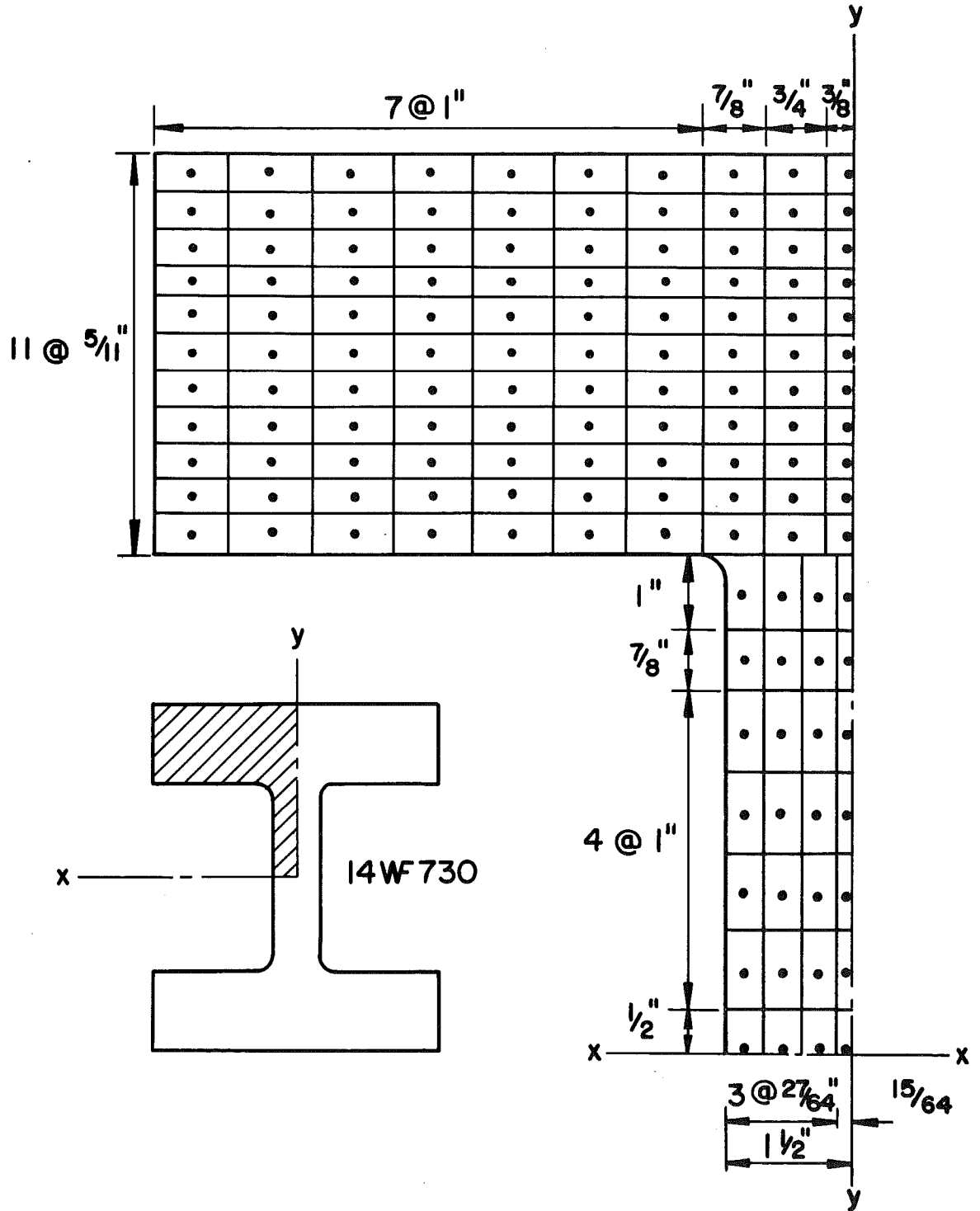
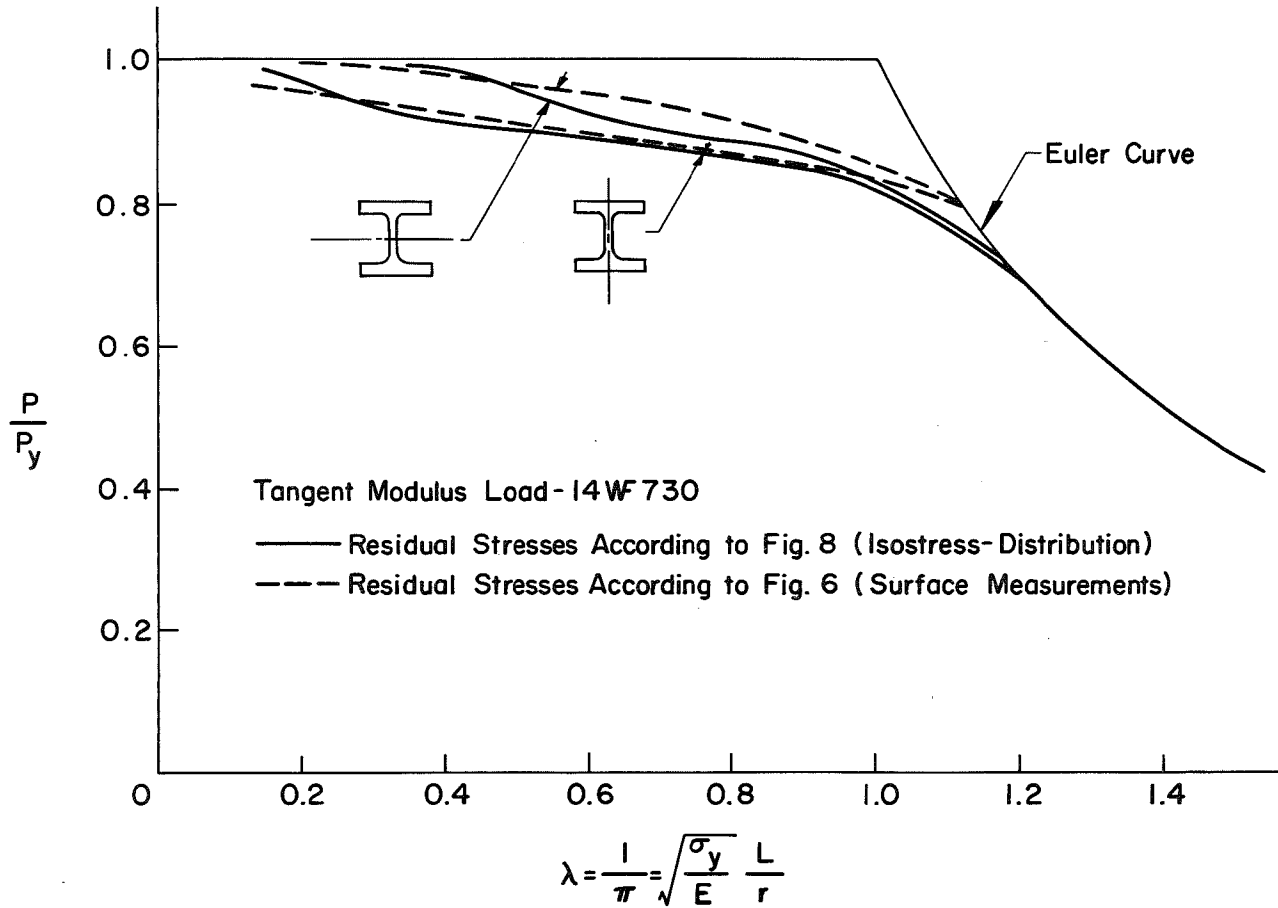Fig. 14   Finite Area Meshes

Fig. 15   Tangent Modulus Curves
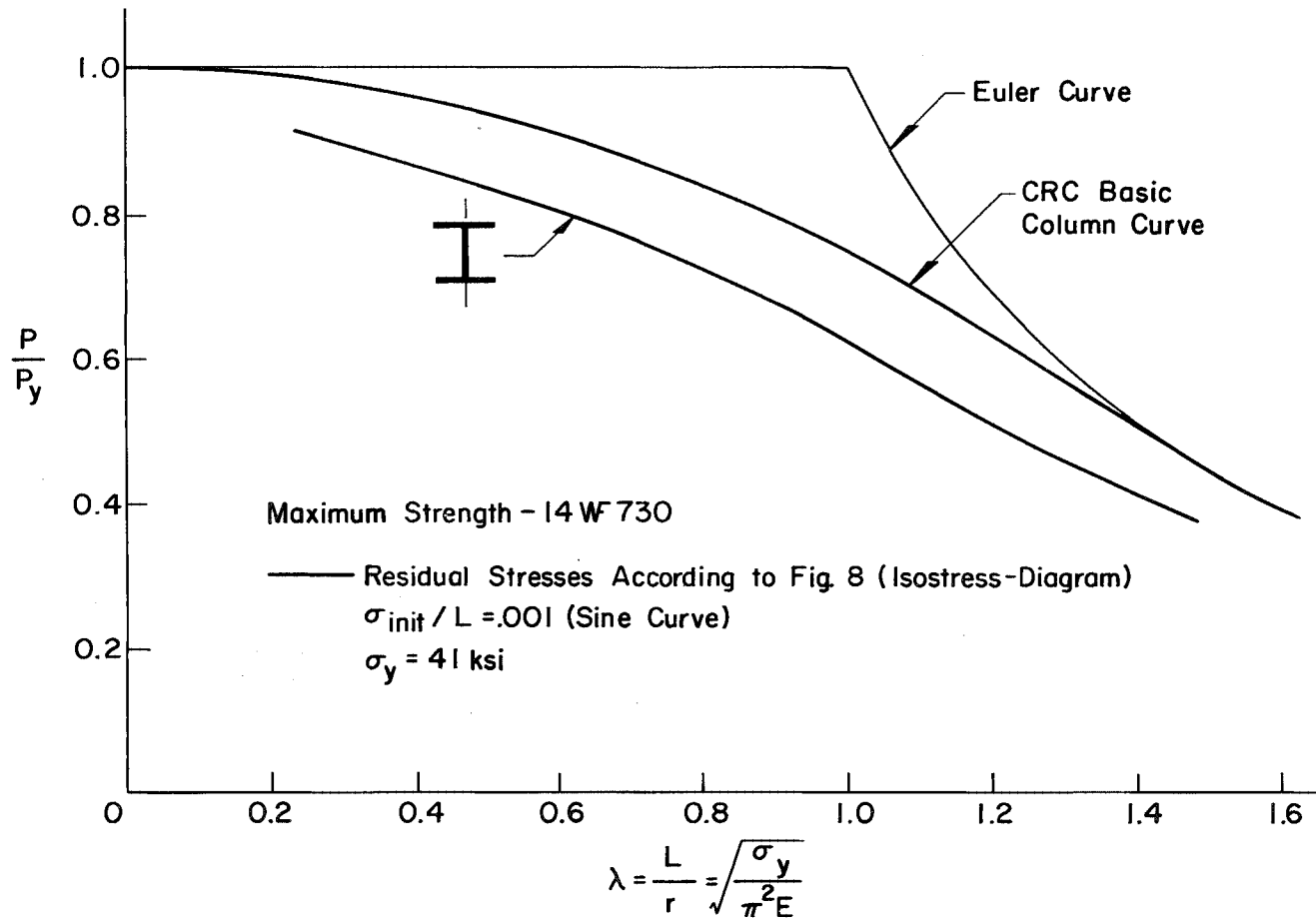
Fig. 16   Maximum Strength with Respect to Weak Axis Bending

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