Residual Stresses in Thick Welded Plates

RESIDUAL STRESSES IN A HEAVY ROLLED SHAPE
14WF730

by
Jacques Brozzetti
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Fritz Laboratory Report 337.10
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This work has been carried out as part of an investigation sponsored jointly by the National Science Foundation and the Column Research Council.

Department of Civil Engineering

Fritz Engineering Laboratory
Lehigh University
Bethlehem, Pennsylvania

January 1970

Fritz Engineering Laboratory Report No. 337.10
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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. INTRODUCTION

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 gage 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 residual 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 residual 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 strength 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 $S_{\text{init}}/L = 0.001$. 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 emphasized 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.
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. 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

This report presents a part of an experimental investigation carried out in the research project "Residual Stresses in Thick Welded Plates". The research program is being conducted at Fritz Engineering Laboratory, Department of Civil Engineering, Lehigh University, Bethlehem, Pennsylvania. Lynn S. Beedle is the Director of the Fritz Engineering Laboratory, and David A. VanHorn is the Chairman of the Department of Civil Engineering.

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.

Thanks are due to Kenneth R. Harpel, Laboratory
Superintendent, and his staff for the preparation of the 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. TABLES AND FIGURES
### TABLE 1 MILL REPORT OF MECHANICAL PROPERTIES AND CHEMICAL COMPOSITION

#### MECHANICAL PROPERTIES

<table>
<thead>
<tr>
<th>Shape Designation</th>
<th>Yield Point (ksi)</th>
<th>Tensile Strength (ksi)</th>
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*The gage length was 2".

#### CHEMICAL COMPOSITION

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<th>P (%)</th>
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<td>.013</td>
<td>.028</td>
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### TABLE 2 TENSION SPECIMEN TEST RESULTS
Flange of the 14WF730
ASTM A36 Steel

<table>
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<tr>
<th>Tension Specimen No.</th>
<th>Static Yield Strength (ksi)</th>
<th>Modulus of Elasticity ( E ) (ksi)</th>
<th>Tensile Strength of Area ( \sigma_u ) (ksi)</th>
<th>Reduction in Area (%)</th>
<th>Elongation in Gage Length (%)</th>
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<td><strong>26.1</strong></td>
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* 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

<table>
<thead>
<tr>
<th>Tension Specimen No.</th>
<th>Static Yield Strength (ksi) $\epsilon = .005$</th>
<th>Modulus of Elasticity E (ksi)</th>
<th>Tensile Strength $\sigma_u$ (ksi)</th>
<th>Reduction of Area (%)</th>
<th>Elongation in Gage Length*** (%)</th>
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* 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.
Fig. 1  Layout of Test Specimens
Fig. 2  Dimensions of the Shape Layout of Gage Holes
Fig. 3  Sectioning and Slicing Details
Fig. 7 Residual Stresses after Partial Slicing
Fig. 5  Residual Stresses after Partial Sectioning
Fig. 6 Residual 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
Fig. 10 Residual Stresses Released by Slicing of Strips 5 and 6
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
Tangent Modulus Curves

Fig. 15 Tangent Modulus Curves
Maximum Strength - 14WF 730

Residual Stresses According to Fig. 8 (Isostress-Diagram)

\[ \sigma_{\text{init}} / L = 0.01 \text{ (Sine Curve)} \]
\[ \sigma_y = 41 \text{ ksi} \]

\[ \lambda = \frac{L}{r} = \frac{\sigma_y}{\sqrt{\frac{E}{\pi^2}}} \]

Fig. 16 Maximum Strength with Respect to Weak Axis Bending
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