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Welded and Rolled T-I Columns

EXPERIMENTAL INVESTIGATION
OF THE BUCKLING OF PLATES
WITH RESIDUAL STRESSES

by
Fumio Nishino
Yukio Ueda
Lambart Tall

Fritz Engineering Laboratory Report No. 290.3
Welded Built-Up and Rolled Heat-Treated T-1 Steel Columns

EXPERIMENTAL INVESTIGATION OF THE
BUCKLING OF PLATES WITH RESIDUAL STRESSES

by
Fumio Nishino
Yukio Ueda
Lambert Tall

This work has been carried out as part of an investigation sponsored by the United States Steel Corporation, the Pennsylvania Department of Highways, and the U. S. Department of Commerce - Bureau of Public Roads. Technical guidance was provided by Task Group 1 of the Column Research Council of the Engineering Foundation.

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Department of Civil Engineering
Lehigh University
Bethlehem, Pennsylvania

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This report is a summary of local buckling tests of plate elements in square columns built-up by welding. The experiments were conducted to verify theories for the elastic and elastic-plastic buckling of plates with emphasis on the effect of residual stress. This was part of a general study on the strength of welded columns and the influence of residual stress on plate buckling. Both ASTM A7 and A514 steels were used.

The square section simulated plates simply supported at the unloaded edges, and the length of the column was chosen so that end conditions had no effect either on the residual stress distribution or on the local buckling strength of the columns. Short columns were tested in the "as-placed" condition in a mechanical-type testing machine. The transverse deflection (local buckling) of the plates was measured at a number of cross sections by a 1/10,000 inch dial gage fixed to a frame held manually.

The "top of the knee" method was used to estimate the bifurcation load. The experimental results showed good correlation with theoretical predictions including the effect of residual stress for elastic buckling and for elastic-plastic buckling based on the total strain theory. The results of experiments indicated that considerable post-buckling strength may be expected for elastic buckling of plates, although not for elastic-plastic buckling.
1. **INTRODUCTION**

An experimental study of the effect of residual stress on the local buckling strength of component plates of welded built-up box columns is presented. Welded built-up members are being used more frequently in steel construction due to economy and convenience. The most economical geometry in built-up compression members is usually determined by the local instability of the component plates. It is only recently that the importance of the residual stress effect on plate buckling has been recognized. The investigation was concerned with component plates in welded built-up columns with rectangular cross-section.

The work reported here consisted of the testing of four sets of short columns. Two of these columns were made from ASTM A7 steel, and the other two were made from ASTM A514 steel.* Two sets of tests were carried out on each column cross section, so that a total number of eight specimens was tested. The width-thickness ratios were chosen such that the critical loads were reached in either the elastic range or the elastic-plastic range for each steel. The lengths of the column were selected in such a way that they were long enough to develop the buckling mode corresponding to the lowest buckling strength including the effect of residual stress, but short enough for column buckling not to take place before the ultimate strength of the component plate.

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* In this case, the steel was USS "T-1" steel.
was reached. Before the column tests were conducted, coupon tests and residual stress measurements for the specimens were carried out. An outline of the test program is shown in Table 1 where all experiments are listed with their specimen numbers.

In the subsequent portions of this paper the experimental procedure and the test results are discussed, and they are compared with theoretical values computed in Refs. 1 and 2.
2. PRELIMINARY TESTS

In order to predict the local buckling stress of component plates of the short column, preliminary tests were made which included tensile coupon tests to obtain the static yield stress and modulus of elasticity, and residual stress measurements to determine the magnitude and distribution of residual stresses.

2.1 Tensile Coupon Tests

Tensile coupon tests were made to determine the static yield stress\(^{(3,4)}\) of the material used for the specimens. Standard specimens with 8 inch gage length specified by the ASTM standard\(^{(5)}\) were used for all tests.

Figure 1 is a schematic diagram of the location of the coupons with respect to the cross-section. Four specimens were tested from each fabricated column in a 120-kip mechanical screw-type testing machine. The strain was recorded and plotted automatically.

2.2 Residual Stress Measurements

The "method of sectioning"\(^{(6)}\) was used to obtain the values of the residual strain distribution. A series of 10 inch gage holes were laid out on the specimen and measured with a 1/10,000 inch Whittemore strain gage. The difference in length before and after sectioning is a measure of residual strain. The section cut out is at a sufficient
distance from the ends to offset any edge effect. Measurements were carried out only on the outside surface of the box shape, since direct measurements of strain inside the box shape were not possible. However, the thickness of all the component plates was $\frac{1}{4}$ inch, from which it was expected that the residual stress would be constant in the thickness direction.\(^{(7,8)}\) The residual stress distribution was measured over a 10 inch gage length on the complete cross section of each fabricated column.
3. **PLATE BUCKLING TESTS**

The experimental program included four sets of buckling tests of plate elements in square columns built up by welding, each set consisting of tests of two short columns for local buckling.

Two columns were fabricated from structural steel of ASTM designation A7, with sheared plates. The other two were fabricated from A514 steel* with flame-cut plates. The welding details are given in Fig. 2. After small tack welds were deposited to fix the shape, submerged arc welding was employed throughout the fabrication.

The length of the test columns were chosen such that column buckling could not occur (upper limit), and such that the end disturbances would affect neither the buckling behavior of the test section nor the distribution of residual stresses (lower limit).

The width-thickness ratios were chosen such that bifurcation loads were reached in both the elastic range and the elastic-plastic range for each steel. The geometry of the specimens is given in Table 2.

3.1 **Test Set-Up**

All columns were tested in an 800,000 pound screw-type universal testing machine.

* In this case, USS "T-1" Type A was used.
The ends of each specimen were milled to aid in the alignment of the column. The end fixtures consisted of a flat plate at the base and a plate with a set of wedge discs at the top. The set of discs was used for alignment so that all four component plates were loaded uniformly. Thus, each component plate satisfied conditions of simple supports at the unloaded edges. The test set-up is shown in Fig. 3.

Before testing, the external dimensions of the specimen were measured. The results obtained are shown in Table 2, where width b and thickness t are tabulated for the average values of all four plates.

The instrumentation consisted of SR-4 gages and dial gages. Four SR-4 gages were attached to the corners of the cross-section at mid-height to obtain the load-strain relationship. Each SR-4 gage was placed as close to the corner as possible to avoid disturbance due to deflection of the plate, Figs. 3 and 4. The deflections of the side plates were measured with the mechanical gage shown in Fig. 4. The simple equipment consists of a bar frame and dial gages of 1/10,000 inch accuracy. The frame is seated on the side plates with a conical point bearing on a gage hole at one edge of the plate. The areas at which the deflections are measured are polished for better accuracy, Fig. 4.

The deflection was measured at the center of the width of each side plate throughout the specimens as well as at additional two quarter-points of the width of one side plate out of the four, except
for the smallest specimens, T-2A and T-2B.

The points for measurement were located along the length with certain intervals over the center portion for specimens S-1, S-11, S-2, and S-21. They were located throughout the length for the rest of the specimens, with closer intervals so that the deflected configuration of the side plate could be obtained.

The column was whitewashed with hydrated lime to indicate undesirable yielding that might occur in the process of aligning the column. The flaking of the whitewash also gives an indication of the extent of yielding during the actual test as well as the buckling mode at failure. Since the whitewash flaking reflects the flaking of mill scale, it was used in the A514 columns purely for esthetic reasons; A514 steel, being heat-treated, has very little mill scale.

3.2 Alignment

Before the actual experiment, the specimen was aligned by adjusting the wedge-discs placed at the top of the specimen.

Since the plates were assembled into one column, no separate alignment was possible for each plate, and the alignment was checked only for the column as a whole.

The column was first carefully centered. It was then loaded up to a load value which was considerably less than the proportional limit of the cross-section or buckling strength of the plate, whichever was the lower. The alignment was based on the four SR-4 gages on each corner of the cross-section at mid-height. No particular
difficulty was encountered in determining the adjustments on the wedge-discoes necessary to attain an even strain distribution at the different alignment loads. The alignment was made until the strain recorded by the SR-4 gages showed a maximum deviation of 5% from the average readings.

3.3 Test Procedure

After alignment, the test was started with an initial load of 5 to 10% of the expected ultimate load to avoid any initial disturbances which might exist. During the test, increments of load were applied in the elastic range. After the attainment of the load at which yielding commenced, the increments of loading were controlled by both increments of axial strain and of deflection of plates. The readings were taken 20 minutes after the application of each load increment in the elastic-plastic range in order to stabilize both the load and the yielding. Once the load-deflection relationship indicated a relatively sharp knee, the increments of loading were kept comparably small such that the ultimate load of the specimen would be noted on the load-deflection curve.
4. TEST RESULTS AND DISCUSSION

4.1 Preliminary Tests

A total of 16 standard tensile coupons were tested in a 120,000 lb screw-type testing machine. Table 3 gives the test results. Typical load-strain curves are shown in Figs. 5 and 6 for A7 and A514 steels, respectively. The average static yield stress of column No. 1 (A7 steel) was 39.6 ksi with a maximum deviation of 5.8 ksi. The deviations from the average static yield stress for the rest of the columns were not so large. Column No. 2 (A7 steel) had an average value of 38.6 ksi. Columns No. 3 and No. 4 (A514 steel) had average values of 115.9 and 103.1 ksi, respectively.

The residual stress distribution was measured for each fabricated piece, Figs. 7 and 8. The residual stress patterns show tensile residual stress at the weld metal and its nearby area. Compressive residual stresses were distributed over the rest of the cross section. Although the preparation of A7 plates and A514 plates were different, (sheared versus flame-cut), no particular difference can be seen in the distribution of residual stress in the respective specimens. This is due to the welding at the edges of the plates during fabrication. The welding of the edges of a plate changes the state of residual stress distribution present due to the edge preparation and thus the resulting residual stress pattern is due only to welding. (9)

The magnitude of tensile residual stresses at the weld metal and nearby area were slightly larger than the yield stress of the
parent material in A7 specimens, while they were slightly below the yield stress for A514 specimens. An E60 electrode was used for the welding of the A7 specimens leading to the weld metal being stronger than the parent metal. Similarly, the use of an E70 electrode in the A514 specimens gave weld metal with a yield stress lower than that of the parent material. The tensile residual stress decreased rapidly away from the weld bead and the large portion of the cross section was covered with compressive residual stress. The magnitudes of compressive residual stresses were larger for the small cross sections than for the large cross sections due to equilibrium requirements.

The most important factor in the analysis of the effect of residual stress on the local buckling strength is the ratio between the magnitude of compressive residual stress and the static yield stress of the material.\(^{(1,2)}\) The larger the ratio for this pattern of residual stress distribution, the more pronounced the reduction of plate buckling strength is due to the presence of residual stress.\(^{(1,2)}\) No great difference exists in the magnitude of compressive residual stress of the A7 and A514 specimens, while the static yield stress of A514 is almost three times of that of A7 steel and consequently the ratio mentioned above is far less in A514 specimens. Table 4 shows the ratio for the test specimens. This fact, together with the theoretical analyses of Refs. 1 and 2, suggests that the effect of residual stress on the local buckling strength of an A514 box column is less pronounced as compared to the effect on the local buckling strength of an A7 steel column.
4.2 Plate Buckling Tests

The results of the buckling tests are summarized in Table 5. The data given in the table include the ratios of the average compressive residual stress and the static yield stress of the material, both theoretically predicted and experimentally obtained buckling loads, the ultimate loads and the yield loads of the cross sections. The theoretical prediction was obtained in Refs. 1 and 2 for plates simply supported at all four edges with an idealized distribution of residual stresses. The analysis was made under the following conditions and assumptions such that the conditions of local buckling of a square welded built-up column were satisfied:

1. The loading is applied uniformly at two opposite edges of each plate.

2. The residual stress exists only in the direction of loading.

3. The tensile residual stress is the static yield stress at the two unloaded edges.

4. The compressive residual stress is distributed uniformly in the mid-portion of the width.

5. The gradient from the tensile residual stress at the edges to the compressive residual stress in the mid-portion of the plate is linear, and is determined such that the equilibrium of residual stress is satisfied.
6. For the yielded portion of the width, the stress-strain law of Bijlaard\(^{10}\) is used. The incremental theory is included as a special case of the stress-strain law.

Figure 9 shows the edge and the loading conditions and the assumed pattern of residual stress distribution of a plate used in the analysis. The assumed pattern is close to patterns of residual stress distributions actually present in the test specimens as presented in Figs. 7 and 8, and thus the experimental results may be compared with the theoretical results obtained in Refs. 1 and 2.

The load-versus-deflection relationship is necessary to obtain the experimentally determined buckling loads. As a natural consequence of unavoidable out-of-flatness and other imperfections, each component plate showed a slightly different load-deflection relationship. Load-deflection relationships of all four component plates at one cross section and the average of the four readings are shown in Fig. 10 for one test. The experimental buckling load may be determined preferably by the load-deflection relationship of the average of the four readings rather than from the relationship of each separate component plate. Examples of buckling waves along the length are shown in Fig. 11 for the 7" x 7" A514 specimens. The curves are the averages of the four component plates. The cross section where the maximum readings were obtained was chosen for each specimen and the load-deflection curves of Figs. 12 and 13 are plotted taking the average readings of the four faces of these cross sections.
The buckling loads were determined by the so-called "top of the knee method." \(^\text{[11]}\) The buckling load according to this method is, essentially, the load corresponding to the top of the knee of a curve of load versus lateral deflection. The loads thus determined are also shown in Figs. 12 and 13. The determination, however, is not definite and a slight personal influence can not be avoided. It is noted that, in both the A7 and A514 specimens, the wider specimens (specimens with a large width-thickness ratio) showed a significant increase of deflection in the post buckling range.

The load-versus-axial strain relationships are shown in Figs. 14 and 15. Again, the test points are the averages of the four SR-4 readings attached to the four corners of the specimens at mid-height. If no buckling takes place, the load-strain relationship is expected to be linear until partial yielding starts due to the existence of compressive residual stress. The tests of specimens T-1A and T-1B indicate that deviation of the load-strain relationship is due to buckling, and took place before yielding, just as intended for elastic buckling, Fig. 14. On the other hand, the tests of specimens T-2A and T-2B showed that buckling occurred after yielding of the cross section commenced, Fig. 15. In each case, the proportional limit without buckling was determined from a knowledge of the stress-strain relationship and the magnitude of the compressive residual stress. The A7 specimens buckled in the same way as A514 specimens; S-2 and S-21 buckled in the elastic range, while S-1 and S-11 buckled in the elastic-plastic range, as intended.
The test results are compared with theoretical predictions in Fig. 16, where the non-dimensionalized buckling stress is expressed as a function of the ratio of the magnitude of compressive residual stress and the static yield stress for each of the test plates.

All four specimens, S-2, S-21, T-1A and T-1B, which buckled in the elastic region, showed good agreement with the prediction but with a slightly lower buckling stress. Two theoretical predictions were made (1,2) for specimens S-1, S-11, T-2A and T-2B, for which the buckling loads were reached after partial yielding penetrated into the cross-section. One is based on the total strain theory and the other is based on the incremental theory. The incremental theory predicted no buckling until the specimen reached the yield load, whereas the analysis based on the total strain theory predicted 83% and 92% of the yield loads for both S-1 and S-11, and for both T-2A and T-2B, respectively. Although both predictions were higher than the test results, the difference is very small for the prediction of the total strain theory.

It can be concluded that the experiments correlated well with the theoretical prediction of the elastic buckling of steel plates with residual stresses. Further, it may be added that the elastic-plastic buckling of steel plates with residual stresses can be predicted by the analysis of Refs. 1 and 2 using the total strain theory. The disagreement of the prediction based on the incremental theory was expected from the results of experimental studies on aluminum alloy plates. (10,12,13,14)
The test results of both buckling stress and ultimate strength are also plotted on the non-dimensionalized plate buckling curve (2) in Fig. 17. The four curves in the figure are the results of a theoretical analysis for a plate with the assumed residual stress pattern shown in the figure. The curves clearly indicate that a lower buckling load is expected for a plate with a larger value of the ratio of compressive residual stress to static yield stress. The non-dimensionalized comparison of test results in Fig. 17 shows that the reduction of the buckling strength from the plate buckling curve computed for a plate free of residual stress and limited by the yield stress, is smaller in A514 specimens than in A7 specimens. This fact can be explained best by the difference in the ratio mentioned above for A514 plates and for A7 plates. Nevertheless, it is also noted that the test results include the effect of unavoidable initial out-of-flatness, from which it is concluded that the A514 plate is stronger than the A7 plate including the effect of residual stress and unavoidable initial out-of-flatness when they are compared on a non-dimensionalized plate buckling curve.

All four specimens which buckled in the elastic range, T-1A, T-1B, S-2, and S-21, showed a significant post-buckling strength as seen in Figs. 12, 13 and 17. The other specimens, which buckled in the elastic-plastic ranges, had only a relatively small reserve of post-buckling strength.
5. **SUMMARY AND CONCLUSIONS**

This paper presents a test method for determining the buckling strength of plate elements in square columns built-up by welding. The experiments were conducted to substantiate the theoretical analysis made by the authors, and the results of the tests are presented. Particular attention was given to the effect of residual stress on the buckling strength. Both ASTM A7 and A514 steels were used.

1. The square section used simulated plates simply supported at the unloaded edges, and the length of the column was chosen so that end conditions had no effect on the residual stress distribution or on the local buckling strength of the column.

2. Tension tests were carried out on coupons from the component plates of the test specimens, and the residual stress magnitude and distribution in the shape was measured by the method of sectioning.

3. The transverse deflection (local buckling) of the plates was measured at a number of cross sections by a 1/10,000 inch dial gage fixed to a frame held manually.

4. The "top of the knee" method was used to estimate the bifurcation load.

5. A good correlation exists between the test results and the theoretical analysis of the elastic buckling strength taking into account the residual stresses.
6. The elastic-plastic buckling strength of steel plates can be predicted from considerations of the effect of the residual stresses within them and by using the stress-strain relationship based on the total strain theory for the yielded portion. The analysis based on the incremental theory predicts a higher buckling load for the elastic-plastic buckling of steel plates with residual stresses.

7. Considerable post-buckling strength exists in a plate buckled in the elastic range, while a plate buckled in the elastic-plastic range has a relatively small reserve of post-buckling strength.

8. The effect of residual stress on the buckling strength of a plate is less pronounced for A514 steel than it is for A7 steel.

9. The plate elements of square columns of A514 steel are stronger than those of A7 steel when compared on a non-dimensional basis.
6. ACKNOWLEDGEMENTS

This paper presents the results of one phase of an overall study conducted into the strength of welded built-up and rolled heat-treated T-1 steel columns. Parts of this phase were applicable to another study into the strength of welded columns of structural carbon steel.

The investigation was conducted at Fritz Engineering Laboratory, in the Department of Civil Engineering, Lehigh University in Bethlehem, Pennsylvania. The United States Steel Corporation and the Pennsylvania Department of Highways sponsored the investigation. Column Research Council Task Group 1, under the chairmanship of John A. Gilligan, provided valuable guidance.

Special thanks are given to Charles G. Schilling of the United States Steel Corporation for his help in the procurement and preparation of the specimens, and for his advice throughout the study. Acknowledgement is due also to Enver Odar and to Ching-Kuo Yu for their assistance in conducting the tests.
7. NOMENCLATURE

b width of plate
E Young's modulus of elasticity
P load
$P_{cr}$ buckling load
$P_u$ ultimate or maximum load
$P_y$ load corresponding to fully yielded cross section
t thickness of plate
$\sigma_{cr}$ buckling stress
$\sigma_{rc}$ compressive residual stress in plate
$\sigma_{rt}$ tensile residual stress in plate
$\sigma_y$ static yield stress
8. TABLES AND FIGURES
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<th>Material Fabricated Piece No.</th>
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### Table 2: Dimensions of Specimens

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<th>t* (in.)</th>
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* Average value of four faces
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</tr>
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<td>125.9</td>
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<td>Ave.</td>
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<tr>
<td>C-41</td>
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<td>111.6</td>
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<td>29.8</td>
<td>103.5</td>
<td>111.5</td>
</tr>
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<td>C-43</td>
<td>29.7</td>
<td>104.0</td>
<td>111.6</td>
</tr>
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<td>C-44</td>
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<td>103.1</td>
<td>111.5</td>
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<tr>
<td>Ave.</td>
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<td>111.5</td>
</tr>
<tr>
<td>Fabricated Piece No.</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>---------------------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Material</td>
<td>A7</td>
<td>A7</td>
<td>A514</td>
</tr>
<tr>
<td>Static Yield Strength (ksi): $\sigma_y$</td>
<td>39.6</td>
<td>38.6</td>
<td>116</td>
</tr>
<tr>
<td>Average Compressive Residual Stress (ksi): $\sigma_{rc}$</td>
<td>12~14</td>
<td>10~11</td>
<td>11~12</td>
</tr>
<tr>
<td>$\sigma_{rc}/\sigma_y$ (approx.)</td>
<td>0.32</td>
<td>0.27</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Table 5  Test Results and Theoretical Predictions

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Test Results</th>
<th>Theoretical Prediction</th>
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<tr>
<td></td>
<td>$\sigma_{rc}^*$</td>
<td>$P_{cr}$</td>
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<tr>
<td>S-1</td>
<td>0.23</td>
<td>340</td>
</tr>
<tr>
<td>S-11</td>
<td>0.23</td>
<td>355</td>
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<tr>
<td>S-2</td>
<td>0.16</td>
<td>260</td>
</tr>
<tr>
<td>S-21</td>
<td>0.16</td>
<td>270</td>
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<tr>
<td>T-1A</td>
<td>0.10</td>
<td>500</td>
</tr>
<tr>
<td>T-1B</td>
<td>0.10</td>
<td>490</td>
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<tr>
<td>T-2A</td>
<td>0.15</td>
<td>620</td>
</tr>
<tr>
<td>T-2B</td>
<td>0.15</td>
<td>640</td>
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</tbody>
</table>

* Ratio between average compressive residual stress and static yield stress

$P_{cr}$ = buckling load; $P_u$ = ultimate load; $P_y$ = yield load of the cross section
Fig. 1  Location of Tensile Coupons

Fig. 2  Detail of Welding
Fig. 3  Test Setup (Specimen at Ultimate Load)

Fig. 4  Measurements of Deflection
Fig. 5  Load Strain Curve (A7 Steel)

Fig. 6  Load Strain Curve (T-1 Steel)
Fig. 7  Residual Stress Distribution (A7 Specimens)

Piece 1 (Specimens S-1, S-11)  
Piece 2  Specimens (S-2, S-21)
Fig. 8 Residual Stress Distributions (A514 Specimens)
Fig. 9 Plate for Theoretical Analysis
Fig. 10  Load Deflection Curve Column T-1A
Fig. 11  Deflected Shapes of Plates
Fig. 12  Load Deflection Curve (A7 Specimens)
Fig. 13  Load-Deflection Curves (A514)
Fig. 14 Load Strain Curve (T-1A, T-1B)
Fig. 15 Load Strain Curve (T-2A, T-2B)
Precicted by the Incremental Theory

Predicted by the Total Strain Theory

\[ \sigma_{cr} \]

\[ \sigma_{cy} \]

\[ \frac{\sigma_{cr}}{\sigma_{cy}} = 1.64 \]

\[ \frac{b}{t \sqrt{\frac{\sigma_{cy}}{E}}} = 2.28 \]

(a) Tests S-1 and S-11

(b) Tests S-2 and S-21

Fig. 16 Comparison of Local Buckling Test with Prediction
Prediction by the Total Strain Theory

\[ \frac{b}{t} \sqrt{\frac{\sigma_y}{E}} = 2.61 \]

Prediction by the Incremental Theory

\[ \frac{b}{t} \sqrt{\frac{\sigma_y}{E}} = 1.64 \]

(c) Tests T-1A and T-1B
(d) Tests T-2A and T-2B

Fig. 16 Comparison of Local Buckling Test with Prediction (Cont'd)
Fig. 17  Local Buckling Tests of Welded Square Tubes
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Predicted by the Total Strain Theory

\[ \frac{\sigma_{cr}}{\sigma_y} \]

\( S-1 \circ \)
\( S-11 \triangle \)
\[ \frac{b}{t} \sqrt{\frac{\sigma_y}{E}} = 1.64 \]

\( \frac{\sigma_{rc}}{\sigma_y} \)

\( S-2 \circ \)
\( S-21 \triangle \)
\[ \frac{b}{t} \sqrt{\frac{\sigma_y}{E}} = 2.28 \]

Fig. 16 Comparison of Local Buckling Test with Prediction

(a) Tests S-1 and S-11

(b) Tests S-2 and S-21
Prediction by the Total Strain Theory

\[ \frac{b}{t} \sqrt{\frac{\sigma_y}{E}} = 2.61 \]

Prediction by the Incremental Theory

\[ \frac{b}{t} \sqrt{\frac{\sigma_y}{E}} = 1.64 \]

(c) Tests T-1A and T-1B

(d) Tests T-2A and T-2B

Fig. 16 Comparison of Local Buckling Test with Prediction (Cont'd)
Fig. 17 Local Buckling Tests of Welded Square Tubes
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