THE EFFECT OF RESIDUAL STRESS
ON THE COLUMN STRENGTH OF MEMBERS
OF HIGH STRENGTH STEEL

by

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I. INTRODUCTION

(1) Definition of Residual Stress

Residual stresses of the type considered herein are the initial or "lock-in" stresses which exist within a structural member when there are no loads on the structure. Since equilibrium must at all times be maintained, the resultant of internal forces and moments due to these stresses will be equal to zero.

Residual stresses arise from a number of conditions. The major ones of these are as follows:

(a) Welding,
(b) Plastic Deformation (Cold Bending), and
(c) Differential Cooling After Hot Rolling.

In this work only the third one of these is considered and Fig. 1 shows an idealized residual stress distribution of longitudinal stresses that would be expected in a WF column shape. In this figure the negative sign denotes compression; the positive, tension.

Generally speaking, it can be shown that that part of the cross section which cools slowest will remain in residual tension. For the type of section in question this would occur where the flanges and the web join. The actual distribution, however, will depend primarily on the geometry of the various elements comprising the cross section.

Longitudinal residual strains superimpose with other strains in exactly the same way and to the same degree as strains arising from other sources superimpose within the
elastic range. It can therefore be shown that residual stress has a definite influence upon the average or nominal stress-strain relation of a structural steel member as a whole.

(2) Importance of Residual Stress on Column Strength

As early as 1888 residual stresses were investigated. It is interesting to note, however, that the effect of these stresses on column strength has only been considered in recent years. Figure 2 illustrated for a general stress-strain relationship (one which included the influence of residual stresses) the influence of residual stress on column strength.

At Fritz Engineering Laboratory, Lehigh University, investigations of residual stress and compressive properties of ASTM A-7, mild structural grade steel have been carried out. It was found, in that investigation, that for such "as-delivered" steel columns, the maximum reduction in column strength due to residual stress may amount to as much as 35 per cent(4).

In Reference 4, which deals with the behavior of columns of A-7 steel, the general equations of the column curves in terms of the tangent modulus were given as follows:

for bending in weak axis

\[ \sigma_{cr} = \frac{\tau^3 E}{(\frac{L}{r})^2} \]  

(1)

for bending in strong axis

\[ \sigma_{cr} = \frac{\tau r^2 E}{(L/r)^2} \]  

(2)

These were obtained by assuming a general pattern of residual stress of the type shown in Fig. 1. \( \tau \) in each of these equations corresponds to the ratio of the tangent modulus to Young's modulus for the stress in question. That is,

\[ \tau = \frac{E_t}{E} \]  

(3)

In equations (1) and (2) it is assumed that \( E_t \) (and thereby \( \tau \)) will be determined from a stub column test. (For a detailed description of this procedure, see Reference 4.)

(3) Purpose of this Investigation

The theoretical methods mentioned above have been verified by tests of mild structural steel columns(4). The purpose of this work is to further corroborate the theoretical methods by tests of members of high strength steel (ASTM Grade A-242 steel) and to correlate and compare the results with those obtained from A-7 steel.

The \( \delta WF31 \) shape of A-7 steel is one of the most commonly used rolled sections for structural columns and for this reason it was extensively investigated as part of the earlier study(4). To afford a "tie-in" with that work, this same (\( \delta WF31 \)) shape was selected as the member size to be considered in this investigation.
(4) Material Descriptions

All of the material of this study was from the same rolling and was produced at the Bethlehem Plant of the Bethlehem Steel Company. It is a high tensile, titanium steel meeting ASTM A-242 Specification. Table 1 gives the chemical properties as supplied by the manufacturer. The material was in all cases tested in the as-rolled condition. It was not rotarized, gaged, nor in any way cold-straightened. The measured residual stresses should therefore be due to cooling alone. Figure 3 shows the specimens as related to their position in the rolling.

II. DESCRIPTION OF TESTS

(1) Test Program

In summary, the test program for this investigation was as follows:

(A) Nine tension coupon tests
(B) Two compression coupon tests
(C) One set of residual stress measurements
(D) One stub column test
(E) Two axial column tests where bending was allowed in the weak direction

Column curves were derived from the foregoing, and were compared against each other. Two columns of length 12 ft. and 9 ft. (L/r=72, and L/r=54) were tested as a
check of the theory. Comparisons were also made between the results of this investigation and those obtained from the A-7 study.

(2) Tension Coupon Tests

Nine tension coupons were tested, using a 120,000 electronically operated, screw type Tinius Olsen testing machine. The coupons were cut from the flanges and the web of the cross section, as shown in Figure 4. The dimensions of these coupons were according to ASTM Standard\(^{(5)}\) (full thickness of the material and 1-1/2 in. width over an 8-in. gage length).

An 8-in. Moore extensometer connected to an automatic recorder was used to record the strains, and the rate of straining was in each case 3 micro in/in/sec. Some of the specimens were strained into the strain hardening range, at which time the strain rate was changed to 30 micro in/in/sec. The Modulus of Elasticity was determined directly from the recorded load-strain diagram. The percentage of elongation was computed, based on the measurements of the original and the broken specimen as prescribed by the ASTM Standard\(^{(5)}\). Table 3 summarizes the results of these nine tension coupons.

(3) Compression Coupon Tests

Two compression coupons were tested, using the same Tinius Olsen Machine that was used for the tension coupons.
The specimens were cut from the tip of one of the flanges and the center of the web, as shown in Figure 5. The dimensions were: 0.6" x 0.433" x 1.80" and 0.45" x 0.288" x 1.35", respectively. These dimensions followed the recommendations of Research Committee A of the Column Research Council. That is:

\[
\begin{align*}
&b > t \\
&L \leq 4.5t \\
&L \geq 2b + g \\
&b \leq g + 2b
\end{align*}
\]

where \( g \) is the gage length (1/2-in. was used for these tests). Strains were measured by means of an averaging compressometer, whose measuring element was SR-4 gages. The straining rate for these compressive coupon tests was 1 micro in/in/sec in both the elastic and plastic ranges.

Coupons rested on a bearing block and were provided with a spherical bearing on top of the specimen. Alignment under load was carefully checked before the test. In these preliminary (or alignment) tests a load less than one-third of the estimated yield load was used. When necessary, thin aluminum foils were inserted as shims. The alignment was considered satisfactory when the maximum strains varied no more than \( \pm 5\% \) from the average strain value. The stress-strain curves for these tests are shown in Figure 5.

* Width x thickness x length

° ASTM Bulletin No. 215, July 1956

/ See Reference 6
(4) Residual Stress Measurement - By Sectioning Method

A direct measurement of the residual strains (and thereby stresses) was obtained by considering the length of the specimen in the original material and then measuring it in the released state. (That is, after sectioning.) These readings were taken over a 10-inch gage length with a 1/10,000 Whittemore strain gage on a series of previously laid out holes. The final strains were measured after the 11-inch section had been sawed into strips of 1/2-inch width, each strip containing a pair of gage holes. A standard 10-inch mild steel bar was attached to the specimen for correction of readings due to temperature changes. Figure 6 indicates the layout used in the sectioning method.

The residual stress specimen was cut near the stub column test specimen (see Fig. 3). It was carefully selected to be free from yield lines.

The resulting distribution of residual stress is as shown in Figure 7a. It is compared to that obtained for the A-7 series in Figure 7b.

(5) Stub Column Test

The stub column test was carried out to obtain a direct averaging stress-strain curve which would take into account the effect of the residual stress distribution across the whole section.

The length of the specimen was selected such that it would be short enough to prevent column buckling and
long enough so that the cutting at the ends, which somewhat releases the residual stresses, would not affect the initial stresses in the "gage section". The length selected was 30 inches. The specimen was tested in compression in an 800,000-lb. screw-type Riehle testing machine. The ends of the specimen were milled flat and between the upper end and the head of the testing machine a spherical bearing block and plates were used.

Strains were measured by both SR-4 gages of one inch gage length (type A-I1) and a pair of 1/10,000 dial gages over a 10-inch gage length acting against a "frame" attached at the middle of the flanges. Figure 8 shows the positions of the strain gages. Near the four tips of the flanges, the average shortening of the stub column was also measured, using four 1/1000 dial gages and thin rods between the top and bottom bearing plates. These corner dial gages were used for alignment.

The alignment was considered satisfactory when the maximum deviation of one corner gage from the average of the four gages was within ±5%. The maximum alignment load was about one-third of the anticipated proportional limit.

The specimen was whitewashed with a solution of hydrated lime. This afforded a means of observing the yielding process during the test.

The load increments were determined from the load strain curve plotted during the test. Above the propor-
tional limit, criterion measurements were made and final readings were taken when both the load and strains had stabilized.

Testing was continued beyond the point at which the yield level was reached, until the load dropped 10 per cent and the specimen was severely buckled. At this stage, two of the 1/10,000 dial gages could no longer be attached to the specimen.

Average stress versus strain for the various gages is shown in Figure 8.

(6) Column Test

The columns were tested in the same 800,000-lb. screw-type machine as the stub column. The axial load was applied through a set of special end fixtures. A detailed description of these fixtures and test setup using them is given in Reference 7. Strains were measured by means of SR-4 gages of type A-II (one inch gage length) located at the center section and at positions near both ends of the columns. The alignment was checked by these SR-4 gages. Every reasonable effort was made to ensure as concentric a loading as possible.

Both columns were tested such that failure would occur in the weak direction. Initial crookedness was measured before the tests and was found to be essentially of a "single curvature type", having maximum values equal to 3/16-in. and 3/32-in. for C-1 and C-2. The corresponding
ec/r² values were 0.186 and 0.093 respectively. A small eccentricity of the application of load was adjusted during the alignment such that the effect of the initial deflection to the load-deflection relationship was partially compensated.

During the test, deflections were measured by means of a transit and three 1/100 inch scales clamped tightly to the flange of the column at the center section and near both ends. The center line deflection curves are shown in Figures 9 and 10.

While testing, load-strain and load-center deflection curves were plotted. The load increments were selected from a consideration of the load-center deflection curve. Criterion measurements were made when the load approached the critical values. These specimens were also white-washed so that the yielding process could be followed during the test.

III. TEST RESULTS AND A COMPARISON WITH THE A-7 STEEL TEST SERIES

(1) Coupon Test

The results of the tension and compression coupons are listed in Table 4 and Table 5, respectively. The results obtained for the A-7 steel members having the same shape (8WF31) are also given.

The Young's modulus of the coupon tests was ob-
tained from an enlarged stress-strain diagram by direct measurement. The proportional limit was determined from this diagram as the point at which deviation from linearity first occurred. The yield stress was the average stress in the plastic range.

Percentage of $\sigma_p/\sigma_y$ was determined for both the A-7 and A-242 steels, as shown in Table 4 and Table 5. For the tension coupon tests, it should be pointed out that the strain rate was 1 micro in/in/sec. for the A-7 steel and 3 micro in/in/sec. for the A-242 steel. For the compression coupons, however, both speeds were 1 micro in/in/sec.

(2) Residual Stress Measurement

The residual stress distribution across a section was computed by using $E = 30,000,000$ psi and the measured residual strains. The maximum value at the flange edge was found to be 14.8 ksi in compression, and at center of the flange was 11.7 ksi in tension. The residual stress pattern as was pointed out earlier is as shown in Figure 7a.
In Figure 7b, both the results of the A-7 steel and the high strength steel are plotted for the purpose of comparison. It is seen that they have approximately the same magnitude and distribution. Assuming that this result is indicative of the general trend, the conclusion can be made that the effect of residual stress on members of high strength steel is relatively less than for members of the same size of A-7 steel.

Note that in Figure 7a the variation of residual stress is very close to the idealized linear cooling residual stress pattern as indicated in Figure 1.

(3) Stub Column Test

The flanges of the stub column specimen of 30 inches length buckled as indicated in Figure 8 before the full yield stress level could be reached. The stress-strain diagram therefore dropped instead of maintaining a relatively constant yield level. In general, it has been found that this phenomena can be expected if the flange width to thickness ratio is greater than 17. For the 8WF31 shape, the value of b/tₚ is 18.5.

From the stub-column tests, it was found that the Young's Modulus $E = 31,200,000$ psi and the proportional limit $\sigma_p = 39.2$ ksi. The yield stress was 56.4 ksi. The first yield line, as determined by flaking of the white-wash, occurred at the flange edge at 51 ksi. In the web, the first yield line appeared at a stress equal to 55.5


ksi (about one kip smaller than the yield stress).

The nominal stress-strain curves obtained from the 10-inch gage length dial gages and the SR-4 strain gages are plotted in Figure 8. The average compression coupon test result is also plotted for comparison. Since the SR-4 gage has only a one-inch gage length, the strain readings could be seriously affected by the yield condition within its length. The column curve was therefore determined from the 10-inch gage stress-strain curve.

The stress-tangent modulus diagram (Figure 11) was obtained by measuring the slope of an enlarged version of the stress-strain curve for the 10-inch gage at certain stress values. From Figure 8 and Figure 11 the column curve was constructed as shown in Figure 12, with the assumption that the residual stress pattern has a linear variation \( I_0(2) \) and that the influence of the web could be neglected. The maximum reduction in column strength (for bending in the weak direction) was found to be about 22 per cent less than the idealized column strength neglecting residual stress, and occurred at a slenderness ration of 74. As pointed out earlier, for members of A-7 steel the maximum reduction in some cases has been as high as 35 per cent for bending in the weak direction.

Table 6 gives the comparison of the values obtained from the compression coupons and the stub column test. As will be noted, the \( E \) values did not agree very well. This
was possibly due to the inaccuracy of the gage factor of the compressometer used in the compression coupons. The value of the gage factor was taken as the average value of the results from three calibrations, each of which was slightly different. Since the values obtained from both tension coupons and stub columns are identical, the value $E = 31,200 \text{ ksi}$ was considered reliable.

(4) Column Tests

The axially loaded columns of 12 ft. and 9 ft. ($L/r = 72$ and 54) respectively were tested and their maximum strengths were plotted on Figure 12. The load versus center deflection curves were obtained during the tests (Figure 9, Figure 10).

At the point of bifurcation in the weak direction, the flange tips are yielded due to residual stress and the stress due to the externally applied axial load. The effective stiffness of the column is therefore reduced over that of the fully elastic case. Once the column starts buckling, it will continue to deflect at a relatively fast rate until equilibrium can again be restored. As a result, it is extremely difficult to obtain any data within this range for a column with a slenderness ratio in the neighborhood where the Euler curve and the yield stress meet. Column C-1 in Figure 9 is an indication of this phenomenon. The center deflection changed suddenly from 0.07-inch to 2.5 inches. For shorter members, however, this condition is not so
pronounced and unloading points can be obtained. These are shown in Figure 10 for test column C-2.

During the tests, deflections from the straight configuration were observed before the theoretical tangent modulus load was reached. This no doubt was due to the imperfection of the alignment and the initial crookedness of the columns. The maximum load obtained for C-1 was 400.3 kips and that for C-2 was 421.5 kips, while the predicted values from stub column test results were 398 kips and 429 kips, respectively.

The dimensionless column curves (plotting $\frac{\sigma}{\sigma_y}$ vs a function of $L/r$) for both A-7 steel and A-242 steel for the same shape 8WF31 are shown in Figure 13. The parameters are determined from the relationship

$$
\sigma_{cr} = \frac{\pi^2 E}{(L/r)^2} \text{ or } \frac{\sigma_y}{\sigma_{cr}} = \frac{1}{\pi^2} \cdot \frac{\sigma_y}{E} \cdot \left(\frac{L}{r}\right)^2
$$

and

$$
\lambda = \frac{1}{\sqrt{\frac{\sigma_{cr}}{\sigma_y}}} = \frac{1}{\pi} \sqrt{\frac{\sigma_y}{E} \cdot \frac{L}{r}}
$$

(4)

IV. CONCLUSIONS

1. Residual stresses are present in high strength steels and they do affect the carrying capacity of compression members.

2. For the one section studied (Figure 7b - 8WF31),
the magnitude and distribution of residual stresses are comparable to those of the A-7 series.

3. Since the residual stresses in the A-242 study and in the A-7 investigation were about equal, and since their yield points are quite different, the relative influence of residual stress on the compressive strengths of members of high strength material is less pronounced.

4. Because the yield points are materially different, however, the maximum deviation due to residual stress would occur in relatively shorter members for the high strength material (maximum deviation at $L/r = 75$) than for the A-7 (maximum deviation at $L/r = 90$). For the weak axis condition, the maximum reduction due to residual stress, as compared to the full yield value, $P_y$, would be 22 per cent and 35 per cent* respectively.

5. As mentioned in the beginning of this report, the high strength materials tested were from the same ingot. Therefore the conclusions apply in the strictest sense to only this one situation. It is considered, however, that they are indicative of the general trend to be expected. If more conclusive results are required, further investigations on various shapes and rollings should be made.

* Reference 4, page 19
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## VI. NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cross-sectional area</td>
</tr>
<tr>
<td>b</td>
<td>Flange width</td>
</tr>
<tr>
<td>d</td>
<td>Depth of Section</td>
</tr>
<tr>
<td>E</td>
<td>Young's Modulus</td>
</tr>
<tr>
<td>E_t</td>
<td>Tangent Modulus</td>
</tr>
<tr>
<td>g</td>
<td>Gage length</td>
</tr>
<tr>
<td>I</td>
<td>Moment of Inertia</td>
</tr>
<tr>
<td>L</td>
<td>Length of column</td>
</tr>
<tr>
<td>L/r</td>
<td>Slenderness ratio</td>
</tr>
<tr>
<td>P</td>
<td>Axial load in column</td>
</tr>
<tr>
<td>P_{cr}</td>
<td>Critical load on column</td>
</tr>
<tr>
<td>P_p</td>
<td>Proportional load</td>
</tr>
<tr>
<td>P_t</td>
<td>Tangent modulus load</td>
</tr>
<tr>
<td>P_y</td>
<td>Load at yield level</td>
</tr>
<tr>
<td>r</td>
<td>Radius of gyration</td>
</tr>
<tr>
<td>t</td>
<td>Flange thickness</td>
</tr>
<tr>
<td>w</td>
<td>Web thickness</td>
</tr>
<tr>
<td>ε</td>
<td>Unit strain</td>
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<tr>
<td>σ_p</td>
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<tr>
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<td>Critical stress (Correspond to elastic buckling load)</td>
</tr>
<tr>
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<td>Yield stress level</td>
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</tr>
<tr>
<td>σ_{yu}</td>
<td>Upper yield stress</td>
</tr>
<tr>
<td>τ</td>
<td>E_t/E</td>
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<tr>
<td>σ_{ult}</td>
<td>Stress correspond to ultimate load</td>
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VII. ACKNOWLEDGMENTS

This investigation, jointly sponsored by the Column Research Council, The Pennsylvania Department of Highways and Bureau of Public Roads and the National Science Foundation, has been carried out as part of a project being directed by Dr. Lynn S. Beedle at the Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania. Professor W.J. Eney is the Director of the Fritz Engineering Laboratory and the Head of the Department of Civil Engineering.

Messrs. S.J. Errera, Engineer of Tests, and K.R. Harpel, Foreman of the Fritz Engineering Laboratory, prepared the setup and tests. Messrs. A. Nitta, L.W. Lu, L. Tall and J.W. Fisher assisted in the tests. Their help is sincerely appreciated by the authors.
### TABLE 1 - CHEMICAL PROPERTIES OF 8WF31

**HIGH STRENGTH TITANIUM STEEL**

<table>
<thead>
<tr>
<th>Chemicals</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Va</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>0.15</td>
<td>1.09</td>
<td>0.027</td>
<td>0.027</td>
<td>0.04</td>
<td>0.013</td>
</tr>
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<table>
<thead>
<tr>
<th>Chemicals</th>
<th>Si</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
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<tbody>
<tr>
<td>%</td>
<td>0.22</td>
<td>0.08</td>
<td>0.05</td>
<td>0.02</td>
<td>0.14</td>
</tr>
</tbody>
</table>

### TABLE 2 - PHYSICAL PROPERTIES OF 8WF31

**HIGH STRENGTH TITANIUM STEEL**

<table>
<thead>
<tr>
<th>Thickness in.</th>
<th>Yield Point psi</th>
<th>Tensile Strength psi</th>
<th>Elongation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.29</td>
<td>55,720</td>
<td>76,720</td>
<td>21.6</td>
</tr>
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</table>

The above reports were supplied by the Manufacturer.
### TABLE 3 - SUMMARY OF TENSION COUPON RESULTS

**8WF31 (High Strength)**

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>E  ksi</th>
<th>$\sigma_p$ ksi</th>
<th>$\sigma_{yu}$ ksi</th>
<th>$\sigma_{y(st)}$ ksi</th>
<th>$\sigma_y$ ksi</th>
<th>$\sigma_{ult}$ ksi</th>
<th>% Elongation</th>
<th>% Area Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>30,400</td>
<td>45</td>
<td>59.20</td>
<td>55.84</td>
<td>54.2</td>
<td>76.48</td>
<td>28.28</td>
<td>59.25</td>
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<tr>
<td>T2</td>
<td>30,560</td>
<td>41.4</td>
<td>55.64</td>
<td>51.41</td>
<td>51.0</td>
<td>76.48</td>
<td>28.15</td>
<td>58.93</td>
</tr>
<tr>
<td>T3</td>
<td>31,600</td>
<td>45.7</td>
<td>57.54</td>
<td>54.62</td>
<td>55.1</td>
<td>76.01</td>
<td>26.35</td>
<td>53.65</td>
</tr>
<tr>
<td>T4</td>
<td>32,800</td>
<td>46</td>
<td>56.46</td>
<td>52.74</td>
<td>54.6</td>
<td>74.62</td>
<td>20.5</td>
<td>53.15</td>
</tr>
<tr>
<td>T5</td>
<td>32,260</td>
<td>—</td>
<td>61.52</td>
<td>55.07</td>
<td>55.3</td>
<td>76.04</td>
<td>27.95</td>
<td>48.39</td>
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<tr>
<td>T6</td>
<td>30,000</td>
<td>45.8</td>
<td>57.58</td>
<td>53.19</td>
<td>53.8</td>
<td>75.16</td>
<td>28.19</td>
<td>52.53</td>
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<tr>
<td>T7</td>
<td>32,000</td>
<td>46.5</td>
<td>57.92</td>
<td>53.76</td>
<td>57.0</td>
<td>75.68</td>
<td>30.40</td>
<td>58.14</td>
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<tr>
<td>T8</td>
<td>30,860</td>
<td>42.9</td>
<td>55.25</td>
<td>51.39</td>
<td>52.5</td>
<td>75.62</td>
<td>24.19</td>
<td>55.59</td>
</tr>
<tr>
<td>T9</td>
<td>31,640</td>
<td>—</td>
<td>60.96</td>
<td>51.39</td>
<td>56.7</td>
<td>75.31</td>
<td>33.53</td>
<td>60.28</td>
</tr>
</tbody>
</table>
### TABLE 4 - COMPARISON OF AVERAGE TENSION COUPON RESULTS
OF A-7 AND A-242 STEELS
(All Values in ksi)

<table>
<thead>
<tr>
<th>Type</th>
<th>Shape</th>
<th>E</th>
<th>$\delta_p$</th>
<th>$\delta_y(u)$</th>
<th>$\delta_y$</th>
<th>$\frac{\delta_p}{\delta_y}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-7</td>
<td>8WF31</td>
<td>Flange 30,010</td>
<td>32.0</td>
<td>39.1</td>
<td>37.4</td>
<td>85.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Web 29,270</td>
<td>27.7</td>
<td>42.6</td>
<td>35.7</td>
<td>77.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weighted 29,820</td>
<td>30.9</td>
<td>39.9</td>
<td>37.0</td>
<td>83</td>
</tr>
<tr>
<td>A-242</td>
<td>8WF31</td>
<td>Flange 31,180</td>
<td>44.3</td>
<td>58.4</td>
<td>54.4</td>
<td>81.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Web 31,690</td>
<td>45.9</td>
<td>58.5</td>
<td>54.6</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weighted 31,300</td>
<td>44.6</td>
<td>58.4</td>
<td>54.5</td>
<td>82</td>
</tr>
</tbody>
</table>

### TABLE 5 - COMPARISON OF AVERAGE COMPRESSION COUPON RESULTS
OF A-7 AND A-242 STEELS
(All Values in ksi)

<table>
<thead>
<tr>
<th>Type</th>
<th>Shape</th>
<th>E</th>
<th>$\delta_p$</th>
<th>$\delta_y$</th>
<th>$\frac{\delta_p}{\delta_y}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-7</td>
<td>8WF31</td>
<td>Flange 28,940</td>
<td>30.4</td>
<td>39.6</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Web 30,000</td>
<td>30.0</td>
<td>43.3</td>
<td>69.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weighted 29,200</td>
<td>30.3</td>
<td>40.5</td>
<td>75</td>
</tr>
<tr>
<td>A-242</td>
<td>8WF31</td>
<td>Flange 29,850</td>
<td>45.8</td>
<td>54.2</td>
<td>84.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Web 29,680</td>
<td>44.9</td>
<td>57.1</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weighted 29,830</td>
<td>45.5</td>
<td>54.9</td>
<td>82.8</td>
</tr>
</tbody>
</table>

The A-7 Values are taken from Reference 4
### TABLE 6 - COMPARISON OF COMPRESSION COUPON AND STUB COLUMN TEST RESULTS

*(8WF31-A-242)*

*(All Values in ksi)*

<table>
<thead>
<tr>
<th>A-242 Steel</th>
<th>E</th>
<th>( \delta_p )</th>
<th>( \delta_y )</th>
<th>( \text{Ratio of } \frac{\delta_p}{\delta_y} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stub Column (1)</td>
<td>31.2 x 10³</td>
<td>39.2</td>
<td>56.4</td>
<td>(0.86)</td>
</tr>
<tr>
<td>Average Compression Coupon (2)</td>
<td>29.8 x 10³</td>
<td>45.5</td>
<td>54.9</td>
<td>(1.025)</td>
</tr>
</tbody>
</table>

### TABLE 7 - TABLE OF SPECIMEN NUMBERS

<table>
<thead>
<tr>
<th>Tension Coupons</th>
<th>T1, T2, T3, T4, T5, T6, T7, T8, T9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression Coupons</td>
<td>CC-1, CC-2</td>
</tr>
<tr>
<td>Residual Stress Measurement</td>
<td>R.S.-1</td>
</tr>
<tr>
<td>Stub Column</td>
<td>S.C.-1</td>
</tr>
<tr>
<td>Columns</td>
<td>C-1, C-2</td>
</tr>
</tbody>
</table>
Fig. 1 - IDEALIZED RESIDUAL STRESS DISTRIBUTION

Neglecting Residual Stress

Including Residual Stress

\( E_t = \frac{d\sigma}{d\varepsilon} \)

Average \( \sigma - \varepsilon \) Curve of Section as a Whole

Neglecting Residual Stress

Strong Axis

\[ \sigma_{cr} = \frac{\pi^2(E)\frac{E_t}{E}}{\left(\frac{L}{r}\right)^2} \]

Weak Axis

\[ \sigma_{cr} = \frac{\pi^2(E)\frac{E_t}{E}}{\left(\frac{L}{r}\right)^2} \]

Euler

Fig. 2 - EFFECT OF RESIDUAL STRESS ON COLUMN STRENGTH
FIG. 3 - POSITIONS OF INDIVIDUAL SPECIMENS

Shaded Portion: Discarded
Specimen Numbers: See Table 7
Fig. 4(a) - DIMENSIONS OF TENSION COUPONS

Specimen T9
Cross-Sectional Area
0.648 sq in.
Young's Modulus 31,600 ksi

Specimen T5
Cross-Sectional Area
0.434 sq in.
Young's Modulus 32,300 ksi

Fig. 4(b). TENSION COUPON \( \sigma - \varepsilon \) DIAGRAM (A-242 STEEL)
Fig. 5 - DIMENSIONS AND 6 - ε DIAGRAMS OF COMPRESSION COUPONS (A-242 STEEL)
Fig. 6: RESIDUAL STRESS DISTRIBUTION BY SECTIONING METHOD
Fig. 7a - RESIDUAL STRESS DISTRIBUTION OF A-242 STEEL (Sectioning Method)
Fig. 7b - RESIDUAL STRESS DISTRIBUTION OF A-7 and A-242 STEELS
Positions Where Strains Were Measured

8WF31 (High Strength)

Fig. 8 - STUB COLUMN $\sigma - \epsilon$ CURVES
Fig. 11 - $6 - E_t$ CURVE DETERMINED FROM STUB COLUMN TEST

$E_t$
ksi

$6$ (ksi)

Fig. 12 - COLUMN CURVE FROM STUB COLUMN TEST
(Based On 1/10,000 Dial Gages)
Fig. 9 - LOAD-DEFLECTION CURVE FOR COLUMN TEST C-1

Fig. 10 - LOAD-DEFLECTION CURVE FOR COLUMN TEST C-2
Fig. 13 - DIMENSIONLESS COLUMN CURVES

* Data Taken From Reference 4