RESIDUAL STRESS AND THE COMPRESSIVE PROPERTIES OF STEEL

Progress Report

"THE MAGNITUDE AND DISTRIBUTION OF RESIDUAL STRESS"

by

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   (Tables and Figures for yield stress and residual stress - Extraction from the papers by F. Campus and C. Massonnet)
1. INTRODUCTION

1.1 Object

At the March 30, 1954 meeting it was suggested that by making measurements on a few extreme cases we might obtain maximum limiting values of residual stress distribution in rolled sections. One can see the range of specimens (as noted by the large circles) in b/t - d/w diagram (Figs. 1 and 2).

It appears that factors that will influence the cooling residual stress magnitude and distribution are thickness of part, b/t ratio and d/w ratio. The most important thing is probably the rate of cooling which is difficult to predict. This will be discussed later.

1.2 Tests

The shapes shown in Table 1 were proposed for residual stress measurement. It will be noted that they represent both "columns" and "beams", the latter being added for completeness.

<table>
<thead>
<tr>
<th>Type</th>
<th>Shape</th>
<th>t</th>
<th>b/t</th>
<th>w</th>
<th>d/w</th>
<th>$\sigma_{Rc}$ ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Column&quot;</td>
<td>14 x 16 (426) WF</td>
<td>3.030&quot;</td>
<td>5.5</td>
<td>1.875&quot;</td>
<td>10.0</td>
<td>-17.8</td>
</tr>
<tr>
<td>&quot;Column&quot;</td>
<td>6 x 6 (15.5) M</td>
<td>.269&quot;</td>
<td>22.3</td>
<td>.240&quot;</td>
<td>25.0</td>
<td>-15.1</td>
</tr>
<tr>
<td>&quot;Column&quot;</td>
<td>14 x 8 (43) WF</td>
<td>.528&quot;</td>
<td>15.2</td>
<td>.308&quot;</td>
<td>44.4</td>
<td>-9.0</td>
</tr>
<tr>
<td>&quot;Beam&quot;</td>
<td>36 x 12 (150) WF</td>
<td>.940&quot;</td>
<td>12.7</td>
<td>.625&quot;</td>
<td>57.3</td>
<td>-10.8</td>
</tr>
<tr>
<td>&quot;Beam&quot;</td>
<td>12 x 4 (14) J</td>
<td>.224&quot;</td>
<td>17.7</td>
<td>.200&quot;</td>
<td>59.6</td>
<td>-4.1</td>
</tr>
</tbody>
</table>

Note: $\sigma_{Rc}$ = Residual stress at flange tip.

The shapes were cooled separate from the rest of the specimen. (See Fig. 3.)
Table 2 which was taken from the progress report (1), is also shown.

Table 2

<table>
<thead>
<tr>
<th>Type</th>
<th>Shape</th>
<th>t</th>
<th>b/t</th>
<th>w</th>
<th>d/w</th>
<th>$\sigma_{rc}$ ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 WF 13</td>
<td>.345&quot;</td>
<td>11.8</td>
<td>.286&quot;</td>
<td>14.5</td>
<td>-13.0</td>
<td></td>
</tr>
<tr>
<td>8 WF 24</td>
<td>.398&quot;</td>
<td>16.3</td>
<td>.245&quot;</td>
<td>32.4</td>
<td>-10.0</td>
<td></td>
</tr>
<tr>
<td>8 WF 31</td>
<td>.433&quot;</td>
<td>18.5</td>
<td>.288&quot;</td>
<td>27.8</td>
<td>-15.0</td>
<td></td>
</tr>
<tr>
<td>8 WF 67</td>
<td>.933&quot;</td>
<td>8.9</td>
<td>.575&quot;</td>
<td>15.6</td>
<td>-8.0</td>
<td></td>
</tr>
<tr>
<td>12 WF 50</td>
<td>.641&quot;</td>
<td>12.6</td>
<td>.371&quot;</td>
<td>32.9</td>
<td>-6.0</td>
<td></td>
</tr>
<tr>
<td>12 WF 65</td>
<td>.606&quot;</td>
<td>19.8</td>
<td>.390&quot;</td>
<td>31.1</td>
<td>-20.0</td>
<td></td>
</tr>
</tbody>
</table>

Average $-12.0$ ksi

1.3 Procedure

Measurement procedure and method are the same as reported before (2). Strains were measured over a 10-in. gage length by 1/10,000 Whittemore gage on a series of previously laid out holes. Assuming $E = 30 \times 10^6$ psi, residual stresses were calculated to $\pm 600$ ksi.

Through the kindness of Professor C. Massonnet, the tables and Figures of yield stress and residual stress measurements, are able to be shown in Appendix as reference.

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2. TEST RESULTS

The results of residual stress measurements are shown in Figs. 3 to 8. The solid line indicates residual stress distribution on the outer surfaces of the flanges, while the dotted line is for the inner surfaces of the flanges. Residuals in the web are shown as solid and dotted lines for the one and another side respectively. (In Figs. 3, 4 and 5; the mean curves only are drawn.)

The summary of the tests is shown in Table 3 and in Fig. 9 schematically. (Fig. 9 is a supplement to Fig. 20 of the report (1) just issued).

In order to find the influence of cooling rate, two 14 WF 43 specimens were prepared. One was cooled on bed in the usual way and another was cooled separately. As can be predicted, the latter has the higher residual stresses approximately 40% in web (41.5 ksi) and 25% (25 ksi) in the intersection of flange and web respectively. (Fig. 3)

This shows that the magnitude of residual stress would depend on the cooling rate. The difference in residual stress magnitude is larger in web center and in the intersection of web and flange rather than in flange tips. This residual stress in web center is the measured highest one (but it is under special condition - cooled separately) and it seems almost yield stress.

The maximum residual stress, approximately - 29 ksi is measured in the web of 14 WF 43 under usual condition. The highest and the lowest of the average maximum residual
stress in flange tips are approximately -18.0 and -4.0 ksi respectively. The average value of the residual stresses in flange tips is approximately -11~12 ksi. The following facts will be notable that the magnitude of residual stress in WF shapes are not so much different in the range from 14 WF 426 to 14 WF 43 (See Fig. 1), and all the patterns of the residual stresses are the similar parabolic shape except in the web of 14 WF 426.

It can be easily seen that as the flange thickness becomes greater, the difference in residual stresses between the outer and inner faces of a flange becomes larger.

Table 3 Residual Stresses (Average)

<table>
<thead>
<tr>
<th>Shape</th>
<th>Flange Tip</th>
<th>Flange Center</th>
<th>Web Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 14 WF 426</td>
<td>-17.8 ksi</td>
<td>+8.5 ksi</td>
<td>+14.0 ksi</td>
</tr>
<tr>
<td>2 6 M 15.5</td>
<td>-15.1</td>
<td>+10.5</td>
<td>-0.9</td>
</tr>
<tr>
<td>3 14 WF 43</td>
<td>-9.0</td>
<td>+19.5</td>
<td>-29.0</td>
</tr>
<tr>
<td>4 36 WF 150</td>
<td>-10.8</td>
<td>+14.3</td>
<td>-15.0</td>
</tr>
<tr>
<td>5 12 J 14</td>
<td>-4.1</td>
<td>+8.3</td>
<td>-8.8</td>
</tr>
<tr>
<td>Average</td>
<td>-11.4</td>
<td>+12.2 ksi</td>
<td></td>
</tr>
</tbody>
</table>

Especially, the intersection of flange and web exhibits the maximum gradient of residual stress in the direction of thickness. (This may require the necessity of measurements on both faces of a flange in the shapes which have the thick flanges.

Even in large sections (for example 14 WF 426, 36 WF 150), the difference in residual stresses as measured by partial cutting and strip cutting is very small (See Figs.
This again confirms that in general, partial cutting is good enough for residual stress measurements.

As mentioned in the beginning of this report, the magnitude of residual stress should be related in some way to the proportions of shape. However, actual measured data do not show any clear relationship between residual stress and the geometry.

An example of an effort to establish a correlation is shown in Fig. 12 as a diagram $\sigma_{rc}$ vs. $\frac{b/t}{d/w}$. Though wide scattering exists in the data of Fig. 12 there seems to be some qualitative tendency. The most reasonable explanation of the scattering seems to be:

1. The cooling rate after rolling is not the same for all pieces,
2. The cooling during rolling is different for each shape and, of course, the distribution of temperature is already not uniform at this time.

It would be necessary to carry out a rather involved series of tests on specimens subjected to a carefully-controlled heating and cooling cycle to study these relationships more precisely. However, this is not considered practical, because actual columns and beams are subjected to arbitrary cooling conditions.

It is gratifying that the most consistent observation from these tests (Tables 2, 3 and Fig. 20 in Ref. (1)), is the average magnitude of compressive stress at flange tips. A value of about 12 ksi seems to be quite reasonable. In no case were tensile stress found at flange tips.
Residual stress patterns seem to take three forms which do not depend on shape clearly (Fig. 11).

1) Type I was observed most frequently. The maximum cooling rates would be in flange tips and web center.

2) Type II would be produced by relatively rapid cooling rate in flange tips.

3) Type III could be caused by rapid cooling rate in whole flange, then rapid cooling rate in the web center.

In Fig. 11, specimens were classified by using measured residual stress patterns.
3. SUMMARY

1. 14 WF 43 cooled separately shows about 25-40% higher residual stresses than 14 WF 43 cooled on bed. Except at flange tips, which were at the flanged hot spot, the residual stress in the web was about 25 ksi in the web of 14 WF 43. The highest and the lowest of the average maximum residual stress in flange tips are approximately -18.0 and -4.0 ksi respectively.

2. The maximum residual stress was found approximately 29 ksi in the web of 14 WF 43. The highest and the lowest of the average maximum residual stress in flange tips are approximately -18.0 and -4.0 ksi respectively.

3. There is wide scattering in the data, but the average residual stress in flange tips is approximately -12 ksi for all shapes studied.

4. In general, both faces of a flange have the same residual stress pattern and magnitude. However, when flange thickness is more than about 1.0 in, measurements on both faces are required.

5. For all shapes, partial cutting is good enough to measure residual stresses.

6. There seem to be three types of residual patterns which would depend on cooling rates.

7. Qualitatively we may say that the residual stress in flange tips would become larger as \( \frac{b/t}{d/w} \) increases.

8. These results show that we can proceed on the basis of the Pilot report conclusions.
ACKNOWLEDGMENTS

The author wishes to express his appreciation to the sponsors of this program, namely, the Column Research Council, the Pennsylvania Department of Highways and the Bureau of Public Roads.

The cooperation of the Bethlehem Steel Company in cutting certain of the pieces is very much appreciated.

Acknowledgment is also due to T. Kawai, Kenneth R. Harpel, Foreman and the Mechanists and Technicians for their help and cooperation.

The kindness of Professor C. Massonnet for permission to use his test data is greatly appreciated.

This work has been carried out at Fritz Engineering Laboratory of which Professor William J. Eney is Director. The project on "Residual Stress and the Compression Properties of Steel", of which this report is a part, is being directed by Lynn S. Beedle.
FIG 2

CROSS-SECTION DIMENSIONS
FIG. 3(b) WF BEAMS
LIGHT BEAMS
JUNIOR BEAMS

\[
\frac{d}{w} = 34 \\
\text{(compression)}
\]

\[
\frac{d}{w} = 42 \\
\text{(bending)}
\]

\[
\frac{17}{t} = 17
\]
Fig. 3 RESIDUAL STRESS DISTRIBUTION
Fig. 4 RESIDUAL STRESS DISTRIBUTION

- Outer surface
- Inner surface
Fig. 5  RESIDUAL STRESS DISTRIBUTION
Fig. 6 RESIDUAL STRESS DISTRIBUTION
Fig. 7 RESIDUAL STRESS DISTRIBUTION (Partial cutting)
Fig. 8 RESIDUAL STRESS DISTRIBUTION
(Strip Cutting)
Fig. 9  RESIDUAL STRESS DISTRIBUTION  
(Schematic Diagram)
Fig. 10. Cutting for residual stress measurement

Type I  12/F50, 12/F65, 14/F43, 6/F15, 6/F150, 12J14

Type II  4/F13, 8/F31, 14/F426

Type III  8/F24, 8/F67

Fig. 11 Type of residual stresses
Fig. 12  $\sigma_{rc}$ vs. $\frac{b/t}{d/w}$
Table 4: Lower yield point ($R_{el}$) in tension coupon and 0.2% offset in tension ($R_{et}$) and compression ($R_{ec}$) coupon.*

<table>
<thead>
<tr>
<th>Shape</th>
<th>Flange</th>
<th>Web</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_{el}$ psi</td>
<td>$R_{et}$ psi</td>
</tr>
<tr>
<td>1 4WF10</td>
<td>34,300</td>
<td>34,300</td>
</tr>
<tr>
<td></td>
<td>39,900</td>
<td>41,100</td>
</tr>
<tr>
<td></td>
<td>39,900</td>
<td>40,700</td>
</tr>
<tr>
<td>2 8WF31</td>
<td>29,900</td>
<td>31,900</td>
</tr>
<tr>
<td></td>
<td>36,300</td>
<td>39,000</td>
</tr>
<tr>
<td></td>
<td>36,500</td>
<td>37,600</td>
</tr>
<tr>
<td>3 8118,4</td>
<td>37,400</td>
<td>38,100</td>
</tr>
<tr>
<td></td>
<td>35,900</td>
<td>37,500</td>
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<tr>
<td></td>
<td>35,700</td>
<td>36,400</td>
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<td>35,600</td>
<td>35,800</td>
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<tr>
<td></td>
<td>--</td>
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<tr>
<td></td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

*This data is taken from "RAPPORT SUR LES ESSAIS DE FLAMBELEMENT DE COLONNES EN ACIER 37, A PROFIL EN DOUBLE TE, SOLLICITEES OBLIQUEMENT" par F. CAMPUS et C. MASSONNET, Professeurs à l'Université de Liège.
### Table 5: Yield stresses (0.2% offset) in compression coupon ($R_{ec}$)*

<table>
<thead>
<tr>
<th>Sheet No. in Reference</th>
<th>Shape (Approx.)</th>
<th>Flange Tip</th>
<th>Flange Center</th>
<th>Web Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>4WF10</td>
<td>33,400 psi</td>
<td>39,010 psi</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>8WF31</td>
<td>32,150</td>
<td>37,000</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
<td>8I18.4</td>
<td>36,500</td>
<td>32,600</td>
</tr>
</tbody>
</table>

### Table 6: Residual Stresses*

<table>
<thead>
<tr>
<th>Sheet No. in Reference</th>
<th>Shape (Approx.)</th>
<th>Flange Tip</th>
<th>Flange Center</th>
<th>Web Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>4WF10</td>
<td>-10,380 psi</td>
<td>+6,190</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>8WF31</td>
<td>-18,200</td>
<td>+13,530</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>8I18.4</td>
<td>-8,530</td>
<td>+11,890</td>
</tr>
</tbody>
</table>

* This data is taken from "RAPPORT SUR LES ESSAIS DE FLAMBEMENT DE COLONNES EN ACIER 37, A PROFIL EN DOUBLE TE, SOLLICITEES OBLIQUEMENT" par F. CAMPUS et C. MASSONNET, Professeurs à l'Université de Liège.
Fig. 13  RESIDUAL STRESS DISTRIBUTION