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FRITZ ENGINEERING LABORATORY
LEHIGH UNIVERSITY
BETHELHEM, PENNSYLVANIA

FRITZ ENGINEERING LABORATORY
LEHIGH UNIVERSITY
REPORT

COMPRESSIVE PROPERTIES OF ROLLED STRUCTURAL STEEL

TO
Submitted to Mr. L.S. Beadle for requirements of the Course C.E. 213.

BY
Alfons W. Huber
COMPRESSIVE PROPERTIES OF ROLLED STRUCTURAL STEEL

A Report Submitted to Mr. L. S. Beedle
for Requirements of the Course C. E. 213

By

Alfons W. Huber

Lehigh University

Summer 1951
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SYNOPSIS

A series of small coupons from 14 WF 30 & 8 WF 31 rolled steel sections were tested up to 14% strain. A gage was designed in order to carry the investigation well into the strain hardening range.

Residual stress measurements were made on those two sections and short columns were tested which still had an appreciable amount of residual stress in them.

The test results indicated that it is hardly justified to take the tangent modulus from coupon stress-strain curves, in order to predict buckling of columns in the elasto-plastic range.

It is recommended to test short column units of rolled sections and use this stress-strain relation for the prediction of buckling.

INTRODUCTION

A number of small compression coupons from the flanges of the 14 WF 30 section used in the continuous beam program were available. It was desirable to carry these compression tests well into the strain hardening range. A gage was designed for this purpose.

Residual stress measurements were also made on a 14 WF 30 section and a 20" long unit was tested in compression in order to compare the behavior of a whole cross-section containing stress with individual coupons.
In the current column program which is under way in the laboratory now we found that 8 WF 31 tested under axial load and pin-ended conditions with an I/r ratio of 56 failed at an average stress below the lower yield point stress predicted by coupon tests. This reduction of stress was considered to be the effect of residual stress.

One object of this investigation therefore was to find a procedure to take into account the influence of residual stress in rolled steel members under compression.

All tests were carried out under room temperature conditions.

**COUPON TESTS**

Fifteen coupons from the web and the flanges of a 14 WF 30 section were tested. Eight specimens were from the flanges of the section used in the continuous beam program. The other seven coupons were from the flanges and the web of the section which was used for residual stress measurements. Five coupons from the web and the flanges of a 8 WF 31 section used in the column program were also tested.

**DIMENSIONS AND INSTRUMENTS**

In the notes on compression testing of Subcommittee A of the Column Research Council the following dimensions for rectangular section are recommended:
The specimen length L will usually have to be made the limit 4.5t. The gages available in the laboratory determine usually the gage length. All but two specimen were tested with a pair of Buggerberger strain gages of \( \frac{3}{4} \)" gage length (Figure 16). Two coupons (UF1, A) were tested with SR-4, A-7 gages with \( \frac{1}{4} \)" gage length.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>L</th>
<th>b</th>
<th>t</th>
<th>L: b: t</th>
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<td>1.50</td>
<td>.75</td>
<td>.30</td>
<td>5:2.5:1</td>
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<tr>
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<td>1.12</td>
<td>.29</td>
<td>5:2.86:1</td>
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<tr>
<td>8 WF 31</td>
<td>1.30</td>
<td>1.12</td>
<td>.28</td>
<td>5:2.95:1</td>
</tr>
</tbody>
</table>

The coupons had been prepared several years ago with the exception of the seven specimens which were cut out of the piece of the 14 WF 30 section which was used for the residual stress determination. (Figure 9b)

**COMPRESSION GAGE (Figure 15)**

Previous tests in our laboratory on compression coupons have never been carried into the strain hardening range while the measurement was made over a short gage length.

The gage length is \( .48 \)". The strain on the cross-bar of the gage frame is measured by two SR-4, A-7 strain gages (\( \frac{1}{4} \)" gage length). This setup measures bending strain only, cancelling the effect of
direct strain. The relation of the strain on the specimen and the measured strain on the cross-bar of the gage is linear with a ratio of 85.75. The gage can be used up to a strain of 20%, the corresponding load on the pins being approximately 20%. The practical sensitivity is about .00017 in/in, corresponding to a strain indicator reading of 2 micro inch/in. The probable error in the actual strain is about, .0003 in/in or 1.5% of the 20% range.

DESIGN

Certain limitations governed the design of the gage:

1. The stiffness of the frame determines the load on the pins.
2. The strain in any part of the gage must be below the yield strength of the material and the latter must be suitable for machining.
3. The dimensions of the gage are limited by the coupon size and test set-up (Figure 17).

\[ \varepsilon^* \text{ = strain at the cross-bar} \]
\[ \varepsilon_i \text{ = } \frac{10 - l_i}{l_0} = \frac{\Delta l_i}{l_0} \]
An aluminum alloy 24 S-T4 plate of 1" thickness was selected. The yield strength (set 0.2%) is 48,000 #/in² both in tension and compression. Using a working stress of 30,000 #/in² and an E of 10×10⁶ #/in² we obtain a max. permissible strain of \( \varepsilon^* = 0.003 \text{ in/in in the gage.} \)

Temperature effect:

Assumed temperature change of \( \Delta t = 10^\circ \text{F}. \)

Temperature coefficient for steel \( c_s = 0.000067 \)

" " for aluminum \( c_a = 0.000130 \)

and the strains due to \( \Delta t \) are

\[
\varepsilon_s = c_s \Delta t = 0.000067 \quad \Delta \varepsilon_s = \varepsilon_s l_0 = 0.0000335 \\
\varepsilon_a = c_a \Delta t = 0.000130 \quad \Delta \varepsilon_a = \varepsilon_a l_3 = 0.000130
\]

The relative movement \( \Delta l = \varepsilon \Delta l_a - \Delta l_s \approx \pm 0.0000965 \)

and \( \varepsilon^* = \varepsilon \frac{1}{2} \frac{\Delta l}{b_0} \approx \pm 2 \text{ microinch/in} \)

Making: \( t_1 = t_2 = 0.2" \quad I_1 = I_2 = \frac{1}{3000} \text{ in}^4 \quad l_0 = 0.5" \quad l_1 = 3.0" \quad l_2 = 3.2" \quad l_3 = 1.0" \)

we obtain \( \frac{\varepsilon_1}{\varepsilon^*} = 188 \) \( P = 59.1 \varepsilon_1 \) (**) and for \( \varepsilon_1 = 1 \) : \( \varepsilon^* = 0.00053 < 0.003 \) \( P = 5.91 \)

Using one SR-4 gage as the active gage and the other one as the dummy gage we obtain the double output which makes \( \frac{\varepsilon_1}{\varepsilon^*} = 94. \)
CALIBRATION

The gage was calibrated by mounting it on a 1/10000 Ames dial gage (Figure 15). The strain was computed from the dial deflections which were obtained by weight increments of a scale (Figure 14). The calibration gave a perfectly linear relation \( \frac{\varepsilon_i}{\varepsilon_a} = 85.75 \). After the first series of tests this calibration was checked again and it was found that the ratio of the strains was unchanged.

The gage was fabricated in the workshop of our laboratory at an approximate cost of $30.00.

COUPON TEST PROCEDURE

Dimensions were obtained by micrometer readings to .0001". Both a subpress (Figure 15, 16, 17) and an adjustable bearing block with a spherical bearing block on the upper end of the specimen were used in the tests. The maximum alignment load was between 1/3 and 1/2 of the expected yield load.

A testing speed of about 1 microinch/in. sec. was used in the elastic range throughout all tests. The same valve opening of the 60,000 # hydraulic testing machine was kept in the plastic range. Readings were taken according to load increments up to 80 % of the expected yield load and then according to strain increments or smaller load increments.
The first eight coupons of the 14 WF 30 section (except UFL which was tested with SR-4s, A-7) of the beam program were tested with Huggenberger strain gages up to 30,000 \#/in\(^2\). Then the loading was stopped and the replacement made by the new gage.

All the other specimen were tested with the Huggenberger gages beyond the yield-point. Then the loading was reduced until no change occurred in the strain reading. This was accompanied by a drop of the load of about 10 \%. Then the gages were exchanged and the test continued with the previous valve opening. The tests were terminated when buckling could be observed which was at strains over 5 \%. Some specimens were tested further without the gage and the maximum load carried was recorded.

**TEST RESULTS**

The table on page 22 summarizes the coupon test results. The graphical definition of the terms is given in Figure 1. Summarizing curves are presented in Figures 3 to 8. It should be noted that nominal stresses and strains have been recorded on all graphs.

**DISCUSSION OF STRESS-STRAIN RELATIONS AND TEST RESULTS**

We will assume constant temperature. If we plot stress versus strain we get a diagram similar to the one in Figure 9. We assume that the strain does not change with the time in the elastic range,
up to $\sigma_p$ (Figure b). The plastic strain is composed of two parts.

The first part (slip) occurs over a small finite time element followed by the slow increase of plastic strain, (creep) under constant stress.

If we select a convenient time intervals $\Delta t$ and record for each stress level the corresponding plastic strain and connect these points we obtain a group of curves which are called the iso-stress lines (Figure c). If a material had instantaneous slip only one iso-line would result which also would be the stress strain diagram.

There are three methods of speed control in a test:

1. constant stress-rate
2. constant strain-rate
3. constant cross-head speed

In the elastic range all three are equivalent $\frac{d\sigma}{dt} = \frac{d\varepsilon}{dt} = \frac{\varepsilon dl}{\lambda_0 dt}$ where $\lambda_0$ is the initial length of the specimen and $\varepsilon = \frac{l - \lambda_0}{\lambda_0}$ assumed to be uniform throughout the whole specimen. The slope of the stress-.
strain diagram is not influenced by the speed of testing. It represents the iso-stress line for instantaneous (zero time) loading (to in Figure a).

As soon as local yielding starts we obtain a different behavior.

$$\sigma = \sigma(\varepsilon, d\varepsilon/dt)$$  \hspace{1cm} \text{(Temperature constant)}.

For \(d\varepsilon/dt = 0\) we obtain the iso-stress line \(t_\infty\), for \(d\varepsilon/dt = \infty\) the iso-stress line \(t_0\), the two limits of the iso-stress lines. The upper yield point represents a condition of instability affected by the rate of loading, surface condition, and other factors. The lower yield point is well defined being the nearly constant stress at increasing strain.

**CONSTANT STRESS RATE**

The stress strain diagram will have a sharper knee than the iso-stress lines and will approach one of them asymptotically with progressing loading. The stress increment is assumed to be instantaneously applied (following a line parallel F) and is followed by a deformation over the time element \(\Delta t\) under constant stress (Figure d).

The iso-stress lines in the flat portion of the stress-strain diagram tend to become parallel, the stress rate being zero. The strain rate is determined from the E-t diagram, (Figure e). The strain rate measured in the plastic range on coupon B2F7 was almost uniform (Figure 2a). When strain-hardening commences we have an increase in stress under slope C. For the earlier part of the curve this slope is almost
constant; \( \frac{dx}{dt} = C \frac{d\varepsilon}{dt} \), similar to the equation for the elastic range. The stress and strain rates are again proportional (Figure 2b and 2c).

**CONSTANT STRAIN RATES**

We can obtain the stress diagram for constant strain rate from the iso-stress diagram by a step by step procedure similar to the one we obtained for constant stress rate (Figure 1).

**UNIFORM CROSS-HEAD SPEED**

As long as the gage length will deform uniformly, \( \frac{d\varepsilon}{dt} = \text{const.} \). This is however not the case in a test since yielding progresses from local points. The rate of straining varies most rapidly during the transition from the elastic to the plastic range. This fact alone disregarding the effect of residual stresses makes questionable the use of the stress-strain diagram as obtained by small coupon tests as a basis to predict inelastic column behavior.

During the coupon tests a certain valve opening was maintained (corresponding to a rate of strain of one microinch/inch second in the elastic range) which gives a rather constant strain speed for the three parts of the stress-strain diagram (Figure 2), however, not in
the transition from the elastic to the plastic range.

The coupons F and G from the flange centers of the 14 WF 30 section had a reduced lower yield point of about 36 ksi (Figure 7). $\varepsilon_s$ was also reduced to a strain of about 0.006 in/in.

A reduction of the yield point could be expected if the steel had been stressed previously above the yield point in tension (Bauschinger effect). However, considering the cooling process this is not the case at the flange centers, which cool slower than the rest of the cross-section and could yield only in compression. When the outsides of the flanges are cool and the center starts to cool we get compressive residual stress at the outside and tension at the flange centers.

All the other stress-strain curves from the 8 WF 31 section (Figure 4) had a tendency to increase their slope in the upper part between proportional limit and yield point. A standstill of gages may happen though the stress is increasing if the specimen yields outside the gage length. This phenomenon makes the curve useless in the upper part for predicting the buckling stress. It should be noted that the 8 WF 31 coupons were wider than the recommended values by Subcommittee A of the CRC what might have influenced the specimen behavior.

The stress is not absolutely constant within the plastic range (flat portion) but varies slightly due to the nonuniform yielding within the gage length. If the properties of the material within
the gage length very considerably. If there are inclusions for instance, it may effect the stress-strain relation similar to the one observed on coupon B2W4 (Figure 8).

The slope of the strain hardening range is about constant up to a stress of $130\% \sigma_y$ (Figure 5). The transition from the plastic to the strain hardening range is not abruptly but gradually.

No visible effect of slight buckling has been observed upon the stress-strain diagram.
CROSS-SECTION TESTS

In many cases the presence of residual stresses is ignored, however it has been shown (7) that in rolled steel sections we usually find residual stresses of a magnitude to one half of the yield stress and more. It was therefore of interest to study the influence of residual stress upon the compressive stress-strain properties.

The first section used was a 14 WF 30 which was selected because a series of coupon data was available from the same ingot.

The investigation was twofold:

1. It was necessary to determine the length of the member so that the residual stresses were not appreciably changed over the gage length when the specimen was cut. This was done by a process in which the length of the member was gradually decreased by cutting short sections from each end (Figure 9a). The change in length was measured over a 10" gage length with a 1/10000 Whittemore gage. The magnitude of the residual stresses (uniaxial) was determined by the sectioning process (Figure 9b) from an immediately adjacent 11" long piece.

2. The member was tested in a 800,000 # testing machine and the loads and strains were recorded.

* Figures in parenthesis refer to the bibliography at the end of the report.
RELAXATION AND RESIDUAL STRESS MEASUREMENTS

14 WF 30: The cutting sequence was led out on an 84" long section and the holes for the Whittemore strain gage were drilled (Figure 9a, 9b). An attempt was made to measure the relaxation (Figure 9d) in addition with SR-4 strain gages. Their performance was unsatisfactory because of drift since the period between the cutting process took a few days. After the 11" long section was sawed out all the gage lengths were isolated by sawing 1/2" on either side of each pair of holes. The results of these measurements are shown in Figure 9e. The coupons A-G were prepared out from the 1" wide strips after the measurements had been made.

8 WF 31: In general the same procedure was followed. No relaxation measurements were made on the test piece which length was made 20" as the length determined for the 14 WF 30, since the relaxation of the 11" long piece which was cut out first indicated a similar behavior. Thirty-six pair of holes were used for the residual strain measurement (Figure 10a) and the width of the strips was reduced to one halfinch.

COMPRESSION TEST PROCEDURE

The general testing set up can be seen in Figures 20 to 23. Between the machined end of the section and the base plates thin
copper sheets were inserted in order to get satisfactory alignment. A spherical bearing block was used between the top plate and the cross-head of the testing machine. The maximum alignment load was about 40% of the yield load predicted by coupons. The specimens were whitewashed to follow conveniently the progress of yielding.

On the 14 WF 30 section only SR-4, A-11 gages were used for the strain measurements. These gave a strain picture which was too localized and therefore a series of SR-4s and four 1/1000 dial gages measuring the deflection between the bearing plates were used in the next test on the 8 WF 31 section. Welding or the use of set screws for gage fixtures had to be avoided in order not to disturb the residual stress pattern.

The load was applied in appropriate increments which were considerably reduced when the curve started to flatten out. Strain readings were taken when both load and strains showed negligible change during a 15 minute period. After the maximum load was passed a small load increment was applied and the readings taken after load and gages had stabilized.

**PLATE CONTAINING RESIDUAL STRESS**

C. H. Yang presents in his dissertation (8) the solution of a plate under uniform compression for a given residual stress pattern \( f(x) \). Consider Figure a. The stress required to start yielding at the edges is \( \sigma_1 = \sigma_y - f(a) \). The average stress at the ends of the plate is

\[
\sigma_2 = \frac{P}{A} = \frac{1}{a} \int_0^a (\sigma_y - f(x)) \, dx + \frac{x_0}{a} (\sigma_y - f(x_0))
\]
Assume the strain being constant over the whole area of the cross-section and determined by the elastic area only: 

\[ E_T \Delta \varepsilon = \varepsilon A e \]

\[ E_T = \frac{A e}{A} E \quad A e = \text{elastic area} \]

\( x_0 \) can be computed from \( \sigma_A \) when \( f(x) \) is known.

We shall consider here only the 8 WF 31 section. The residual stress measurements are presented in Figure 10b. Assuming the residual stress distribution to be parabolic in the web and consisting of two straight lines in the flanges we obtain the following equations for \( f(x) \) from the measured average values:

- flanges: \( f(x) = 4.5x - 5 \)
- web: \( w(x) = 0.384x^2 - 9.3 \)

and substituting into equation for \( \sigma_A \) we obtain the following equations which give respective \( x_0 \) values for the flanges and the web.

The outside part of the flanges will start to yield when \( x_0 = 4" \) and \( \sigma_A = \frac{48}{1.78} = 27 \text{Ksi} \). The maximum stress the flanges are able to carry will be when \( x_0 = 0 \) and \( \sigma_A_{\text{max}} = \frac{64}{1.78} = 36 \text{Ksi} \).

The reduction of the yield strength is 10% due to residual stress, neglecting the effect of strain hardening and the compensating effect of local buckling. The web will start to yield at the fillets when \( x_{01} = 4" \) and \( \sigma_A = \frac{574}{15.82} = 43.1 \), and the maximum stress will
be when $x_{01}$ and $\sigma_{\text{max}} = \frac{73.8}{1562} = 47.25$ ksi.

The maximum load taken by the cross-section will be composed of the following two parts:

$$P_1 = 36 \times A = 36 \times 3.2 = 331 \text{ kips}$$

$$P_2 = (47.25 - 36) A_{\text{w}} = 20.2 \text{ kips}$$

$$P_{\text{max}} = 351.2 \text{ kips}$$

The maximum load reached in the test was 343.5 kips. The calculation shows that we have to expect a reduction of the maximum load. The discrepancy between calculated and actual maximum load is due to the following:

1. The actual residual stress distribution is not exactly as assumed.

2. Local buckling has been completely neglected.

The tangent modulus determined for the flanges alone is

$$E_T = \frac{E_A t (64 - 178 \sigma_A)^{1/2}}{L/A}.$$ 

For stresses below $\sigma_A = 27$ ksi, $E_T = E = 30 \times 10^6$

Using above expression for $E_T$ we can calculate a column strength curve

$$\frac{L}{r} = \frac{E_T}{\sigma_A}.$$ 

This curve has been plotted in Figure 13.

**TEST RESULTS**

Figures 9 to 13 present summarizing graphs and curves of the test results, Figures 18 to 23 are photographs of the test specimens. A better method for the measurement of residual strains would be very effective. The error involved in the measurements was of the order of ± .00002 in/in strain.

The elastic modulus seems to be unaffected by residual strain as
one would expect. The relaxation measurements (Figure 9d) indicate that to a certain length the relaxation is negligible, then however increasing very rapidly.

As mentioned before the measurements on the 14 WF 30 section gave a localized strain picture. The maximum load was reached before yielding had started in the gage lengths. The stress-strain diagram was a straight line up to a stress of 30 ksi (yielding started at 28 ksi). Then the relatively thin walled section started to buckle locally. The maximum stress was 36 ksi where the local buckling effect became visible. Yielding had progressed to the gages and collapse followed rapidly causing severe local buckling (Figure 18).

The 8 WF 31 section started to yield at the flange in the center of the specimen at a stress of 29 ksi (Figure 19). The effect of local yield lines on the stress-strain behavior can be seen in Figures 11 and 12. The overall measurements by the dial gages gave a smooth curve while yielding within a gage length offsets the points of the curve towards higher strains.

The uniformity of the strain distribution in the elastic part was quite satisfactory. No local buckling of the web was measured. The outside flange (with gages No. 10 and 14 mounted on opposite sides) showed a tendency to buckle locally by standstill of the gages No. 13 and 14, while gage No. 10 continued to have about equal increments with the other gages. There was no visible evidence of local buckling after the test had been finished.

The tangent modulus of the stress-strain curve obtained from the
dial gage readings had been used to compute the column curve in Figure 13. The result of one column test performed in our laboratory under pin ended conditions lies right on this column curve. A comparison is made with the computed column curve from the stress-strain data of the coupon B2F7.

CONCLUSIONS

A rather large number of coupons is required to obtain good average values. However it is not possible to obtain the effect of residual stresses.

For the compressive properties of rolled steel sections it is therefore suggested to test short specimens which are not too thin-walled. First it would be necessary to determine the shortest possible gage length for different cross-sections without affecting an appreciable release of residual stress.

The measurements performed in the cross-section compression tests included not only the effect of residual stresses but also local buckling.

In order to perform the compression tests described in this report economically a gage fixture with four dial gages could be used that measures the average deformation over the gage length.

A similar investigation could be made for tension tests. The initial yield and maximum stress will be different for tension and compression for the same residual stress pattern.

Another important object for further research would be an investigation of the variation of residual stress along a rolled member.
Since the prediction of structural strength is based on the results of simple tests on small specimens the methods of investigation of the latter deserve our special attention.

ACKNOWLEDGEMENT

The author wishes to express his sincere appreciation to Mr. Lynn S. Beedle for his supervision of the research program and valuable advise during the preparation of this report.

The author also wishes to express his appreciation to Mr. Kenneth R. Harpel, foreman of the machine shop at Fritz Laboratory, for his cooperation and suggestions.

For the typing of this report the author is deeply indebted to Miss Emily Hoffman.
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# APPENDIX

## TABLE OF COUPON TEST RESULTS

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<th>Specimen</th>
<th>E $\times 10^{-6}$</th>
<th>$\varepsilon_0$</th>
<th>$\sigma_x$</th>
<th>$\varepsilon_\gamma$</th>
<th>$\sigma_\gamma U$</th>
<th>$\sigma_\gamma L$</th>
<th>$\varepsilon_\gamma$</th>
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<th>$\sigma_{\text{max}}$</th>
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<td>30.6</td>
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<td>37.500</td>
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<tr>
<td>B</td>
<td>30.1</td>
<td>(.00119) (41.000)</td>
<td>.00135</td>
<td>.00119 (41.000)</td>
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<tr>
<td>C</td>
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<td>.00104</td>
<td>32.000</td>
<td>0.00129</td>
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<tr>
<td>D</td>
<td>31.5</td>
<td>.00100</td>
<td>33.000</td>
<td>0.00128</td>
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<tr>
<td>E</td>
<td>30.7</td>
<td>.00085</td>
<td>28.000</td>
<td>0.00129</td>
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<td>F</td>
<td>29.4</td>
<td>.00094</td>
<td>27.000</td>
<td>(.00120)</td>
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<td></td>
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<tr>
<td>G</td>
<td>29.0</td>
<td>.00105</td>
<td>30.000</td>
<td>(.00125)</td>
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<td>Av. UF30</td>
<td>30.39</td>
<td>.00100</td>
<td>30.900</td>
<td>.00130</td>
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<td>B2F2</td>
<td>29.2</td>
<td>.00069</td>
<td>20.000</td>
<td>.00144</td>
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<tr>
<td>B2F3</td>
<td>28.8</td>
<td>.00139</td>
<td>40.000</td>
<td>.0174</td>
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<td>B2F4</td>
<td>29.2</td>
<td>.00059</td>
<td>17.000</td>
<td>(.00146)</td>
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<tr>
<td>B2F6</td>
<td>28.2</td>
<td>.00133</td>
<td>38.800</td>
<td>(.0115)</td>
<td>810,000</td>
<td>74,700</td>
<td>74,700</td>
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<td>B2F7</td>
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<td>.00138</td>
<td>39.000</td>
<td>.0148</td>
<td>750,000</td>
<td>78,437</td>
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<tr>
<td>Av. SWF31</td>
<td>28.82</td>
<td>.00139</td>
<td>38.950</td>
<td>.0169</td>
<td>707,000</td>
<td>74,940</td>
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</tbody>
</table>

**NOTE:** Figures in brackets have not been taken into account for the average values.
Plastic Range ~ Strain Hardening

GRAPHICAL DEFINITION OF TERMS

FIG. 1

FIG. 2a

Coupon B2F7 Plastic Range
\( \frac{de}{dt} = 14 \text{ microin/in/sec} \)

Strain in/in

Time sec.

100 200 300 400 500 600 700 800 900

FIG. 2b

Coupon B2F7 Strain Hardening
\( \frac{de}{dt} = 6.4 \text{ microin/in/sec} \)

Strain in/in

Time sec.

200 400 600 800 1000 1200 1400 1600 1800

FIG. 2c

Coupon B2F7 Strain Hardening
\( \frac{d\sigma}{dt} = 4.9 \text{ lb/in}^2\text{sec} \)

\( C = \frac{d\sigma}{d\varepsilon/dt} = 765,000 \text{ lb/in}^2 \)

Stress lb/in²

Time sec.

200 400 600 800 1000 1200 1400 1600 1800
COMPRESSION COUPONS

14WF30  (Huggenberger Gages)  8WF31

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>F2</th>
<th>F3</th>
<th>W4</th>
<th>F6</th>
<th>F7</th>
</tr>
</thead>
</table>

Stress lb/in²

- 40,000
- 30,000
- 20,000
- 10,000

Strain in/in
COUPON STRESS-STRAIN CURVES

Legend:
1-14WF30, LF4 Visible Buckling at 10% Strain
2-14WF30, A Visible Buckling at 8% Strain
3- 8WF31, F7 Visible Buckling at 4% Strain
AVERAGE STRESS-STRAIN CURVE FOR 14WF30 COUPONS (UFL - LF4)

Variation of the Properties*

<table>
<thead>
<tr>
<th>Stress lb/in²</th>
<th>E</th>
<th>G (MPa)</th>
<th>ε (MPa)</th>
<th>C (lb/in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000</td>
<td>31 x 10⁶</td>
<td>42,000</td>
<td>0.0160</td>
<td>800,000</td>
</tr>
<tr>
<td>20,000</td>
<td>30 x 10⁶</td>
<td>40,000</td>
<td>0.0140</td>
<td>700,000</td>
</tr>
<tr>
<td>30,000</td>
<td>29 x 10⁶</td>
<td>38,000</td>
<td>0.0120</td>
<td>600,000</td>
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<tr>
<td>40,000</td>
<td>31,600</td>
<td>42,500</td>
<td>0.0137</td>
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</tr>
<tr>
<td>40,360</td>
<td>30,24 x 10⁶</td>
<td>43,600</td>
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</tbody>
</table>

Average Value

* See also Table of Coupon Test Results
AVERAGE STRESS-STRAIN CURVE FOR 14WF30 COUPONS (A - G)

Variation of the Properties:

- Average Value
- See also Table of Coupon Test Results

C = 671,000 lb/in²
AVERAGE STRESS-STRAIN CURVE FOR 8WF31 COUPONS (B2F2 - B2F7)

Variation of the Properties*

$E$  $\sigma_y$  $\epsilon_3$  $C$

| 28x10^6 | 28.8x10^6 | 38,950 | 0.0169 |
| 30x10^6 | 41,000    | 0.0170 |
| 900,000 |

$C = 707,000$ lb/in$^2$

* See also Table of Coupon Test Results
RESIDUAL STRAIN MEASUREMENTS
14WF30

Test Specimen Resid. Strain
7 5 3 3 20" 3 3 5 11" 24"

Cut Sequence 2 4 6 8 A 3 7 5 3 B 1

Position of Holes

A - A

B - B

Compression Tension Strain in/in

.002 0 .002

A Opposite Points

Web: 6.00007
6'.00010 Compression

Relaxation of Test Piece

Average: 1.1' 3'

Elongation

.0004

.0002

.0001

Contraction: 2

Section A - A

.0002

.0001
RESIDUAL STRAIN MEASUREMENTS

Test Piece | Resid. | SWF31, B2

Position of Holes

1 2 3 4 5 6 7
0 0 0 0 0 0 0
1' 2' 3' 4' 5' 6' 7'

Section A-A
9 0 9'
10 0 10'
11 0 11'
13' 14' 12'
0 0 0
13 14 15 16 17 18 19

Strain in/in
--- Strain after the 11" long section was cut out

FIG. 10a

FIG. 10b

Points on the opposite side
SWF31 CROSS-SECTION STRESS - STRAIN DIAGRAM

1 Average 1/1000 Dial Gages
2 Average SR-4,4-11 Gages

Position of SR-4
Strain Gages and
Dial Gages

Stress lb/in²

Strain in/in

Fig 1
SWF31 CROSS-SECTION STRESS-STRAIN DIAGRAM

- **Average SR-4 No 1 - 4**
- **SR-4 No 2**
- **Average SR-4 No 6 - 9**
- **SR-4 No 7**
- **Average SR-4 No 10 - 13**
- **SR-4 No 12**

Maximum Stress

**FIG. 12**
COLUMN CURVES FROM STRESS-STRAIN CURVES

Euler Curve 8WF31
8WF31 Specimen
Coupon E2F7, 8WF31
Theoretical Curve
Actual Column Test of 8WF31, E2 L/r 55

\[ L/r = \frac{\sqrt{E}}{\frac{1}{\sigma}} \]

Stress lb/in²

<table>
<thead>
<tr>
<th>Stress (lb/in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40,000</td>
</tr>
<tr>
<td>38,000</td>
</tr>
<tr>
<td>37,300</td>
</tr>
<tr>
<td>36,000</td>
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</tbody>
</table>

L/r

<table>
<thead>
<tr>
<th>L/r</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
</tr>
<tr>
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<tr>
<td>60</td>
</tr>
<tr>
<td>80</td>
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<td>100</td>
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<td>120</td>
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<tr>
<td>180</td>
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<tr>
<td>200</td>
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</table>

Fig. 13
CALIBRATION SET-UP. A SCALE WAS USED AS LOADING DEVICE.
CALIBRATION DETAIL. THE GAGE IS MOUNTED ON A 1/10000 AMES DIAL GAGE.
TEST SET-UP FOR COUPON COMPRESSION TEST. 
NOTES SUB-PRESS AND HUGHESBERGER STRAIN GAUGES.

FIG. 16
THE NEW GAGE MOUNTED ON A COUPON.
14750 COMPRESSION SPECIMEN AFTER THE TEST.
HEAVY DEFORMATION DUE TO LOCAL BUCKLING.

FIG. 18
87FeL COMPRESSION SPECIMEN. FIRST YIELD LINES APPEARED AT A STRESS OF 27 ksi.
SUPERYIELD LINES AT A STRESS OF 33 ksi.

FIG. 20
SPLIT FLAT LENSES AT A STRESS OF 37 ksl.
Swaged specimen after the test. No deformation due to local buckling.