RESIDUAL STRESS AND THE COMPREHENSIVE PROPERTIES OF STEEL

Progress Report

ON THE YIELD PROPERTIES OF STRUCTURAL STEEL SHAPES

by

Lambert Tall
Robert L. Ketter

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Fritz Engineering Laboratory
Department of Civil Engineering
Lehigh University
Bethlehem, Pennsylvania

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SYNOPSIS

This report is a summary of certain aspects of the work on the general project "Residual Stress and the Compressive Properties of Steel". As a necessary foundation for the complete study, the program included as one phase a determination of the basic yield stress level of A.S.T.M. A7, mild structural steel of which columns of the type found in civil engineering structures would be fabricated. It is with respect to this basic yield strength that this report is concerned.
1. INTRODUCTION

At first glance, there are enough levels of yield stress to satisfy even the most exacting connoisseur of definitions. It would appear that whichever reasonable value be estimated at random for use in design, justification of it, to a greater or lesser degree, exists. Furthermore, it is common knowledge that increase in the speed of testing of a coupon may increase the yield stress level, and that such a value has limited use, unless it is defined by a strain rate.

Studies of the magnitude of the yield stress of ASTM Designation A7 steel have been the subject of more or less continuous research over the past decades.

It is the purpose of this paper to consider certain of the factors that have an influence on the yield stress, and to indicate how a prediction of this value is possible from the mill reports for yield point. To deduce and substantiate the conclusions, the mill coupon tests were simulated under strict speed control in the laboratory. Further data were deduced from stub column tests, using the full cross section. To make the study as complete as possible, data from other investigations were also included where required.
II. DESCRIPTION OF TESTS AND DEFINITION OF TERMS

1. Yield Stress - definition

The following terms defined graphically in Figure 1, are relevant in describing the yield strength of a steel coupon:

The upper yield point, \( \sigma_{uy} \), "the first stress in a material, less than the maximum attainable stress at which an increase in strain occurs without an increase in stress". (ASTM definition of 'yield point'.)\(^{18}\)

The lower yield point, \( \sigma_{ly} \), the lowest level of yield stress immediately following \( \sigma_{uy} \).

The yield stress level, \( \sigma_y \), the average stress during actual yielding in the plastic range, which remains fairly constant, provided the strain rate remains constant. (ASTM definition of yield strength: "the stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain.")

The proportional limit, \( \sigma_p \), "the greatest stress which a material is capable of developing without any deviation from proportionality of stress to strain" (ASTM definition.) \( \sigma_p \) is very closely equal to \( \sigma_y \) for a coupon, particularly if the coupon is annealed. This is not necessarily the case for the cross section as a whole.

Also, where no definite yield stress level may exist, as is the case occasionally, a 0.2% offset in strain from the initial linear stress-strain relationship is used to define a value for comparative purposes. The ASTM Standards\(^{18}\) suggest the use 'of the offset method (usually 0.2%), or, of the total extension under load method (usually 0.5%).' The offset method would tend to give quite an accurate value of the yield point, whereas the latter method is better for comparative purposes, as it records the magnitude of the yield stress level at a strain which is approximately midway between the yield point and the onset of strain-hardening.

It is seen from Figure 1 that a great variation in the magnitude of the stress associated with the different terms defined above does not exist. This has lead to some confusion of terms.

Until recently, both the upper and the lower yield points have been used as a basis for the estimation of the yield stress. Indeed, it is common practice in the testing of coupons to record the "yield" as the
reading indicated by the free 'follower' pointer on the load indicator dial, the actual load having dropped somewhat. **This paper will define the yield strength as the yield stress at the static level:** that is, the value for $\sigma_y$ when the strain rate is zero. (The effect of strain rate will be discussed in section III-6.) Use of this static level is logical, since most structural loads can be considered as primarily static. Furthermore, the upper yield point is no real material constant, but depends to a high extent on the testing machine used, form of the test piece, method of testing, and on other variables.16,19,20.

2. Stub Column Tests

A number of stub column tests, with material supplied by different manufacturers, were conducted so that an evaluation could be made of the behavior of the full cross section of WF shapes. See Figure 2. The results obtained provide an important basis for correlation of the actual yield strength of the shape with test coupons and mill test data.

The stress-strain curve determined from such a stub column test is of decided use in column strength predictions. As shown in Reference 9, this overall stress-strain picture enables use of the tangent modulus concept. Further, other relevant data can be obtained, as shown below, for the full cross section:

1. Young's Modulus, $E$.
2. Proportional limit, $\sigma_p$.
3. The maximum residual stress ($\sigma_r = \sigma_y - \sigma_p$), the evidence of this being at the position of the first flaking of mill scale, or the deviation from linearity of the load-deformation diagram. With as-rolled WF shapes, this yielding usually occurs at the flange tips.
4. The static yield level, $\sigma_{ys}$.
5. The overall effect of the residual stresses on the cross section, as evidenced by the 'knee' of the stress-strain curve.

In general the speed of testing for these stub columns may be regarded as static\textsuperscript{3}. Increments of load were applied slowly and once yielding had begun, care was taken that both strain and load had stabilized before readings were recorded\textsuperscript{9}. The tests were conducted in either a 5,000,000 pound capacity hydraulic or an 800,000 pound capacity screw-type mechanical universal testing machine.

3. Tension Coupon Tests

These tests were carried out for a wider range of shapes than were the stub column tests, due to both their ease of testing and their economy.

The coupons were cut from the web and flange as shown in Figure 3, and then shaped to ASTM standards, (see Figure 4). The coupons were all tested in a 120,000 pound Tinius Olsen universal testing machine, of the screw-power-type with a positive control over the speed of the cross head. In a few cases, the limited capacity of the machine required that the test be continued to rupture in a larger capacity testing machine. Automatic electronic recording equipment was used to plot the load-strain curve, which usually just reached into the strain hardening range on the recording paper.

The tests were conducted so that the static level of yield stress was also obtained. The speed of testing used was that recommended in Reference 4, being chosen so that the mill test of a steel manufacturer could be simulated. This is the ASTM recommendation\textsuperscript{18}. (Crosshead speed shall
not exceed 1/16 in. per minute per inch of gage length.) However, it should be noted that all strain rates were calculated on the basis of an adjusted length of the reduced portion of the coupon rather than on the gage length as such. The "standard" strain rate, to be discussed later, is that recommended above, but by the very wording of the recommendation, it is obvious that ostensibly similar strain rates actually differ if the gage length used is different, even though the specimens may be otherwise identical.

From the load-strain curve then, the following data were obtained; Young's Modulus, Proportional Limit, Upper and Lower Yield Levels if any, the yield stress level at the strain rate used, the static yield level, and, where it occurred on the recording paper, an estimation of the strain hardening modulus. Combination of data from web and flange according to their respective areas in the full cross section was employed to show, by comparison whether the use of such methods will give an accurate indication of the yield stress and other data.

The effect of strain rate on the apparent strength of steel has been given considerable attention, and data is presented that will enable predictions to be made of the static yield strength knowing the speed of testing. Although it had been recognized in the past that the strain rate had an effect, very little data for slow strain rate was available.

4. Correlations

Comparisons were made between the results of all the tests; stub columns, coupons, mill reports, as well as data obtained in other investigations.
The steel for both tension coupons and stub column tests was supplied by two different companies, Company "A" and Company "B". The results are shown both separately and combined, for in some cases it was felt that combination of the data obtained from the steels of the different companies could lead to inconsistencies. The data where the values have been combined will be useful in strength predictions when the origin of the material in question is unknown.
III. RESULTS

The test results are tabulated in Tables I and II. Table I gives the results for material of Company A, with Table II that for Company B.

1. The Static Level of Yield Stress

(a) Stub Column Tests

From Tables I, II, and Figure 5, to be described later;

material "A" $\sigma_{ys} = 33.1$ ksi mean value (20 specimens)

"B" $\sigma_{ys} = 35.0$ ksi mean value (13 specimens)

Average $\sigma_{ys} = 33.9$ ksi mean value (33 specimens)

Note: The 14WF426 had no apparent yield stress level, i.e. the material continually strain-hardened. This stress-strain curve is shown in Figure 2. No explanation for the loss of the horizontal yield portion is apparent. This occurrence happens sometimes in both coupon and stub column tests, but has been observed to occur only for the very heavy sections. Also shown in Figure 2 is a typical stress-strain curve of a stub column test showing the flat yield level. The photo shows a stub column test nearing completion, the shape tested being the one showing no horizontal yield level.

(b) Simulated Mill Tests

These are the weighted mean of the individual coupon tests. The individual data is recorded in Tables I and II, and in Figure 6.

material "A" $\sigma_{ys} = 32.8$ ksi mean value (22 specimens)

"B" $\sigma_{ys} = 34.6$ ksi mean value (13 specimens)

Average $\sigma_{ys} = 33.5$ ksi mean value (35 specimens)

2. Statistical Presentation of Data

The most advantageous manner of presenting the data of the various
tests is to have the group results for any parameter separate, rather than to have the results classified according to the specimen. A logical outcome of this, then, is to have the data tabulated in a statistical manner. This has been done in two ways, by the histogram, and by a cumulative plot of the results on probability paper, using the assumption of a normal distribution; See Figures 5a and 5b.

If the distribution be plotted on a cumulative basis, the resulting curve is a cumulative distribution function, which again, if plotted on probability paper is a straight line for a normal distribution. The advantage of a straight line is that the comparison of the statistical parameters becomes very simple.

The data obtained were comparatively small in number so that an estimation of a normal distribution curve from the histogram was out of the question. However, the number of results is sufficient for an estimation of a straight line in the cumulative plot on probability paper.

For a cumulative normal distribution, by symmetry, the mean value for the function considered is obtained from the 0.50 cumulative probability ordinate. (See Figure 5.) Further, it may be shown that the 0.841 ordinate (or the 0.159 ordinate) defines the standard deviation, \( s \). For a normal distribution 68% of any sample of results is expected to fall within the range \( \bar{x} \pm s \), where \( \bar{x} \) is the mean.

The standard deviation, also known as the standard error, is a value for describing the scattering of the observations about the mean. The straight line cumulative probability plot, by its slope, shows the range of the distribution, e.g. the steeper the slope, the narrower the distribution,
and vice versa.

Generally, the curves were plotted from the same classified groupings as used for the histograms.

A summary of the relevant statistical results is presented in Table III.

3. The "Mill Reports" for Yield Strength

The mill report for the yield strength of steel is based on a tension test of a coupon cut from the web of the particular shape carried out in the manufacturer's own laboratory, as part of his control on production. The tests are conducted at speeds allowed by ASTM and approximately the same as those advised in Reference 4. The results then give the yield strength for a "dynamic" level $\sigma_{yd}$, where dynamic is used as opposed to static. It will be further defined later.

The "simulated" mill tests were tension coupon tests conducted in Fritz Laboratory as outlined in section II-3, on web coupons cut from the WF shapes. The speed of testing "simulated" that of mill laboratory practice, and was according to the speed recommended in the previous paragraph.

(a) **Mill Tests, Figure 7.**

- material "A" $\sigma_{yd} = 42.8$ ksi mean value (24 specimens)
- "B" $\sigma_{yd} = 41.5$ ksi mean value (14 specimens)
- Average $\sigma_{yd} = 42.3$ ksi mean value (38 specimens)

**NOTE:** 3000 material "B" mill tests gave: $\sigma_{yd} = 44.1$ ksi (Reference 5)

(b) **"Simulated" Mill Tests, Figure 8.**

- material "A" $\sigma_{yd} = 40.1$ ksi mean value (24 specimens)
"B" $\sigma_{yd} = 41.4$ ksi mean value (13 specimens)
Average $\sigma_{yd} = 40.6$ ksi mean value (37 specimens)

4. Comparison of Mill Test Results with the Static Level of Yield Stress

To allow a prediction to be made of the static level of yield stress, $\sigma_{ys}$, from the mill test reports, a comparison of these results was made as a ratio of the former to the latter, (that is, $\sigma_{ys}/\sigma_{y\text{mill tests}}$.)

Tabulation of the results is shown in Tables I and II, with the distribution shown in Figure 9. The yield stress is taken as the weighted static value from the coupon tests, it being shown later that such a value is essentially equivalent to that obtained from a stub column test.

(a) Comparison Using Mill Results, $\sigma_{ys}/\sigma_{y\text{mill}}$, Figure 9

material "A", ratio = 76% mean value (20 specimens)
"B", ratio = 84% mean value (13 specimens)
Average ratio = 79% mean value (33 specimens)

(b) Comparison Using "Simulated" Mill Results, Figure 9

These results have very little direct application and are recorded only for indirect comparison of mill and laboratory testing speeds.

material "A", ratio = 81% mean value (22 specimens)
"B", ratio = 84% mean value (13 specimens)
Average ratio = 82% mean value (35 specimens)
5. Evaluation of $\sigma_{ys}$, Static Level of Yield Stress

by comparison of values from stub columns and from tension coupons.

This set of comparisons was made to determine whether the static yield stress of a WF shape, obtained from the tension coupons by weighting and averaging according to respective areas of flanges and web, could approximate the value of the static yield stress obtained from a stub column test on the full cross section.

$$\frac{\sigma_{ys \text{ stub column}}}{\sigma_{ys \text{ weighted coupons}}}$$, Figure 10

material "A" ratio = 99.1% mean value (18 specimens)

"B" ratio = 100.5% mean value (6 specimens)

Average ratio = 99.5% mean value (24 specimens)

Evidently, the two methods give the same results.

6. Variation of Yield Strength with the Strain Rate

The yield strength of steel is directly affected by the rate of straining. This may be regarded as a property of steel, and the phenomenon has been studied and observed on numerous occasions in the past. Generally speaking the greater the speed of straining, the higher the yield point tends to become, until the limit when the ultimate load is reduced without yielding.

It is realized therefore that the definition of the testing speed of a coupon is of the utmost importance when defining a yield strength as a particular type of steel could have an infinite number of such values.
Actually, this is exactly what does happen! Nor do the specifications take account of size effect in coupons, and differences in testing machines. Although the ASTM has tentative specifications limiting the maximum testing rate, it would appear that some investigators use lower rates than others with the result that discrepancies exist as high as 20% in the measured value for yield strength. At this juncture it should be noted that strain rate does not account for all the variation between tests - it cannot account for material differences or manufacturing methods. However, the difference due to chemical and other manufacturing properties can be more clearly evaluated if these superimposed artificial discrepancies of strain rate are removed.

This influence of strain rate was investigated by Marshman. Further tests, covering a wider range of materials, were carried out in the present series. This chapter will briefly describe the problems of strain rate and will indicate some of the results that were obtained. (All of the results from reference 6 have been included in this paper.)

The greatest practical difficulty associated with strain rate is its measurement. Although this is not difficult if special apparatus is used, it is not possible to use an indicated free moving crosshead speed as the strain rate for any particular machine. This is particularly true with a hydraulic testing machine. Due to the fact that during testing, the machine itself is deforming, an adjustment must be made to the indicated free-running crosshead speed to obtain the actual rate of straining. It is in the elastic portion of the loading that this effect has its greatest influence. As the load increases the strains and thereby the deformations of the various parts of the machine also increase. The result is that the indicated testing speed (free-running) is progressively decreased. This state of affairs continues until the yield point is reached. At this instant, when the specimen starts
to plastically deform, the load is essentially constant and no further elastic deformation of the machine can take place. For such a case, the movement between the crossheads is entirely due to the plastic yielding of the specimen. That is, except for a negligible part of the strain rate being taken up with keeping the deformed testing machine in equilibrium under the applied, and for practical purposes now constant load, the specimen is "straining" at the indicated free-running speed.

Tests for strain rate were run during the yielding of a number of tension coupons, with the indicated strain rate being recorded at both the crosshead and on the specimen itself. See Figure 11. Differences up to 25% in the strain rate, as measured by these two independent methods, were recorded. The strain rate measured from crosshead motion was 370 micro in/in/sec. Figure 11 shows differences of -25%, -8% and -3% respectively, in the one coupon test. As would be expected, the larger strain rate was that calculated from the crosshead speed, using as the gage length, the adjusted length of the reduced section of the coupon. The adjusted length is an approximation made for the length through which the coupon is straining. The coupon does not strain only on the gage length, but in the complete length of the reduced section. When used for comparative purposes, then, the ASTM recommended strain rate \(^4,18\), the "standard" strain rate, should always be qualified by the gage length used, as it is defined by the gage length.

It was determined that the crosshead speed indicated, the free-running speed, was essentially the same under a yielding load. The recording of the strain rate on the specimen was achieved by the use of a timing device acting on the automatic stress-strain recording paper. See Figure 12. This figure shows the set-up of a solenoid connected to a clock, used to record the time
marks which are shown on the top of Figure 11.

Although the indicated strain rate below yield point is not representative of the actual strain rate, and therefore cannot be used, once the yield point has been reached and the load and strain rate have stabilized, the indicated ratio of dynamic to static yield points has a definite level which is dependent on the testing speed. A plot of this ratio versus testing speed is shown in Figure 13. It should be noted that the curve is a band showing the results of a number of coupon tests of plate specimens and of WF sections (with coupons from both web and flange), as well as one test on a stub column. All tests, except for the stub column, were carried out on the same mechanical testing machine.

Figure 13 shows that a definite bend exists for the relationship between the yield level and strain rate. The upper or lower limits do not appear to be a function of the type of coupon, e.g. whether from bar or WF stock, although a general tendency was noted that the ratio decreases with increasing .

The dynamic yield stress, , is defined as the yield stress at a particular strain rate other than the zero strain rate. The static yield stress is the limit case and is defined as the yield stress at the zero strain rate.

Tests by Marshman have shown that the static yield level may be determined without actually conducting the experiment in its entirety at a zero strain rate, which, moreover, would be impossible. All that is required is that the strain rate be decreased to zero in the plastic region and that a few minutes be taken to allow the load to decrease to the minimum. (In the
case of hydraulic machines, care must be taken that the static level is approached from the positive side; that is, no strain reversal is to be allowed.)

The effect of this on a stress-strain curve is shown in Figure 14, a typical stress-strain curve from the series of coupon tests run on the screw-type mechanical testing machine. Marshman's tests showed that the load always fell to the same value, and the present series of tests confirmed his findings. The following observations show that the drop is wholly a property of strain rate rather than of the momentum or elasticity of the testing machine.

a. as the load dropped, the strain increased  
b. the static level position was checked by "jogging" the load slightly, i.e., a small increase in strain rate, with an immediate reduction back to the value corresponding to zero strain rate. If the static position were a function of machine elasticity, i.e., a function of the momentum of the elastic recovery of the testing machine, then the static position would take up some other level of equilibrium due to the smaller momentum of the "jogging", as is shown in the insert of Figure 14.

c. dial gages were used with hydraulic machines to ascertain whether the static position was a function of strain rate only. No strain reversal was recorded. Strain reversal, and hence a lower equilibrium load, however, will be recorded in hydraulic machines over a length of time due to oil leakage in the system.

Figure 15 records a stress-strain curve for a test on a complete cross section, as conducted in a mechanical testing machine. Due to the fact that recording is manual, rather than electronic as with the coupons, the
strain rate was in the very slow region, being 30 micro in/in/sec. The observation is recorded in Figure 13. However, correlation with coupon tests for this single case is reasonably good.

Figure 16 indicates a further observation tending to bear out the foregoing conclusions: namely, that in the plastic yield range the $\sigma_{yd}$ depends on the testing speed, whereas, the $\sigma_{ys}$, as obtained by stopping the movement of the crosshead, is relatively constant.

7. Tension Versus Compression Coupons

Although no compression coupons were used in this series of tests, previous investigations have shown that, on the average, tension and compression coupons of this material give results that are almost identical. These results and conclusions will be repeated here in summary form (see Table IV.) Although these particular results are for one shape, 8WF31, experience with other shapes seems to give the same indications.

Quoting from Reference 9:

"The elimination of compression testing of coupons (in the case of rolled structural steel shapes) is thus considered as warranted, particularly in view of larger variation in properties due to other causes."

Compression testing of coupons is much more difficult as compared to the case of testing tension coupons.

Considering the full cross-section, the static yield level as determined from stub column tests was almost identical with that determined from the weighted mean of the tension coupons as shown in Figure 10.

8. Variation in Properties of Specimens from Web and Flange

There is conflicting opinion on the subject of whether the shape and size of a specimen has any appreciable effect on its physical properties. Previous
investigations $^5, ^8, ^17$ have shown that this effect may exist in coupon testing, and the limited number of tests described in this report suggest that lighter sections have a tendency to a higher yield point.

This section presents a summary of certain results, shown in Tables I and II and in some of the figures. The yield strength both at the static and the dynamic level is considered.

(a) $\sigma_{ys}$, Static Yield Stress, refer to Figure 6.

From simulated mill coupon tests, weighted means:

**material "A"**

mean = 32.8 ksi (22 specimens)

range 29-37 ksi: 18WF105, 16WF88, 14WF111
14WF 61, 12WF142, 14WF 78
12WF 92, 12WF 65, 12WF 53
12WF 50, 10WF 66, 10WF 39
10WF 33, 8WF 35

range below 29 ksi: 14WF320 = 22.7 ksi
12WF190 = 26.8
8WF 67 = 26.3

range above 37 ksi: 8WF 31 = 37.9 ksi
8WF 24 = 37.8
6WF15.5 = 43.3
5WF18.5 = 41.3

**material "B"**

mean = 34.6 ksi (13 specimens)

range 29-37 ksi: 18WF105, 16WF88, 14WF111
14WF 78, 14WF61, 12WF190
12WF 53, 10WF66, 6WF15.5
6WF 25

range below 29 ksi: 14WF426 = 28.6 ksi

range above 37 ksi: 14WF142 = 38.0 ksi
5WF18.5 = 37.4

The summary should be considered with Tables I and II. It is then seen that in general, as would be expected, the heavier sections have a lower $\sigma_{ys}$, while lighter sections have a higher $\sigma_{ys}$ than the mean. This tendency was
also pointed out in the final report of the Special Committee on Steel Column Research. 17

Since the flanges are the controlling factor in the determination of column strength of WF members both for buckling and direct loads, the b/t and $\alpha$ (Area of Flange/Area of web) ratios were also considered. The indications from the small number of results on hand are that:

- shapes with $b/t = \text{approx. 10 or less}$, have $\sigma_{ys} < 28\text{ ksi}$
- $b/t = \text{approx. 18 or more}$, have $\sigma_{ys} > 37\text{ ksi}$
- shapes with $\alpha < \text{approx. 2.5}$, have $28 > \sigma_{ys}$
- or $\sigma_{ys} > 37\text{ ksi}$

The stub column values for $\sigma_{ys}$ were also considered. It may be seen that the indications are exactly the same as for the coupons, although the results are less random, that is, the spread is narrower.

(b) $\sigma_{yd}$, Dynamic Yield Stress, Figure 7

mill test - web coupon results

In this case, the same general indications hold as for the cases above. This can be seen from the reasonably constant histogram. It should be noted, however, that the results are more random. Since $\sigma_{yd}$ is not defined for a particular strain rate, testing differences are probably present.

To show schematically the general tendency of higher yield point for lighter sections, Figure 17 plots $\sigma_{yd}$ against the web thickness.
IV. DISCUSSION

1. Yield Strength

The yield strength has many definitions. The static yield stress, $\sigma_{ys}$, however, is the preferred value as it is the easiest to obtain and also is the stress that corresponds best to normal structural loading conditions. In stub column tests, by allowing the load to "settle down", that is, to come to an equilibrium position after a load increment, it is essentially the static value that is obtained. With coupon tests, all that is required is that the rate of straining be decreased to zero anywhere in the plastic yield range. This is easily accomplished in mechanical and hydraulic testing machines, although with the latter a dial gage indicator is required to show movement of the crosshead, and to guard against strain reversal.

From the results (Figures 5, 6, and Section III-I) the approximate mean value for $\sigma_{ys}$ was 33.7 ksi, with a standard deviation of 3.8 ksi. This was the overall average for stub column and simulated mill (weighted average) tests. It is considered that this value is close enough to be taken as the usually accepted specification minimum of $\sigma_y = 33$ ksi.

These results are also shown in a statistical form, both as histograms, and as assumed normal distributions on probability paper.

It is noted that the results were not dependent on chance alone but on many manufacturing factors. For instance, it would be expected that the comparatively heavy sections would give relatively smaller values for $\sigma_y$, while small sections would give the larger values. The amount of cold work, rate of cooling, chemical composition etc., undoubtedly played a major role in this situation.
2. Yield Stress and the Mill Test

Mill test results for the yield strength were approximately 25% higher than the true static level, due probably to two causes:

a. mill tension tests are run on coupons cut from the web, which, being rolled thinner than the flange, has about a 4-7% higher yield level than the flange.

b. the yield strength depends directly on the strain rate as shown in Figure 13. Even with apparently small strain rates, (approaching zero), \( \sigma_{yd} \) can be 5% greater than \( \sigma_{ys} \), whereas at normally accepted mill testing speeds, 13-18% is a more realistic figure.

The strain rate has a pronounced effect. Therefore, unless it is specified for a given test the correlation of the resulting data with other test data is impossible. Indeed, in this series of tests conducted on steel from the same lot, the simulated mill (Fritz Laboratory) tests produced \( \sigma_{yd} \) approximately 5% lower than did the mill tests. The former used the recommended speed of the ASTM A6-54T (and A370-54T)\(^4\), \( \sigma_{ymill} \) while the testing speed of the latter is not known although it should be approximately the same. Testing machine variations could be the factor, as discussed in item 4, below.

One of the more important objects of this investigation was to see whether the yield stress could be defined by the mill test. The results, Figure 9 and Section III-4, are varied. Comparison of the static yield level with both mill and simulated mill results was considered. The range of distribution was reasonably good and the average was equal to 79% for the ratio \( \frac{\sigma_{ys}}{\sigma_{ymill}} \). More consistent results were obtained for the ratio \( \frac{\sigma_{ys}}{\sigma_{ysim.mill}} \) with an average of 82%. (In all cases, \( \sigma_{ys} \) is from weighted coupons.) This again raises the question of a standard strain rate, and the comparatively
good agreement of the simulated mill results above (similar strain rate results from steel of different manufacturers) would bear out the premise. It is not too difficult to draw definite conclusions from the above figures, particularly as previous investigations have obtained \( \frac{\sigma_{ys}}{\sigma_{yd}} \) where \( \sigma_{ys} \) refers to stub column tests. The tests were conducted at a strain rate of approximately 1 micro in/in sec which gives results about 5% higher than at the zero strain rate.

From the above, it is suggested that \( 80\% \pm 5\% \) is a probable value for \( \frac{\sigma_{ys}}{\sigma_{ys\text{mill}}} \).

3. Tension Coupons and Stub Column Tests

The procedure described in the previous paragraph was for the weighted tension coupons, weighted according to respective areas of flange and web, but the same results would have been obtained for \( \sigma_{ys} \) from stub column tests. Figure 10 and Section III-5 show that almost perfect correlation exists for \( \sigma_{ys} \) between stub column and weighted coupons.

Another result of this study is that the strength of the full cross section of a wide flange shape may be estimated, with complete confidence, from tension tests on coupons cut from flange and web. Although economically this may be no saving, it does enable a laboratory with testing machines of a limited capacity to obtain reliable estimates. Unfortunately, \( \sigma_{ys} \) and \( E \) are the only properties that such coupon tests will supply, the important \( \sigma_p \) and "knee" of the \( \sigma - \epsilon \) curve (showing effect of residual stresses) for the full cross section cannot be determined.

4. Strain Rate and Yield Stress

The problem of strain rate and the determination of its effect on the yield stress as shown above can only be overcome by a substantial number of
tests on a wide variety and type of testing machine. Steel from the different manufacturers must also be subject to exhaustive tests. Since the strain rate in the elastic range is not too important if held within reasonable limits, the basis for such a series of tests should be on the free-running speed of the crosshead. It is expected that the outcome of such tests would show a similarity in the $\frac{\sigma_{yd}}{\sigma_{ys}}$ versus strain rate curves for different types of testing machine and steels. This trend has been indicated from the reasonable correlation between the tests of Marshman and the series of tests described in this paper, as well as other tests, carried out on both screw type mechanical and on hydraulic testing machines. Such tests would indicate whether the difference for $\sigma_{yd}$ between simulated and mill tests was due to the different testing machines or to different strain rates used. Up to the yield level and in the strain hardening range the type of machine and size of specimen has a much larger effect than in the plastic or yield range. This result, however, seems to be of little practical interest. If it is desired to determine this elastic effect of machine deformation when the specimen is strained into the plastic range, a series of strain gages should be attached over the full length of the specimen to correlate the actual strain rate with the "free-running" speed.

Tests have demonstrated that a fast method of obtaining $\sigma_{ys}$ is to decrease the strain rate to zero once or twice in the plastic yield range (ensuring no strain reversal).

5. Tension and Compression Coupons

It was shown that compression and tension coupons give almost identical results. This statement is based upon the work of previous investigations. The difficult compression coupon test can therefore be eliminated in all but confirmatory cases.
6. Size of Section and Yield Stress

Generally speaking, heavier sections have a lower yield stress than lighter sections. Similar general statements can be made for the b/t and α ratios.
V. CONCLUSIONS

1. This series of tests indicates a probable value for the yield stress of the full cross-section of a WF shape to be:

\[ \sigma_{ys} = 33.9 \text{ ksi with } s = 3.8 \text{ ksi} \] (Figure 5).

Because of the magnitude of the standard deviation, it is suggested that the specification minimum value be used as a reasonable basis for design:

\[ \sigma_{ys} = 33 \text{ ksi} \]

The yield stress is defined as the static yield stress.

2. The yield stress should be defined by the "static" yield stress level because this level corresponds best to normal structural loading conditions, and is the easiest to obtain. (Figures 13, 14). It also affords the most reasonable basis for comparison of different test results. (See Section IV).

3. The effect of strain rate on the yield stress level has been discussed in Section III. An increase in the strain rate leads to a higher yield level. (Figure 13). For more authoritative conclusions regarding the influence of this variable, a substantial number of tests on steels from different manufacturers would have to be conducted using a wide variety and type of testing machine. To obtain this more precise correlation between strain rate and static yield stress level as well as between different manufacturers and testing machines, it would be necessary that the rate of testing of the mill coupons be observed for each coupon test. Then Figure 13 could be substantiated, or revised.
This itself would allow the static yield stress of any coupon to be immediately determined, knowing the dynamic yield stress and the speed of testing.

4. This series of tests further indicated that the "static" level of yield stress for a WF shape is \(80\% \pm 5\%\) of the mill test value of a tension coupon cut from the web of the section. (Figure 9) Standardization to a definite testing rate may change this value.

5. The yield stress for a given shape can be estimated accurately from test results on coupons cut from flange and web if the weighted average according to respective areas is used. (Figure 10) This is of use where only small capacity testing machines are available.

6. The elimination of compression testing of coupons is warranted in the case of rolled structural steel shapes. Tension coupons accomplish the same purpose with greater ease.\(^9\)}
VI. ACKNOWLEDGMENTS

This report presents a part of the theoretical and experimental studies made on a research program on the influence of residual stress on column strength which is currently being carried out at the Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania, of which William J. Eney is Director.

The Pennsylvania Department of Highways and the Bureau of Public Roads, the National Science Foundation and the Column Research Council jointly sponsor the research program.

The authors are greatly indebted to Dr. Lynn S. Beedle for his advice and suggestions. Professor A. M. Freudenthal of Columbia University suggested the plotting of the results as a cumulative function, on probability paper.

Many test specimens were prepared in the machine shop of Fritz Engineering Laboratory. Sincere appreciation is expressed to Mr. Kenneth R. Harpel, Foreman, and to the Laboratory Staff.

Messrs. George Lee, Robert Wagner, Diethelm Feder and Theodore Galambos assisted in the tests and in the preparation of the data. Their cooperation is gratefully acknowledged.
VII. APPENDIX

1. Nomenclature
2. Tables
3. Figures
1. Nomenclature

\( b \) Flange width

\( d \) Depth of WF section between centerlines of flanges

\( E \) Young's modulus of elasticity

\( s \) Standard deviation, a statistic measure of the scattering of observations

\( t \) Flange thickness

\( w \) Web thickness

\( \alpha \) Ratio of area of flanges to area of web

\( \varepsilon \) Strain (in/in)

\( \dot{\varepsilon} \) Strain rate in the plastic range (in/in/sec)

\( \sigma \) Stress

\( \sigma_y \) Yield stress

\( \sigma_{ymill} \) Yield stress of mill tension coupon. (as obtained from the mill report)

\( \sigma_{ys} \) Yield stress at zero strain rate: "static" yield stress

\( \sigma_{yd} \) Yield stress at a particular strain rate other than the zero strain rate: "dynamic" yield stress

\( \sigma_{uy} \) Upper yield point

\( \sigma_{ly} \) Lower yield point

\( \sigma_p \) Proportional Limit
2. Tables
TABLE I

General Experimental and Analytical Data for Material of Company "A"

NOTE: All values of stress are in kip/inch^2 units; all values of areas are in square inches

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<td></td>
</tr>
<tr>
<td>9b</td>
<td>$\sigma_{ys}/\sigma_{yd}$ (Mill)</td>
<td>A</td>
<td>20</td>
<td>76.4%</td>
<td>6.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sigma_{ys}/\sigma_{yd}$ Sim. Mill</td>
<td>A</td>
<td>22</td>
<td>81.2%</td>
<td>4.9%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>13</td>
<td>83.8%</td>
<td>4.3%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE IV
Summary of Coupon Test Results
8 WF 31
Compression Coupons (as-delivered)
(Average Values in ksi)

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sigma_{uy}$</th>
<th>$\sigma_{yd}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA1 Flange</td>
<td>38.4 (8)*</td>
<td>38.0 (9)*</td>
</tr>
<tr>
<td>IA1 Web</td>
<td>42.7 (2)</td>
<td>42.7 (2)</td>
</tr>
<tr>
<td>Ave. -2**</td>
<td>39.4 (10)</td>
<td>39.2 (11)</td>
</tr>
<tr>
<td>IA2 Flange</td>
<td>39.8 (3)</td>
<td>39.8 (3)</td>
</tr>
<tr>
<td>IB2 Flange</td>
<td>39.6 (6)</td>
<td>39.6 (6)</td>
</tr>
<tr>
<td>IB2 Web</td>
<td>43.6 (2)</td>
<td>43.3 (2)</td>
</tr>
<tr>
<td>Ave. -2</td>
<td>40.6 (8)</td>
<td>40.5 (8)</td>
</tr>
<tr>
<td>Total Ave. -2</td>
<td>40.0 (21)</td>
<td>39.8 (22)</td>
</tr>
</tbody>
</table>

Tension Coupons (as-delivered)
(Average Values in ksi)

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sigma_{uy}$</th>
<th>$\sigma_{yd}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA1 Flange</td>
<td>42.8 (3)</td>
<td>39.1 (3)</td>
</tr>
<tr>
<td>IA1 Web</td>
<td>44.8 (1)</td>
<td>43.3 (1)</td>
</tr>
<tr>
<td>Ave. -2</td>
<td>43.3 (4)</td>
<td>40.1 (4)</td>
</tr>
<tr>
<td>IA2 Flange</td>
<td>39.1 (9)</td>
<td>37.4 (6)</td>
</tr>
<tr>
<td>IA2 Web</td>
<td>42.6 (2)</td>
<td>35.7 (2)</td>
</tr>
<tr>
<td>Ave. -2</td>
<td>39.9 (11)</td>
<td>37.0 (8)</td>
</tr>
<tr>
<td>IB2 Flange</td>
<td>43.5 (3)</td>
<td>40.5 (3)</td>
</tr>
<tr>
<td>IB2 Web</td>
<td>46.6 (1)</td>
<td>44.2 (1)</td>
</tr>
<tr>
<td>Ave. -2</td>
<td>44.2 (4)</td>
<td>41.4 (4)</td>
</tr>
<tr>
<td>Total Ave. -2</td>
<td>41.6 (19)</td>
<td>38.9 (16)</td>
</tr>
</tbody>
</table>

Mill Report Tension Test (as-delivered)

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{uy}$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Web</td>
<td>---</td>
<td>43.3</td>
</tr>
</tbody>
</table>

* Number of specimens
** Weighted average in proportion of flange and web areas
3. Figures
Plastic Range Strain Hardening

Unit Strain

\[ \frac{d \sigma}{d \varepsilon} = E_{st} \]

Elastic Range

Plastic Range

Strain Hardening Range

\[ E = \frac{d \sigma}{d \varepsilon} \]

\[ \sigma_p \]

\[ \sigma_y \]

\[ \sigma_{uy} \]

\[ \sigma \]

Graphical Definition of Terms

Figure 1
STRESS-STRAIN CURVE
Figure 2(a) STUB COLUMN TEST

Figure 2(b) STRESS-STRAIN CURVES FROM STUB COLUMNS
Figure 3
SHOWING POSITION OF TENSION COUPONS CUT FROM FLANGE AND WEB OF A WF SHAPE

Figure 4
DIMENSIONS OF TENSION COUPON
(Shaped to ASTM Specification18)
STUB COLUMN TEST RESULTS

The Static Level Of Yield Stress, $\sigma_{ys}$

Histograms

Material "A"
20 Specimens

Material "B"
14 Specimens

Average
34 Specimens

Figure 5(a)
Figure 5(b)

STUB COLUMN TEST RESULTS

The Static Level Of Yield Stress, $\sigma_{ys}$

Normal Distribution Probability Curves

Material "A" 20 Specimens, Mean = 33.1
Material "B" 14 Specimens, Mean = 35.0
Average: 34 Specimens, Mean = 33.9
Material "A"
22 Specimens

Material "B"
13 Specimens

Average
35 Specimens

Figure 6(a)
The Static Level Of Yield Stress, $\sigma_{ys}$
As Determined From "Simulated" Mill Tests
(Weighted Mean Of Flange And Web Coupons)
Figure 6(b)

The Static Level Of Yield Stress, $\sigma_{ys}$, As Determined From "Simulated" Mill Tests (Weighted Mean Of Flange And Web Coupons) Normal Distribution Probability Curves
Figure 7(a)

MILL TESTS (Web Coupons)
The Dynamic Level Of Yield Stress, $\sigma_{yd}$

Histograms
Material "A": 24 Specimens, Mean = 42.8
Material "B": 14 Specimens, Mean = 41.5
Average: 38 Specimens, Mean = 42.3

Figure 7(b)
MILL TESTS (Web Coupons)
The Dynamic Level of Yield Stress, σy mill
Normal Distribution Probability Curves
Figure 8(a)
"SIMULATED" MILL TESTS (Web Coupons)
The Dynamic Level Of Yield Stress, \( \sigma_{yd} \)

- Material "A"
  24 Specimens
  \( \sigma_{yd} \)

- Material "B"
  13 Specimens
  \( \sigma_{yd} \)

- Average
  37 Specimens
  \( \sigma_{yd} \)
Figure 8(b)

"SIMULATED" MILL TESTS (Web Coupons)

The Dynamic Level of Yield Stress, $\sigma_{yd}$

Normal Distribution Probability Curves

Material "A": 24 Specimens
Mean = 40.1

Material "B": 13 Specimens
Mean = 41.4

Average: 37 Specimens
Mean = 40.6
(a) Mill Test: $\frac{\sigma_{ys}}{\sigma_{y_{mill}}}$, with $\sigma_{ys}$ from weighted coupon average.

(b) Simulated Mill Tests, $\frac{\sigma_{ys}}{\sigma_{y_d}}$

Figure 9(a)
RATIOS OF STATIC YIELD STRESS TO MILL YIELD STRESS
Histograms
Figure 9(b)
RATIOS OF STATIC YIELD STRESS TO MILL YIELD STRESS
Normal Distribution Probability Curves
Figure 10
RATIO OF STATIC YIELD STRESS, STUB COLUMN TO WEIGHT COUPONS

Histogram

Material "A"
18 Specimens

Frequency %

99.1

\[ \frac{\sigma_{ys \text{ Stub Column}}}{\sigma_{ys \text{ Weighted Coupon}}} \]
Time marks 1.0 sec. interval

Crosshead speed: 0.2 in/min. gives $\varepsilon = 370 \text{ micro in.}$ in sec.
computed on the basis of 9" reduced length of coupon

Figure 11
LOAD-STRAIN AND STRAIN-RATE DIAGRAM
Figure 12
MEASUREMENT FOR STRAIN RATE
Test Set-Up Showing Stress-Strain Recorder,
Recording Directly From Tension Coupon,
And Timing Device Which Includes Clock At Top
And Solenoid With Pen At Side
NOTE: All strain-rates have been determined on the basis of the adjusted length of the reduced portion of the coupon.

Coupons From:
- bars 6
- flange 8WF24
- plates

--- suggested limits

Figure 13

$\frac{\sigma_{yd}}{\sigma_{ys}}$ AS A FUNCTION OF THE STRAIN RATE

The vertical broken line at $\dot{\varepsilon}=1040$ should be identified as: "Standard" Strain Rate ASTM Maximum
Confirmation of Resistance
Of Static Level
See Section III.6
Figure 15
CROSS-SECTION TEST 8WF24

\[ \sigma \text{ [ksi]} ]

\[ \frac{\sigma_{yd}}{\sigma_{ys}} = 1.065 \]

strain-rate \( \dot{\varepsilon} \approx 30 \text{ micro in.} \text{ in sec.} \)

\[ \varepsilon [10^{-3}] \]
Strain Rate = 235 \frac{\text{micro-inch}}{\text{inch-sec.}} \quad \text{Strain Rate} = 98 \frac{\text{micro-inch}}{\text{inch-sec.}}

\sigma_{yd} = 35.4

\sigma_{yd} = 34.2

\sigma_{ys} = 31.2

Figure 16
STRESS-STRAIN CURVE FOR FLAT PLATE TENSION COUPON, SHOWING EFFECTS OF DIFFERENT STRAIN RATES
Figure 17  YIELD POINT AND SECTION SIZE
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