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LEHIGH UNIVERSITY INSTITUTE OF RESEARCH

due

MATERIAL PROPERTIES OF STEEL

by

Lambert Tall

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Fritz Laboratory Report No. 220A.28

This study has been carried out as a Structural Research problem, Course No. CE 404, being part fulfillment of the requirements for the degree of Master of Science.

This report is submitted to Dr. R.L. Ketter, Assistant Professor of Civil Engineering.

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I. SYNOPSIS

This report is the summary of certain aspects of the work on Project 220A, this phase of the project being concerned with the relationship between material properties and the strength of columns.

The overall objectives of the project were the determination of the behavior of columns containing residual stresses, and the magnitude and distribution of these stresses, and the development of methods of predicting the influence of residual stresses on column strength. As a necessary foundation for the complete study, the program included a determination of the basic yield stress level of the material of which steel columns would be fabricated. This report is mainly concerned with this basic yield strength.

The determination of the yield stress level and associated properties, will give a better understanding of the behavior of mild structural steel as defined under ASTM Designation A7. The results of this investigation will define the yield stress level and provide further information, enabling a realistic meaning to be given to the factor of safety used with steel design today.

Further, an exact definition and evaluation of the yield strength is a necessity at the very crux of plastic design[*1]; a problem hitherto of only academic interest. Indeed,

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[*] See References. No. 1

to use this method effectively, it would be a retrogression to apply factors of safety to a nominal undefined value of the yield strength.

Methods and correlations used will be shown, so that the extent and trends in the variation of the strength of steel will be apparent. The strength of steel will be considered with both its elastic and plastic properties.

Generally, however, the results will indicate, particularly in the case of residual stress prediction, that a far greater sample of specimens will have to be tested before authoratative conclusions may be drawn.

II. THE YIELD STRESS

(a) INTRODUCTION

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

It is the purpose of this chapter to consider the factors that have an influence on the yield stress, and to show how a prediction of this value is possible from the mill reports. 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 included where required.

(b) DESCRIPTION

1. Yield Stress - definition

The following terms are relevant in describing the yield strength of a steel coupon, see Figure 1.

- The upper yield point, σ_{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'.)
- The lower yield point, $\sigma_{\ell y}$, the low level of yield stress immediately following σ_{uy}.

- The yield stress level, σ_y, the stress during actual yielding, 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, σ_p, the greatest stress which a material is capable of developing without any deviation from proportionality of stress to strain (ASTM definition.) σ_p is very closely equal to σ_y for a coupon, particularly if the coupon is annealed. This is not the case for the section as a whole.
- Also, where no definite yield stress level may exist, as is the case occasionally, an offset is used to define a value for comparative purposes.

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

<u>This paper will define the yield strength as the yield stress at the static level</u>, that is, the value for σ_y when the strain rate is zero. (Strain rate will be discussed at length in section C-6.) In the past, 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 testing coupons to record the yield as the reading indicated by the free 'follower' pointer on the load indicator dial, the actual load having dropped off somewhat. Use of the static level is perfectly logical, since most structural loads can be considered as primarily static.

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. The results obtained provided an important basis for correlation of the yield strength with test coupons, and mill test data.

The stress-strain curve obtained from such a stub column test is of immense use in column strength predictions. As shown in Reference 2, the overall stress-strain picture enables use of the tangent modulus concept. Further, other relevant data is obtained as shown below, which may be interpreted immediately for the full cross section:

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

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

3. Tension Coupon Tests

These tests covered a wider range of shapes than did the stub column tests, due to both their ease of testing and economy.

The coupons were cut from the web and flange as shown in Figure 2, and then shaped to ASTM standards, (see Figure 3). 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 generally just reached into the strain hardening range.

The tests were conducted so that the static level of yield stress was also obtained. The speed of testing used was that recommended in Fritz Laboratory publication No. 220A.15, being chosen so that the mill test of a steel manufacturer could be simulated. (Crosshead speed shall not exceed 1/16 in. per minute per inch of gage length.)

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 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 in testing has been given considerable attention, and data is presented that will enable predictions for the static yield strength knowing the speed of testing. Although it has been known in the past that the strain rate has an effect, very little data was available and the subject was generally ignored.

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 was supplied by Company "A" and by Company "B", for both tension coupon and stub column tests. The results are shown both separately and combined, for in some cases it was felt that combination of the data obtained from the different steels 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.

(c) RESULTS

1. The Static Level of Yield Stress

Refer to Section C-5 on strain rate.

(a) Stub Column Tests

From Tables II, III, and Figure 4, it is seen that:

material "A" σ_{ys}= 33.1 ksi mean value (20 specimens)
"B" σ_{ys}= 35.0 ksi mean value (13 specimens)
Average σ_{ys}= 33.9 ksi mean value (33 specimens)

(b) Simulated Mill Tests

These are the weighted mean of the individual coupon tests. The individual data is recorded in Tables 1 and 2, and in Figure 5.

material "A" σ_{ys}= 32.8 ksi mean value (22 specimens)
"B" σ_{ys}= 34.6 ksi mean value (13 specimens)
Average σ_{ys}= 33.5 ksi mean value (35 specimens)

2. The "Mill Reports" for Yield Strength

The mill report for the yield strength of steel is based on a tension test on 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 approximately the same as those advised in Fritz Laboratory publication No. 220A.15. The results then give the yield strength for a "dynamic" level σ_{yd}, where dynamic is used as compared to static. It will be further defined later.

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

(a) Mill Tests, Figure 6.

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

NOTE[4]: 3000 material "B" mill tests gave: σ_{yd}= 44.1 ksi

(b) "Simulated" Mill Tests, Figure 7.

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

3. Comparison of Mill Test Results with the σ_{ys}

To allow a prediction to be made of the static level of yield stress σ_{ys}, from the mill test reports, a comparison of these results was made as a ratio of the former to the latter, (that is, σ_{ys}/σ_{y} mill tests.) Tabulation of the results is shown in Tables II and III, with the distribution shown in Figure 8. Except for some material "B" results, as shown in Table III, the yield stress is taken as the weighted static value from the coupon tests, it being shown later that such a value is completely equivalent to that obtained from a stub column test.

(a) Comparison Using Mill Results, σ_{ys}/σ_{y} mill, Figure 8

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 8

These results have very little application and are recorded only for comparison. Assuming that the materials are equal, they do indicate however that company "A" appears to run its mill tests at a higher testing speed than company "B".

material "A" ratio = 81% mean value (22 specimens)
"B" ratio = 84% mean value (13 specimens)
Average ratio = 82% mean value (35 specimens)

4. Evaluation of σ_{ys}, Static Level of Yield Stress

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

This set of comparisons was made to see 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.

Ratio: $\frac{\sigma_{ys} \text{ stub column}}{\sigma_{ys} \text{ weighted coupons}}$, Figure 9.

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)

5. 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[5]. Generally speaking the faster the steel is loaded, the higher the yield point tends to become until the limit, when the ultimate load is reached without yielding.

It is seen therefore that the testing speed of a coupon is of the utmost importance as a particular type of steel could have an infinite number of values for the yield strength. Actually, this is exactly what does happen today! Although the ASTM have tentative specifications limiting the testing rate, it would appear that some investigators use lower rates than others since 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 manufacturing methods. It should be noted however, that 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 topic was investigated at length by Marshman[5], and the reader is referred to this publication for complete details. None-the-less, this chapter will briefly describe the problems of strain rate and will indicate some of the results obtained.

The greatest practical difficulty associated with strain rate is its measurement. Although this is not difficult if specially measured, it is not possible to use an indicated free moving cross-head speed as the strain rate for any particular machine. This is particularly true with an hydraulic testing machine. This is due to the fact that, during testing, the machine itself is deforming so that an adjustment must be made to the indicated free-running cross head speed to obtain the actual rate of straining. It is in the elastic portion of the loading that this effect has its greatest influence, for as the load increases 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 till the climax is reached at the yield point. At this instant the specimen starts to yield, the load is constant and no further deformation of the machine takes place, all the movement being 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, for practical purposes now constant load, the specimen is "straining" at the indicated free-running speed. 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 10. It should be noted that the curve is the result of a number of tests of plate specimens from one manufacturer (Company "B"). All tests were carried out on the same mechanical testing machine.

The dynamic yield stress, σ_{yd}, is defined as the yield stress at a particular strain rate other than the zero strain rate. The static yield stress on the other hand is defined as the yield stress at the zero strain rate.

Tests[5] have shown that the static yield level may be determined without actually conducting the experiment in its entirety at a zero strain rate. 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 particularly, 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 11, a typical stress-strain curve from the series of coupon tests run on the screw-type mechanical testing machine. This property has not been proved conclusively on a large number of tests, but it is felt that the series conducted[5] may be regarded as indicative of the behavior to be expected due to their excellent correlation.

Figure 12 indicates a further observation, bearing out the foregoing conclusions; namely, that in the plastic yield range the σ_{yd} depends on the testing speed, whereas, the σ_{ys}, as obtained by stopping the movement of the cross-head, is relatively constant.

6. 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 give results that are almost identical[6]. 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 give the same indications.

Quoting from the above referred reference:

> "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 from the weighted mean of the tension coupons as shown in Figure 9.

7. 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 the physical properties. Previous investigations[7] have shown that this effect is negligible in coupon testing, but recent tests indicated no conclusions in either direction.

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

(a) σ_{ys} Static Yield Stress, refer to Figure 5.

From simulated mill coupon tests, weighted means:

material "A" mean = 32.8 ksi (22 specimens)

range 29-37 ksi: 18WF105, 16WF 88, 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

NOTE: 14WF426 had no apparent yield stress level.

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 above summary should be considered with Tables II and III. It is then seen that in general, as would be expected, the heavier sections have a lower σ_{ys}, while lighter sections have a higher σ_{ys} than the mean.

Since the flanges are the controlling factor in column strength both for buckling and direct loads, the b/t and α (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 = approx. 10 or less, have $\sigma_{ys} < 28$ ksi
b/t = approx. 18 or more, have $\sigma_{ys} > 37$ ksi

shapes with α < approx. 2.5 $28 > \sigma_{ys}$ or $\sigma_{ys} > 37$ ksi

The stub column values for σ_{ys} were also considered, and 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) σ_{yd}, Dynamic Yield Stress, Figure 6

mill test - web coupon results

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

(c) $\sigma_{ult,\ actual}$ The Ultimate Stress, Based on Reduced Area.

Refer to Tables II, III and to Figure 20. (from simulated mill coupon tests, weighted means.)

35 specimens were considered and to obtain a more realistic picture the ultimate stress was based on the reduced area at failure. From the histogram, it is seen that the spread of results is extremely narrow with only the following shapes not in the range 120-150 ksi.

material "A": 18WF105 = 110.5 ksi
14WF228 = 187.5
12WF 53 = 114.5
material "B": 14WF426 = 106.5 ksi
14WF142 = 154.3
14WF 61 = 157.5

These results appear to be random displacements from the mean, rather than due to any physical properties of the cross-sectional shape.

III. RESIDUAL STRESSES

(a) INTRODUCTION AND DESCRIPTION

The study of residual stresses has been extremely intensified in the last five years. This is mainly due to an increasing appreciation of their effect on the buckling strengh of columns. These studies have brought to light many factors that have explained past failures of correlation between experimental and predicted values for column strengths[9]. While residual stresses have also been studied in built up columns, this paper will only be concerned with the structural rolled shapes of A-7 steel.

Residual stresses are stresses that remain in a member after it has been manufactured. These, in the main, are due to uneven cooling of the member after hot rolling. Residual stresses are also formed by various fabrication methods, such as welding and cold bending. As a general rule however, the effect of these types of stresses is less pronounced.

The measurement of residual stresses of the type in question is best accomplished by the "sectioning" method, whereby the member is measured before and after cutting into longitudinal strips. The cutting releases the stresses enabling the sectioned strips to deform freely according to the relaxation of their internal forces. This method is explained at length in Reference 6.

A typical residual stress distribution diagram for a WF shape is shown in Figure 13 where the terminology is also explained. Generally, these distributions may be approximated quite well by straight line segments. From a knowledge of this distribution it is possible to predict the average $\sigma-\epsilon$ curve for the full cross section and the procedure is described in Reference 6.

It has been shown in these previous studies that an actual stub column test gives a more accurate and far simpler means of obtaining the average $\sigma-\varepsilon$ curve than the lengthy calculations that are required starting from a measured residual stress distribution. The importance of this average curve is that the apparent tangent modulus values obtained can be related to the carrying capacity of the member and thus column strengths can be predicted. It should be pointed out however, that while the "knee" of the average $\sigma-\varepsilon$ curve shows the effect of the residual stress distribution, it does not enable the specific distribution to be determined except for σ_{rc}. σ_{rc} is generally the largest inherent residual stress and defines the proportional limit.

(b) RESULTS

1. Residual Stress Distribution in WF Shapes

The results of the previous investigations are summarized in Table V, while Table VI gives the individual detailed results. This will give an indication of the distribution of residual stress in WF shapes. In all cases the method of "sectioning" was used.

2. Residual Stress from Stub Column Tests

The limit of proportionality of the stress strain curve defines the magnitude of the residual stress, σ_{rc}, since in all cases that have thus far been measured the flange residual stresses have been higher than those in the web.

$$(\sigma_{rc} = \sigma_y - \sigma_p)$$

To take account of local high residual stresses and to obtain by interpolation a basic value for σ_{rc} presumed to exist when these are not present, a $\sigma-\epsilon$ curve of the type shown in Figure 14 it was modified in the following manner: The portion of the curve above the proportional limit, although with a very slight curvature, may be considered as a straight line. The tangent point of this line with the "knee" of the curve is then taken as a pseudo-porportional limit, thus defining what in this report will be regarded as a basic value for σ_{rc}.

The results following and shown in Figure 15 are of two types, the actual residual stress average and the average modified as explained above, where necessary.

To show whether σ_r, the maximum residual stress as determined from a stub column test, is a function of the yield stress or not, the ratio σ_r/σ_{ys} has also been considered with σ_r both modified and unmodified. The results are shown in Figure 16.

(a) σ_r from Stub Column. Figure 15.

material "A" σ_r = 13.5 ksi mean value (19 specimens)
$\sigma_{r_{mod}}$ = 10.5 ksi mean value (19 specimens)

material "B" σ_r = 14.6 ksi mean value (7 specimens)
$\sigma_{r_{mod}}$ = 12.6 ksi mean value (7 specimens)

average σ_r = 13.8 ksi mean value (26 specimens)
$\sigma_{r_{mod}}$ = 11.1 ksi mean value (26 specimens)

(b) σ_r/σ_{ys} from Stub Column. Figure 16.

material "A" σ_r/σ_{ys} = 41.1% mean value (19 specimens)
$\sigma_r/\sigma_{ys_{mod}}$ = 32.9% mean value (19 specimens)

material "B" σ_r/σ_{ys} = 41.5% mean value (7 specimens)
$\sigma_r/\sigma_{ys_{mod}}$ = 35.6% mean value (7 specimens)

average σ_r/σ_{ys} = 41.2% mean value (26 specimens)
$\sigma_r/\sigma_{ys_{mod}}$ = 33.6% mean value (26 specimens)

3. Residual Stress Prediction

Attempts have been made in the past[9] to correlate the residual stresses of a shape with its physical properties, such as b, d, t, w. This has also been attempted in the present investigation. Unfortunately, the only statement that can be made regarding these studies is that no definite tendencies seem to exist.

Probably the most intricate and complete endeavor at this prediction has been made by A. Huber[9]. It is felt, however, that his method offers no better accuracy than obtained by merely estimating values from the tables of results already at hand.

For these reasons then, the correlation attempted by the author has not been presented.

IV. OTHER MATERIAL PROPERTIES

(a) INTRODUCTION AND DESCRIPTION

The determination of the yield strength of a material is accompanied usually by the finding of the elastic modulus, and if the test be on a coupon, the ultimate strength and strain hardening modulus are also easily obtained.

This chapter seeks to present additional data on the following properties:

1. Young's modulus, E.
2. Strain hardening modulus, E_{st}.
3. Ultimate strength of a tension coupon.

The two moduli, E and E_{st}, may be defined as the constant ratio of stress to strain in the elastic and at the on-set of the strain hardening ranges.

The procedure of testing with tension coupons has been described above. The results from these tests have been enumerated, and the Young's Modulus will be compared also with the values obtained from stub column tests.

(b) RESULTS

1. Young's Modulus, E.

Tables II and III show the actual experimental values for E from both coupon and stub column. Individual coupon values are shown as well as a combined value for the cross section, weighting the average according to the respective areas of flange and web. To check this method, the results were then compared to those obtained from the full cross section by stub column tests.

(a) E, Weighted Coupon Results, Figure 17.

It is noted that the flange has the lower value for E, as was the case with the other properties obtained from the stress-strain curve.

material "A" $E = 31.2 \times 10^3$ ksi mean value (21 specimens)
material "B" $E = 31.1 \times 10^3$ ksi mean value (11 specimens)
average $E = 31.2 \times 10^3$ ksi mean value (32 specimens)

(b) E, Stub Column Results, Figure 17.

material "A" $E = 31.5 \times 10^3$ ksi mean value (19 specimens)
material "B" $E = 30.4 \times 10^3$ ksi mean value (7 specimens)
average $E = 31.2 \times 10^3$ ksi mean value (26 specimens)

2. Comparison of Coupon and Stub Column Results for E

To check the assumption for weighting the average for E with the coupon tests as was done before with the other material properties, the ratio for E for each particular section, obtained by the above two methods, was compared. See Figure 18.

material "A" $\frac{E_{coupon}}{E_{stub\ column}}$ = 99.7% mean value (16 specimens)
material "B" " =100.7% mean value (6 specimens)
average " =100.0% mean value (22 specimens)

3. Strain Hardening Modulus, E_{st}

At the time of publication the reduction of results for this property was incomplete and cannot be presented here.

4. The Ultimate Strength of a Tension Coupon

Similarly to the method employed with the static yield stress, the ultimate nominal stress in tension for a wide flange shape was determined by the weighted average of the individual coupon tests for web and flange. Further, to account for the reduction in area the ultimate strength is also shown based on the percentage reduction recorded. The individual percentage reductions have been combined according to the weighted average.

It is pointed out that use of this method with coupon ultimate strength is probably extrapolating too far as no account is made of the changed crystal structure due to the "necking". The results should be indicative however, since the values for percentage reduction generally do not differ greatly for flange or web from the same shape.

(a) ° σ_{ult} from Weighted Coupons of "simulated" Tests, Figure 19.

material "A" σ_{ult} = 62.9 ksi mean value (23 specimens)
material "B" σ_{ult} = 65.3 ksi mean value (12 specimens)
average σ_{ult} = 63.7 ksi mean value (35 specimens)

(b) ° $\sigma_{ult_{mod}}$ from Weighted Coupons, Based on Ultimate Cross-Sectional Area, Figure 20.

material "A" $\sigma_{ult_{mod}}$ = 134.9 ksi mean value (23 specimens)
material "B" $\sigma_{ult_{mod}}$ = 135.0 ksi mean value (12 specimens)
average $\sigma_{ult_{mod}}$ = 134.9 ksi mean value (35 specimens)

(c) ° σ_{ult} from Mill Tests (web), Figure 21.

material "A" σ_{ult} = 66.3 ksi mean value (24 specimens)
material "B" σ_{ult} = 68.2 ksi mean value (7 specimens)
average σ_{ult} = 67.4 ksi mean value (31 specimens)

(d) ° σ_{ult} from Silumated Mill Tests (web coupons), Figure 22.

material "A" σ_{ult} = 63.5 ksi mean value (24 specimens)
material "B" σ_{ult} = 65.0 ksi mean value (13 specimens)
average σ_{ult} = 64.0 ksi mean value (37 specimens)

(e) Percentage Reduction in Area, Figure 23.

1. Web material "A" 49.6% (24 specimens)
material "B" 50.8% (14 specimens)
average 50.1% (38 specimens)

(continued)

2. Flange	material "A"	54.0%	(24 specimens)
	material "B"	51.6%	(14 specimens)
	average	53.1%	(38 specimens)
3. weighted mean	material "A"	53.3%	(24 specimens)
	material "B"	51.4%	(14 specimens)
	average	52.6%	(38 specimens)

Average failure is on 47.4% of original area.

5. Typical Stress Strain Curve

A typical stress strain curve has been drawn from the above results, being an average obtained from the stub column tests and other tests conducted. Figure 24.

V. CONCLUSIONS AND DISCUSSION

The following discussion embodies the conclusions and suggestions that follow from the results above.

1. The yield strength has many definitions. The static yield stress, σ_{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 come to an equilibrium position after a load increment, it is 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 cross head, and to guard against strain reversal.

   From the results (Figures 4,5, and Section C-1) the approximate value for σ_{ys} was 33.7 ksi. This was the overall average for stub column and simulated mill (weighted average) tests. Until more extensive tests show otherwise, this value is close enough to be taken as the usually accepted $\sigma_y = 33$ ksi.

   Although an attempt at a frequency curve, rather than a histogram, was made this statistical method of representation could not be carried to fruition. The method was not applicable on a number of counts, the number of results were too small to be a representative sample, the results were not dependent on chance alone but on many manufacturing factors. For instance, it would be expected the comparatively large sections give small values for σ_y, while small sections give larger values. The amount of cold work, rate of cooling, etc., undoubtedly played a major role in this situation.

2. Mill test results for the yield strength were approximately 27% higher than the true static level, due probably to two causes:
   a. these are tension tests run on coupons cut from the web, which being rolled thinner than the flange give about a 4-7% higher yield level than the flange.
   b. the yield strength depends directly on the strain rate as shown in Figure 10. Even with apparently small strain rates approaching zero, σ_{yd} can be 5% greater than σ_{ys}, whereas at normal testing speeds, 13-18% is a better figure.

The strain rate has an obvious and sensitive effect. Therefore, unless it is specified for testing the correlation of results of different tests is impossible. Indeed, in this series of tests conducted on steel from the same lot, the simulated mill (Fritz Laboratory) tests produced σ_{yd} approximately 5% lower than did the mill tests. The former used the recommended speed of the ASTM A6-54T (and A370-54T) while the testing speed of the latter is not known although it should be the same.

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 8 and Section C-3 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, σ_{ys} is from weighted coupons.) This again brings up the question of a standard strain rate, and the good agreement of the simulated mill results above, (similar strain rate results from steel of different manufacturers) would bear out the premise. It is extremely difficult to draw definite conclusions from these figures above, particularly as previous investigations[4] have obtained 85%± 5% as the ratio of $\frac{\sigma_{ys}}{\sigma_{yd}}$.

From the above, it is suggested that 80%± 5% is a probable value for $\frac{\sigma_{ys}}{\sigma_{ymill}}$.

3. The procedure in the previous paragraph was for the weighted tension coupons but the same results would have shown had σ_{ys} from stub column tests been used. Figure 9 and Section C-4 show that almost perfect correlation exists for σ_{ys} between stub column and weighted coupons.

Another result of this study is that the full cross section strength 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, σ_{ys} and E are the only properties that such coupon tests will supply, the important σ_p and "knee" of the $\sigma-\epsilon$ curve (showing effect of residual stresses) for the full cross section cannot be estimated.

4. The problem of strain rate, and its effect on the yield stress as shown above can only be overcome with substantial testing 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, within reasonable limits, the basis for such a series of tests should be on the free-running speed of the cross head. It is expected that the outcome of such tests will show a similarity in the ($\frac{\sigma_{yd}}{\sigma_{ys}}$ versus strain rate) curves for different types of testing machine and steels. This has been indicated from the reasonable correlation between Marshman[5] and Romanelli[5], the former testing on a screw-type mechanical machine and the latter on a hydraulic machine. Such tests would indicate whether the difference for σ_{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 range. This effect, however, seems to be of little practical interest. To check this elastic effect of machine

and specimen in the plastic range, mechanical strain gages would be attached over the full length of the specimen to measure the actual strain rate and to compare them with the "free-running" speed.

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

5. It was shown that compression and tension coupons give almost identical results. The difficult compression coupon test can therefore be eliminated in all but confirmatory cases.

6. Generally speaking heavier sections have a lower σ_y and lighter sections a higher value. Similar general statements were made for b/t and α ratios. The small sample of results, however, precludes any definite conclusions.

7. From the stub column tests conducted, the indicated value for σ_r is 13 ksi. This is the mean of the maximum compressive residual stresses in the cross section and in general occurred at the flange tip. Further, this value is the complement of the proportional limit with respect to the yield stress, indicating that the average value for proportional limit is approximately 20 ksi.

The above value is a realistic estimation deduced from Figure 15 where the "modified" values have also been taken into slight consideration. Attention is drawn to Table V where the values 12.3 and 7.7 ksi (compression) are average values for WF shapes of $d/b \leq 1.5$ and > 1.5 respectively.

Since the histograms for the ratio $\frac{\sigma_r}{\sigma_{ys}}$ have become much wider in distribution, rather than narrower, with respect to the σ_r histograms; it is concluded that σ_r is not a function of the yield stress. This has tended to be confirmed by recent pilot tests on low alloy high strength steel where σ_r was found to be of the same order of magnitude as was measured in A-7 steel.

8. The prediction of the residual stress distribution based on mathematical relationships between the cross sectional physical properties is not warranted until further and more complete test results are at hand. Adequate estimation may be obtained from tabulated results already available such as Tables V and VI of this report.

9. The Young's modulus was found to be 31.2×10^3 ksi, the overall average value obtained from all coupon and stub column tests conducted in this series.

   As with the yield stress, an excellent estimation for the Young's modulus of a full cross sectional shape may be obtained from the weighted average of the coupon values.

   No effects of size on the Young's modulus was noted, although the number of specimens was too small for any definite conclusions.

10. The ultimate strength of tension coupons, Section IV-b-4, Figures 19,21,22 lies within very definite bounds with an average of 64-67 ksi. (This is within the limits 60-72 ksi specified by ASTM A7-55T). These measurements are based on the initial cross sectional area. It should be noted that

the simulated mill tests gave somewhat lower results than the mill tests. However, this small difference was probably due to the slower strain rate after the yield point of the simulated mill tests.

The ultimate strength based on ultimate cross section is likewise within definite bounds with an average of approximately 135 ksi as shown in Figure 20.

The percentage reduction in area although with a slightly wider range, Figure 23, is also reaonably consistent. A difference of 5% between web and flange values was noted suggesting that thickness of rolled section could have an effect. Generally taking a weighted average for all specimens the percentage reduction in area is approximately 53% ± 5%.

VI. SUGGESTIONS

Continuing from the previous chapter on conclusions and discussions with respect to the limited number of tests conducted, the following suggestions become relevant:

1. This series of tests indicates the following probable values for the material properties of the full cross section of a WF shape.

$$\sigma_{ys} = 33 \text{ ksi}$$
$$\sigma_{rc} = 13 \text{ ksi}$$
$$\sigma_{p} = 20 \text{ ksi}$$
$$E = 31\text{x}10^{3} \text{ ksi}$$

$$\left.\begin{array}{ll} \text{on original area } \sigma_{ult} & = 64 \text{ ksi} \\ \text{on reduced area } \sigma_{ult} & = 135 \text{ ksi} \\ \text{percentage reduction in area} & = 53\% \end{array}\right\} \text{coupon tests}$$

2. The yield stress should be defined by the "static" yield stress for reasons discussed in Chapter V.
3. The mill tests should be conducted at some generally accepted speed of testing to enable correlations to be made between different manufacturers and testing machines. This speed could, for convenience, be relatively fast and could be the maximum speed at present allowed by ASTM A6-54T (and A370-54T). The mill report, however, should indicate the speed of testing.
4. The effect of strain rate on the yield stress level has been discussed in Chapter 2-C-5. For definite findings, however, substantial and exhaustive tests on steel from

different manufacturers should be conducted on a wide variety and type of testing machine.

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

6. The yield stress and Young's modulus 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. This is of use where only small capacity testing machines are available.

7. 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.

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IX. 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
E_{st}	Strain hardening modulus
t	Flange thickness
w	Web thickness
α	Ratio of area of flanges to area of web
ε	Strain (in/in)
σ	Stress
σ_y	Yield stress
σ_{ymill}	Yield stress of mill tension coupon
σ_{ys}	Yield stress at zero strain rate: "static" yield stress
σ_{yd}	Yield stress at a particular strain rate other than the zero strain rate: "dynamic" yield stress
σ_{uy}	Upper yield point, see pg. 4
σ_{ly}	Lower yield point, see pg. 4
σ_p	Proportional limit
σ_r	Maximum residual stress determined from stub column test
σ_{rc}	Residual stress at flange edges
σ_{ro}	Residual stress at flange center
σ_{rw}	Residual stress at web center

2. Tables

TABLE I

Schedule of Tests

No.	Shape	Material "A"		Material "B"	
		coupon test (simulated) mill	stub column	coupon test (simulated) mill	stub column
8	18WF105	x	x	x	x
9	16WF 88	x	x	x	x
10	14WF426	x	x	x	
11	14WF320	x	x		
12	14WF228	x	x		
13	14WF142	x	x	x	x
14	14WF111	x	x	x	
15	14WF 78	x	x	x	x
16	14WF 61	x	x	x	x
17	14WF 53	x	x		
18	12WF190	x	x	x	x
19	12WF 92	x	x		
20	12WF 65	x	x		
21	12WF 53	x	x	x	x
22	12WF 50	x	x		
23	10WF 66	x	x	x	
24	10WF 39	x	x		
25	10WF 33	x	x		
26	8WF 67	x	x		
27	8WF 35	x	x		
28	8WF 31	x	x		
29	8WF 24	x	x		
30	6WF15.5	x	x	x	
31	5WF18.5	x	x	x	

TABLE II

General Experimental and Analytical Data for Material "A"

NOTE: All values of stress in kip/inch^2

No.	Shape	Area	Area Flanges	Area Web	$\alpha = \frac{\text{area flg.}}{\text{area web}}$	b/t	σ_{rt} stub column	σ_{rc} mod. stub column	σ_{ys} stub column	σ_{y} mill	σ_{ult} mill	σ_{ult} coupon	
												flange	web
8	18WF105	31.3	21.95	9.32	2.36	13.0	12.8	---	29.8	43.1	62.8	48.3	61.2
9	16WF88	25.5	17.92	7.55	2.37	15.1	18.6	3.9	31.4	42.3	63.9	62.9	63.1
10	14WF426	124.0	100.38	23.57	4.40	5.52	--	---	---	38.2	69.9	64.4	73.4
11	14WF320	93.5	69.88	23.57	2.97	8.0	--	---	---	38.5	65.1	61.7	59.7
12	14WF228	67.3	54.19	13.09	4.14	9.3	9.5	---	25.8	38.2	65.4	62.8	65.3
13	14WF142	41.9	33.11	8.79	3.77	14.7	12.0	---	30.7	37.1	64.2	65.6	68.3
14	14WF111	32.1	25.35	6.72	3.78	16.9	10.2	---	33.0	45.0	71.0	66.2	64.5
15	14WF 78	22.3	16.85	5.45	3.09	16.6	10.2	---	29.4	38.4	60.4	59.3	59.7
16	14WF 61	17.9	12.85	4.96	2.59	15.9	--	---	---	44.3	66.8	60.4	60.0
17	14WF 53	--	---	--	1.71	--	--	---	--	37.1	60.7	58.9	55.5
18	12WF190	55.3	43.66	11.61	3.76	7.37	12.1	---	24.6	34.1	68.6	63.7	61.6
19	12WF 92	27.0	20.97	6.00	3.50	14.3	19.8	10.4	34.4	45.7	74.0	69.3	69.5
20	12WF 65	18.7	14.24	4.14	3.44	20.6	14.6	---	32.6	44.3	67.6	62.8	61.4
21	12WF 53	15.7	11.76	3.87	3.03	--	13.3	---	35.0	44.9	67.8	61.3	63.5
22	12WF 50	14.3	10.13	4.14	2.45	13.0	16.5	---	32.9	42.2	67.5	65.9	64.7
23	10WF 66	19.3	15.21	4.02	3.80	13.6	11.2	---	33.2	46.8	68.3	63.6	63.9
24	10WF 39	11.1	8.11	2.89	2.80	15.8	--	---	37.2	41.9	62.7	60.9	62.0
25	10WF 33	9.8	7.12	2.60	2.74	18.0	11.1	---	32.4	52.0	74.8	60.6	61.1
26	8WF 67	19.3	15.04	4.20	3.59	9.18	8.9	---	26.4	33.5	60.2	59.7	57.1
27	8WF 35	10.5	8.23	2.24	3.68	16.2	15.9	---	35.9	48.3	64.3	63.2	64.7
28	8WF 31	9.37	7.24	2.07	3.50	18.5	6.6	---	36.1	44.4	64.5	64.4	65.0
29	8WF 24	7.00	5.16	1.79	2.88	16.7	24.4	10.4	39.4	47.4	69.2	65.2	70.3
30	6WF15.5	4.57	3.18	1.34	2.37	22.3	23.3	3.8	43.0	51.1	66.4	63.6	64.0
31	5WF18.5	5.31	4.21	1.05	4.18	12.0	6.4	---	38.7	48.8	65.6	63.1	64.4

TABLE II, Continued (a)

No.	Shape	σ_{ys} Coupon		σ_{yd} Coupon		σ_{ys} Weighted Coupon	σ_{yd} Weighted Coupon	$\frac{\sigma_{ys}}{\sigma_{yd}}$ %	$\frac{\sigma_{ys}}{\sigma_{ymill}}$ %	$\frac{\sigma_{ys}\text{ Stub Column}}{\sigma_{ys}\text{ Weighted Coupon}}$ %	$\frac{\sigma_{yd}(\text{Web})}{\sigma_{ymill}}$ %	$\frac{\sigma_{ys}\text{ Weighted Coupon}}{\sigma_{yd}(\text{Web})}$ %
		Flange	Web	Flange	Web							
8	18WF105	28.9	34.2	32.9	40.6	30.4	38.2	79.6	70.7	98.0	94.3	74.9
9	16WF 88	31.1	31.9	39.6	38.3	31.4	39.2	86.4	74.3	100.0	90.5	82.0
10	14WF426	--	30.4	--	34.1	--	--	--	--	---	89.3	--
11	14WF320	22.7	22.8	26.4	26.4	22.7	26.4	86.0	59.0	---	68.6	86.2
12	14WF228	--	29.6	--	35.2	--	--	--	--	---	92.2	--
13	14WF142	28.4	32.7	33.8	38.9	29.3	34.9	83.8	79.2	104.7	104.9	75.3
14	14WF111	32.5	33.2	38.9	39.4	32.7	39.0	83.8	72.7	101.0	87.5	83.0
15	14WF 78	28.8	30.4	35.4	33.6	29.2	35.0	83.4	76.2	100.6	87.5	86.8
16	14WF 61	30.3	31.4	36.0	35.7	30.6	35.9	85.2	69.0	---	80.5	85.8
17	14WF 53	29.6	29.6	40.1	36.7	29.6	--	--	79.7	---	98.7	80.6
18	12WF190	26.9	26.5	29.1	32.9	26.8	29.9	89.7	87.6	91.8	96.6	81.5
19	12WF 92	33.2	35.0	40.7	41.4	33.6	40.8	82.3	73.5	102.4	90.8	81.2
20	12WF 65	32.4	38.6	41.9	38.6	33.8	41.2	82.2	76.2	96.4	87.0	87.6
21	12WF 53	33.4	37.6	38.5	46.3	34.4	--	--	76.5	101.8	103.3	74.2
22	12WF 50	34.0	35.2	39.8	43.1	35.5	40.8	84.1	81.4	95.7	102.0	79.8
23	10WF 66	32.0	33.8	37.6	38.8	32.4	37.9	85.5	69.2	102.6	82.9	83.7
24	10WF 39	34.2	36.1	41.3	44.7	34.7	42.2	82.2	82.7	---	106.6	77.8
25	10WF 33	34.1	34.9	40.7	44.3	34.3	41.7	82.4	66.0	94.5	85.3	77.4
26	8WF 67	25.8	28.3	30.2	34.7	26.3	31.2	84.3	78.6	100.4	103.6	76.8
27	8WF 35	34.7	37.5	40.1	44.7	35.3	--	--	73.2	101.7	92.8	79.0
28	8WF 31	37.3	39.7	44.3	48.8	37.4	45.3	83.7	85.6	95.3	110.0	77.7
29	8WF 24	36.5	41.9	42.0	48.5	37.8	44.0	86.0	79.8	104.3	102.3	78.0
30	6WF15.5	42.9	43.0	48.3	52.1	43.3	49.6	87.3	84.7	99.2	102.0	83.3
31	5WF18.5	40.7	43.8	45.7	44.7	41.3	45.5	91.2	63.2	93.8	91.5	92.8

TABLE II, continued (b)

No.	Shape	$\frac{\sigma_r}{\sigma_{ys}}$ stub column	$\frac{\sigma_r}{\sigma_{ys}}$ mod. stub column	$\frac{\sigma_{ult\,mill}}{\sigma_{wet\,web}}$ coupon %	σ_{ult} weighted coupon	$\frac{\sigma_{ult\,weighted\,coupon}}{\sigma_{ult\,mill}}$ %	% redn.- in area		% redn.- in area weighted average	Redn. area =% of original	$\sigma_{ult\,mod.}$ based on redn. area
							flange	web			
8	18WF105	42.9%	---%	101.3	51.8	82.5	54.9	48.9	53.1	46.9	110.5
9	16WF 88	59.3	12.4	101.3	62.9	98.4	56.1	54.7	56.7	43.3	145.0
10	14WF426	--	--	95.2	66.0	94.3	52.0	30.8	48.2	51.8	127.5
11	14WF320	--	--	109.0	61.2	94.0	54.5	58.1	55.5	44.5	137.5
12	14WF228	36.9	--	100.0	63.3	98.5	69.8	51.6	66.2	33.8	187.5
13	14WF142	39.1	--	93.8	66.2	103.2	54.5	43.3	52.1	47.9	138.0
14	14WF111	30.9	--	110.0	66.2	93.3	55.1	49.9	53.8	46.2	143.5
15	14WF 78	34.7	--	101.3	59.4	98.2	55.1	54.0	54.7	45.3	131.2
16	14WF 61	--	--	111.4	60.2	90.0	57.7	48.8	55.2	44.8	134.4
17	14WF 53	--	--	109.4	--	--	55.5	57.6	56.2	43.8	--
18	12WF190	47.2	--	111.3	63.2	92.2	54.0	47.4	52.7	47.3	133.7
19	12WF 92	57.6	30.2	106.4	69.4	93.8	53.9	48.4	52.7	47.3	146.6
20	12WF 65	44.8	--	110.0	62.6	92.6	57.3	52.5	56.2	43.8	143.0
21	12WF 53	38.0	--	106.8	61.9	91.2	46.7	44.2	45.9	54.1	114.5
22	12WF 50	50.2	--	104.3	65.6	97.1	46.7	50.3	47.7	52.3	125.5
23	10WF 66	33.7	--	106.8	63.7	93.0	48.7	43.8	47.7	52.3	121.6
24	10WF 39	--	--	101.3	61.2	97.8	55.2	50.9	54.2	45.8	133.5
25	10WF 33	34.3	--	122.5	60.7	81.2	52.9	56.0	53.8	46.2	131.5
26	8WF 67	33.7	--	105.4	59.0	98.1	55.5	54.3	55.2	44.8	131.5
27	8WF 35	44.3	--	99.4	63.6	98.8	54.0	46.1	52.2	47.8	133.0
28	8WF 31	18.3	--	99.3	64.5	100.0	51.1	49.7	50.8	49.2	131.1
29	8WF 24	61.9	26.4	98.3	66.5	96.2	50.0	50.4	51.0	49.0	135.5
30	6WF15.5	54.2	8.8	103.8	63.7	96.0	54.0	53.7	53.9	46.1	138.7
31	5WF18.5	16.5	--	101.8	63.3	96.7	51.5	45.7	50.3	49.7	127.4

TABLE II, continued (c)

No.	Shape	E coupon		E coupon weighted	E stub column	$\frac{E_{coupon}}{E_{stub\ column}}$ %
		flange	web			
8	18WF105	31.7	31.9	31.8	30.8	103.4
9	16WF 88	30.6	32.9	31.3	31.8	98.4
10	14WF426	--	32.4	--	33.3	--
11	14WF320	34.1	33.0	33.9	--	--
12	14WF228	--	33.0	--	--	--
13	14WF142	29.8	32.9	30.5	29.1	104.8
14	14WF111	31.3	28.7	30.7	31.2	98.4
15	14WF 78	29.6	30.8	29.9	32.0	93.5
16	14WF 61	29.8	27.8	29.3	--	--
17	14WF 53	30.3	30.6	30.4	--	--
18	12WF190	38.4	34.6	37.7	32.7	115.3
19	12WF 92	29.7	33.0	30.4	31.8	95.6
20	12WF 65	31.1	28.8	30.6	30.0	102.0
21	12WF 53	33.2	30.0	32.4	33.8	95.9
22	12WF 50	33.8	29.6	32.6	32.9	99.2
23	10WF 66	31.8	30.7	31.6	30.1	105.0
24	10WF 39	31.3	30.5	31.1	--	--
25	10WF 33	30.5	30.4	30.5	29.2	104.5
26	8WF 67	30.2	30.7	30.3	--	--
27	8WF 35	30.2	32.2	30.6	31.2	98.2
28	8WF 31	30.1	33.0	30.8	30.2	102.0
29	8WF 24	--	34.4	--	32.2	--
30	6WF15.5	27.8	32.5	29.2	33.5	87.2
31	5WF18.5	29.9	29.6	29.8	32.4	92.0

TABLE III

General Experimental and Analytical Data for Material "B"

NOTE: All values arein kip-inch units.

No.	Shape	Area	Area Flanges	Area Web	α = area flanges / area web	σ_{rc} stub column	σ_{rc} mod. stub column	σ_{ys} stub column	σ_y mill	σ_{ult} mill	σ_{ult} coupon flange	σ_{ult} coupon web
8	18WF105	30.6	21.0	9.5	2.21	13.4	--	33.0	37.7	62.4	61.2	61.5
9	16WF 88	25.7	18.1	7.6	2.38	23.3	9.1	34.4	41.6	68.3	65.5	64.3
10	14WF426				4.40						68.7	66.8
11	14WF320				2.97							
12	14WF228											
13	14WF142	40.6	32.0	8.5	3.76	18.1		38.7	51.2	74.1	70.3	71.3
14	14WF111				3.78						63.2	64.4
15	14WF 78	23.2	17.5	5.6	3.13	14.8		35.8	42.3	68.8	64.5	66.9
16	14WF 61	18.1	13.0	5.0	2.60	9.1		36.7	44.2	68.4	64.8	65.3
17	14WF 53											
18	12WF190	55.7	44.1	11.7	3.77	11.3		30.2	39.6	68.7	66.2	67.6
19	12WF 92											
20	12WF 65							36.6*	39.7*			
21	12WF 53	15.7	11.7	3.95	2.97	12.3		35.0	35.1	66.9	64.1	64.8
22	12WF 50							36.0*	42.6*			
23	10WF 66				3.68						63.3	62.5
24	10WF 39							35.9*	41.2*			
25	10WF 33											
26	8WF 67							31.4*	43.0*			
27	8WF 35							36.7*	40.0*			
28	8WF 31							37.4*	43.3*			
29	8WF 24							34.3*	39.8*			
30	6WF15.5										64.0	63.6
31	5WF18.5										67.1	65.2

*from previous investigations.

TABLE III, continued (a)

No.	Shape	σ_{ys} coupon flange	σ_{ys} coupon web	σ_{yd} coupon flange	σ_{yd} coupon web	σ_{ys} weighted coupon	σ_{yd} weighted coupon	$\frac{\sigma_{ys}}{\sigma_{yd}}$ %	$\frac{\sigma_{ys}}{\sigma_{y\,mill}}$ %	$\frac{\sigma_{ys\,stub\,column}}{\sigma_{ys\,weighted\,coupon}}$ %	$\frac{\sigma_r}{\sigma_{ys}}$ stub column	$\frac{\sigma_r}{\sigma_{ys}}$ mod. stub column
8	18WF105	33.5	31.2	39.4	38.0	32.8	39.0	84.1	87.0	100.6	40.7	
9	16WF 88	34.1	34.6	41.2	39.8	34.3	40.8	83.8	82.5		67.8	26.5
10	14WF426	28.4	29.4	32.7	31.5	28.6	32.5	88.0				
11	14WF320											
12	14WF228											
13	14WF142	37.8	38.5	45.0	45.2	38.0	45.1	84.3	74.2	101.8	46.8	
14	14WF111	33.0	37.0	39.2	43.8	33.9	40.1	84.7				
15	14WF 78	34.6	37.1	40.7	44.2	35.1	41.5	84.7	82.8	102.1	41.4	
16	14WF 61	36.1	36.6	42.2	42.7	36.3	42.3	85.8	82.2	101.2	24.8	
17	14WF 53											
18	12WF190	30.5	32.4	33.8	39.2	30.9	34.9	88.5	78.0	97.7	34.1	
19	12WF 92											
20	12WF 65								92.2*			
21	12WF 53	35.2	35.2	41.4	40.4	35.2			100.3	99.5	35.2	
22	12WF 50								84.5*			
23	10WF 66	34.2	36.6	41.7	41.1	35.5						
24	10WF 39								87.1*			
25	10WF 33											
26	8WF 67								72.8*			
27	8WF 35								91.8*			
28	8WF 31								86.2*			
29	8WF 24								86.2*			
30	6WF15.5	36.6	37.4	42.4	43.0	36.8						
31	5WF18.5	37.2	38.0	40.0	46.6	37.4						

*from previous investigations.

TABLE III, continued (b)

No.	Shape	σ_{ult} weighted coupon	% redn. in area		% redn. in area weighted average	Red. area =% of original	σ_{ult}.mod. based on red. area	E_{coupon}		E_{coupon} weighted	E stub column	$\frac{E_{coupon}}{E_{stub\ column}}$ %
			flange	web				flange	web			
8	18WF105	61.3	56.9	50.2	54.8	45.2	135.8	29.3	28.2	28.9	28.6	101.1
9	16WF 88	69.3	52.2	47.5	50.7	49.3	132.5	30.0	29.4	29.8	31.7	90.9
10	14WF426	68.5	33.7	44.7	35.7	64.3	106.5	33.8	35.6	34.1		
11	14WF320		54.5	58.1	55.5	44.5						
12	14WF228											
13	14WF142	70.7	53.9	51.1	54.2	45.8	154.3	30.8	31.9	31.0	33.8	91.8
14	14WF111	63.3	55.3	44.9	53.0	47.0	134.8	32.6	31.2	32.3		
15	14WF 78	65.2	48.5	53.5	49.7	50.3	129.6	30.4	32.1	30.8	27.5	112.0
16	14WF 61	65.1	55.2	67.4	58.7	41.3	157.5	31.7	32.2	31.9	30.4	105.0
17	14WF 53											
18	12WF190	66.4	53.5	48.3	52.2	47.8	139.0	--	29.4	--	30.9	--
19	12WF 92											
20	12WF 65											
21	12WF 53	64.2	51.9	42.5	49.6	50.4	127.6	32.0	27.4	30.8	29.8	103.5
22	12WF 50											
23	10WF 66	63.2	51.0	53.0	51.3	48.7	129.8	30.9	29.0	30.5		
24	10WF 39											
25	10WF 33											
26	8WF 67											
27	8WF 35											
28	8WF 31											
29	8WF 24		50.4	50.0	50.2	49.8						
30	6WF15.5	63.8	54.1	54.1	54.1	45.9	138.8	31.1	32.0	30.8		
31	5WF18.5	66.7	51.5	45.7	50.2	44.8	133.9	31.9	30.9	31.7		

TABLE IV

Summary of Coupon Test Results
8WF31
Compression Coupons(as-delivered)
(Average Values in ksi)

Material	E	σ_p	σ_{uy}	σ_{yd}
IA1 Flange	29,900 (9)*	30.6 (6)*	38.4 (8)*	38.0 (9)*
Web	28,750 (2)	26.5 (2)	42.7 (2)	42.7 (2)
Ave.-2**	29,580 (11)	29.6 (8)	39.4 (10)	39.2 (11)
IA2 Flange	30,120 (3)		39.8 (3)	39.8 (3)
IB2 Flange	28,940 (6)	30.4 (6)	39.6 (6)	39.6 (6)
Web	30,000 (2)	30.0 (2)	43.6 (2)	43.3 (2)
Ave.-2	29,200 (8)	30.3 (8)	40.6 (8)	40.5 (8)
TOTAL Ave.-2	29,580 (22)	29.6 (16)	40.0 (21)	39.8 (22)
Tension Coupons (as-delivered) (Average Values in ksi)				
IA1 Flange	30,230 (3)		42.8 (3)	39.1 (3)
Web	30,200 (1)		44.8 (1)	43.3 (1)
Ave.-2	30,210 (4)		43.3 (4)	40.1 (4)
IA2 Flange	30,010 (9)	32.0 (6)	39.1 (9)	37.4 (6)
Web	29,270 (3)	27.7 (2)	42.6 (2)	35.7 (2)
Ave.-2	29,820 (12)	30.9 (8)	39.9 (11)	37.0 (8)
IB2 Flange	30,090 (3)		43.5 (3)	40.5 (3)
Web	30,200 (1)		46.6 (1)	44.2 (1)
Ave.-2	30,120 (4)		44.2 (4)	41.4 (4)
TOTAL Ave.-2	29,970 (20)	30.9 (8)	41.6 (19)	38.9 (16)
Mill Report Tension Test (as-delivered)				
Web	--	--	--	43.3

*Number of specimens
**Weighted average in proportion of flange and web areas.

TABLE V

Residual Stresses Due to Cooling in WF Shapes

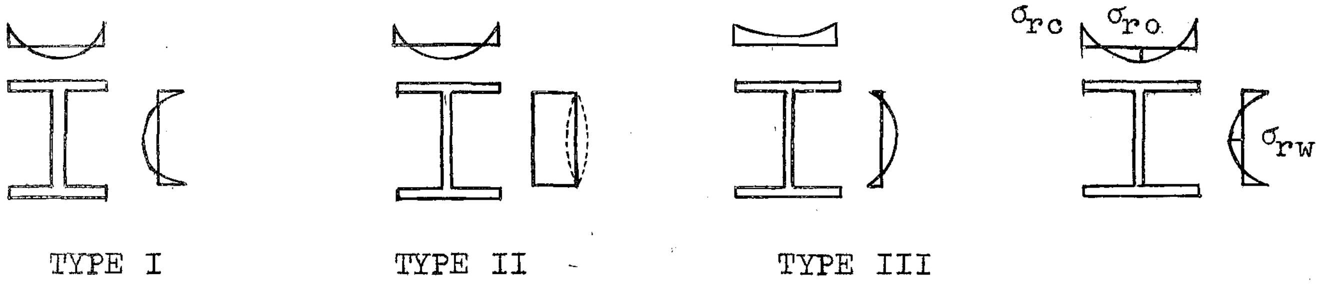
Stress in ksi	Flange Edge			Flange Center			Web Center		
	max.	avg.	min.	max.	avg.	min.	max.	avg.	min.
Columns d/b-1.5	-5.5	-12.3	-18.7	16.5	4.6	-3.7	17.5	3.9	-15.5
Beams d/b 1.5	-4.1	-7.7	-10.8	19.7	14.6	8.3	-8.8	-16.3	-29.5

tension = +
compression = -

These are results of all tests conducted in Fritz Engineering Laboratory on Research Project No. 220A.

TABLE VI

Cooling Residual Stresses in WF Shapes
(Average Values)



	SHAPE	w/t	d/b	σ_{rc}	σ_{ro}	σ_{rw}	TYPE	REMARKS
1	4WF 13	.811	1.022	-10.0	4.0	5.5	II	
2	5WF18.5	.632	1.018	- 7.7	-2.0	16.5	II/III	center beam on cooling bed
3	5WF18.5	.632	1.018	-10.6	3.2	6.0	II	edge beam on cooling bed
4	6LC15.5	.892	1.000	-15.1	10.5	-0.9	I/II	light column
5	8WF 24	.616	1.138	-10.2	0.5	17.5	III/II	
6	8WF 31	.665	1.000	-13.9	5.6	9.3	II	
7	8WF 31	.665	1.000	-11.5	1.1	15.5	II/III	same heat, different rollings
8	8WF 31	.665	1.000	-17.5	4.2	5.0	II	
9	8WF 31	.665	1.000	-16.1	10.1	1.3	I/II	different heat
10	8WF 67	.616	1.088	- 9.5	-3.7	15.5	III	
11	12314	.893	3.000	- 4.1	8.3	-8.8	I	beam
12	12WF50	.579	1.510	- 5.5	9.2	-15.0	I	
13	12WF65	.644	1.011	-18.7	16.5	-15.5	I	
14	14WF43	.584	1.711	- 8.5	19.7	-29.5	I	on cooling bed (slow cooling rate)
15	14WF43	.584	1.711	- 8.5	24.2	-41.0	I	cooled separately (high cooling rate)
16	14WF426	.619	1.120	-17.8	8.5	14.0	II	
17	36WF150	.665	2.990	-10.8	14.3	-15.0	I	beam

3. Figures

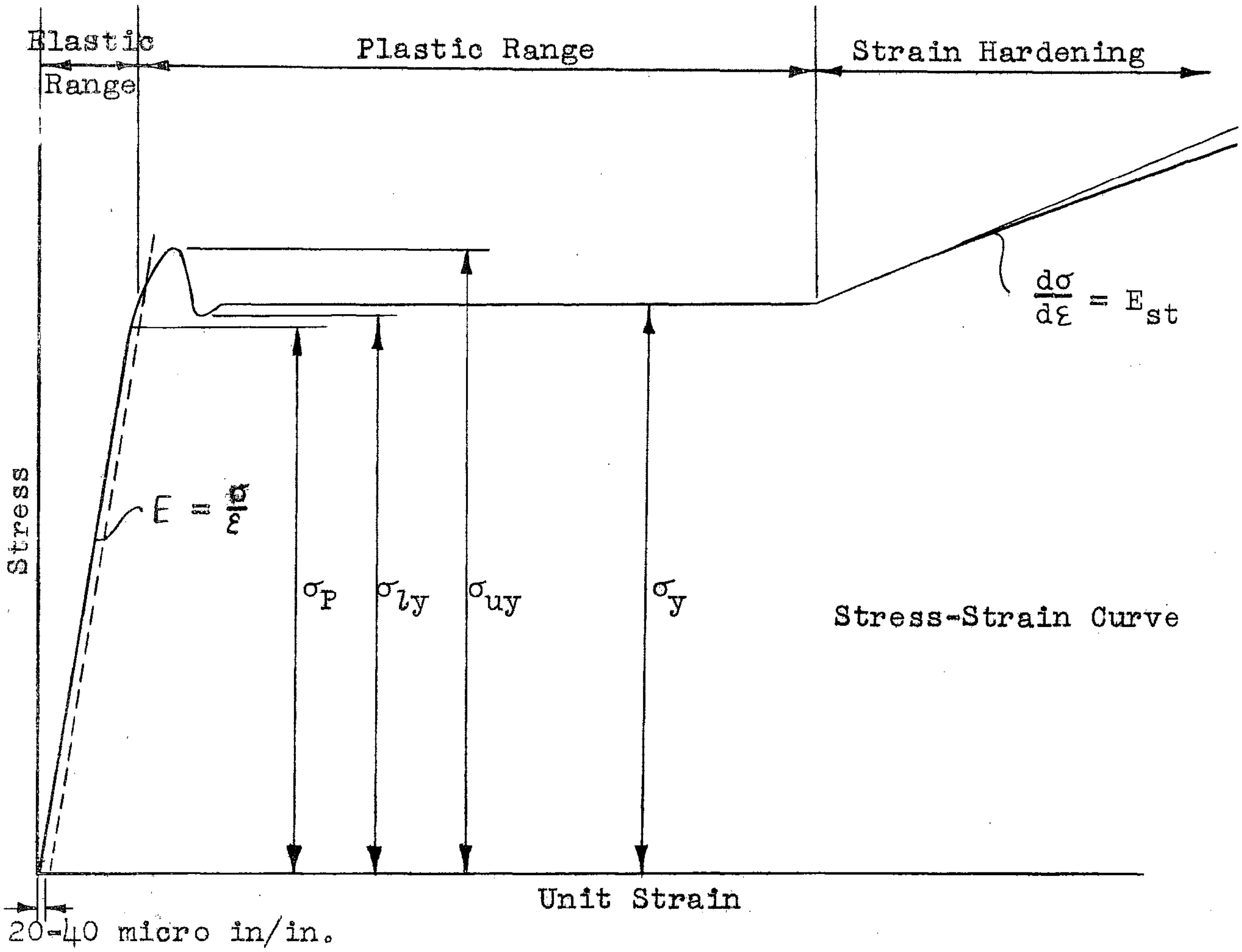


Figure 1

GRAPHICAL DEFINITION OF TERMS

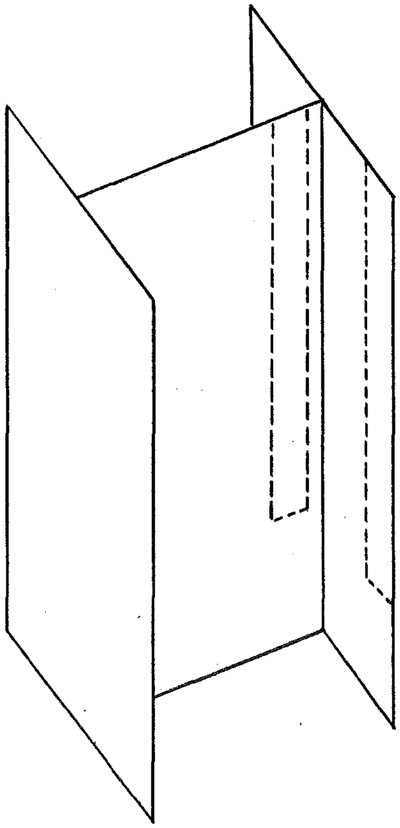


Figure 2

SHOWING POSITION OF
TENSION COUPONS CUT
FROM FLANGE AND WEB
OF A WF SHAPE

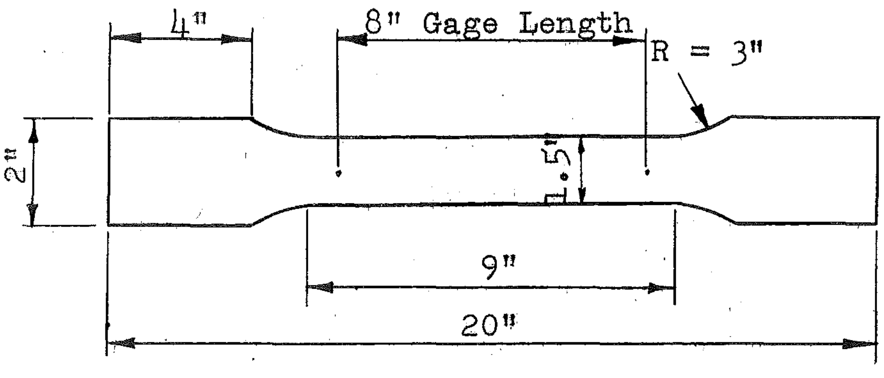


Figure 3

DIMENSIONS OF TENSION COUPON
(Shaped to ASTM Specification)

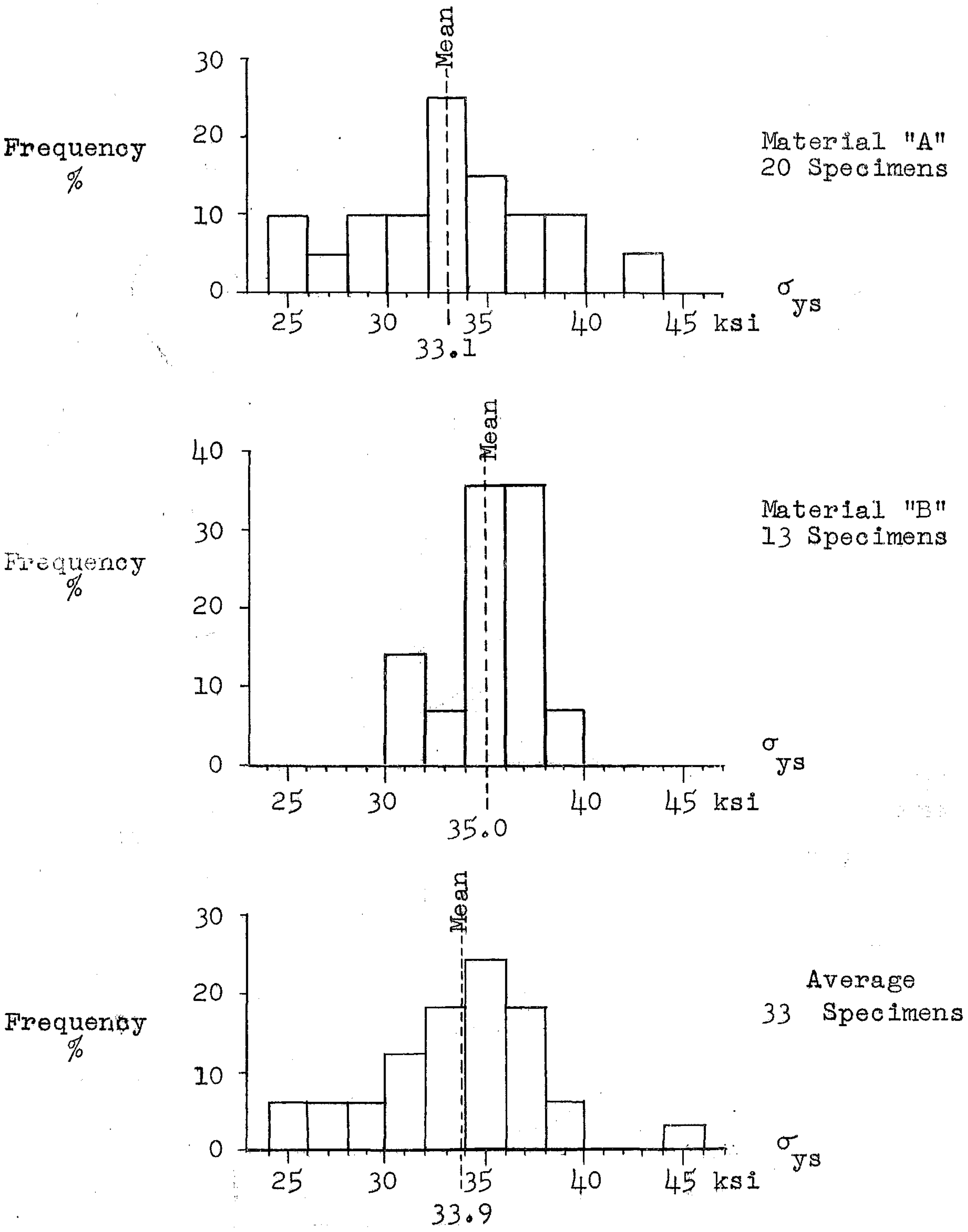


Figure 4

STUB COLUMN TEST RESULTS

The Static Level Of Yield Stress, σ_{ys}

Histograms

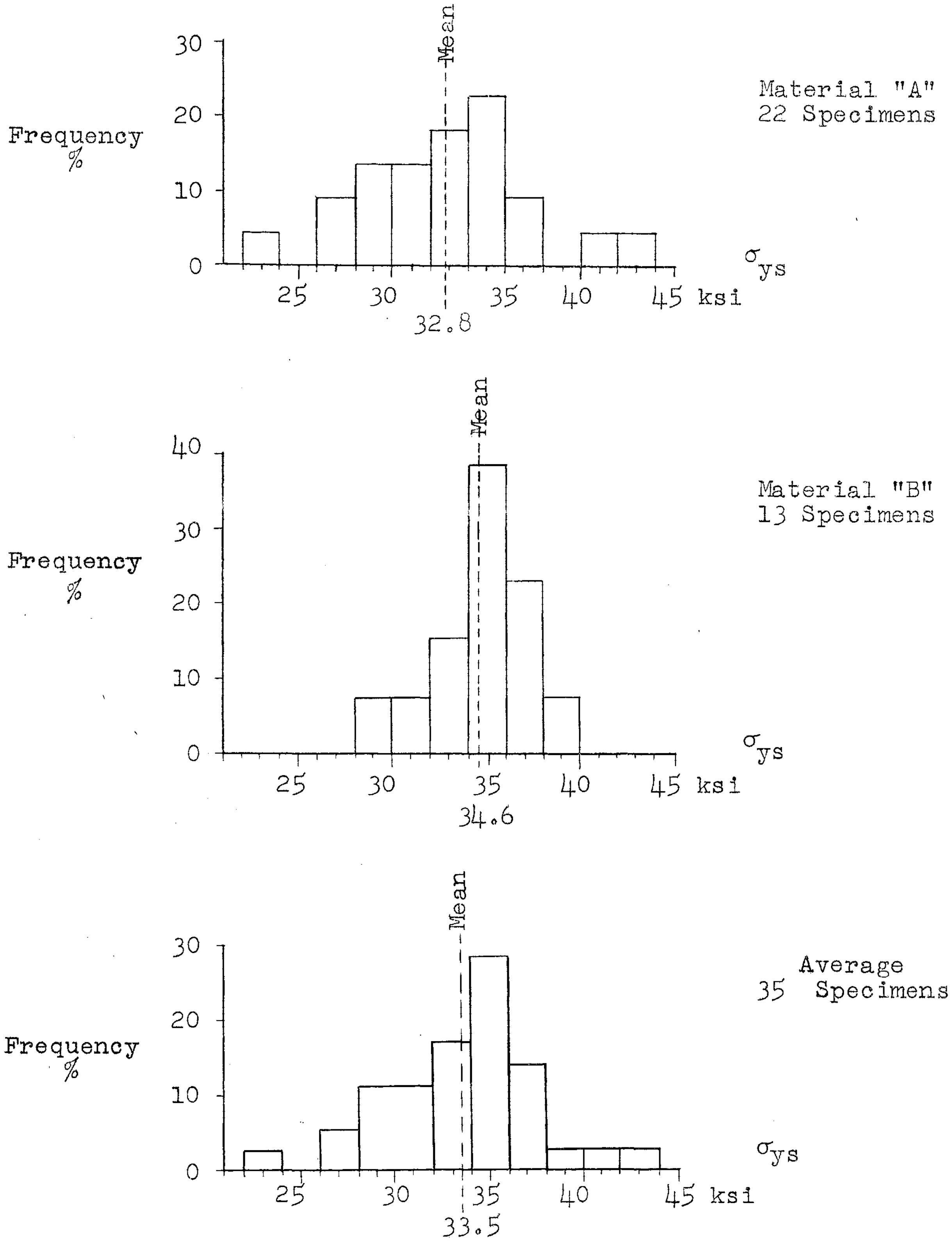


Figure 5

SIMULATED MILL TESTS
(Weighted Mean Of Flange And Web Coupons)

The Static Level Of Yield Stress, σ_{ys}
Histograms

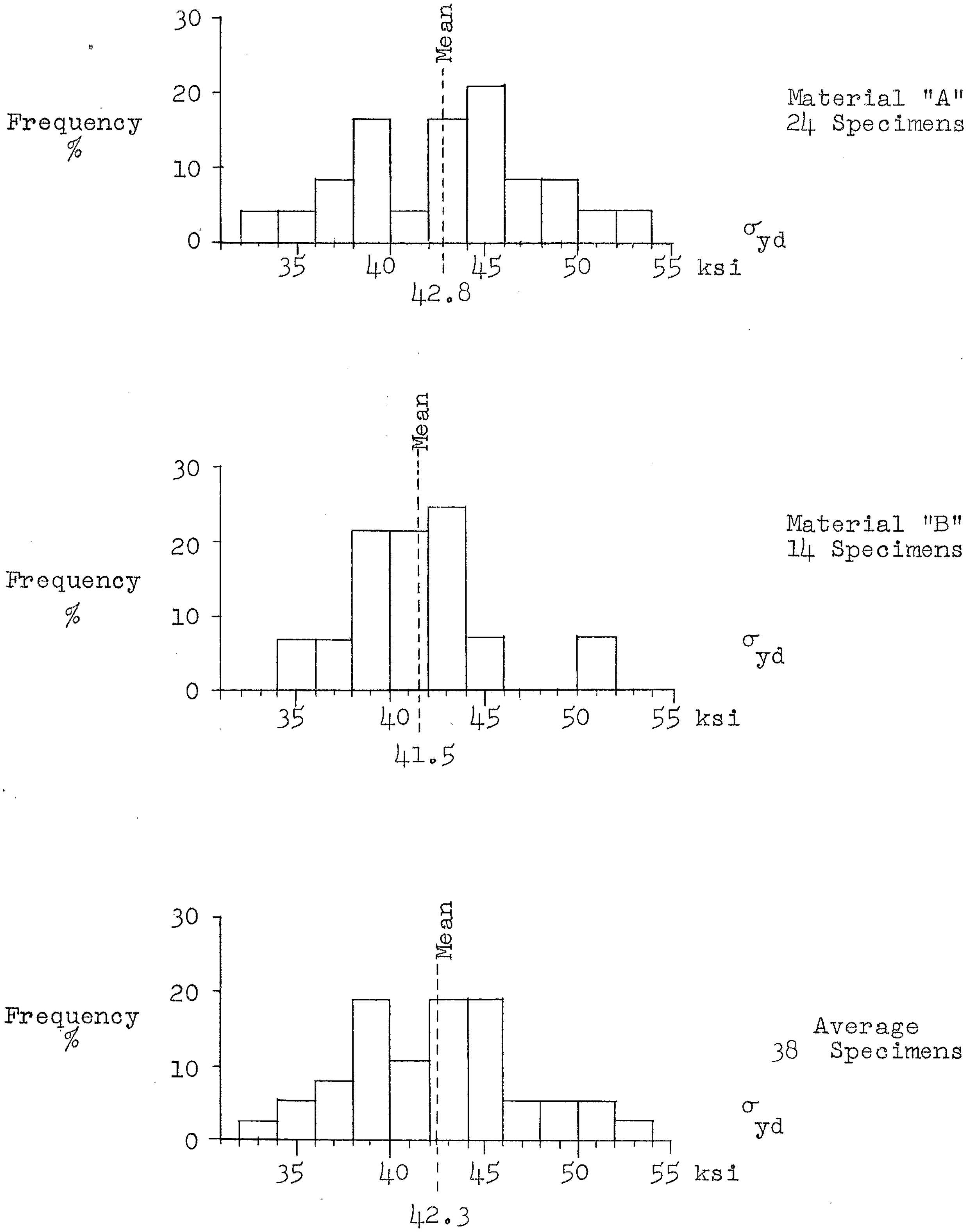


Figure 6

MILL TESTS (Web Coupons)
The Dynamic Level Of Yield Stress, σ_{yd}
Histograms

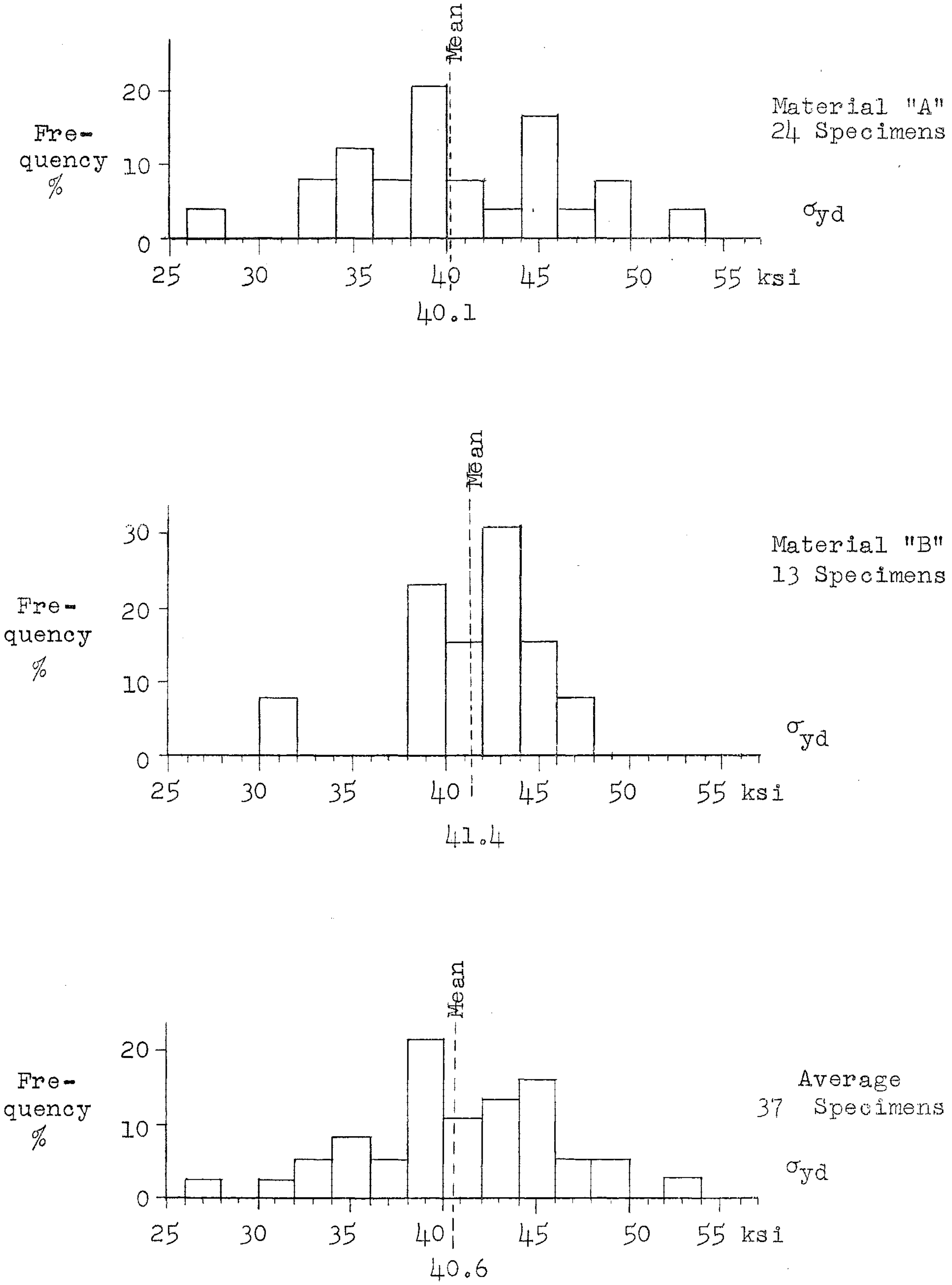
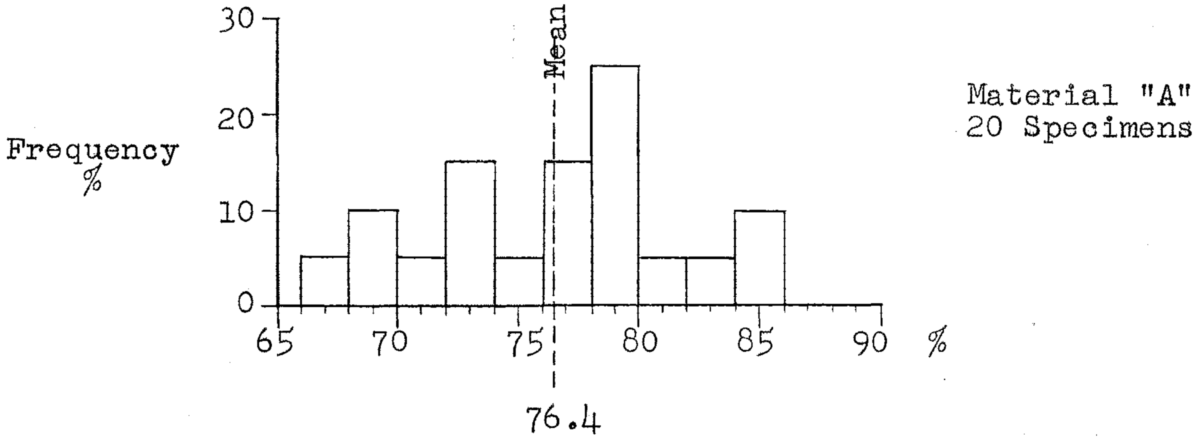


Figure 6

SIMULATED MILL TESTS (Web Coupons)
The Dynamic Level Of Yield Stress, σ_{yd}
Histograms

(a) Mill Test: $\frac{\sigma_{ys}}{\sigma_{ymill}}$, with σ_{ys} from weighted coupon average



(b) Simulated Mill Tests

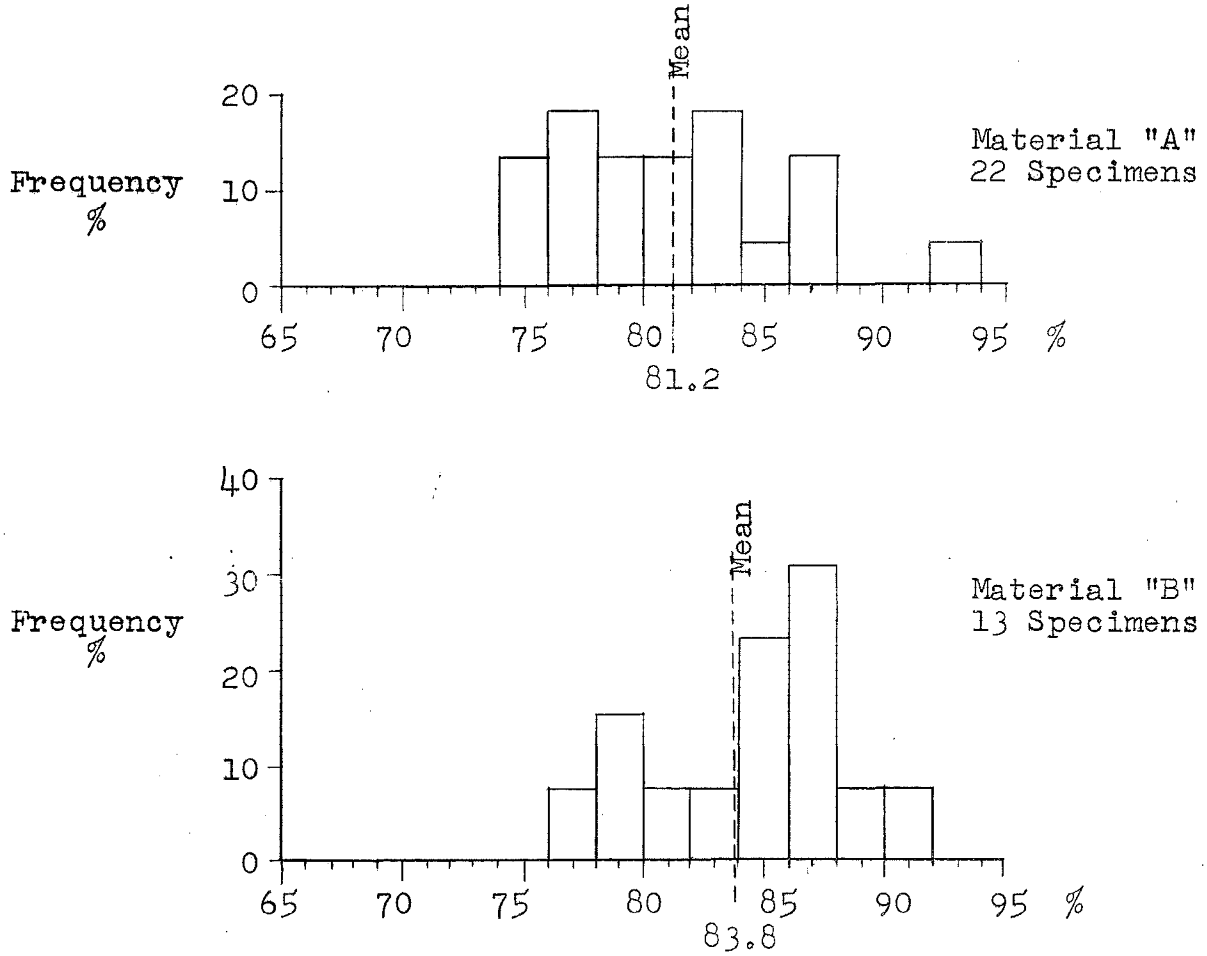


Figure 8

RATIOS OF STATIC YIELD STRESS TO MILL YIELD STRESS
Histograms

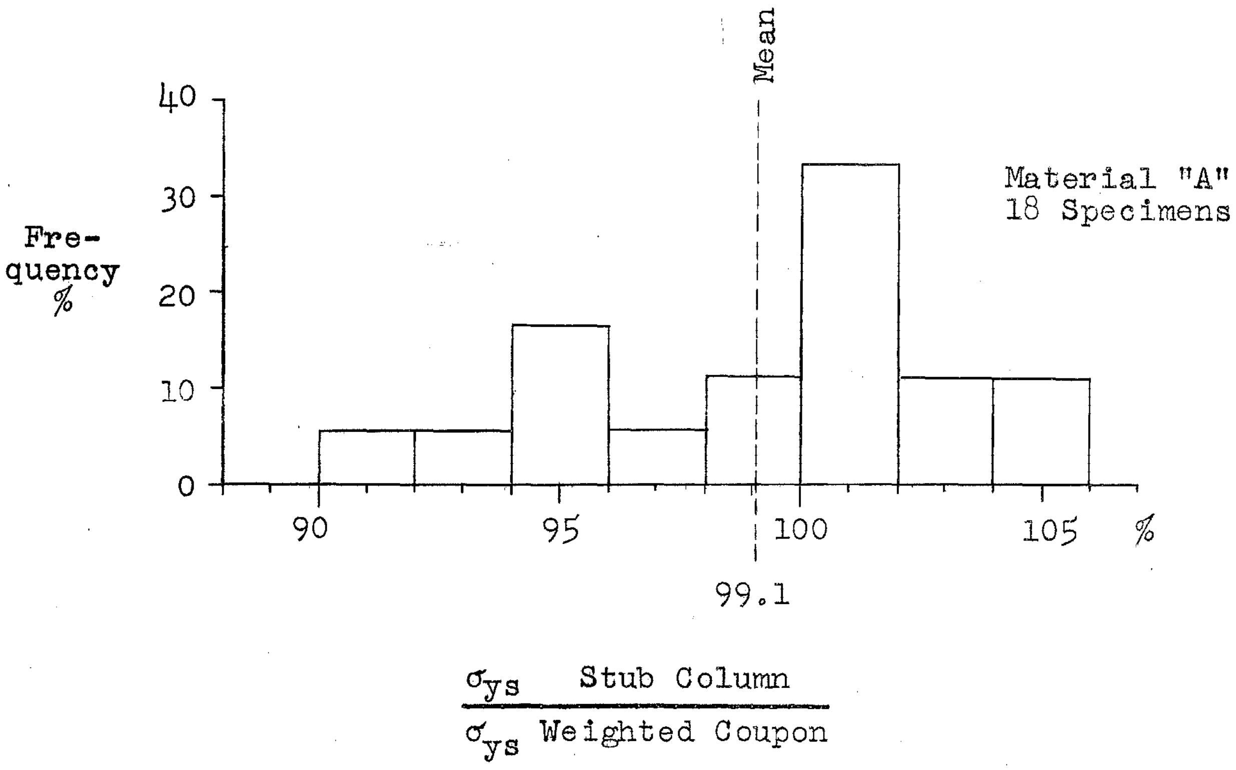


Figure 9

RATIO OF STATIC YIELD STRESS, STUB COLUMN TO WEIGHTED COUPONS

Histogram

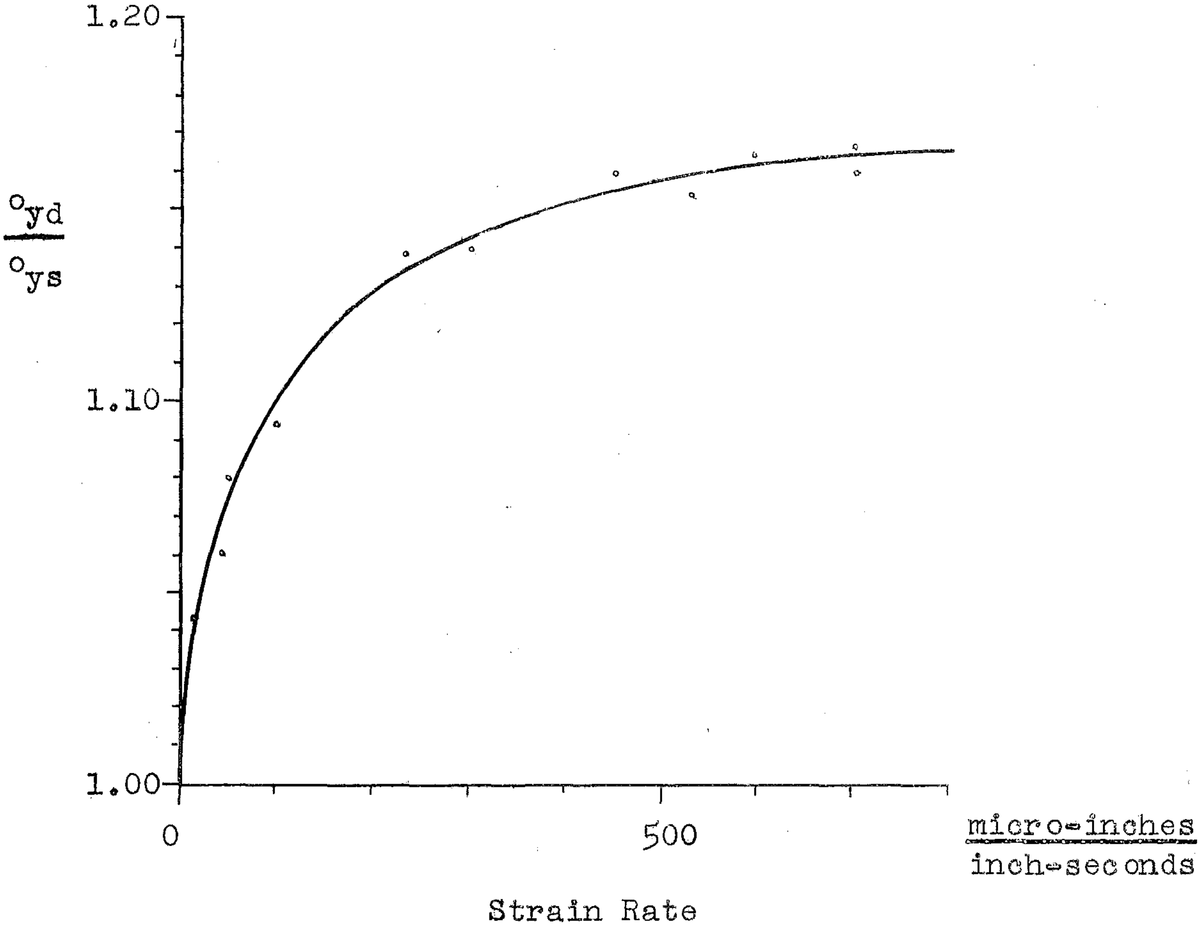


Figure 10

CURVE SHOWING $\frac{\sigma_{yd}}{\sigma_{ys}}$ AS A FUNCTION OF STRAIN RATE,

USING THE 'FREE RUNNING' CROSSHEAD SPEED

(Fig. a, of Reference 5)

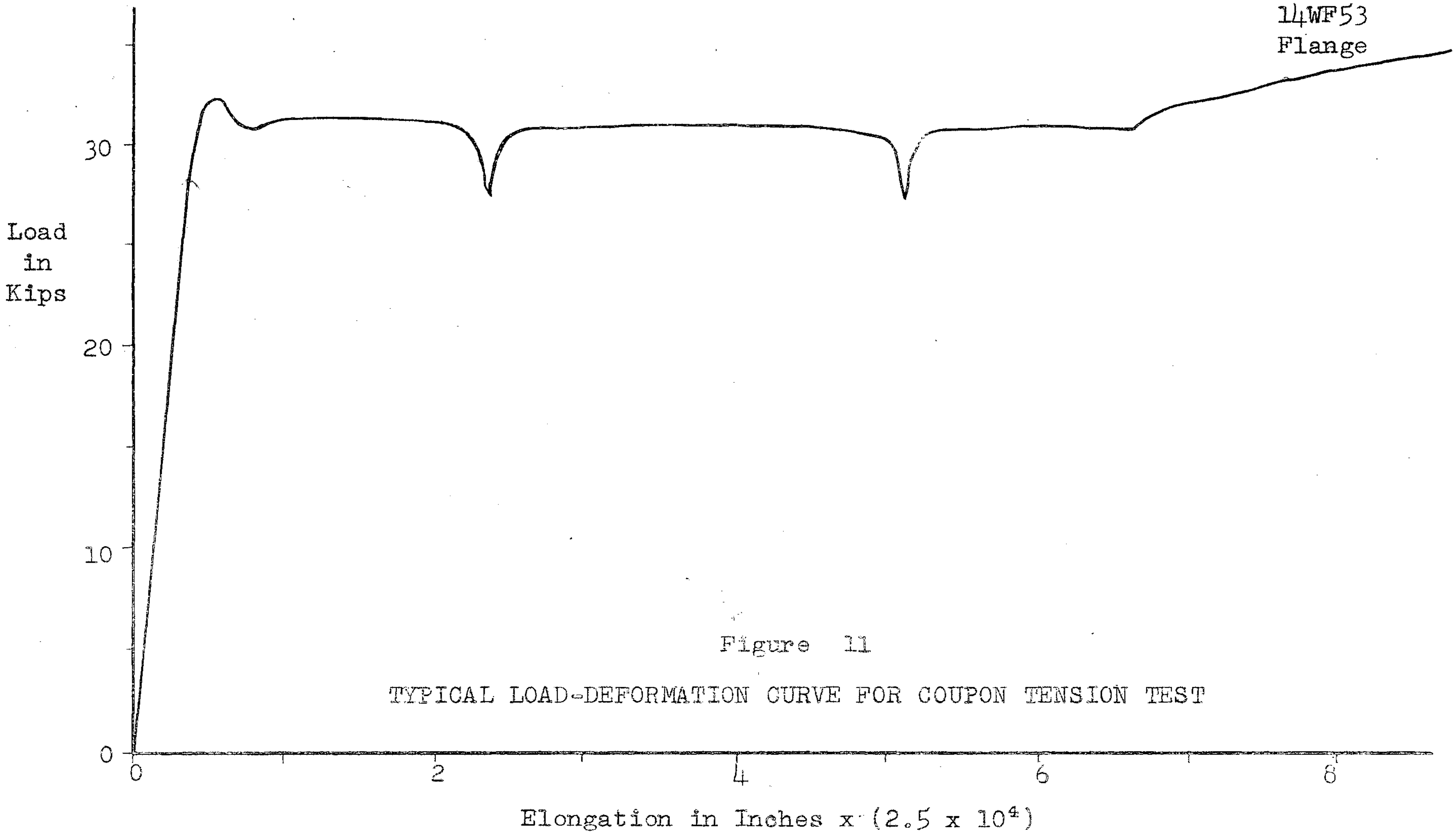


Figure 11

TYPICAL LOAD-DEFORMATION CURVE FOR COUPON TENSION TEST

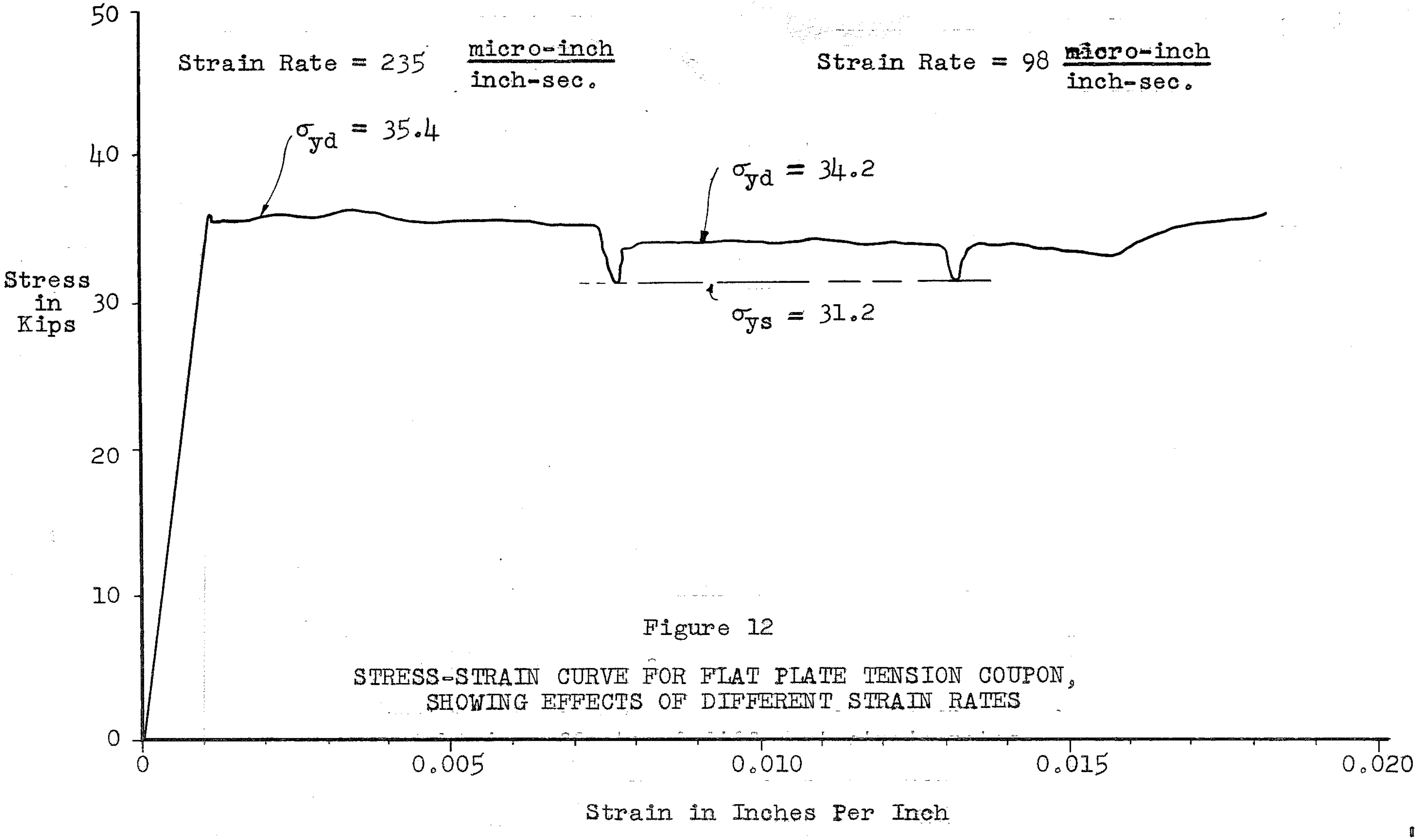
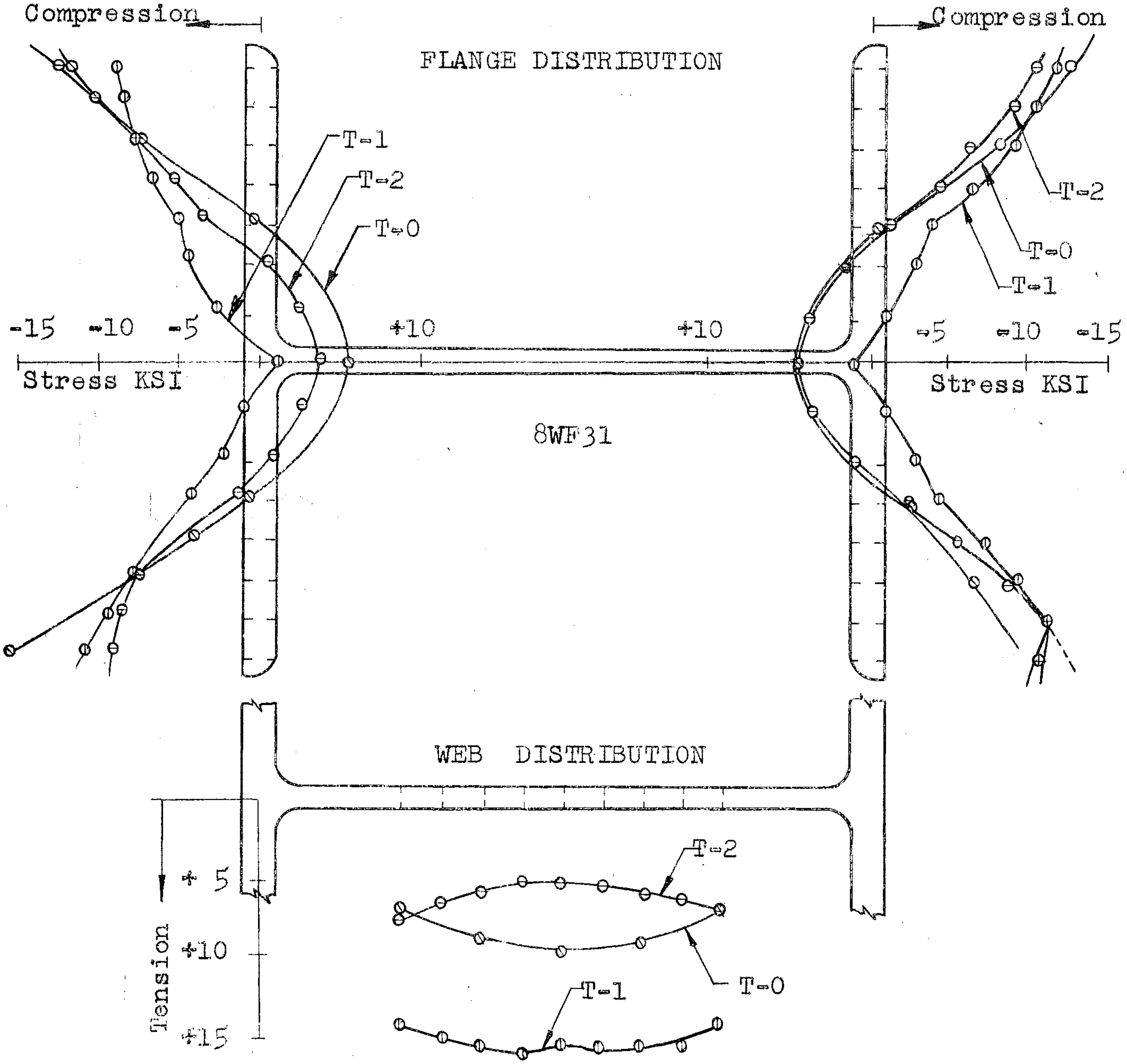


Figure 12

STRESS-STRAIN CURVE FOR FLAT PLATE TENSION COUPON, SHOWING EFFECTS OF DIFFERENT STRAIN RATES

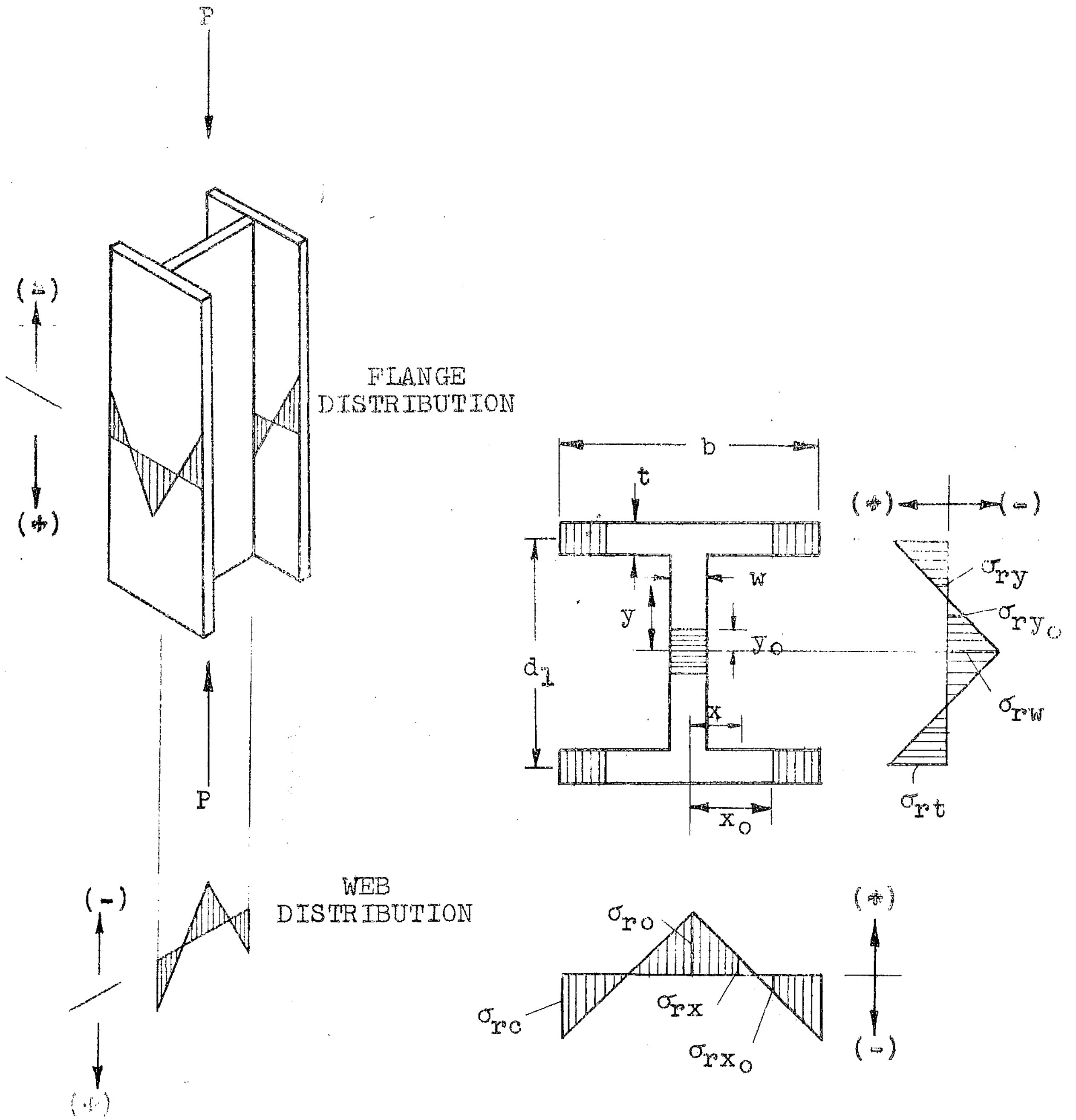


	σ_{rc}	σ_{ro}	σ_{rw}
T-0	-13.9	5.6	9.3
T-1	-11.5	1.1	15.5
T-2	-12.5	4.2	5.0

AVERAGE RESIDUAL STRESSES (KSI)

Figure 13(a)

RESIDUAL STRESS DISTRIBUTIONS (AS DELIVERED)
(Three Specimens)



1: Residual Stress In WF Shape

2: Partially Yielded Cross-Section - Nomenclature

Figure 13(b)

RESIDUAL STRESSES: DISTRIBUTION AND NOMENCLATURE

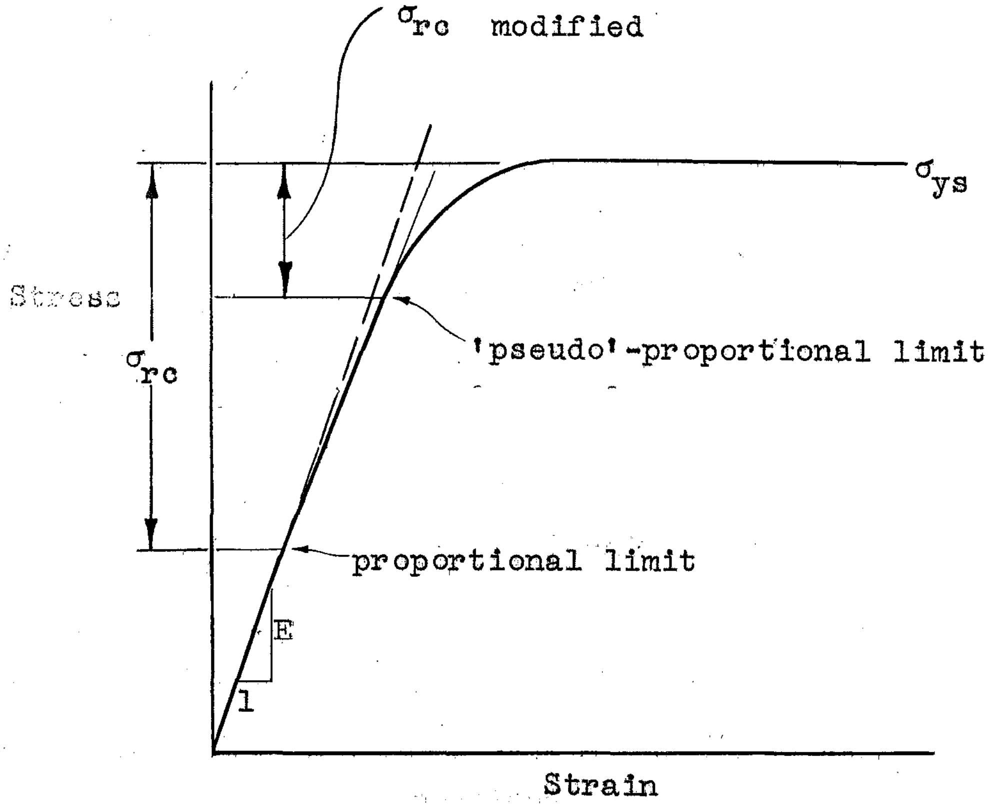


Figure 14

MODIFICATION OF STUB COLUMN STRESS-STRAIN CURVE
WITH HIGH LOCAL RESIDUAL STRESSES IN FLANGES

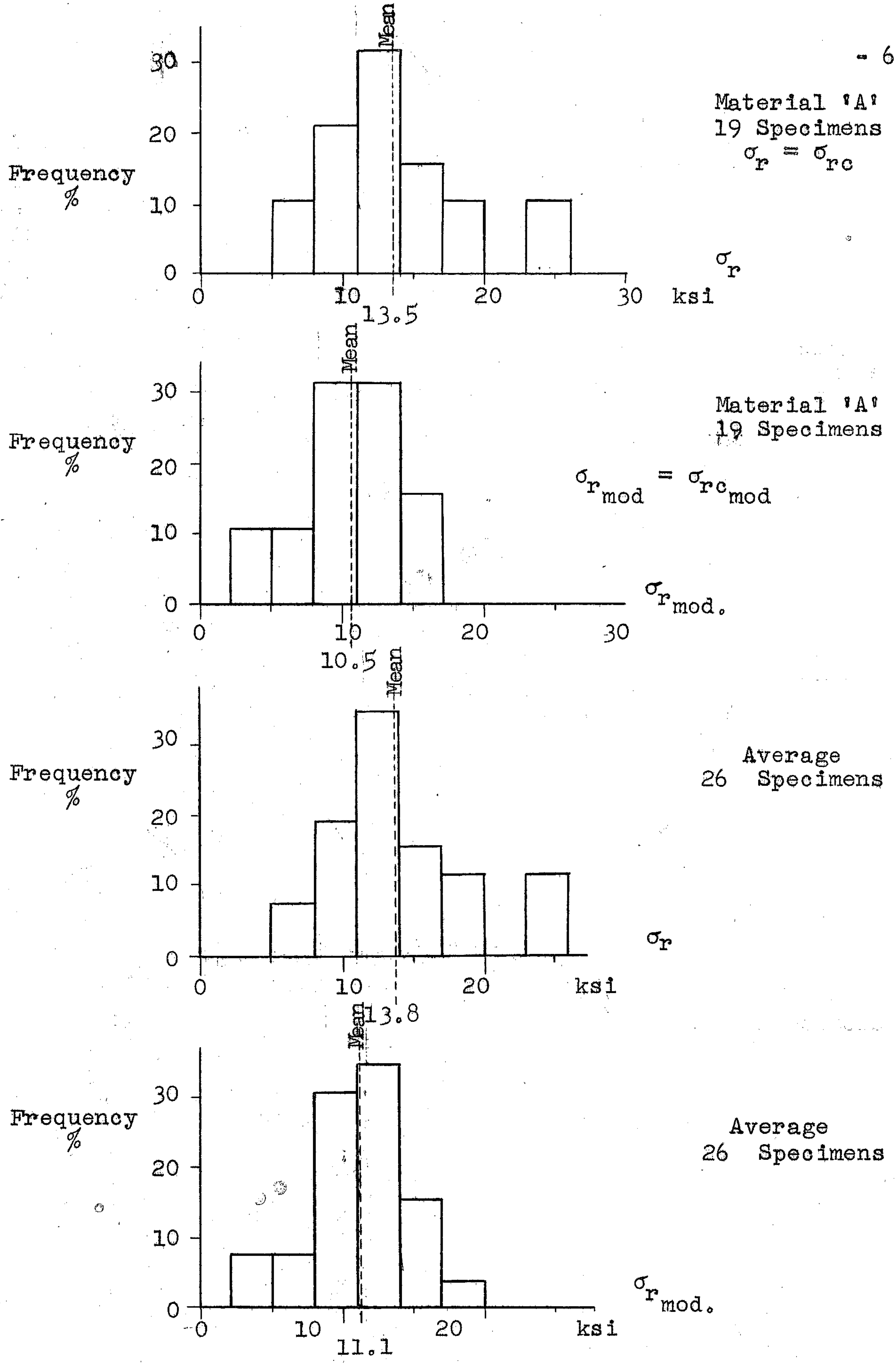
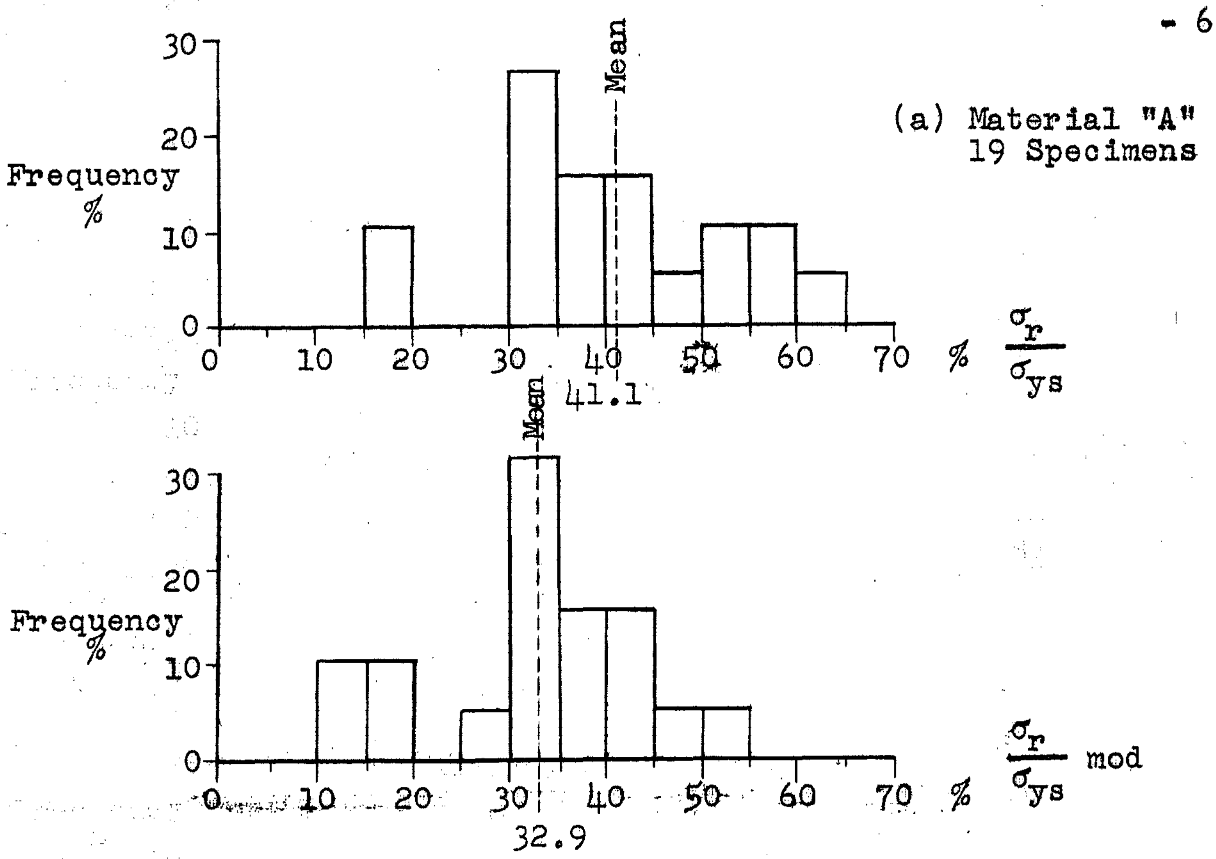


Figure 15
HISTOGRAMS OF THE MAXIMUM RESIDUAL STRESS IN THE FLANGES OF STUB COLUMN, σ_{rc}



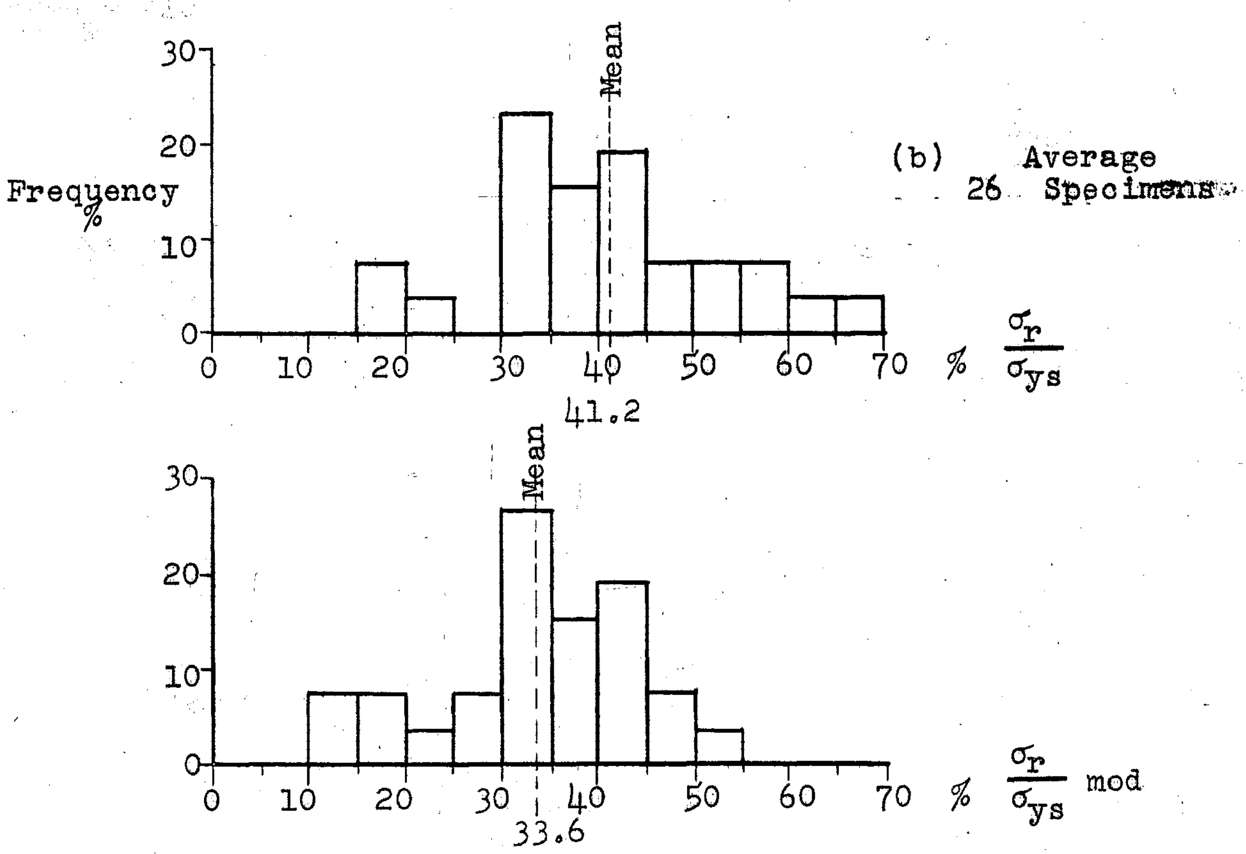


Figure 16

HISTOGRAM OF THE RATIO OF RESIDUAL STRESS
TO STATIC YIELD STRESS

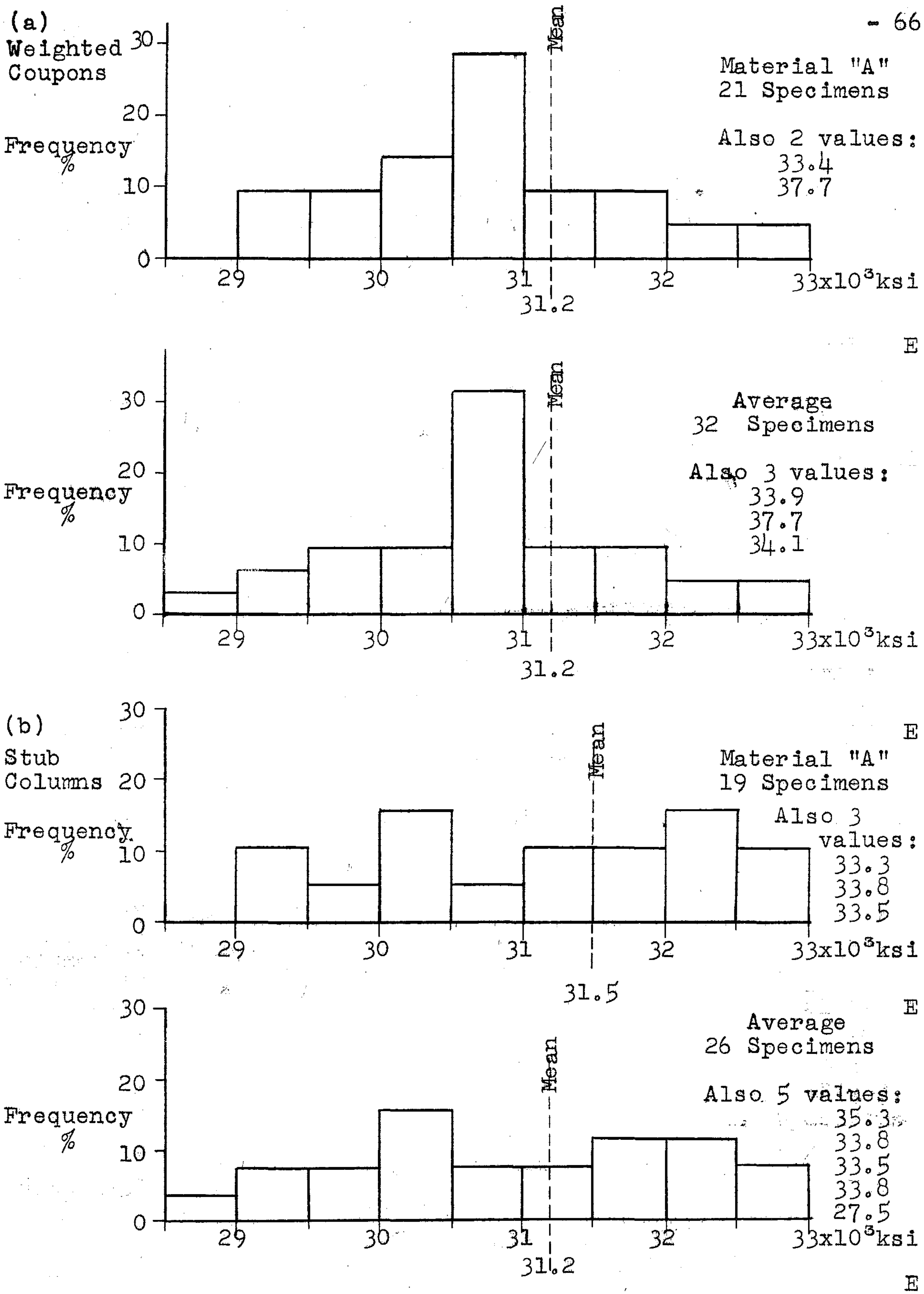


Figure 17

YOUNG'S MODULUS FROM "WEIGHTED" COUPONS AND STUB COLUMNS
Histograms

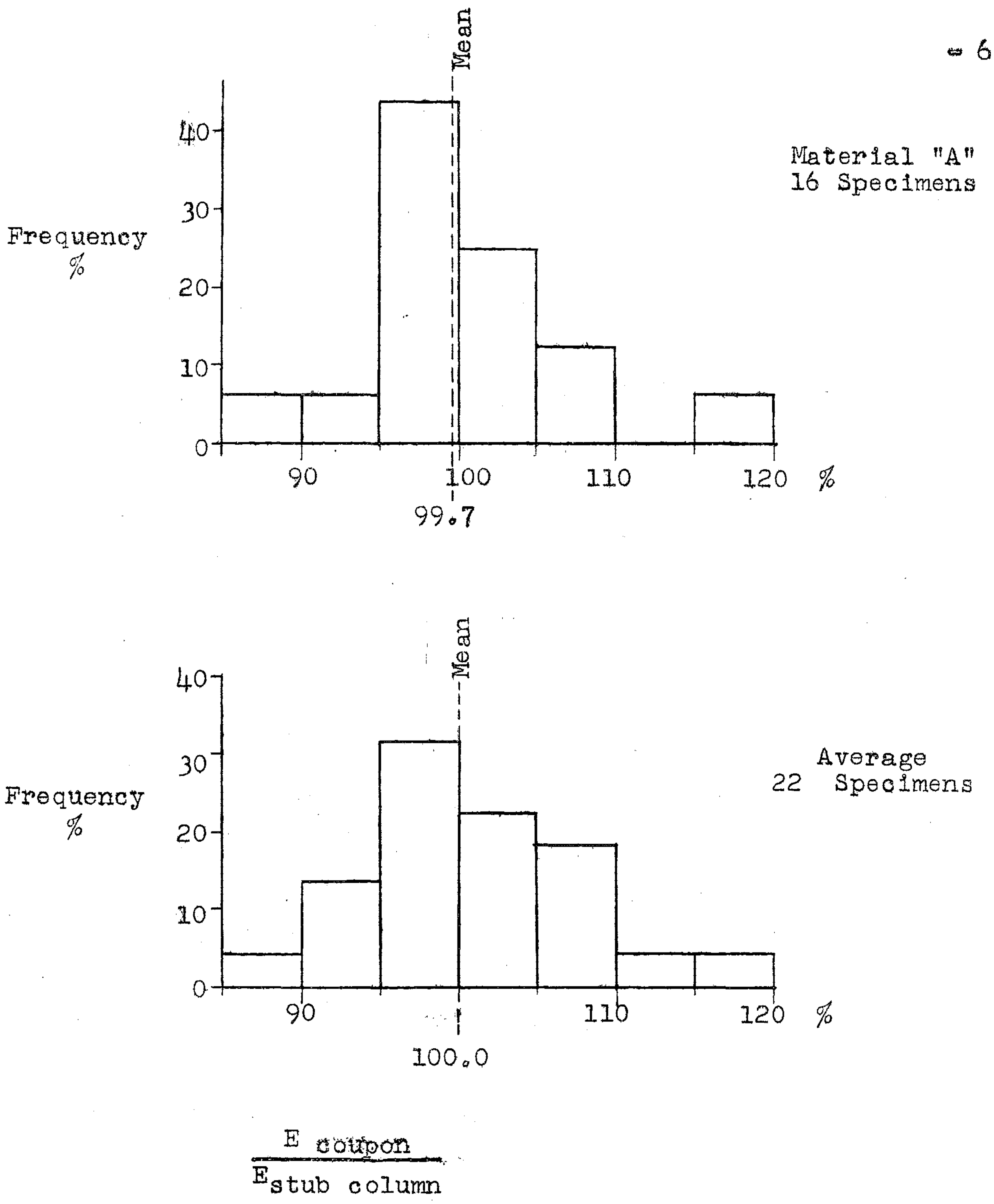


Figure 18

COMPARISON OF COUPON AND STUB COLUMN RESULTS FOR E

Histograms

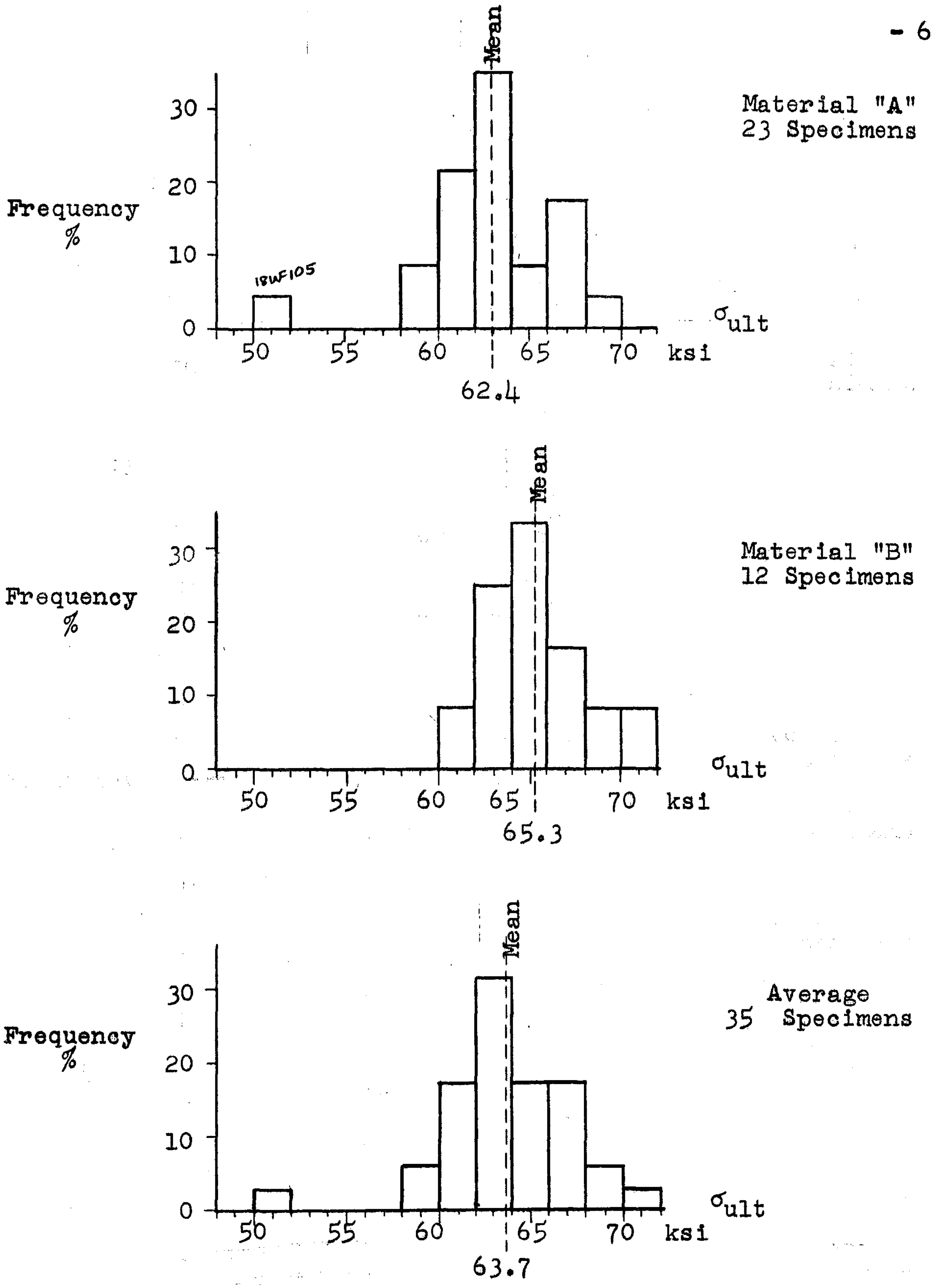


Figure 19

SIMULATED MILL COUPON RESULTS WEIGHTED AVERAGE ULTIMATE STRESS

Histograms

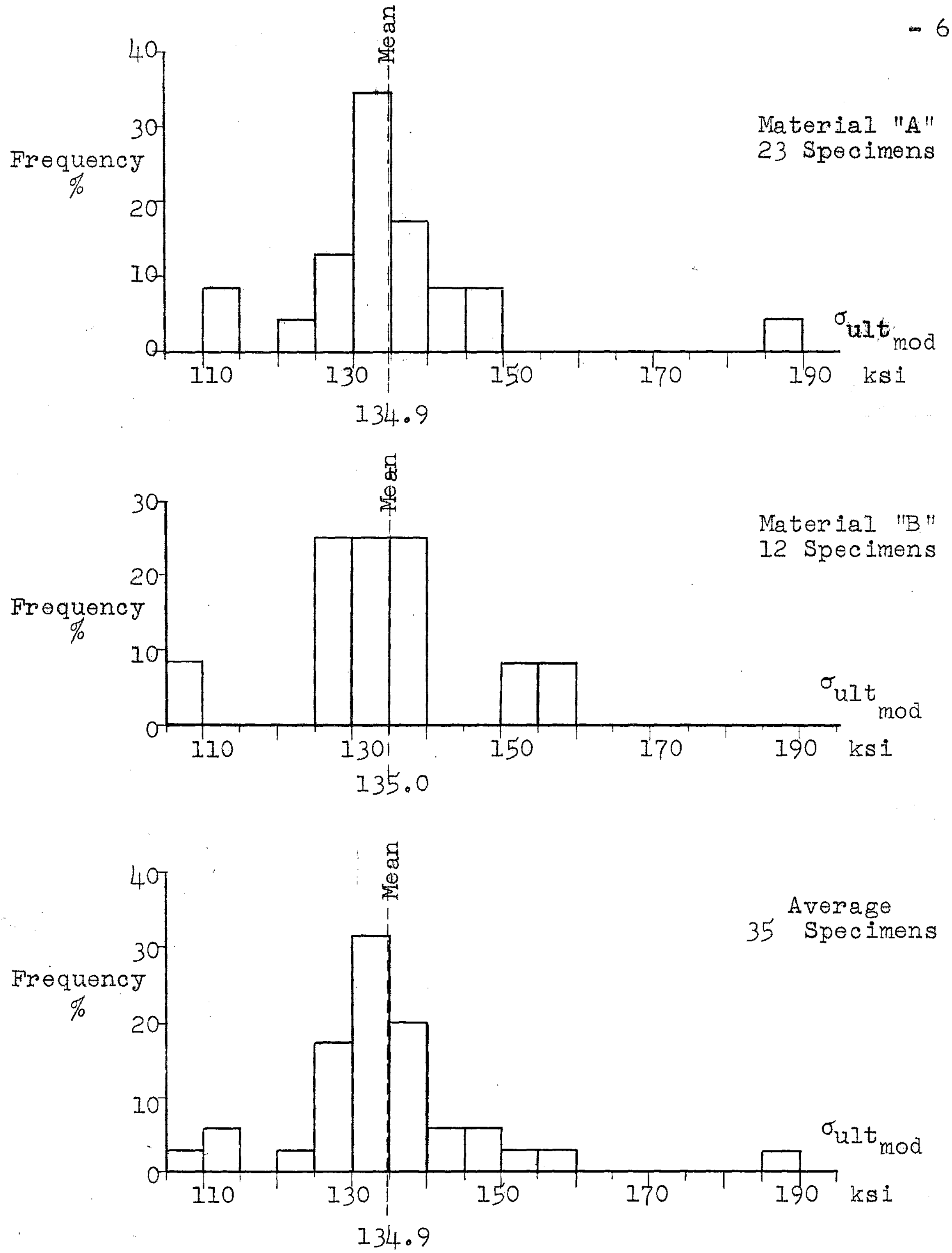


Figure 20

SIMULATED MILL COUPON RESULTS - WEIGHTED AVERAGE ULTIMATE STRESS, BASED ON REDUCED AREA

Histograms

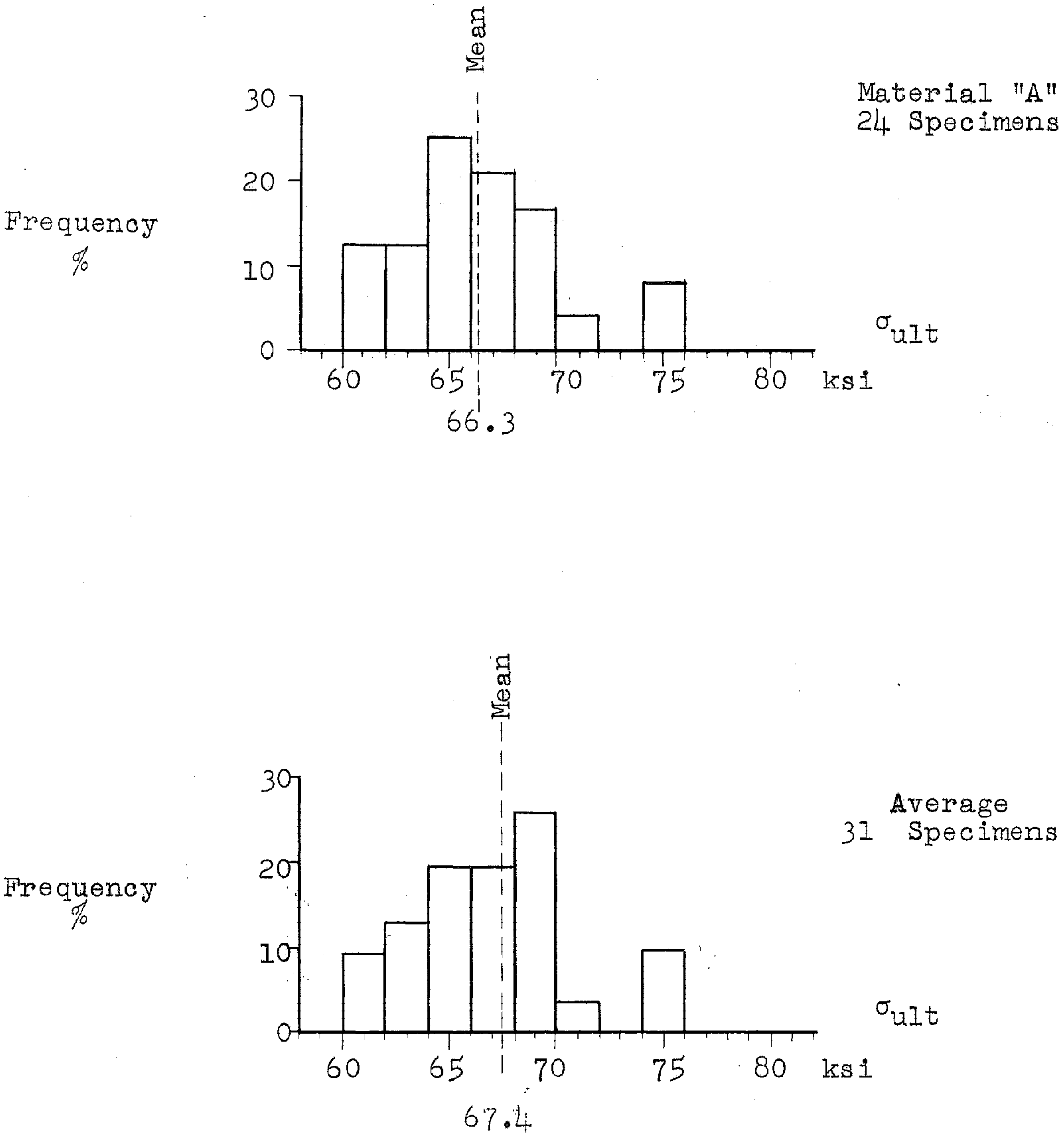


Figure 21

MILL COUPON TESTS (WEB)

ULTIMATE STRESS

Histograms

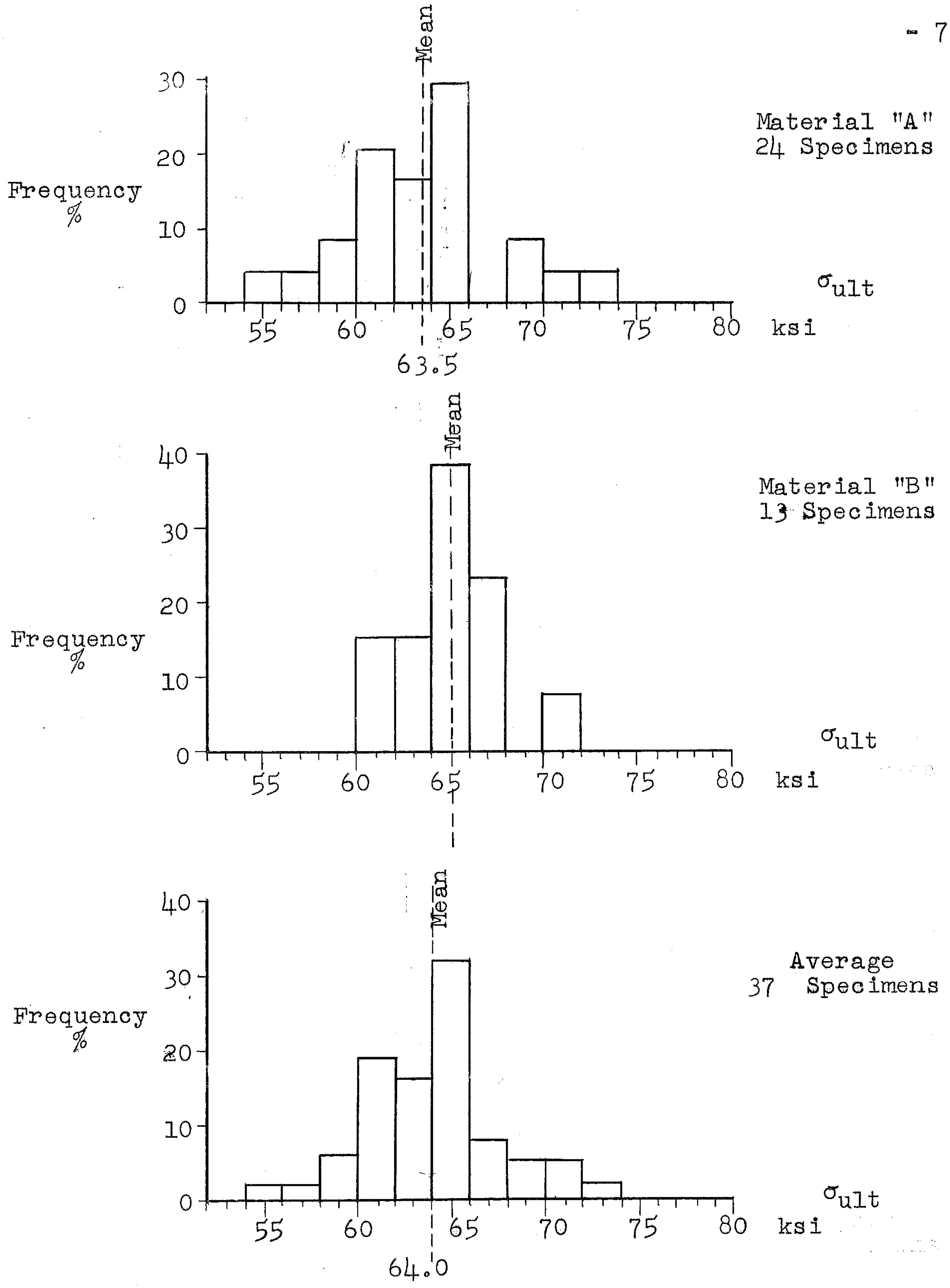


Figure 22

SIMULATED MILL COUPON TESTS (WEB)
ULTIMATE STRESS
Histograms

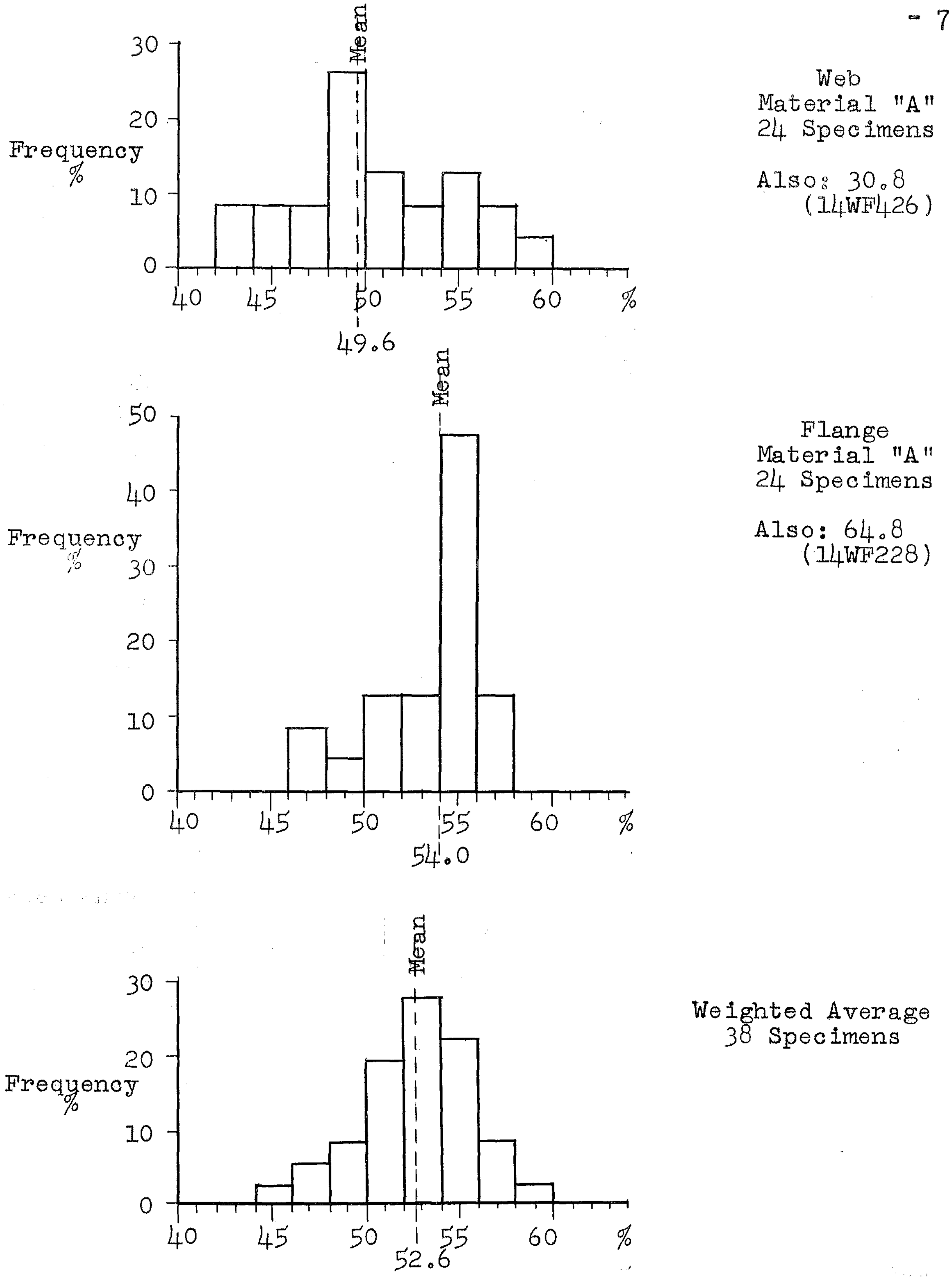
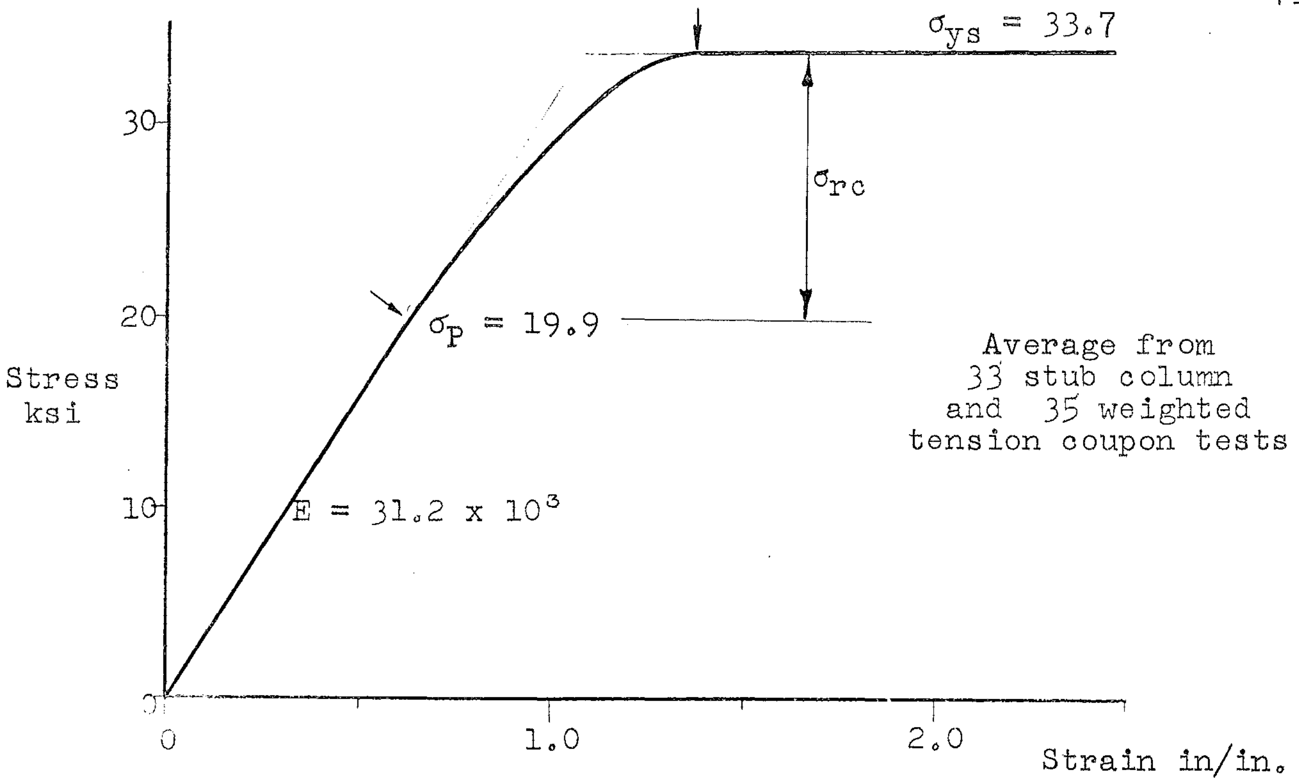
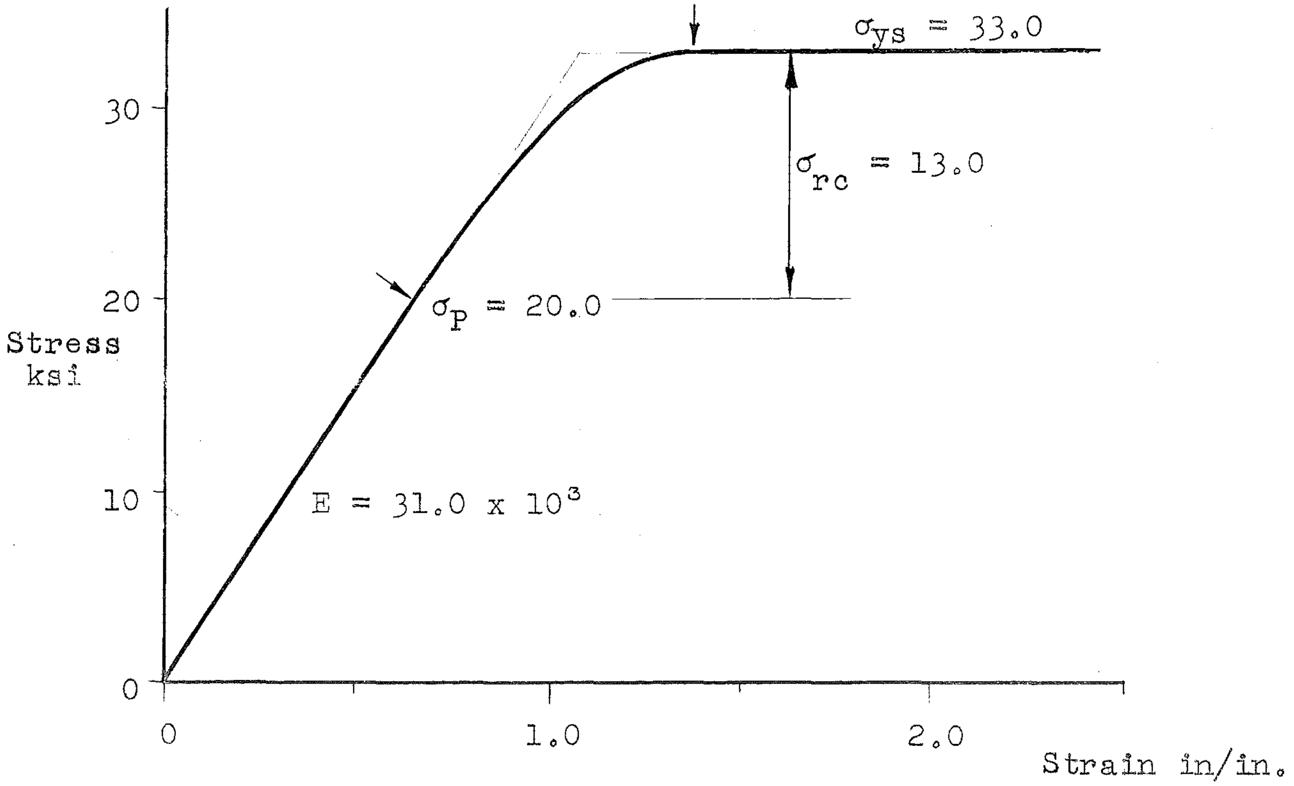


Figure 23

PERCENTAGE REDUCTION IN AREA
TENSION COUPON TESTS
Histogram



Typical Stress-Strain Curve For Stub Column
Average From Test Results



Suggested Typical Stress-Strain Curve
For WF Stub Column Test
Figure 24