1958

Material properties of structural steel, Progress Report, April 1958

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Recommended Citation

Tall, L., "Material properties of structural steel, Progress Report, April 1958" (1958). *Fritz Laboratory Reports.* Paper 1499.
http://preserve.lehigh.edu/engr-civil-environmental-fritz-lab-reports/1499

RESIDUAL STRESS AND THE COMPRESSIVE PROPERTIES OF STEEL

Progress Report

MATERIAL PROPERTIES OF STRUCTURAL STEEL

by

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(Not for Publication)

This work has been carried out as a part of an investigation sponsored jointly by the Column Research Council, the Pennsylvania Department of Highways and Bureau of Public Roads, and the National Science Foundation.

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Bethlehem, Pennsylvania

April 1958

Fritz Laboratory Report No. 220A.28A

SYNOPSIS

This report is the summary of certain aspects of the work on the general project "Residual Stress and the Compressive Properties of Steel", this phase 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, 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 A.S.T.M. A 7, mild structural steel of which columns of the type found in civil engineering structures 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 members made from this material. The results will therefore enable one to obtain a more realistic meaning of the factor of safety used in steel design today.

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

Within the limits indicated, the correlation of the results are good, although a greater sample of specimens would be expected to limit further the range of variation for any particular parameter, particularly in the case of residual stress prediction.

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I. 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 also 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, σ_y, the lowest level of yield stress immediately following σ_{uy}.

-The yield stress level, σ_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, 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 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 is used to define a value for comparative purposes.

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 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 somewhat. <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. (The effect of strain rate will be discussed in section C-5.) Use of this static level is 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 determined from such a stub column test is of decided use in column strength predictions. As shown in Reference 1, the 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, 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 as-rolled WF shapes, 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 evidenced by the 'knee' of the stress-strain curve.

In general the speed of testing for these stub columns may be regarded as static[2]. 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[8]. 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 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 requred 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, (see Figure 11).

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 3, 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.

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 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.

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)

Note: The 14 WF 426 had no apparent yield stress level, i.e. the material continually strain-hardened.

(b) Simulated Mill Tests

These are the weighted mean of the individual coupon tests. The individual data is recorded in Tables II and III, 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 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 3. The results then give the yield strength for a "dynamic" level σ_{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 B-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 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)

<u>NOTE</u>: 3000 material "B" mill tests gave: σ_{yd}=44.1 ksi (Reference 4)

(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 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 slightly 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.

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

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 greater the speed of straining, the higher the yield point tends to become, until the limit when the ultimate load is reached without yielding.

It is realized therefore that the definition of 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! Nor do the specifications take account of size effect in coupons, and differences in testing machines[4]. 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[5]. This chapter will briefly describe the problems of strain rate and will indicate some of the results that were 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 crosshead speed as the strain rate for any particular machine. This is particularly true with an 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 cross head speed to obtain the actual rate of straining. It is in the elastic protion of the loading that this effect has its greatest influence, for 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 till the yield point is reached. At this instance, when the specimen starts to plastically deform, the load is constant and no further elastic deformation of the machine can take place. For such a case, the movement between the cross heads 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, 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, (bar stock.) 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 is the limit case and is defined as the yield stress <u>at the zero strain rate</u>.

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, 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 11, a typical stress-strain curve from the series of coupon tests run on the screw-type mechanical testing machine. This static yield level 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 tending to bear 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 indentical[8]. These results and conclusions will be repeated here in summary form (see Table V). Although these particular results are for one shape, 8WF31, experience with other shapes give the same indications.

Quoting from Reference 8:

> "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 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 its physical properties. Previous investigations[4,7] have shown that this effect may exist in coupon testing, but the tests described in this report seem to indicate that no conclusions can be made 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

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 the determination of column strength of WF members 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 $\alpha <$ approx. 25, have $\begin{cases} 28 > \sigma_{ys} \\ \sigma_{ys} > 37 \text{ ksi} \end{cases}$ or

The stub column values for σ_{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) σ_{yd}, Dynamic Yield Stress, Figure 6
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 σ_{yd} is not defined for a particular strain rate, testing differences are probably present.

(c) $\sigma_{\text{ult. actual}}$ 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-section shape.

III. RESIDUAL STRESSES

A. INTRODUCTION AND DESCRIPTION

The study of residual stresses has been intensified in the last five years. This is mainly due to an increasing appreciation of their effect on the buckling strength 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[8]. While residual stresses have also been studied in built up columns, this paper will only be concerned with the cooling initial stresses in "as-delivered" rolled shapes of A 7 type steel.

Residual stresses are the non-calculated, initial stresses that are present in a structural member prior to the application of load. These, in the main, are due to uneven cooling of the member during and after hot rolling. However, residual stresses may also be formed by various fabrication methods such as welding and cold bending. As a general rule, the effect of these other types of initial stresses in is less pronounced.

The measurement of residual stresses of the type in question (longitudinal stresses) is best accomplished by the "sectioning" method, whereby the member is measured before and after cutting into longitudinal strips. This 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 8.

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 $\sigma-\varepsilon$ curve including the influence of this variable for the full cross section and the procedure is described in Reference 8.

It has been shown in these previous studies[8] that, due to the symmetry of the residual stress pattern, an actual stub column test gives a more accurate and far simpler means of obtaining the average σ-ε 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 σ-ε curve shows the effect of the residual stress distribution, it does not enable the specific distribution to be determined. σ_{rc}, which can be determined, is 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 VI, while Table V 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 gives an indication of the magnitude of the maximum compressive residual stress that occurs in the flange, σ_{rc}.

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

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 σ-ε curve of the type shown in Figure 14 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-proportional limit, thus defining what in this report will be regarded as a basic value for σ_{rc}, when discussing the results of stub column tests.

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

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[10] 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.

It is felt that sufficient accuracy is obtained by estimating values from the tables of results already at hand. ?

III. OTHER MATERIAL PROPERTIES

A. INTRODUCTION AND DESCRIPTION

The determination of the yield strength of a material is usually accompanied by the finding of the elastic modulus. Furthermore, 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, and
2. Ultimate strength of a tension coupon.

The strain hardening modulus, E_{st}, may also be obtained from coupon and stub column tests, but its determination was not included in this program.

The two moduli, E and E_{st}, may be defined as the ratio of stress to strain in the elastic and at the on-set of the strain hardening ranges. E is a constant up to the proportional limit. E_{st} is never constant, and is usually defined at the onset of the strain hardening since it is this value that is important in solving many stability problems.

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 experimentally determined values for E from both coupon and stub column tests. 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.

The experimental values for E, as determined from the coupon tests, were obtained from the measurement of the slope of the elastic portion of the stress strain curve, a typical example of which is shown in Figure 11. The accuracy is of an estimated order of 5-10%, which includes inaccuracies of the automatic plotting, of the calibration of the gage and of the actual measurement of the slope. The value of E for the complete cross section was then obtained by averaging, according to weight, the individual values obtained from coupon tests of web and flange.

Young's Modulus, as determined from a stub column test, is of an estimated 5% accuracy, and is the measurement of the slope of a stress strain curve plotted to an enlarged scale, from experimental results of deformations over a 10" gage length as measured by the mean of two $\frac{1}{10,000}$th dial gages.

(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" $E = 31.2\text{x}10^{3}$ ksi mean value (21 specimens)
material "B" $E = 31.1\text{x}10^{3}$ ksi mean value (11 specimens)
average $E = 31.2\text{x}10^{3}$ ksi mean value (32 specimens)

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

material "A" $E = 31.5\text{x}10^{3}$ ksi mean value (19 specimens)
material "B" $E = 30.4\text{x}10^{3}$ ksi mean value (7 specimens)
average $E = 31.2\text{x}10^{3}$ 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" $\frac{E,\text{coupon}}{E,\text{stub column}}$ = 99.7% mean value (16 specimens)

material "B" " = 100.7% mean value (6 specimens)

average " = 100.0% mean value (22 specimens)

3. 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, which is a more accurate indication of the ultimate stress. The individual percentage reductions have been combined according to the weighted average.

It is conceded 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, based on original cross-sectional area, 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 Simulated 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)
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. Only the initial portion of the curve has been shown, neither the strain hardening region nor the ultimate stress being included. Figure 24

IV. 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. Further, it is independent of time. 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 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, 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 $\sigma_y = 33$ ksi.

   These results are also shown in a statistical form, both as histograms, and as assumed normal distributions on probability paper. This is further discussed in item 11 below.

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 large sections would give small values for σy, while small sections would 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. 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 10. Even with apparently small strain rates,(approaching zero), σyd can be 5% greater than σys, 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 σyd 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 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 8 and Section I-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 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 difficult to draw definite conclusions from these figures above, particularly as previous investigations[4] have obtained 85%± 5% as the ratio of $\frac{\sigma_{ys}}{\sigma_{yd}}$, where σ_{ys} refers to stub column tests.

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

3. 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 σ_{ys} from stub column tests. 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 strength of the full cross section of a wide flange shape may be estimated, with complete confidence, from tension tests on coupon 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 $\sigma - \varepsilon$ curve (showing effect of residual stresses) for the full cross section cannot be determined.

4. 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 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 trend has been indicated from the reasonable correlation between Marshman[5] and Romanelli[6], the former testing being carried out on a screw-type mechanical machine, whereas the latter was 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 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 σ_{ys} is to decrease the strain rate to zero once or twice in the plastic yield range (ensuring no strain reversal).

5. It was shown that compression and tension coupons give almost identical results. This statement is based upon the work of previous investigations[8]. The difficult compression coupon test can therefore be eliminated in all but confirmatory cases.

6. Generally speaking, heavier sections have a lower σ_y than lighter sections. Similar general statements can be made for b/t and α ratios.

7. From the stub column tests conducted, the indicated value for σ_r is 13 ksi, (with a standard deviation of 4.5 ksi.). This is the mean value of the maximum compressive residual stresses in the cross section and generally occurred at the flange tip. Further, this value is the complement of the proportional limit with respect to the yield stess, indicating that the average value for the proportional limit of the sections tested was 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 VI 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, rather than narrower, in distribution, with respect to the σ_r histogram, it is concluded that σ_r is not a function of the yield stress. See also Table IV. 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[11].

8. The prediction of the residual stress distribution based on mathematical relationships between the cross sectional physical properties has not been successful up to this time. However, a good 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, with a standard deviation of 1.5×10^3 ksi, the overall average value obtained from all coupon and stub column tests conducted in this series.

As with the yield stress, a good 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 of cross section on the Young's modulus was noted, among the relatively small number of specimens tested.

The values obtained in this series of tests showed both a greater deviation among themselves, and a higher mean value, than obtained in tests of other investigations.[7,8]

10. The ultimate strength of tension coupons, Section III-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 as shown in Figure 23, is also reasonably consistent. A difference of 5% between web and flange values was noted suggesting that thickness of rolled section could have an effect. Considering a weighted average for all specimens, the percentage reduction in area is approximately 53%± 5%. (A standard deviation of 4.6% was measured, assuming a normal distribution.)

11. 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 results on probability paper, using the assumption of a normal distribution.

Whereas the histogram is a plot of classified values according to actual frequency of distribution in the tests, the cumulative plot, and its line of best fit, is an attempt to obtain a frequency distribution valid for all tests from the small sample of tests at hand. It is obvious then, that if the histogram were to be constructed from a sufficiently large number of values, it would approach the actual frequency distribution for the parameter considered. If this distribution be plotted on a cumulative basis, the resulting curve is a cumulation distribution function, which again, if plotted on probability paper is a straight line for a normal distribution. If the distribution be skew, a plot on logarithmic probability paper would render a straight line. 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. In practically every case, the assumption of a normal distribution was reasonably true. Although in some cases, such as Figure 21, a skew distribution may have given a better approximation.

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 4.) Further, it may be shown[12,13,14], 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.[12,13,14] 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.

It should be noted, that when the experimental data are plotted, the frequency is the ordinate of the curve, but that once the line of best fit has been drawn and hence the normal distribution fixed, the ordinate then is the probability, useful for future estimations.

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 IV.

V. CONCLUSIONS

Continuing on from the previous chapter of 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.

	σ_{ys}	=	33 ksi	with	s =	4 ksi
	σ_{rc}	=	13 ksi			5 ksi
	σ_{p}	=	20 ksi			5 ksi
	E	=	31×10^3 ksi			1.5×10^3 ksi
(on original area)	σ_{ult}	=	64 ksi	Coupon Tests		3 ksi
(on reduced area)	σ_{ult}	=	135 ksi			11 ksi
percentage reduction in area		=	53%			5%

2. The yield stress should be defined by the "static" yield stress level for reasons discussed in Chapter IV.

3. The effect of strain rate on the yield stress level has been discussed in Chapter I. For authoritative conclusions regarding the influence of this variable, a substantial number of tests on steels from different manufacturers should 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 10 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%± 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.

5. 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.

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.

VI. ACKNOWLEDGEMENTS

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 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 author is greatly indebted to Dr. Lynn S. Beedle and to Dr. Robert L. Ketter. Their advice and suggestions are sincerely appreciated. 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 and Theodore Galambos assisted in the tests and in the preparation of the data. Miss Grace Mann typed the manuscript. Their cooperation is gratefully appreciated.

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VIII. 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
s	Standard deviation, a statistic measure of the scattering of observations
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, (as obtained from the mill report).
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" coupon test (simulated) mill	Material "A" stub column	Material "B" coupon test (simulated) mill	Material "B" 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	

* Numbers, 220A Program, August 26, 1954, Phases 4 and 5

TABLE II

General Experimental and Analytical Data for Material "A"

NOTE: All values are in kip-inch units

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	σ_{ult} coupon 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

* No apparent yield load

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	$\frac{\sigma_{ult}\text{mill}}{\sigma_{wetweb}}$ coupon %	σ_{ult} weighted coupon	$\frac{\sigma_{ult}\text{weighted coupon}}{\sigma_{ult}\text{mill}}$ %	% redn.- in area		% redn.- in area weighted average	Redn. area =% of orig- inal	σ_{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 flange	E coupon web	E coupon weighted	E stub column	$\frac{E_{coupon}}{E_{stub\ column}}$ %
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	--	29.6	--
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	$\alpha = \frac{\text{area flanges}}{\text{area web}}$	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				39.9		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
	6WF25										61.3	61.4

*from previous investigations

TABLE III, continued (a)

No.	Shape	σ_{ys} coupon		σ_{yd} coupon		σ_{ys} weighted coupon	σ_{yd} weighted coupon	$\frac{\sigma_{ys}}{\sigma_{yd}}$ %	$\frac{\sigma_{ys}}{\sigma_{y\,mill}}$ %	$\frac{\sigma_{ys\,stub\,column}}{\sigma_{ys\,weighted\,coupon}}$ %	$\frac{\sigma_r}{\sigma_{ys}}$ stub column	$\frac{\sigma_r}{\sigma_{ys}}$ mod. stub column
		flange	web	flange	web							
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						
	6WF25				42.2	34.9						

* 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

Statistical Results Assuming a Normal Distribution

Fig.	Description	Mat'l.	No. of Specimens	Mean ksi	s ksi	Average		
						No. of Specimens	Mean ksi	s ksi
4 b	σ_{ys} Stub Column	A	20	33.1	5.1			
		B	14	35.0	2.2	34	33.9	3.8
5 b	σ_{ys} Sim. Mill	A	22	32.8	4.7			
		B	13	34.6	2.5	35	33.5	3.8
6 b	σ_{yd} Mill (web)	A	24	42.8	5.0			
		B	14	41.5	3.5	38	42.3	4.4
7 b	σ_{yd} Sim. Mill (web)	A	24	40.1	6.0			
		B	13	41.4	3.3	37	40.6	4.9
8 b	σ_{ys}/σ_{yd} (Mill)	A	20	76.4%	6.1%			
	σ_{ys}/σ_{yd} Sim. Mill	A	22	81.2%	4.9%			
		B	13	83.8%	4.3%			
15 b(1)	σ_{rc} (max.)stub column	A	19	13.5	4.2			
		B	7	14.6	4.3	26	13.8	4.7
15 b(2)	$\sigma_{rc_{mod}}$ (max.) stub column	A	19	10.5	4.2			
		B	7	12.6	3.4	26	11.1	4.1
16 b(1)	σ_{r}/σ_{ys}	A	19	41.1%	11.1%			
		B	7	41.5%	12.7%	26	41.2%	12.6%
16 b(2)	$\sigma_{r_{mod}}/\sigma_{ys}$	A	19	32.9%	13.3%			
		B	7	35.6%	9.4 %	26	33.6%	12.0%
17 b(1)	E, weighted coupons	A	21	31.2	1.4			
		B	11	31.1	1.1	32	31.2 x10^3	1.3 x10^3
17 b(2)	E, stub columns	A	19	31.5	1.6			
		B	7	30.4	1.5	26	31.2 x10^3	1.6 x10^3
18 b	E/E, comparison of 17 (a) & 17 (b)	A	16	99.7%	6.1%			
		B	6	100.9%	10.4%	22	100.0%	7.8%
19 b	σ_{ult} Sim. Mill (weighted)	A	23	62.4	2.8			
		B	12	65.3	3.2	35	63.7	3.0
20 b	$\sigma_{ult_{mod}}$ Sim. Mill (based on reduced area)	A	23	134.9	10.1			
		B	12	135.0	12.5	35	134.9	11.1
21 b	σ_{ult} Mill Test (web)	A	24	66.3	3.6			
		B	7	68.2	2.6	31	66.7	3.3

TABLE IV - Continued

Fig.	Description	Mat'l.	No. of Specimens	Mean ksi	s ksi	Average		
						No. of Specimens	Mean ksi	s ksi
22 b	σ_{ult} Sim. Mill (web)	A	24	63.5	4.4			
		B	13	65.0	2.0	37	64.0	3.6
23 b(1)	% red. in area	A web	24	49.6	6.4			
		A flange	24	54.0	4.2	24	53.3	4.6
23 b(2)	% red. in area	B web	14	50.8	7.7			
		B flange	14	51.6	5.7	14	51.4	6.0
23 b(3)	% red. in area weighted average, tension coupon tests.	A	24	53.3	4.6			
		B	14	51.4	6.0	38	52.6	4.7

TABLE V

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 VI

Residual Stresses Due to Cooling in WF Shapes

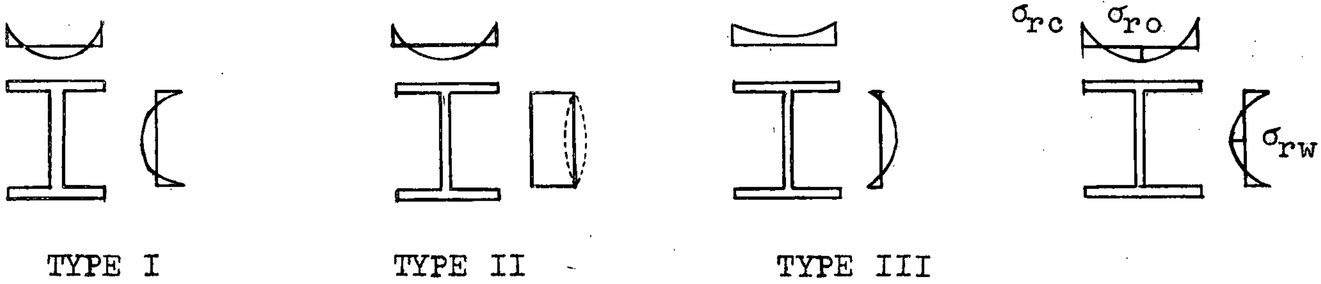
Stress in ksi	Flange Edge			Flange Center			Web Center		
	max.	avg.	min.	max.	avg.	min.	max.	avg.	min.
Columns d/b-1.5	-5.5	-12.3	-18.7	16.5	4.6	-3.7	17.5	3.9	-15.5
Beams d/b 1.5	-4.1	-7.7	-10.8	19.7	14.6	8.3	-8.8	-16.3	-29.5

tension = +
compression = -

These are results of all tests conducted in Fritz Engineering Laboratory on Research Project No. 220A[10]

TABLE VII

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

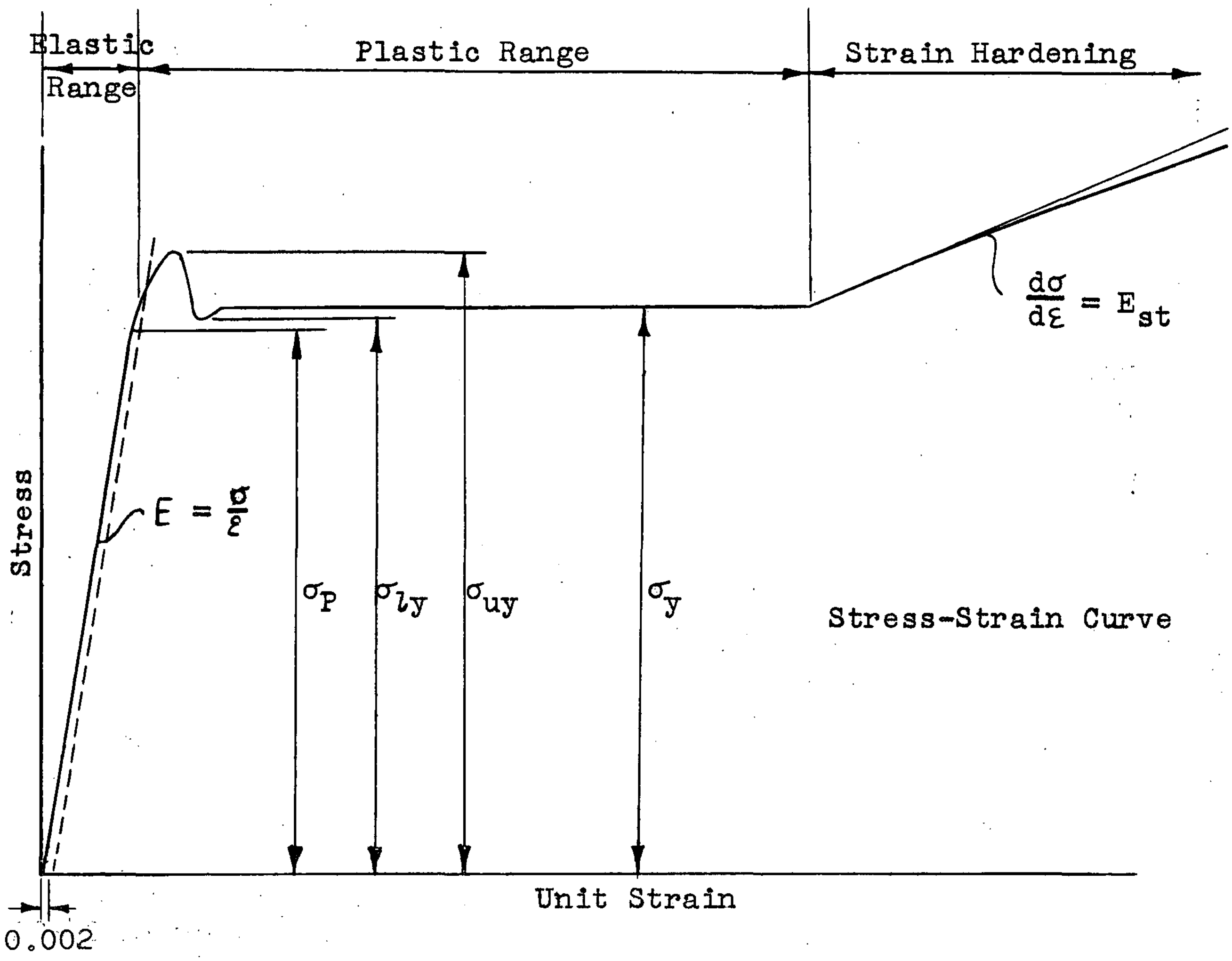


Figure 1

GRAPHICAL DEFINITION OF TERMS

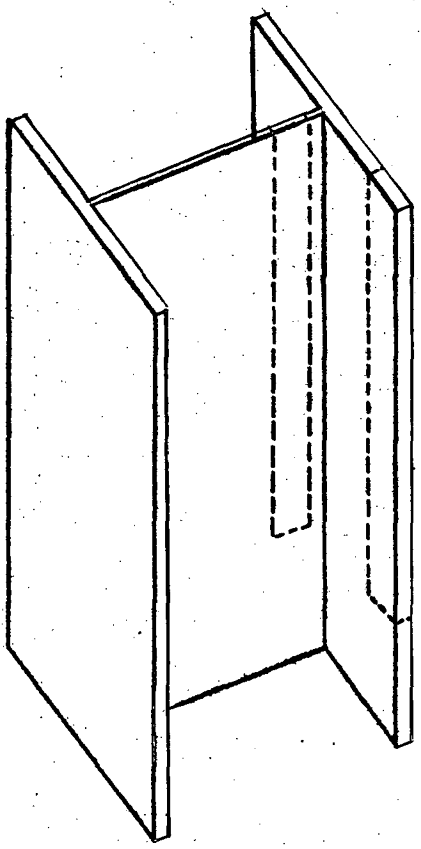


Figure 2

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

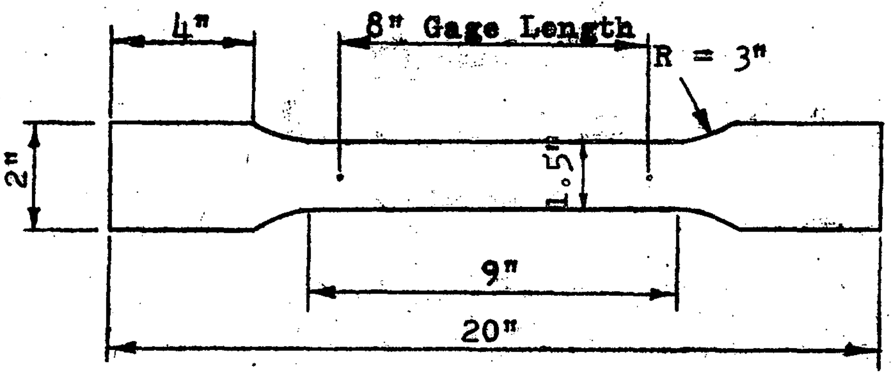


Figure 3

DIMENSIONS OF TENSION COUPON

(Shaped to ASTM Specification)

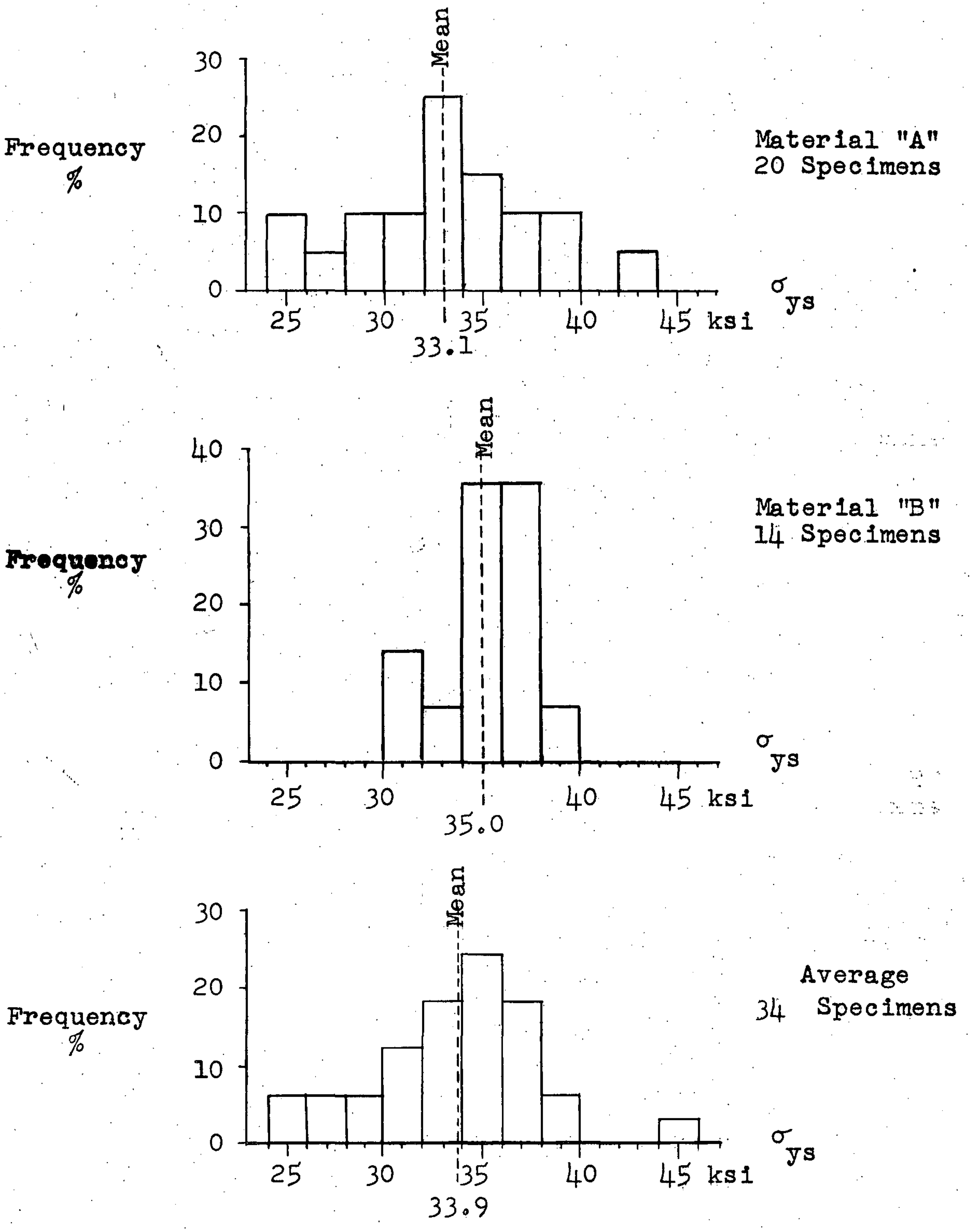


Figure 4(a)

STUB COLUMN TEST RESULTS

The Static Level Of Yield Stress, σ_{ys}

Histograms

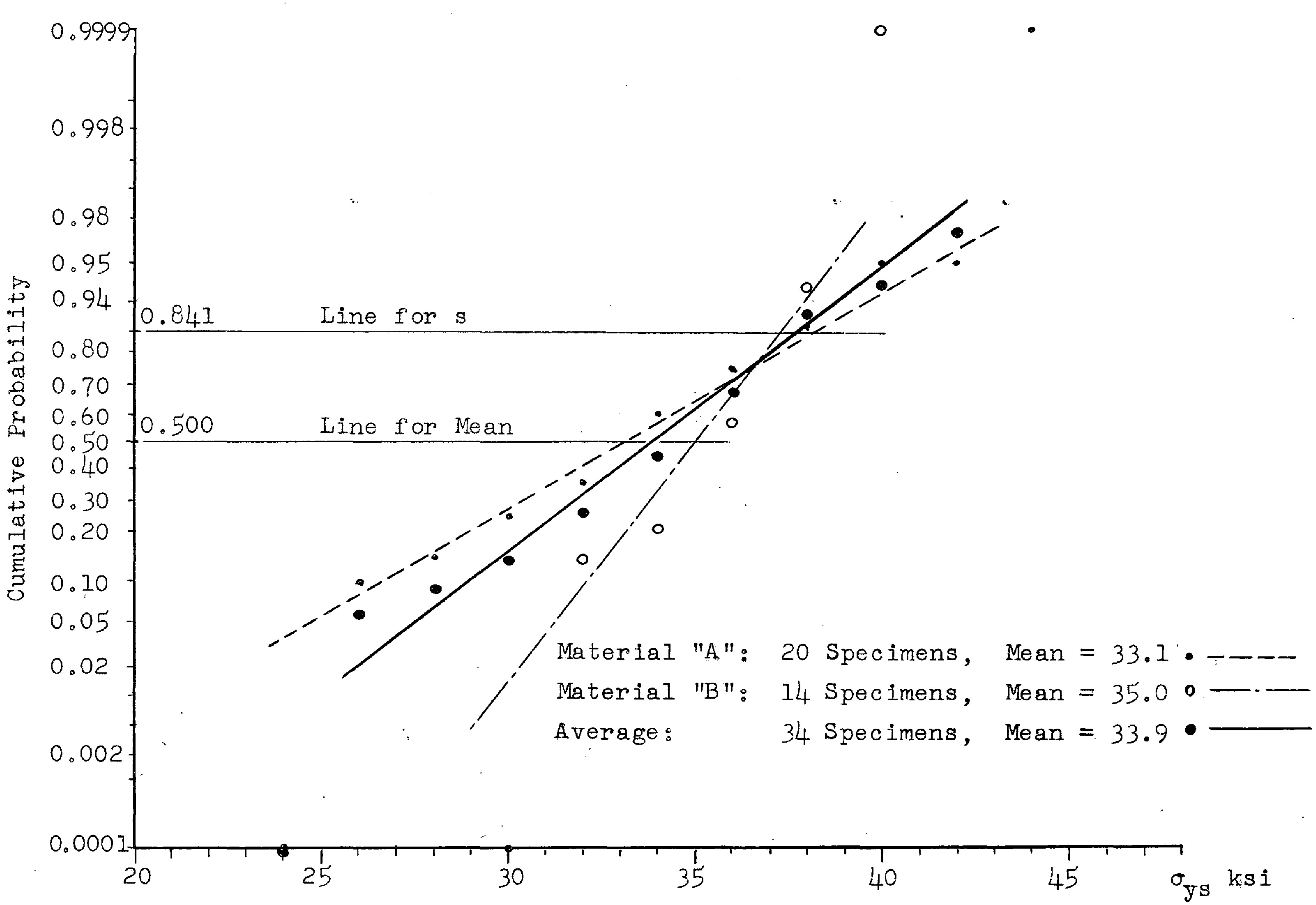


Figure 4(b)

STUB COLUMN TEST RESULTS

The Static Level Of Yield Stress, σ_{ys}

Normal Distribution Probability Curves

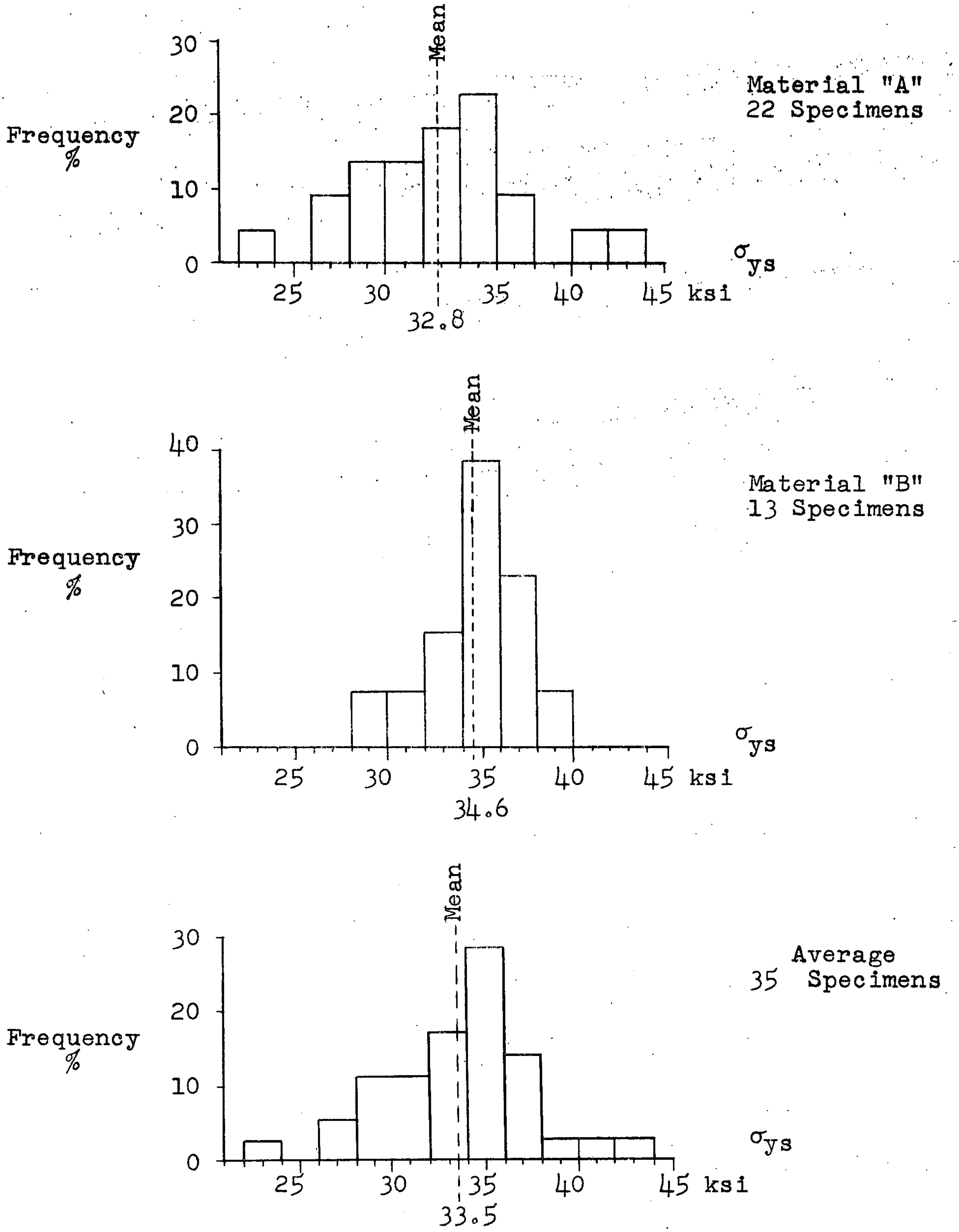


Figure 5(a)

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

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

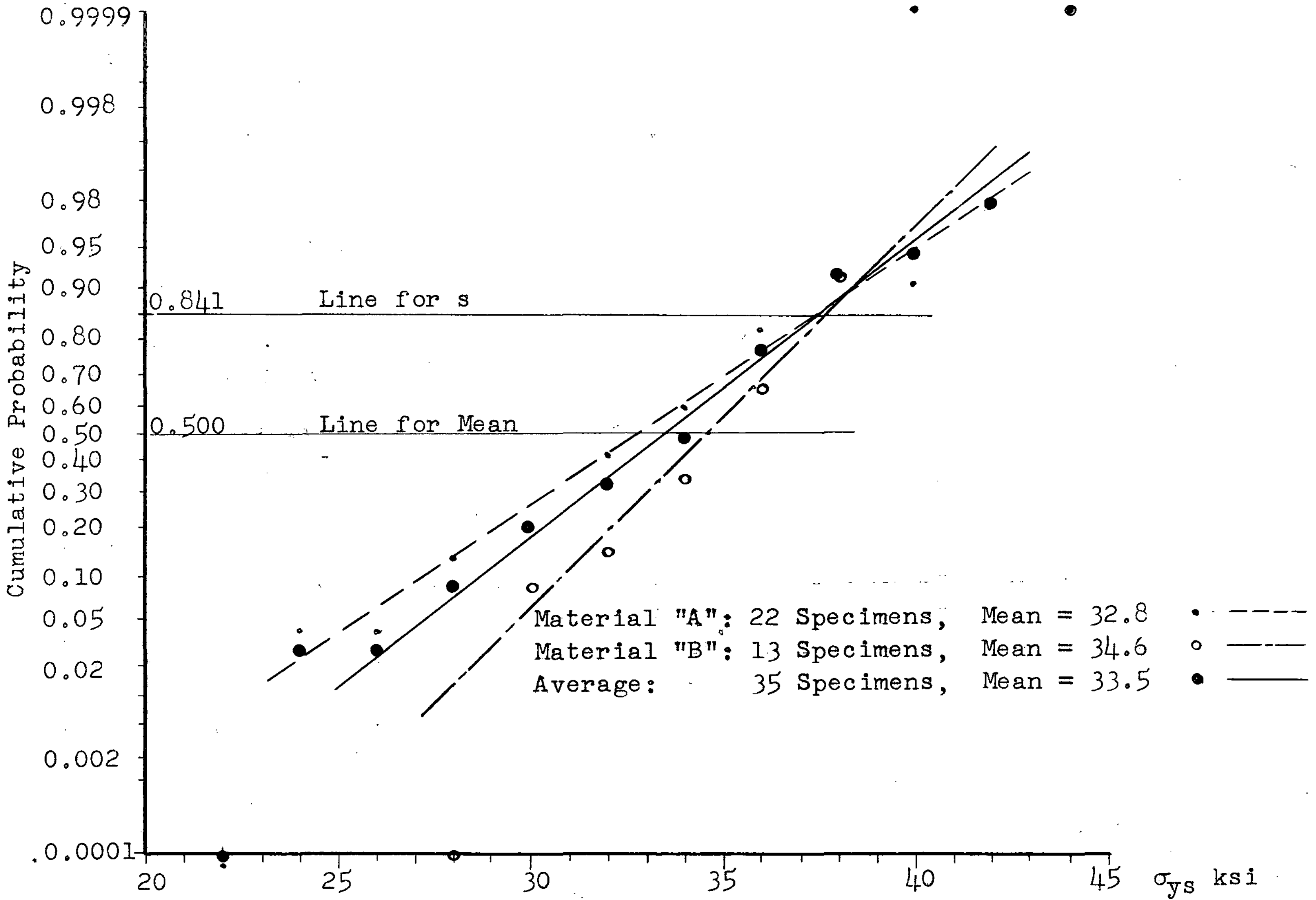


Figure 5(b)

SIMULATED MILL TESTS

(Weighted Mean Of Flange And Web Coupons)

The Static Level Of Yield Stress, σ_{ys}

Normal Distribution Probability Curves

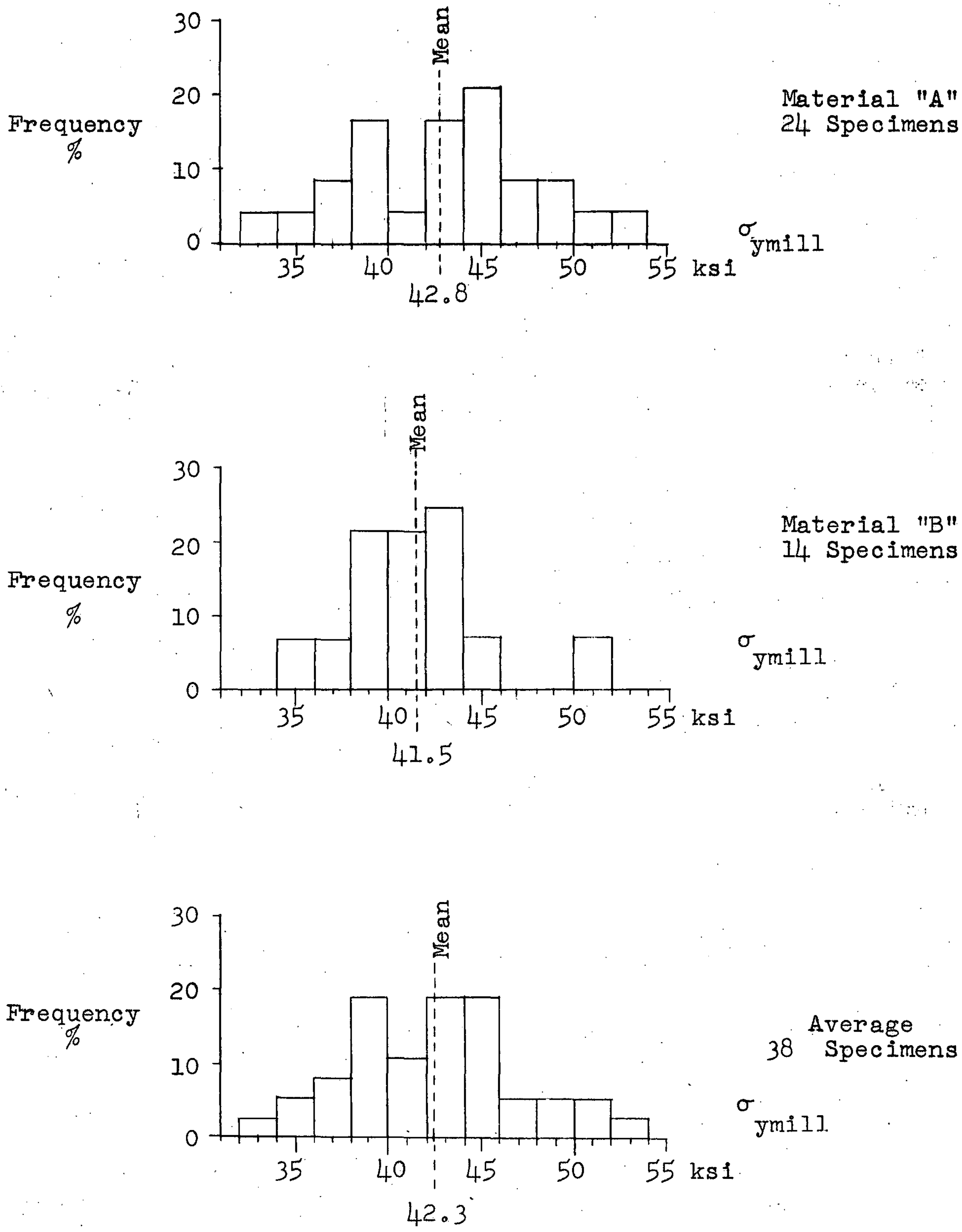


Figure 6(a)

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

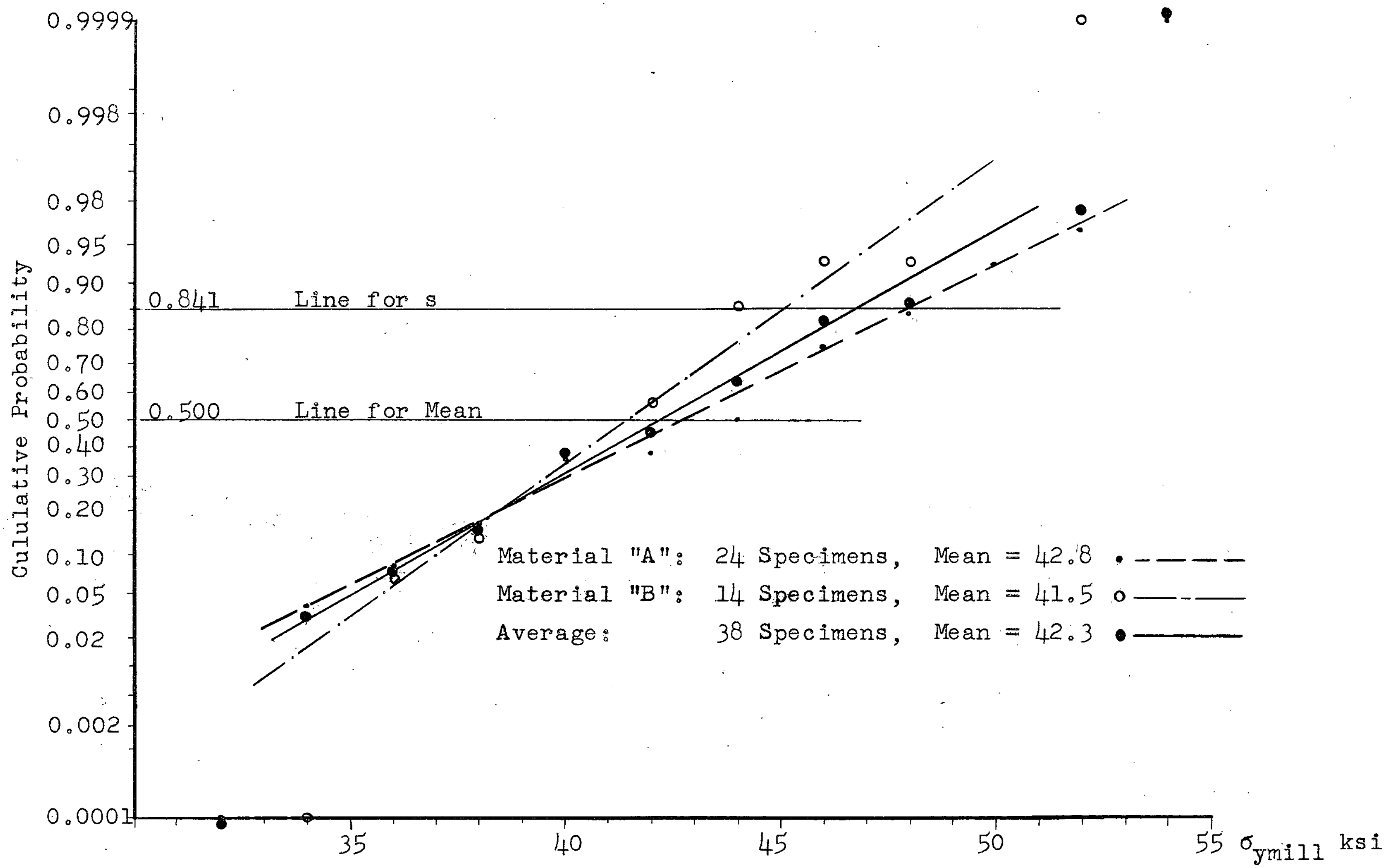


Figure 6(b)

MILL TESTS (WEB COUPONS)

The Dynamic Level of Yield Stress, σ_{ymill}

Normal Distribution Probability Curves

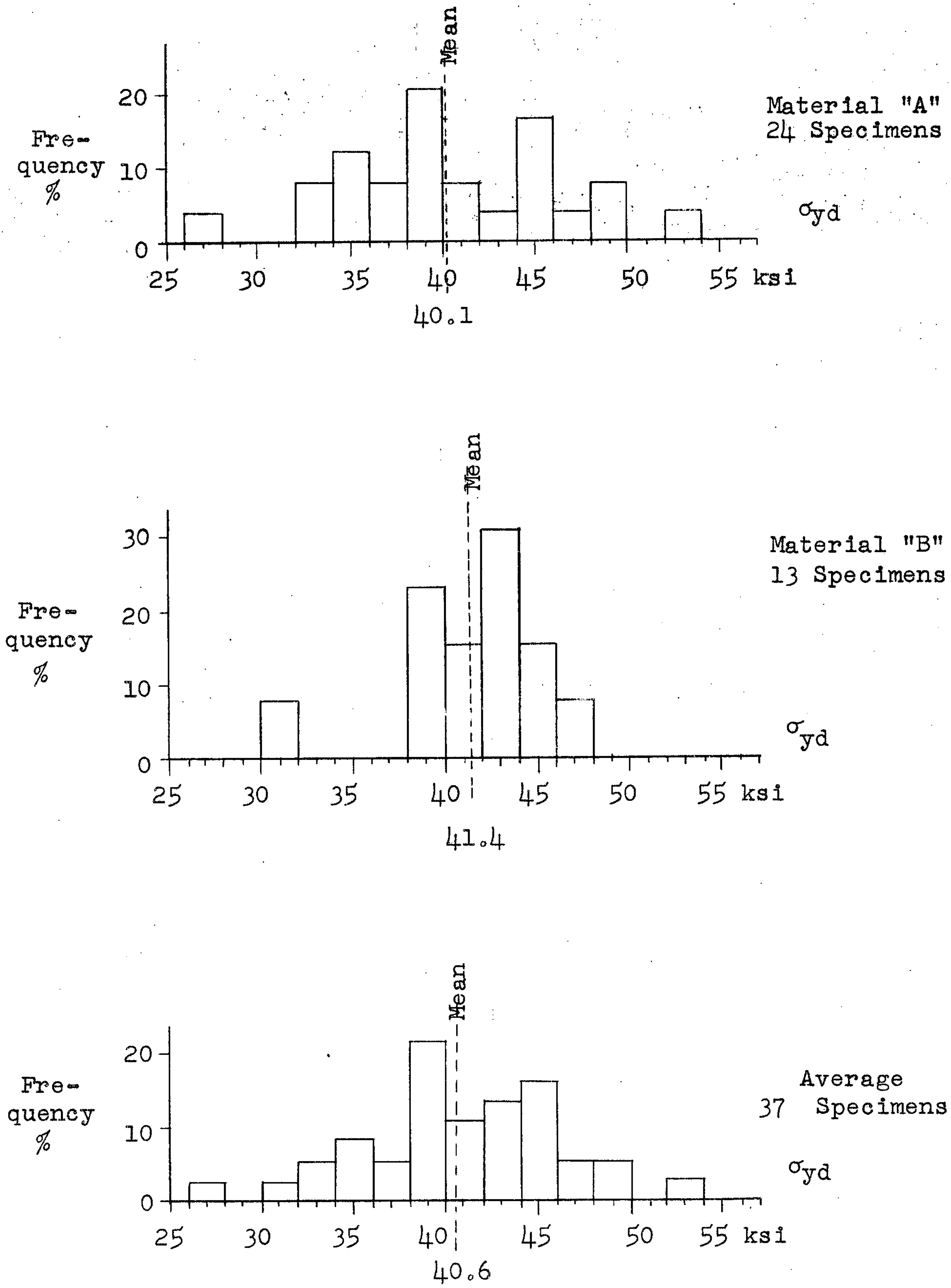


Figure 7(a)

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

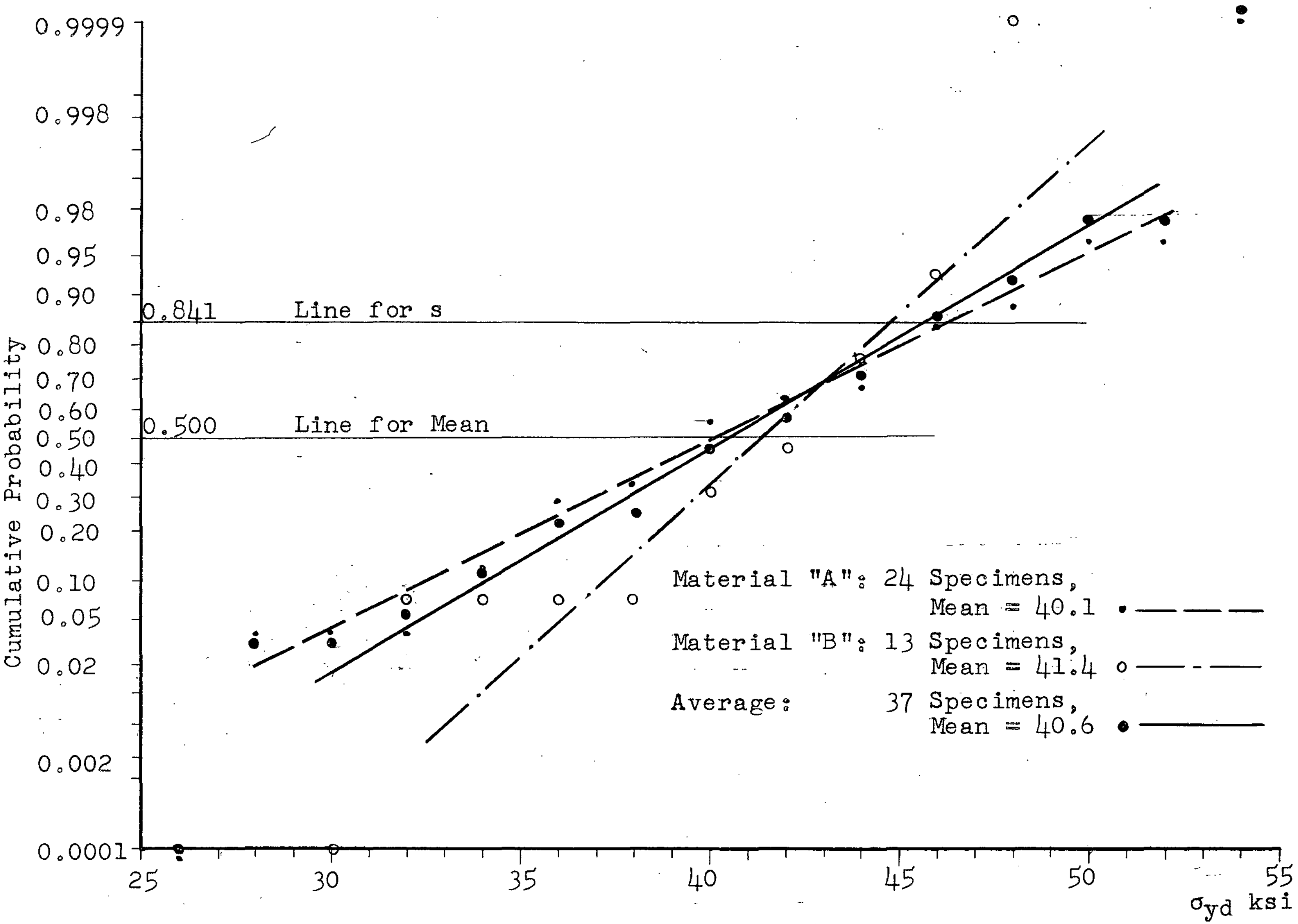


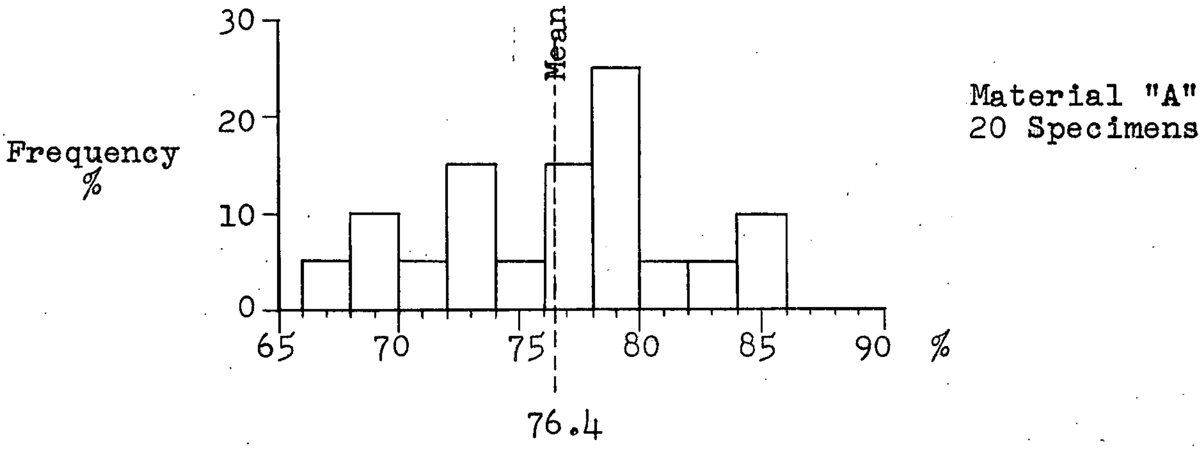
Figure 7(b)

SIMULATED MILL TESTS (WEB COUPONS)

The Dynamic Level of Yield Stress, σ_{yd}

Normal Distribution Probability Curves

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



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

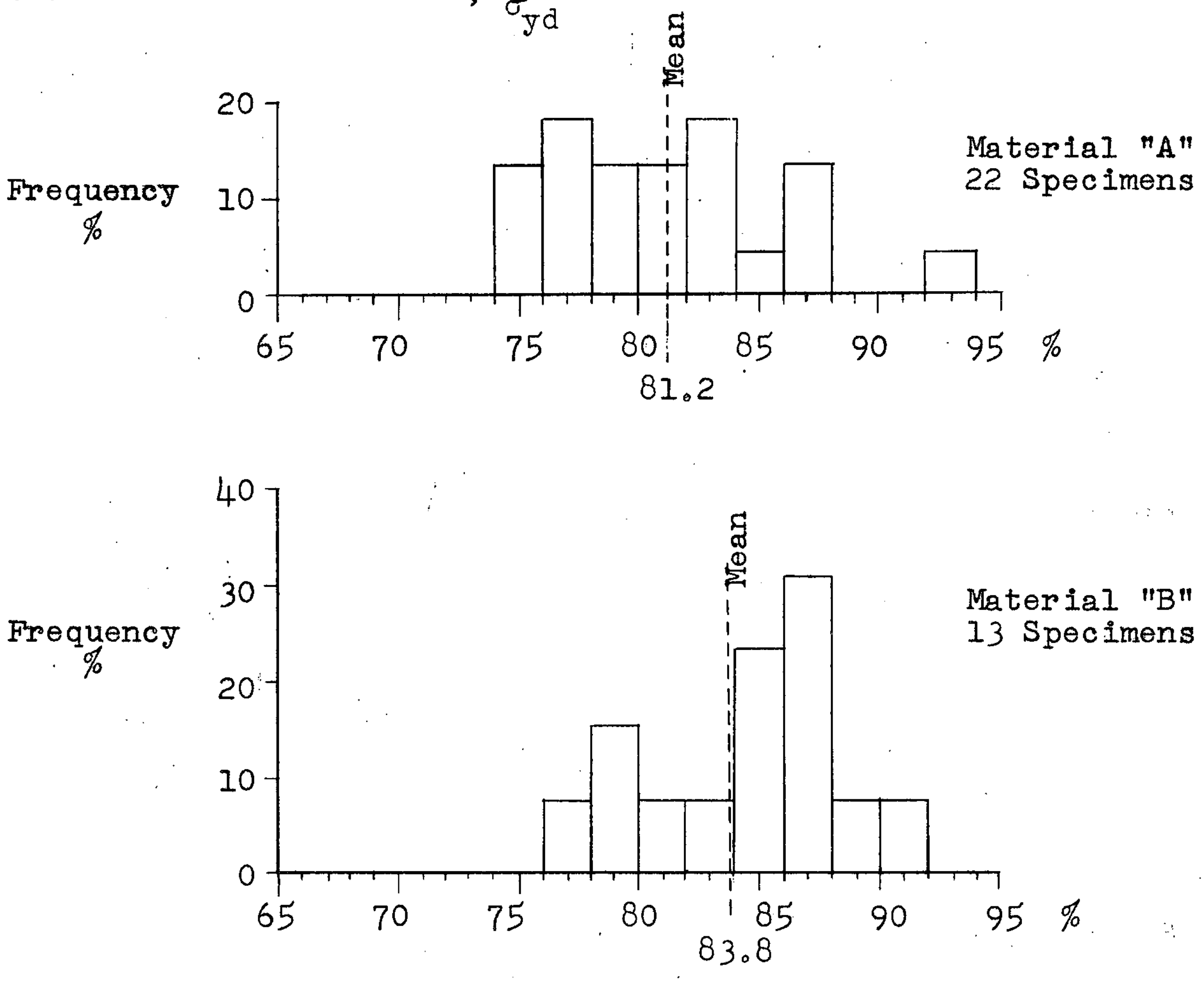


Figure 8(a)

RATIOS OF STATIC YIELD STRESS TO MILL YIELD STRESS
Histograms

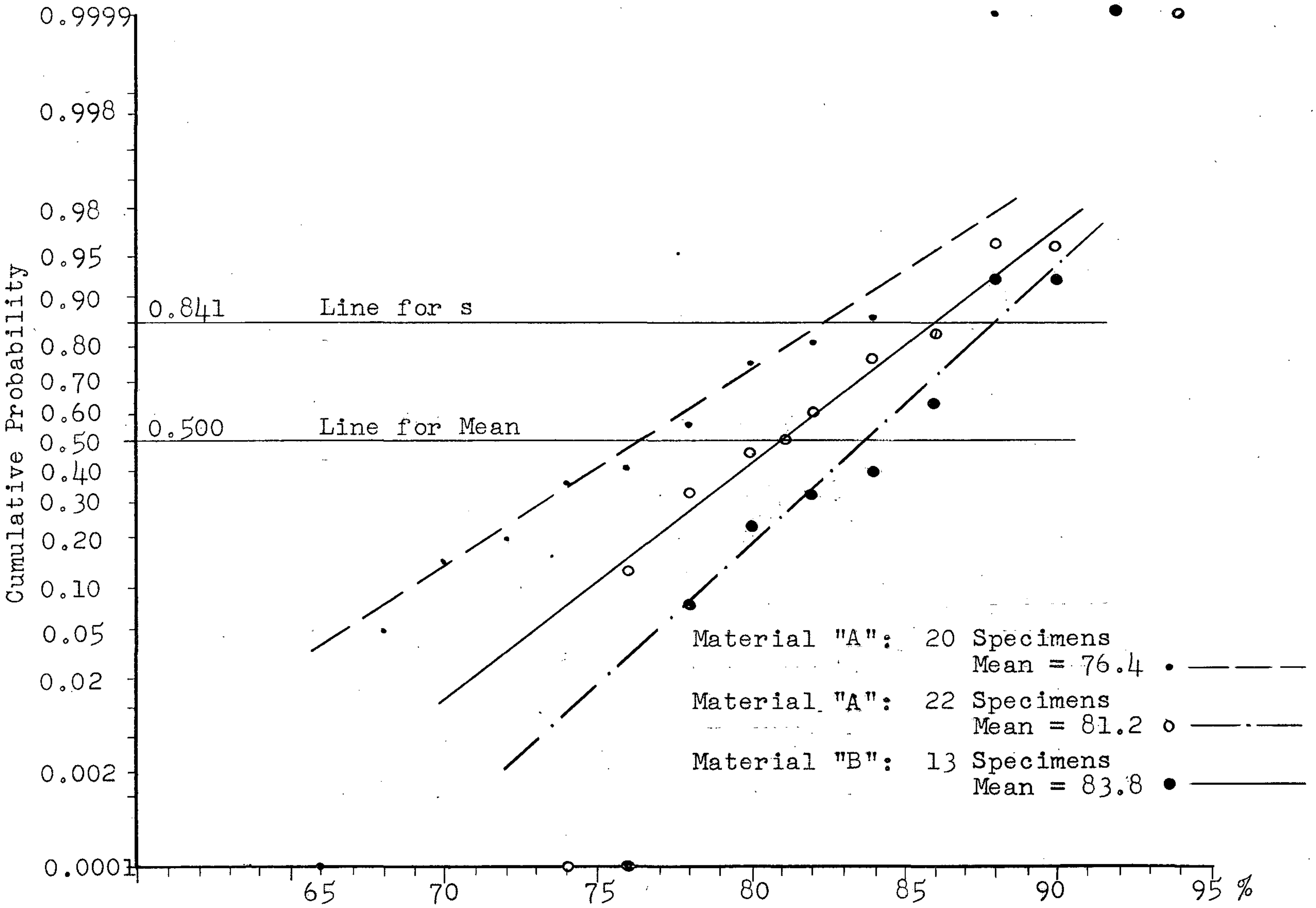
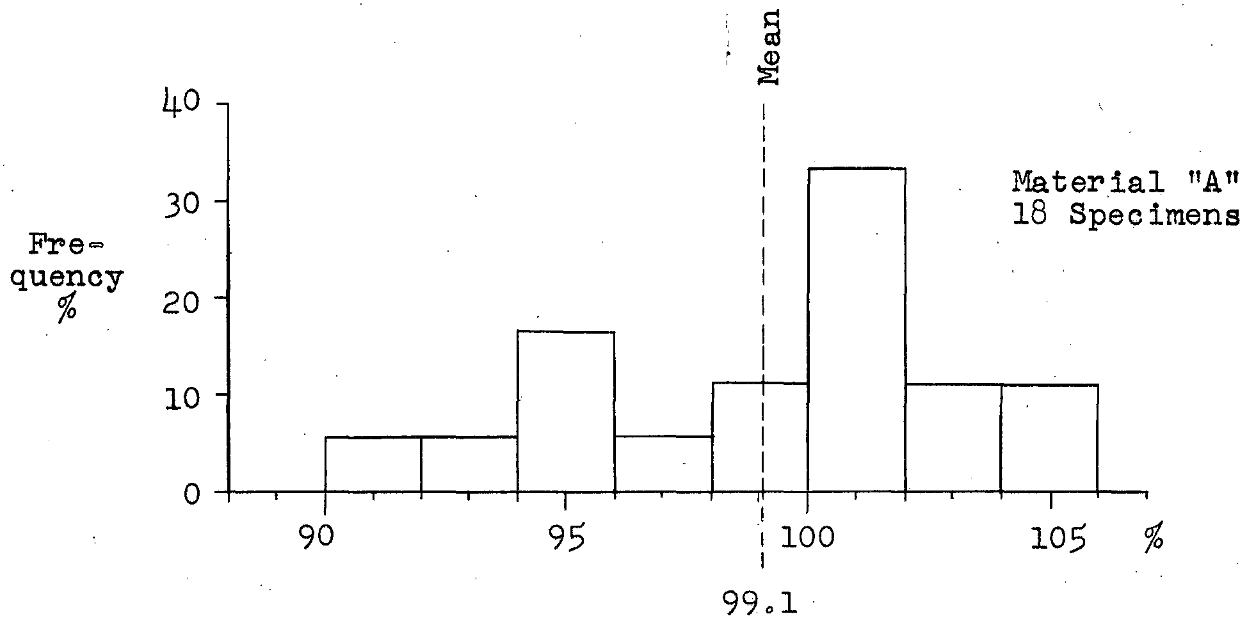


Figure 8(b)

RATIOS OF STATIC YIELD STRESS TO MILL YIELD STRESS

Normal Distribution Probability Curves



$$\frac{\sigma_{ys}\ \text{Stub Column}}{\sigma_{ys}\ \text{Weighted Coupon}}$$

Figure 9

RATIO OF STATIC YIELD STRESS, STUB COLUMN TO WEIGHTED COUPONS

Histogram

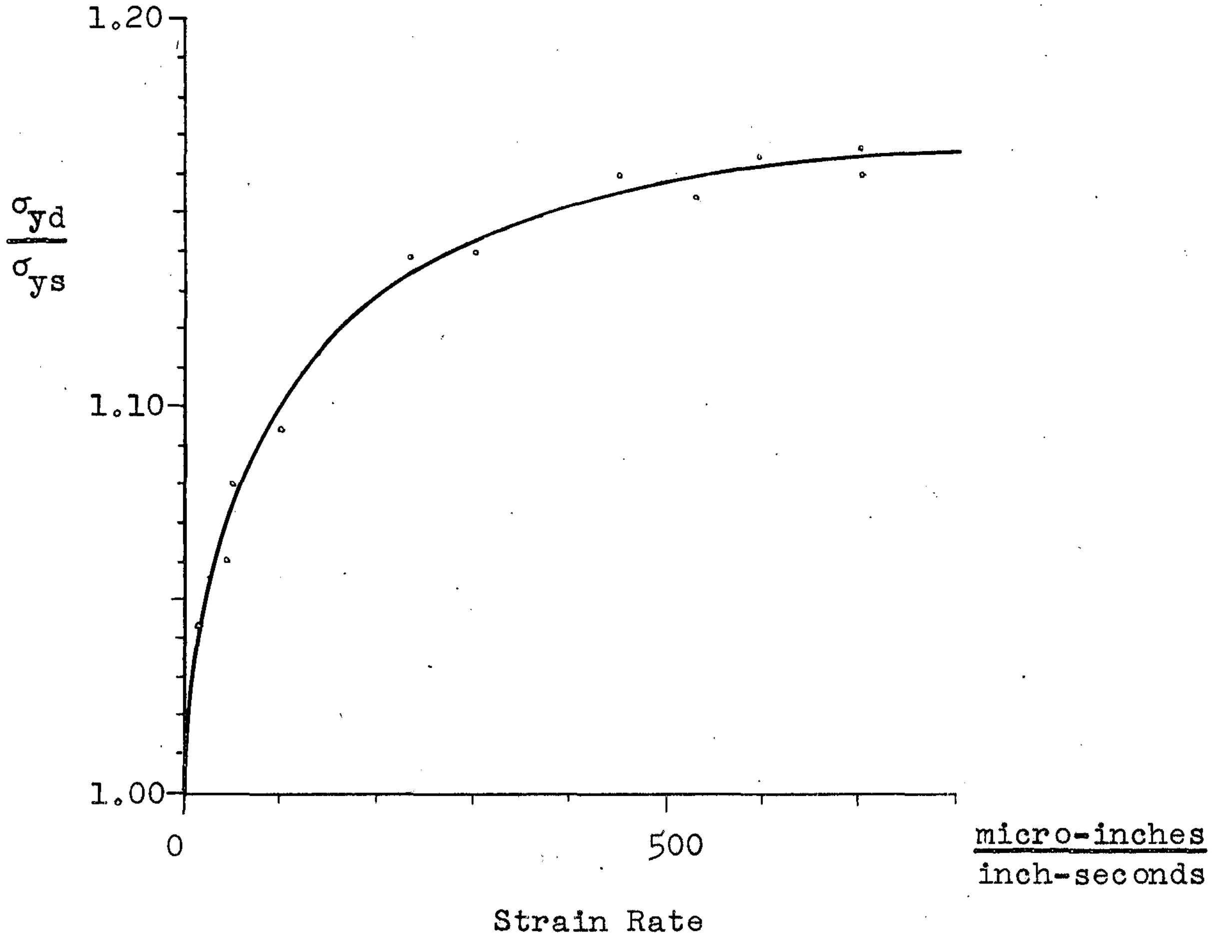


Figure 10

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

USING THE 'FREE RUNNING' CROSSHEAD SPEED

(Fig. a, of Reference 5)

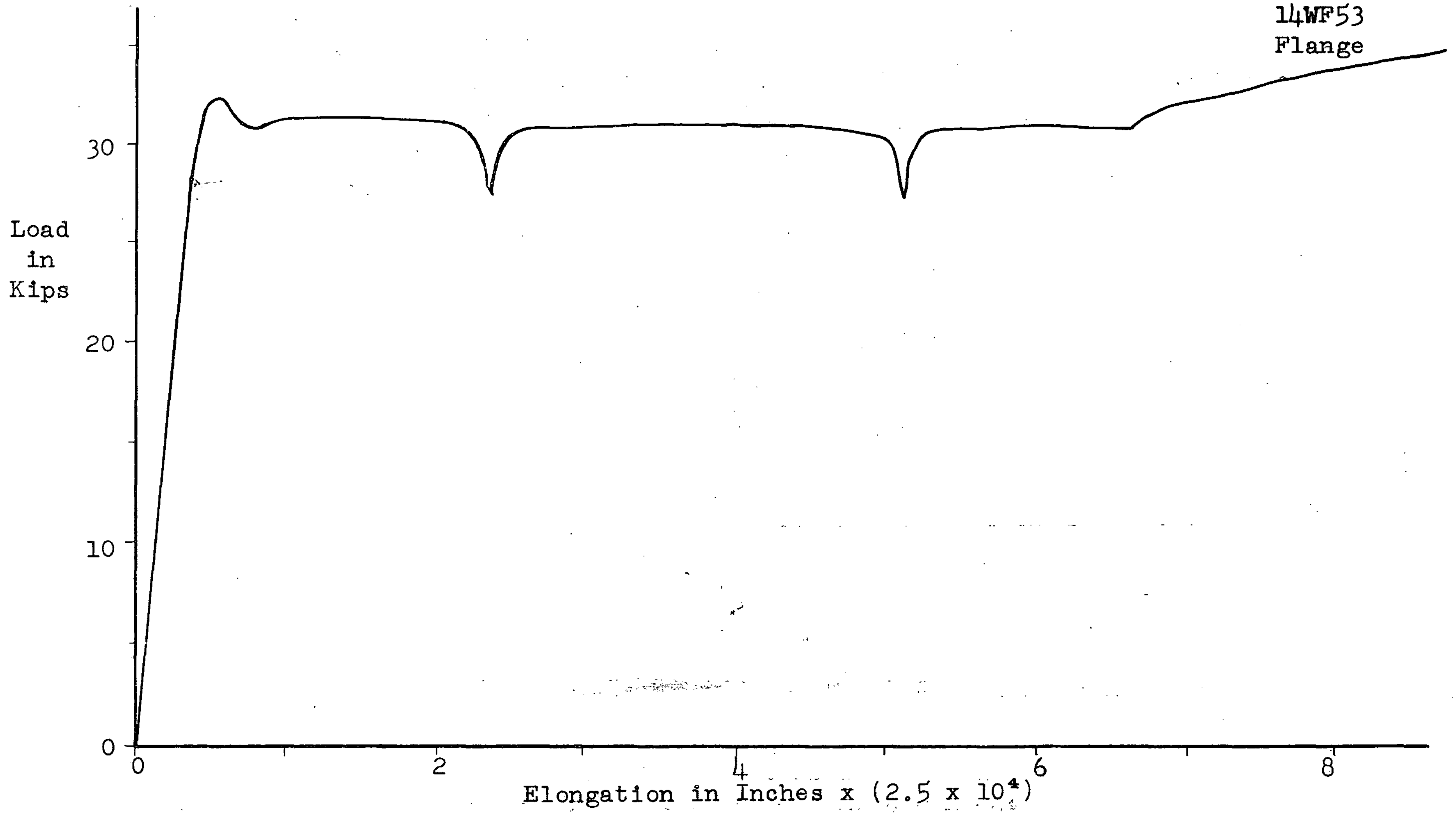


Figure 11

TYPICAL LOAD-DEFORMATION CURVE FOR COUPON TENSION TEST

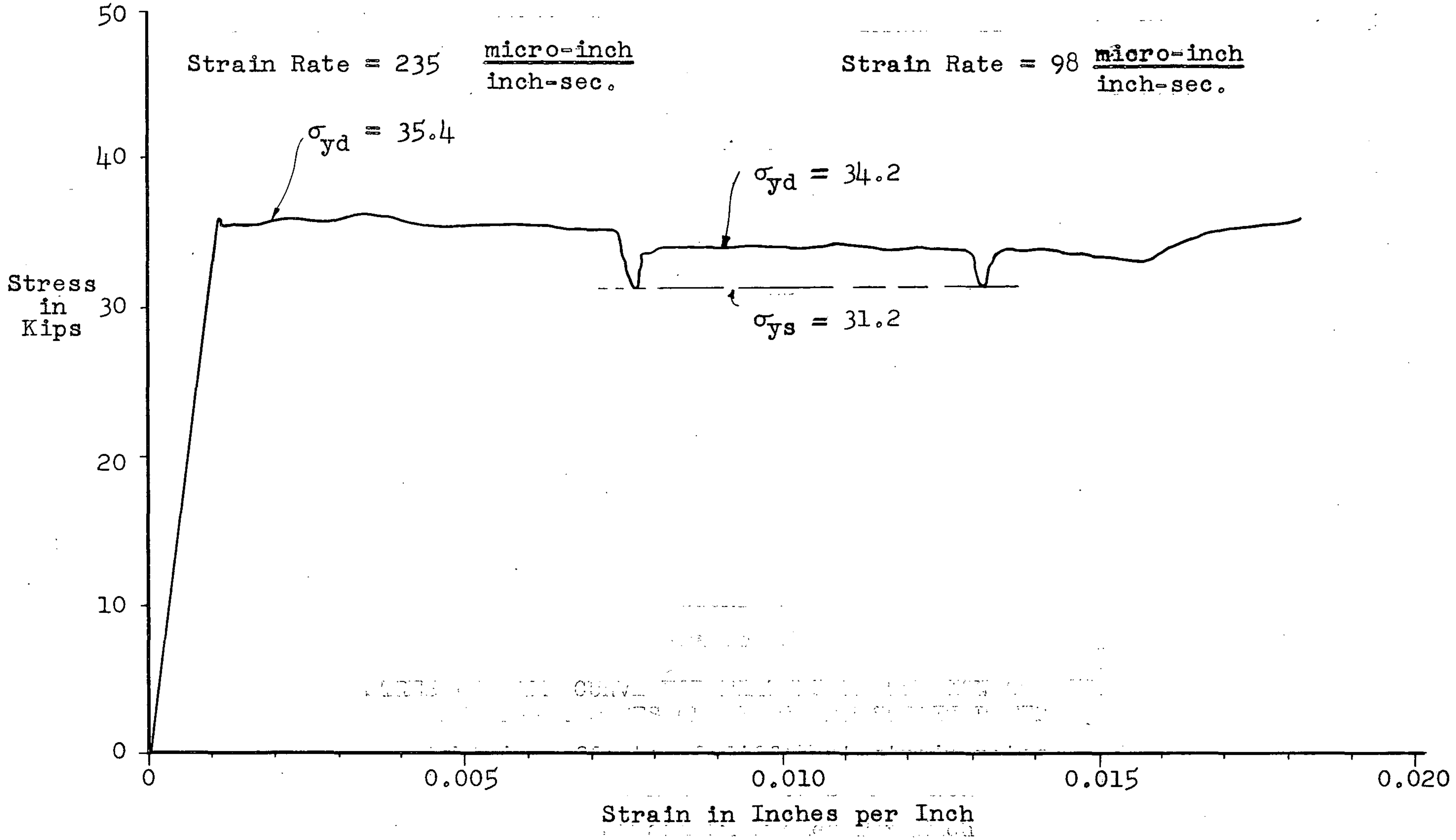
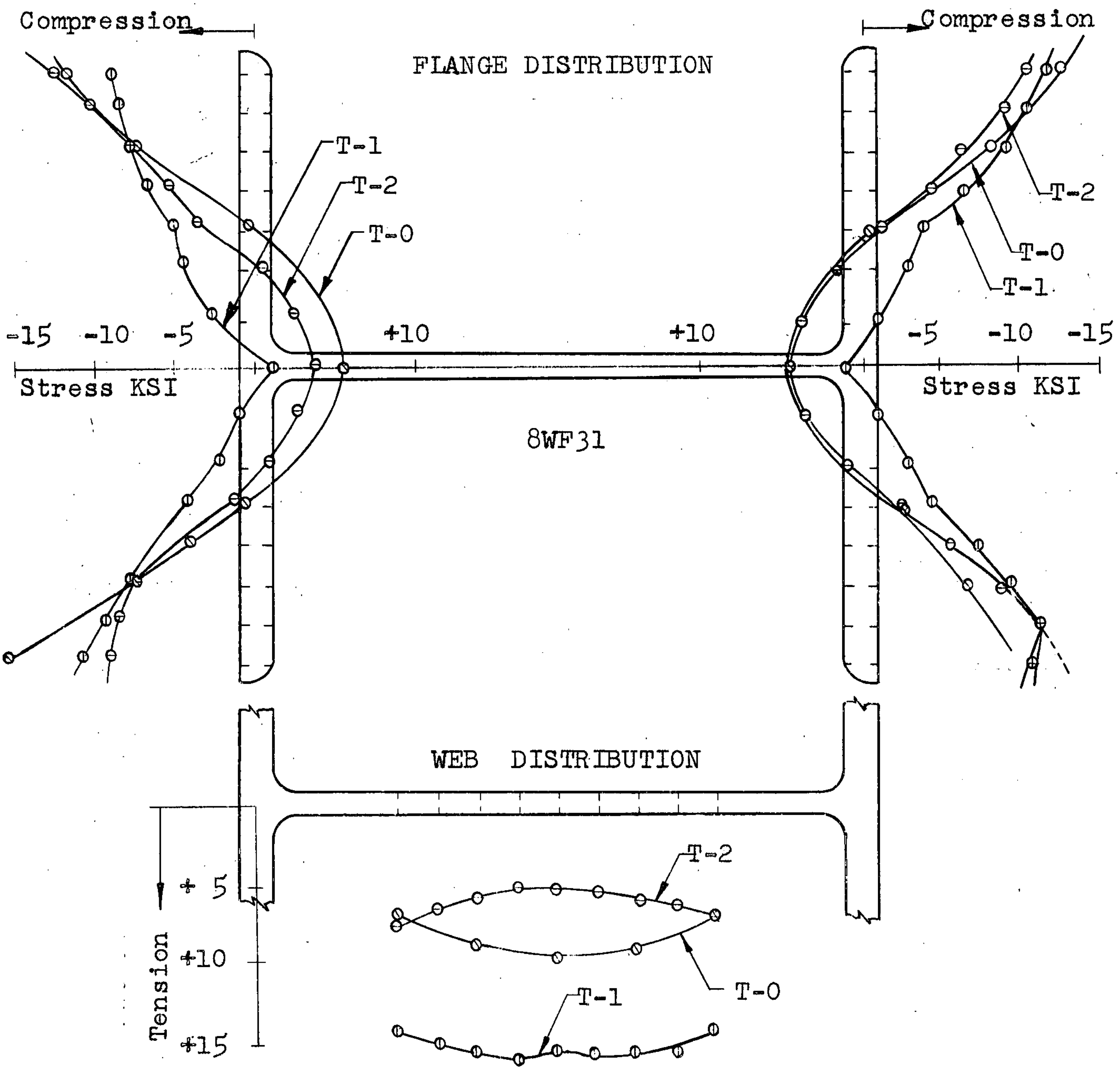


Figure 12
STRESS-STRAIN CURVE FOR FLAT PLATE TENSION COUPON, SHOWING EFFECTS OF DIFFERENT STRAIN RATES

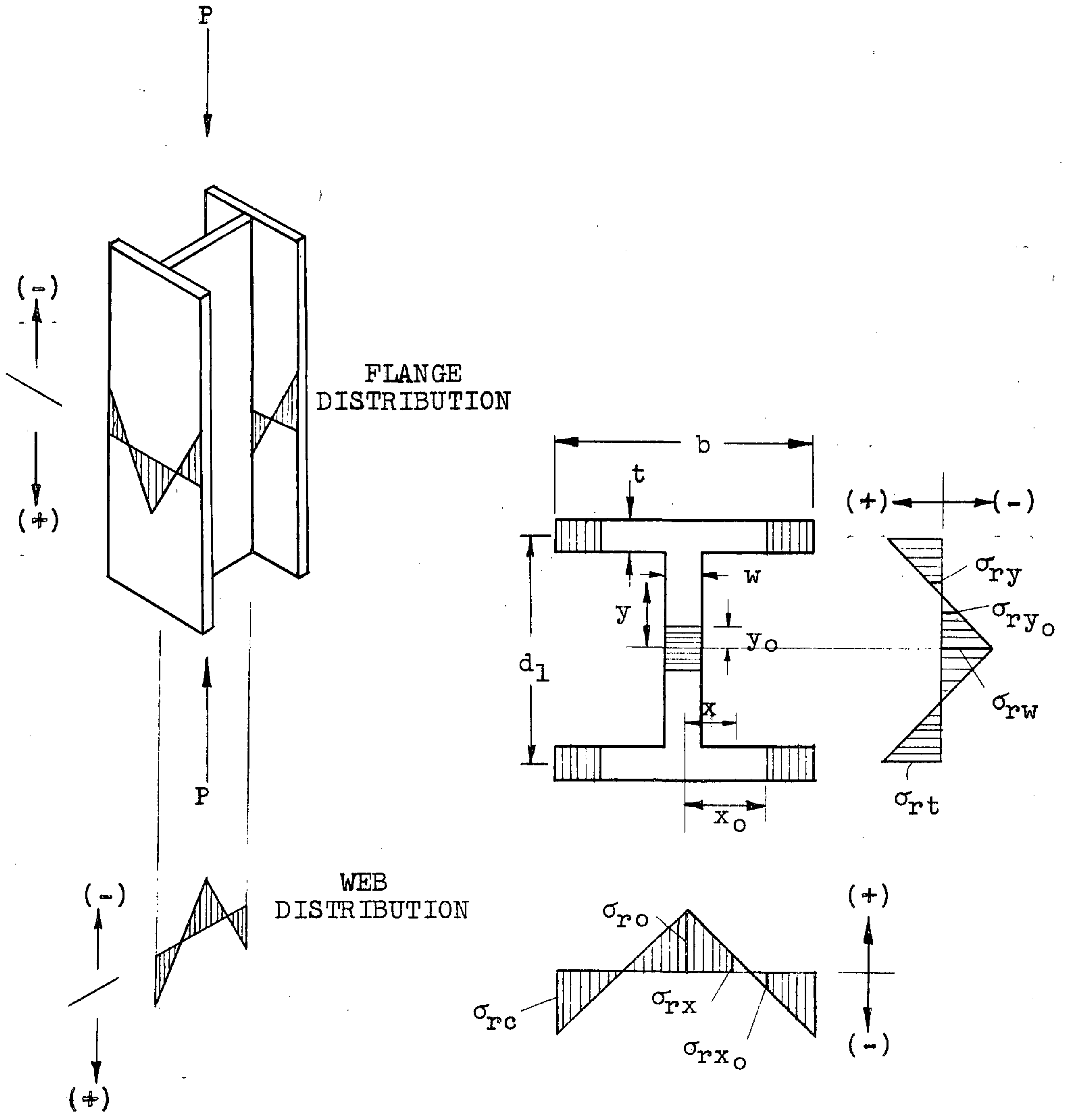


	σ_{rc}	σ_{ro}	σ_{rw}
T-0	-13.9	5.6	9.3
T-1	-11.5	1.1	15.5
T-2	-12.5	4.2	5.0

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

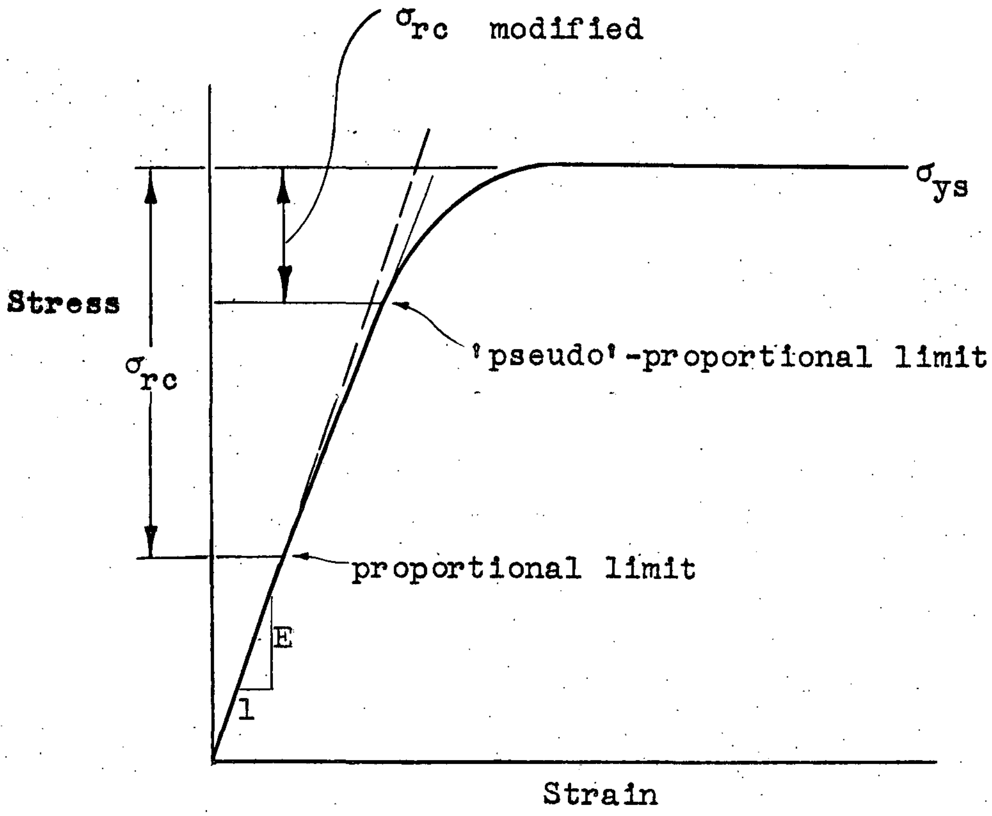


Figure 14

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

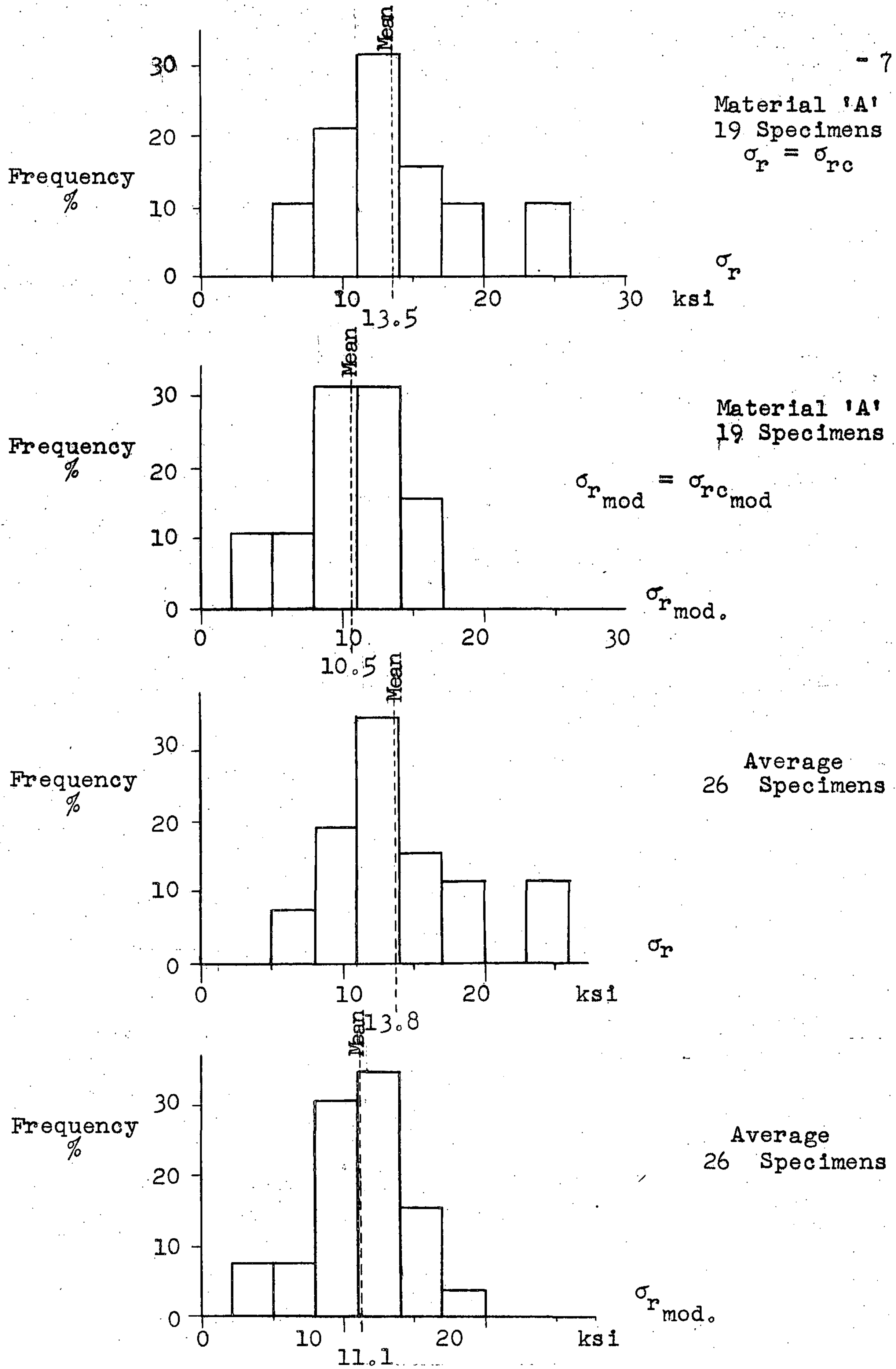


Figure 15(a)
HISTOGRAMS OF THE MAXIMUM RESIDUAL STRESS
IN THE FLANGES OF STUB COLUMN, σ_{rc}

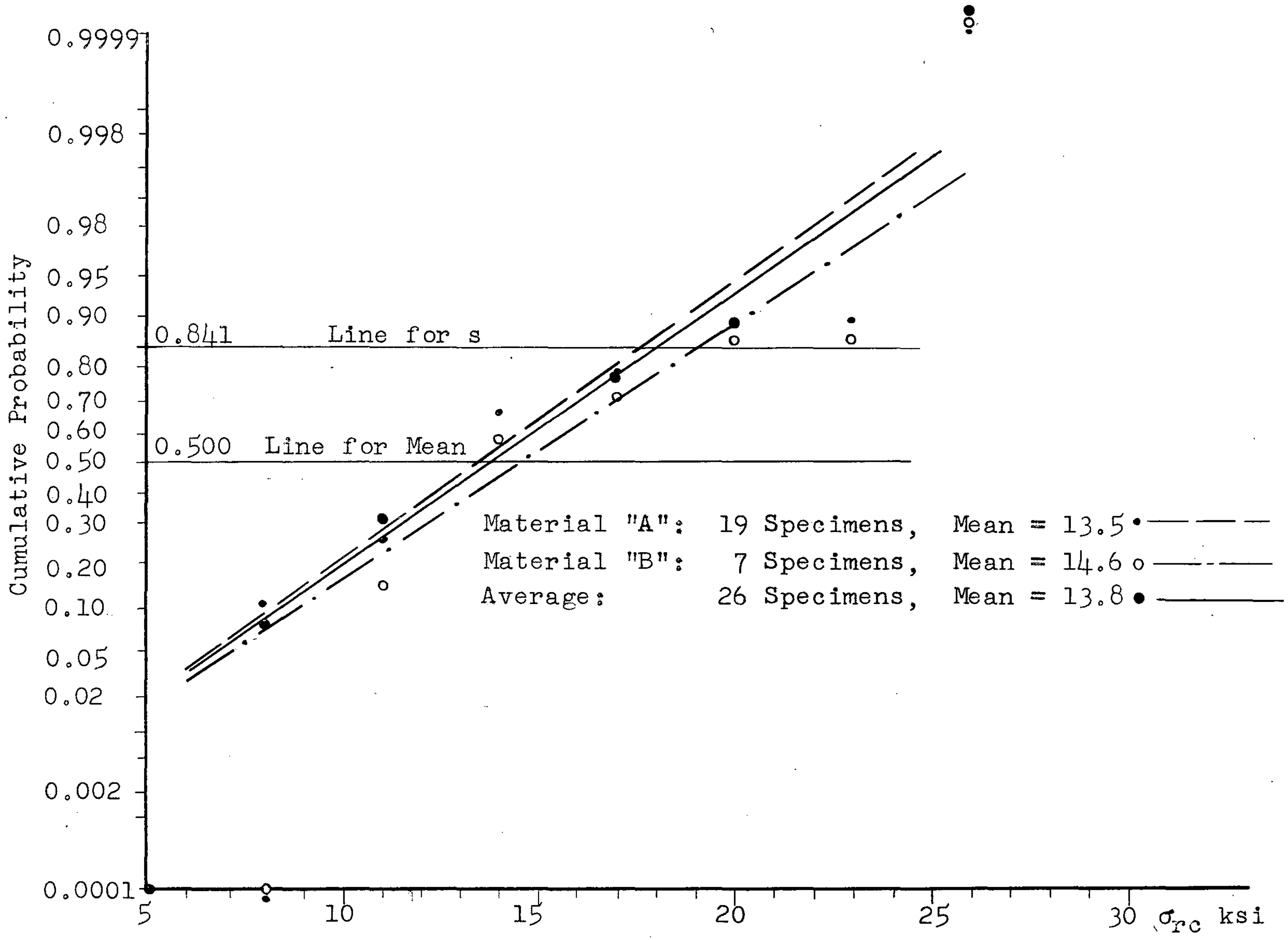


Figure 15(b)1

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

Normal Distribution Probability Curves

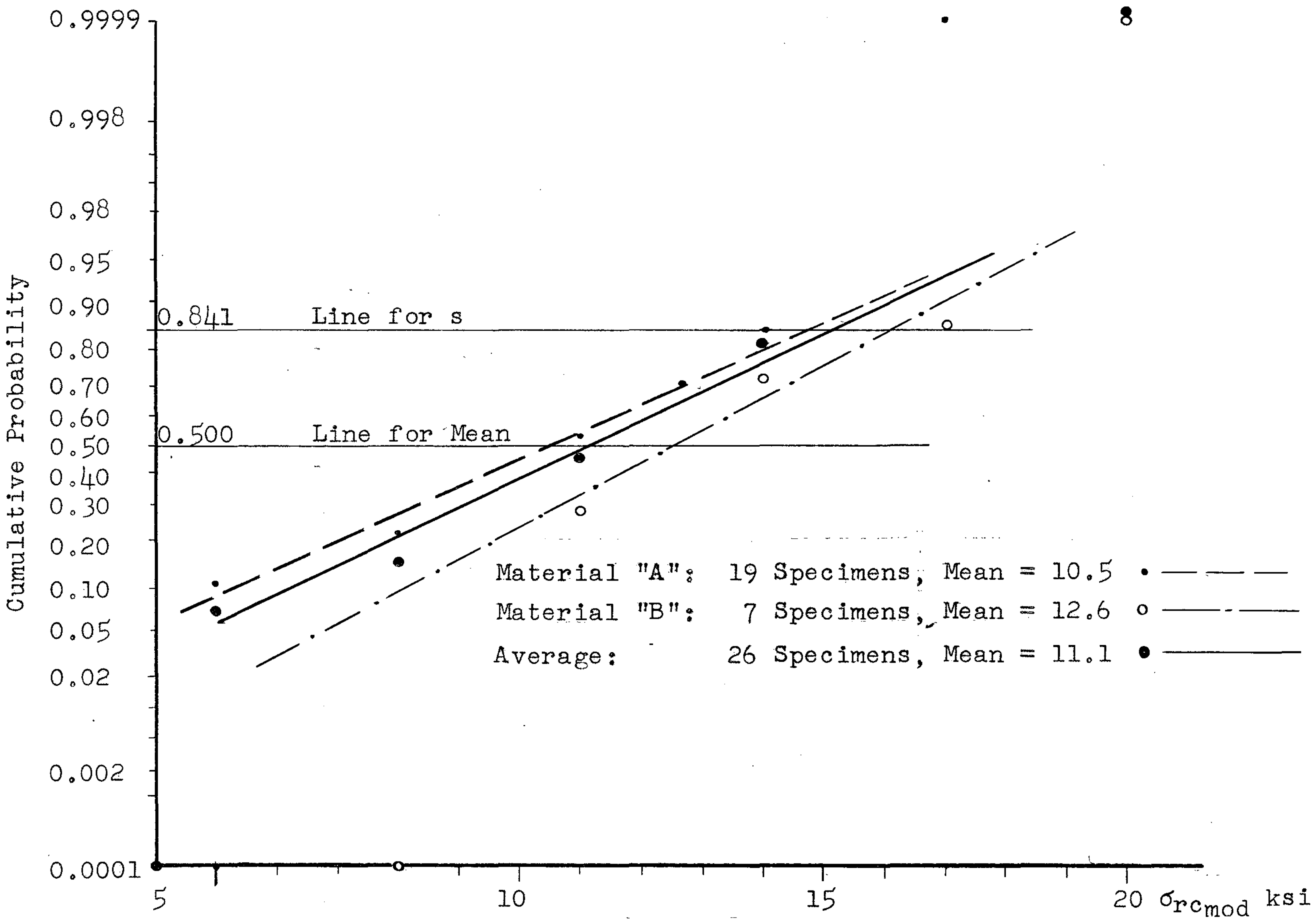


Figure 15(b)2

MAXIMUM RESIDUAL STRESS IN THE FLANGES OF STUB COLUMN, $\sigma_{rc_{mod}}$

Normal Distribution Probability Curves

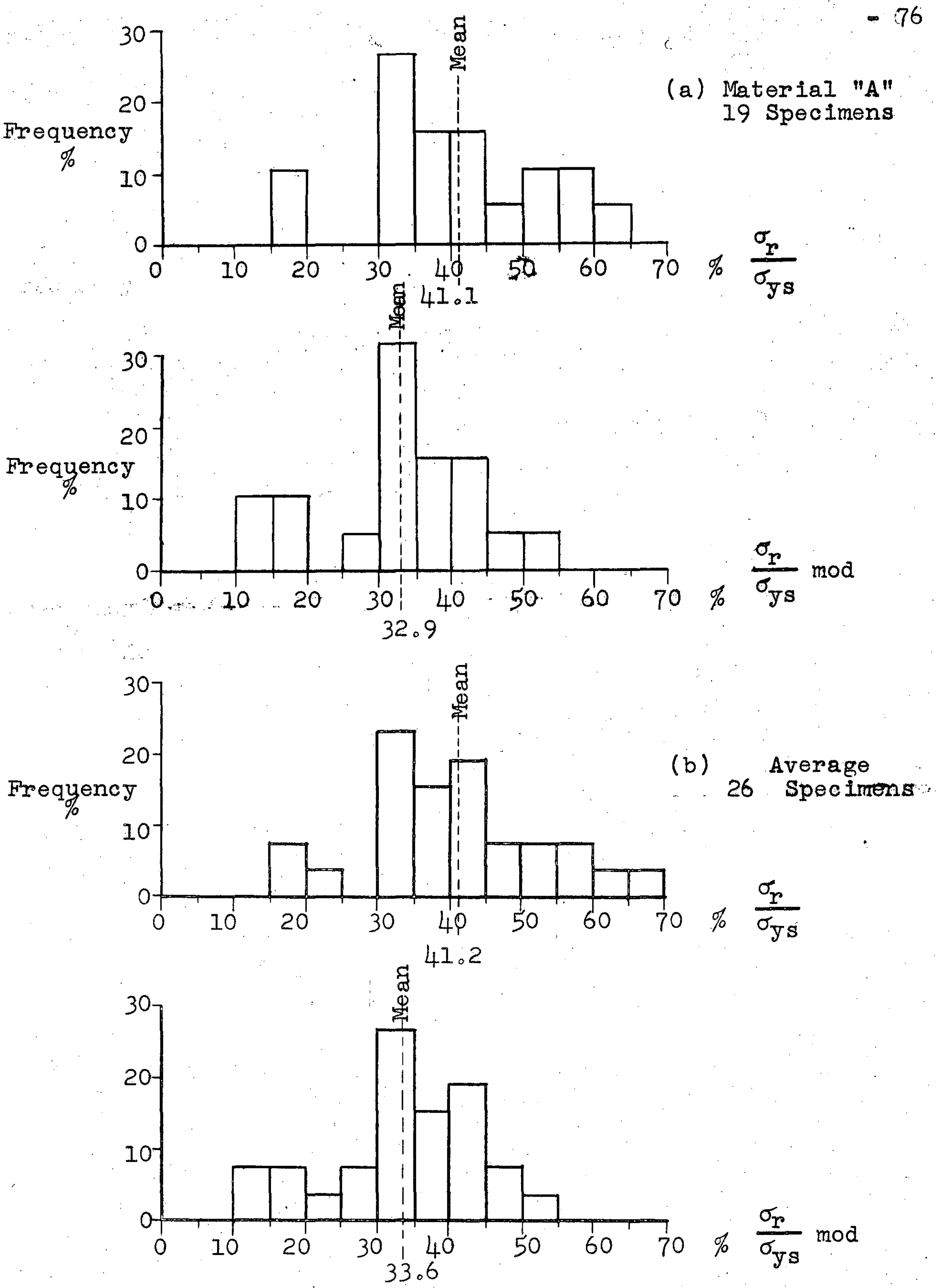


Figure 16(a)

HISTOGRAM OF THE RATIO OF RESIDUAL STRESS
TO STATIC YIELD STRESS

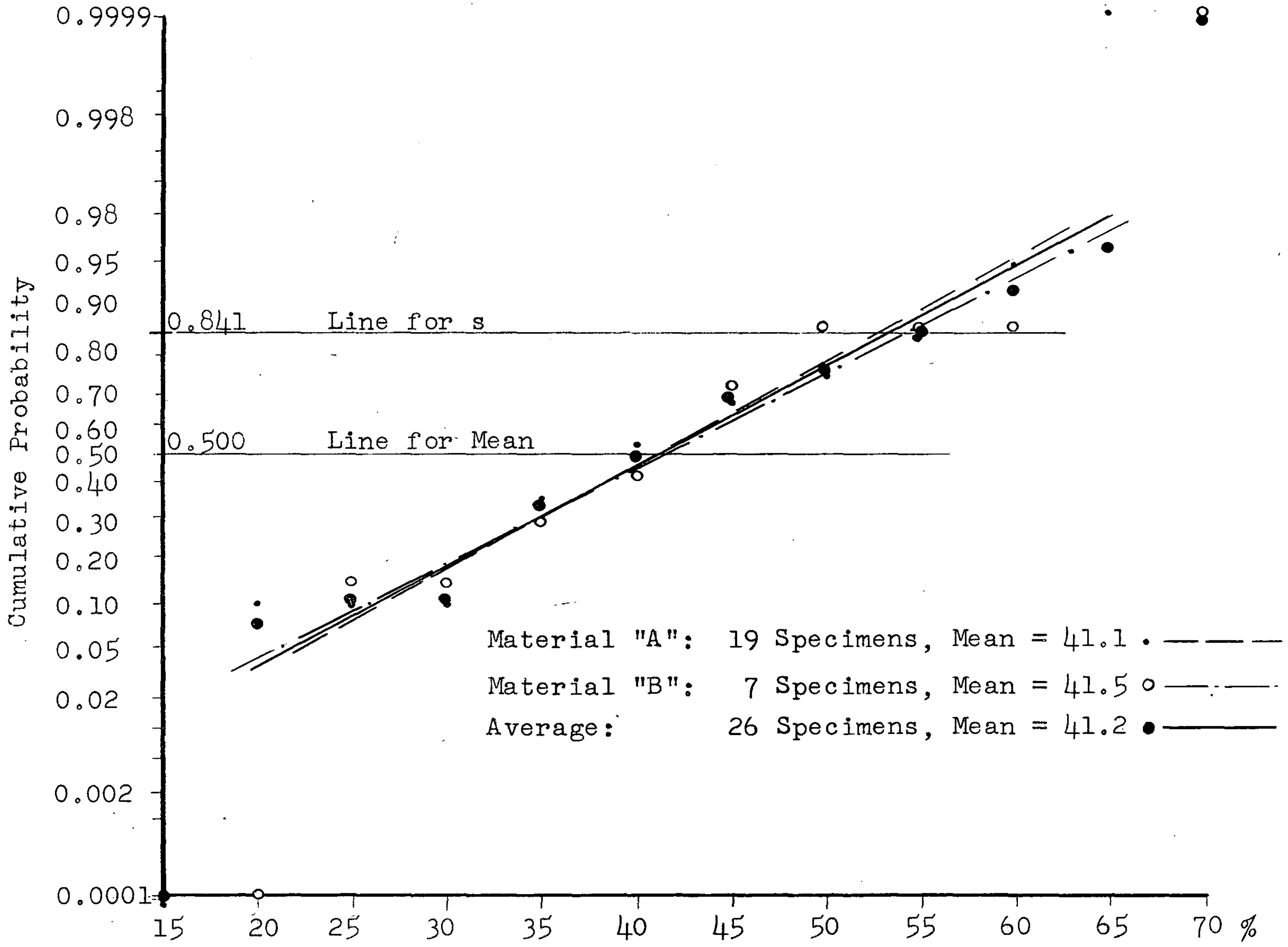


Figure 16(b)1

RATIO OF RESIDUAL STRESS, σ_{rc}, TO STATIC YIELD STRESS

Normal Distribution Probability Curves

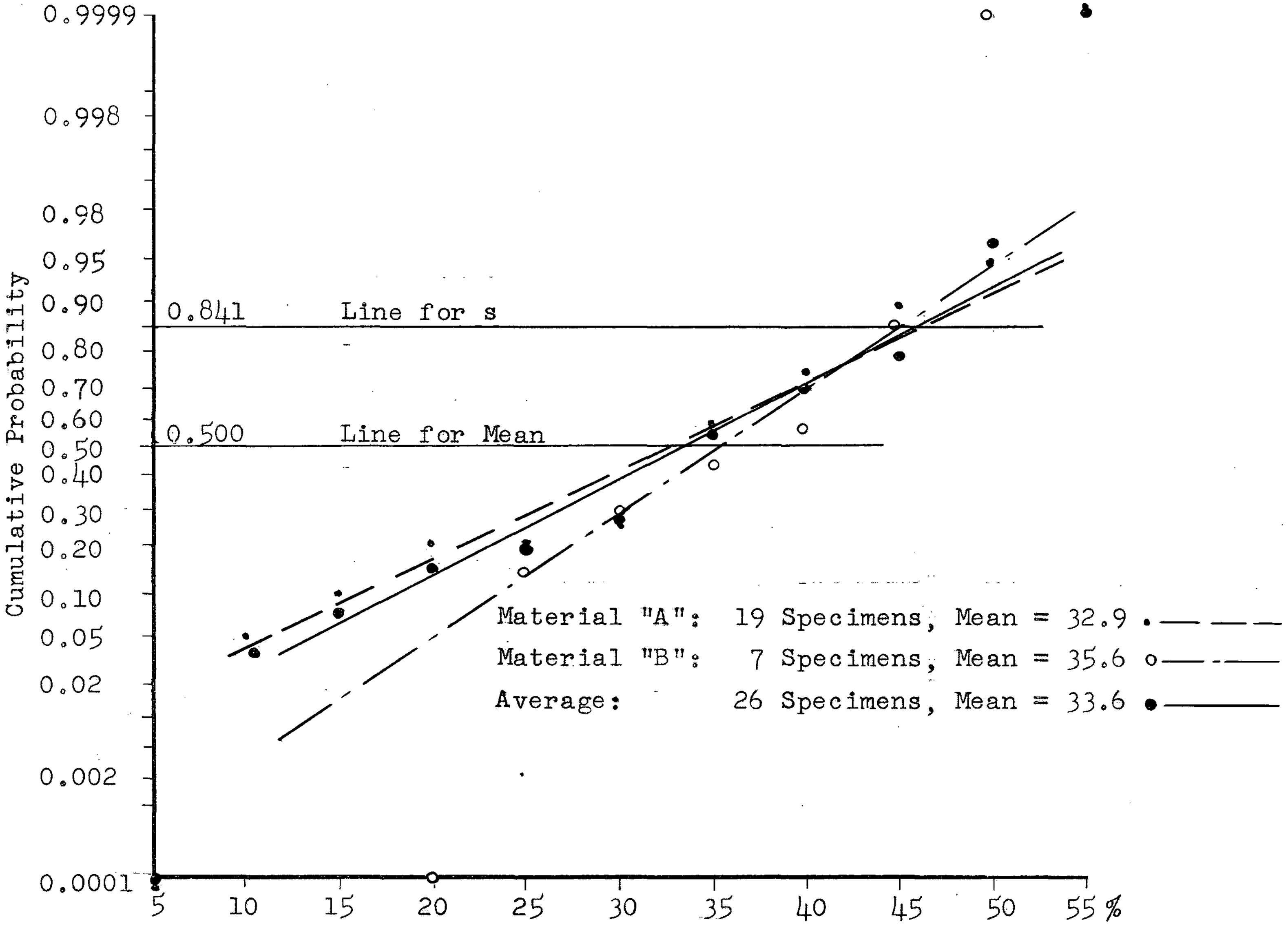


Figure 16(b)2

RATIO OF RESIDUAL STRESS, $\sigma_{rc_{mod}}$, TO STATIC YIELD STRESS

Normal Distribution Probability Curves

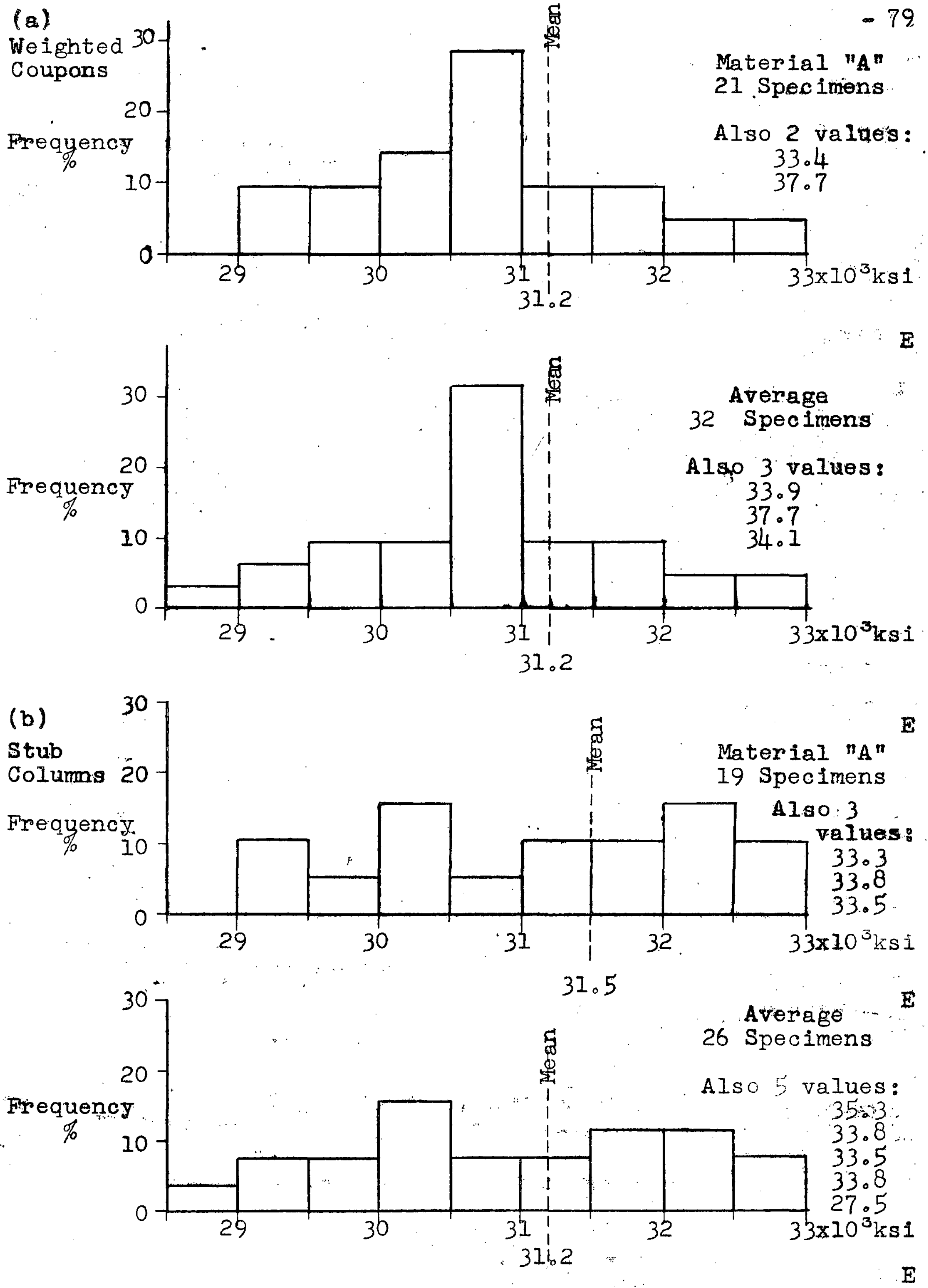


Figure 17(a)

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

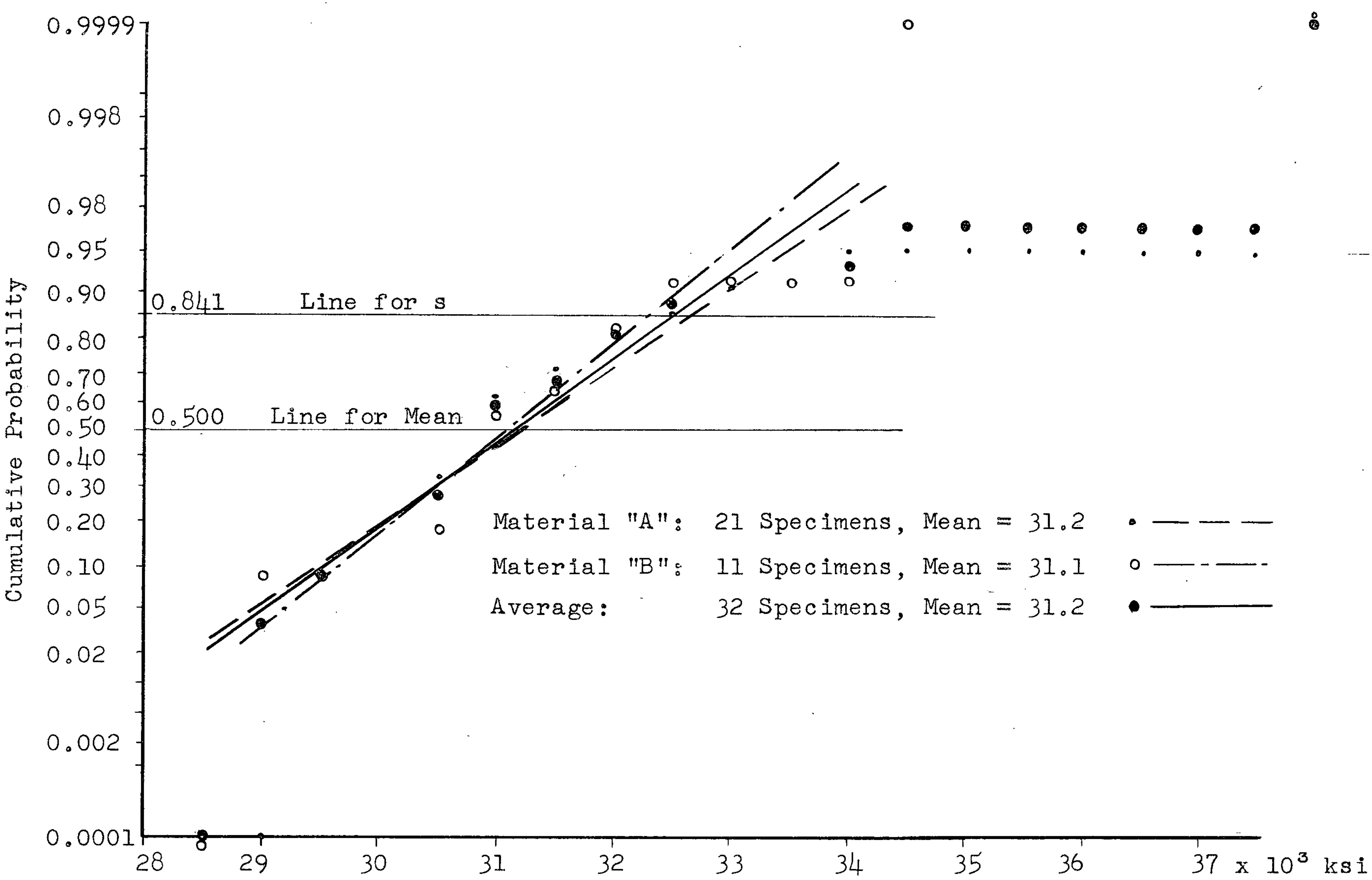


Figure 17(b)1

YOUNG'S MODULUS FROM "WEIGHTED" COUPONS

Normal Distribution Probability Curves

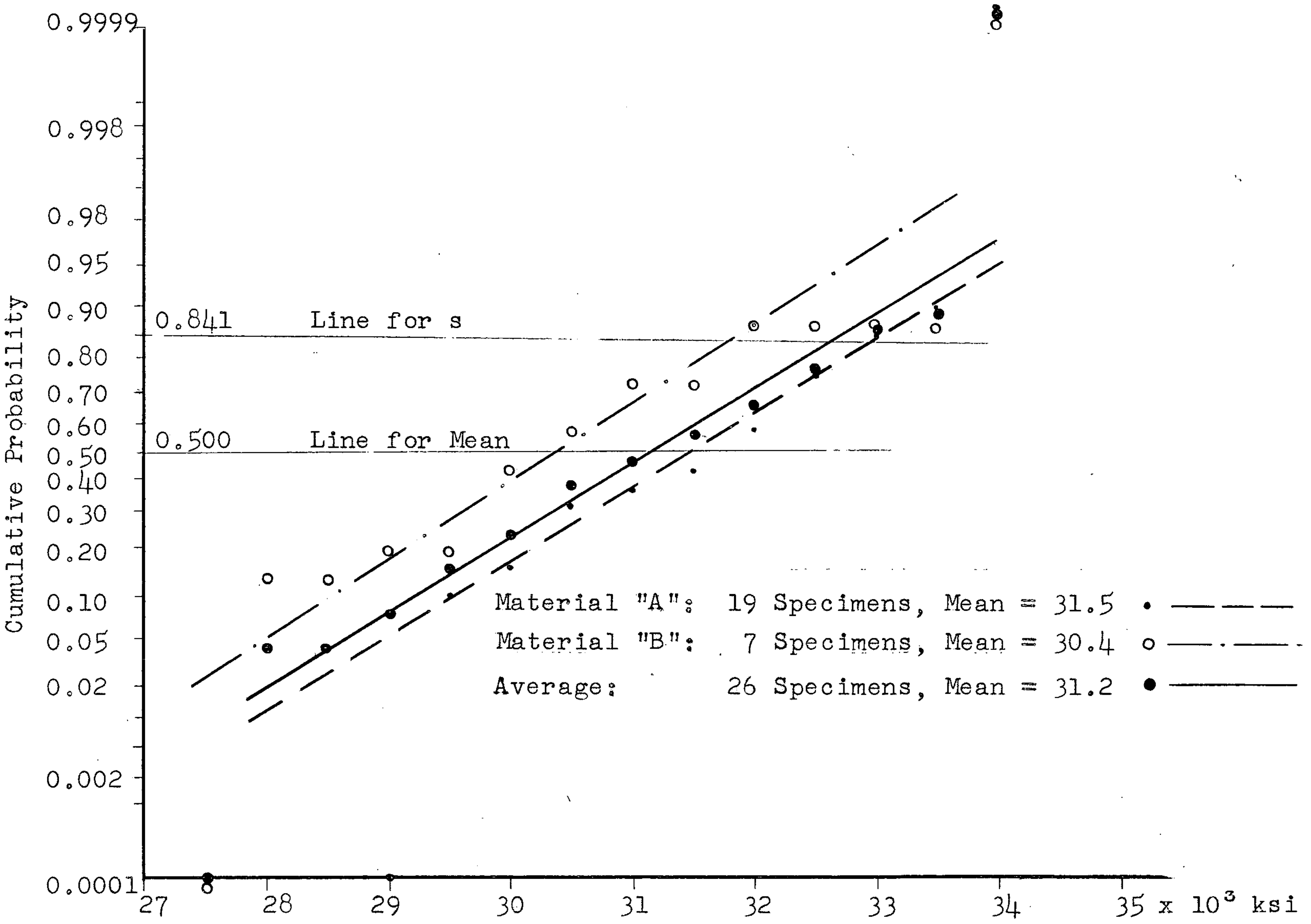


Figure 17(b)2

YOUNG'S MODULUS FROM STUB COLUMNS

Normal Distribution Probability Curves

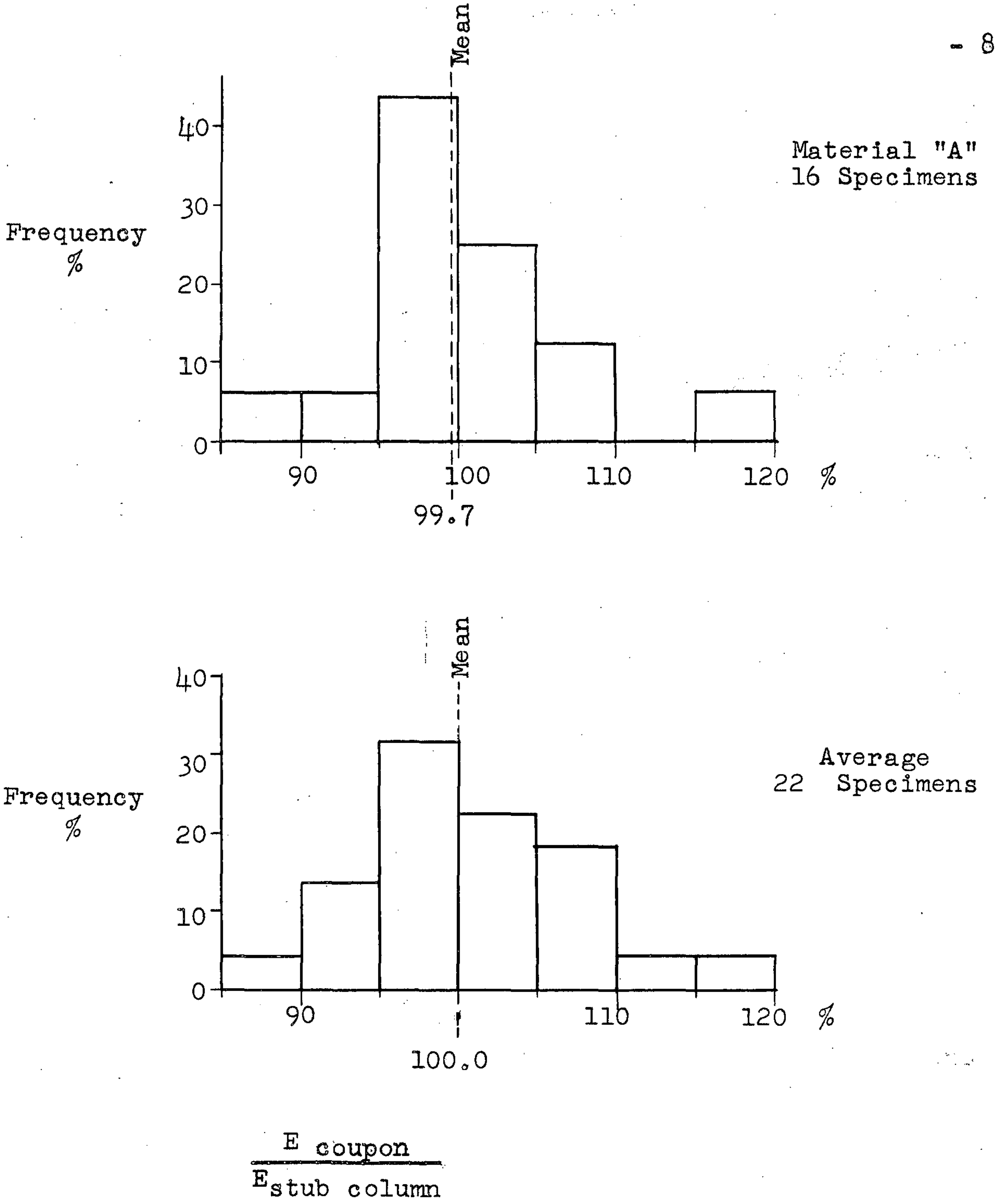


Figure 18(a)

COMPARISON OF COUPON AND STUB COLUMN RESULTS FOR E

Histograms

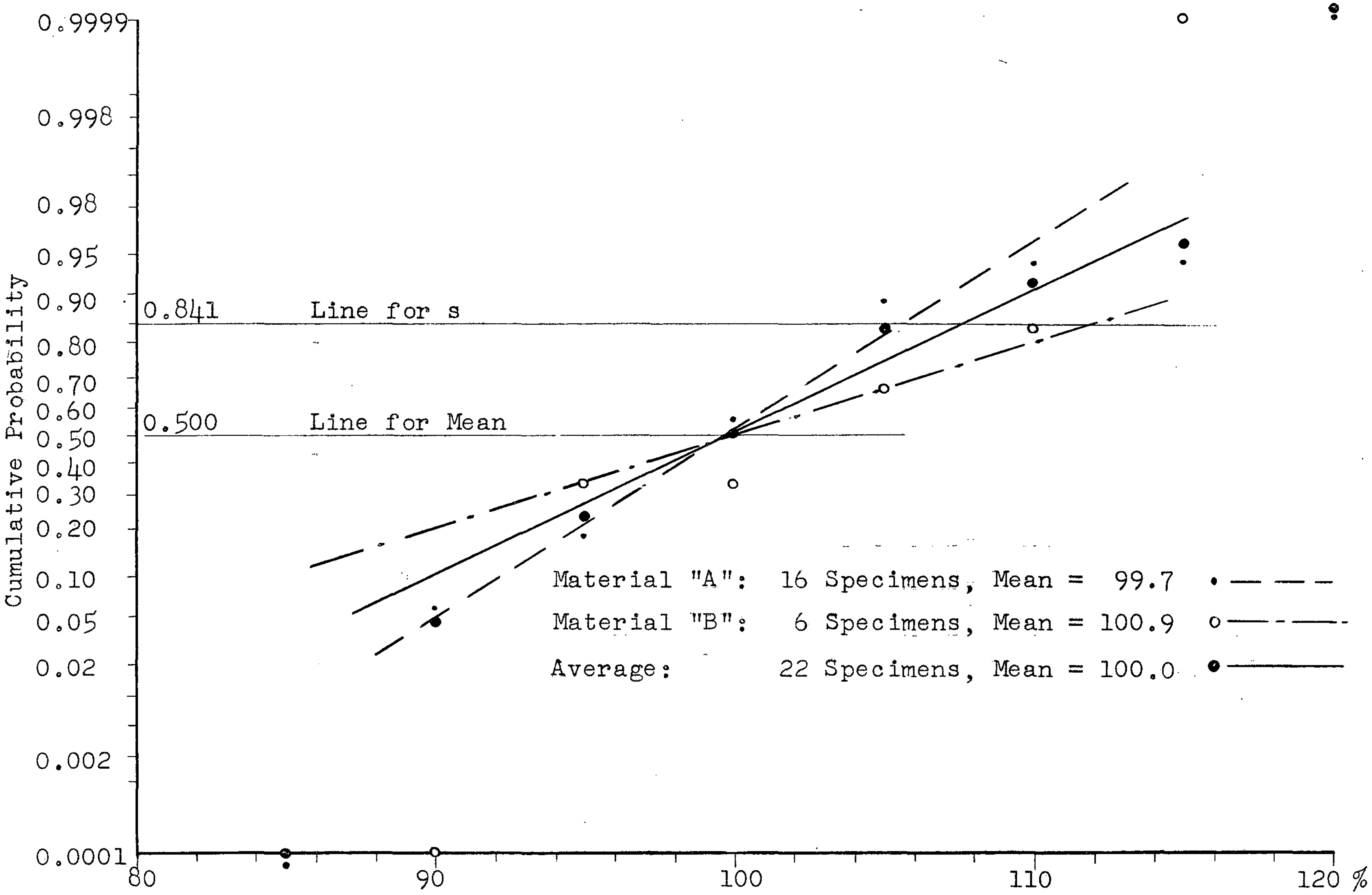


Figure 18(b)

COMPARISON OF COUPON AND STUB COLUMN RESULTS FOR E
Normal Distribution Probability Curves

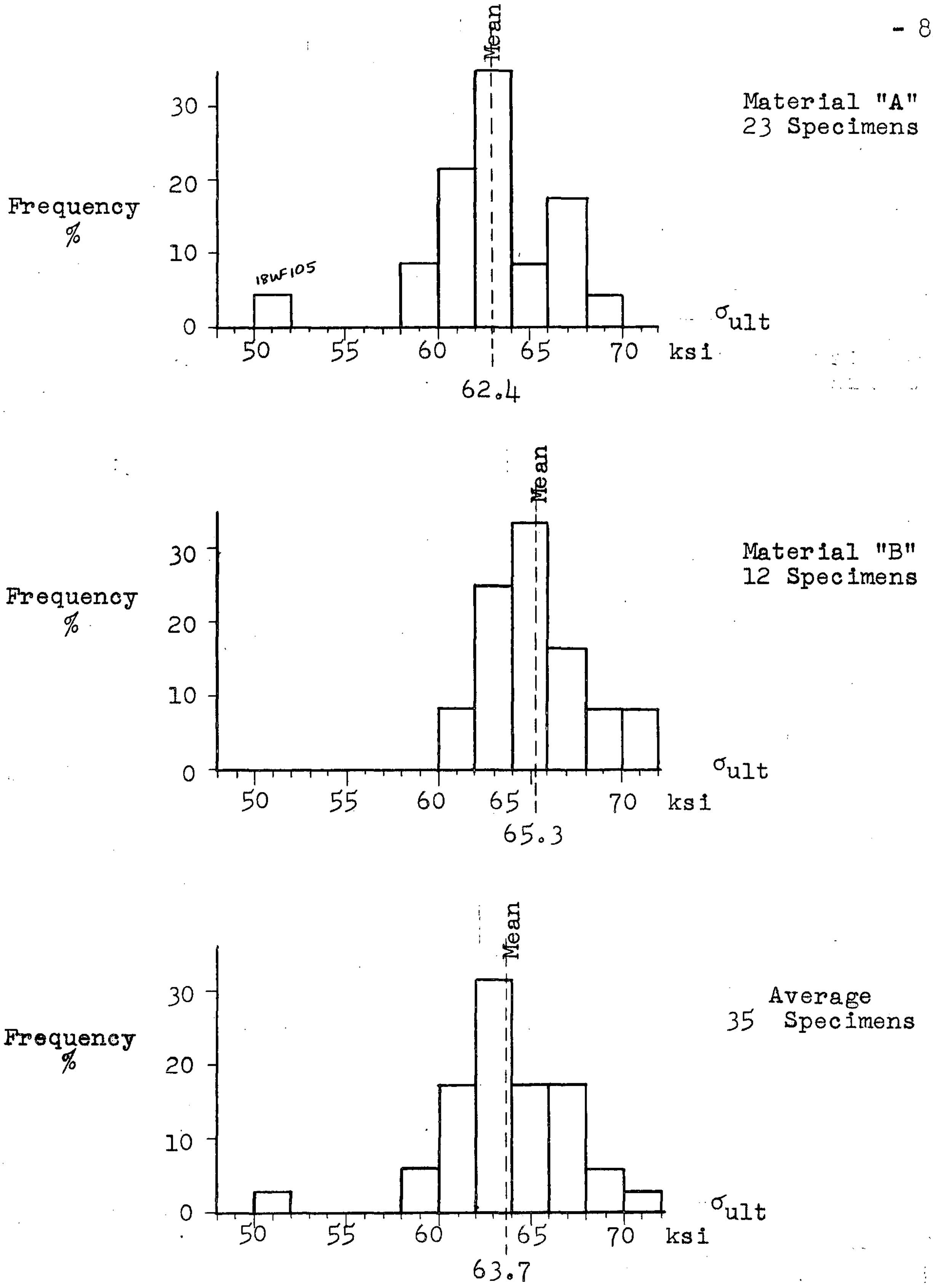


Figure 19(a)

SIMULATED MILL COUPON RESULTS WEIGHTED AVERAGE
ULTIMATE STRESS

Histograms

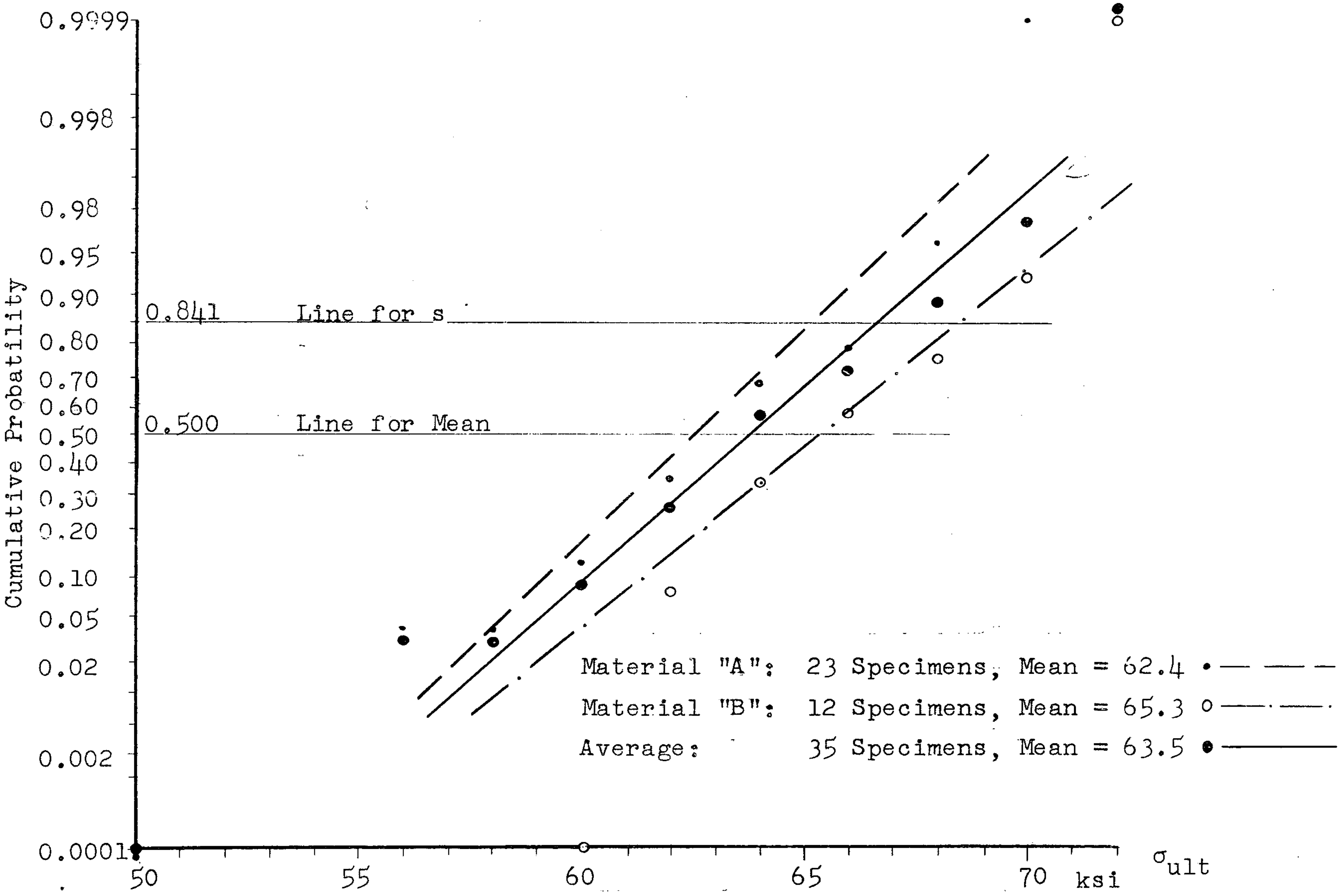


Figure 19(b)

SIMULATED MILL COUPON RESULTS, WEIGHTED AVERAGE, ULTIMATE STRESS
Normal Distribution Probability Curves

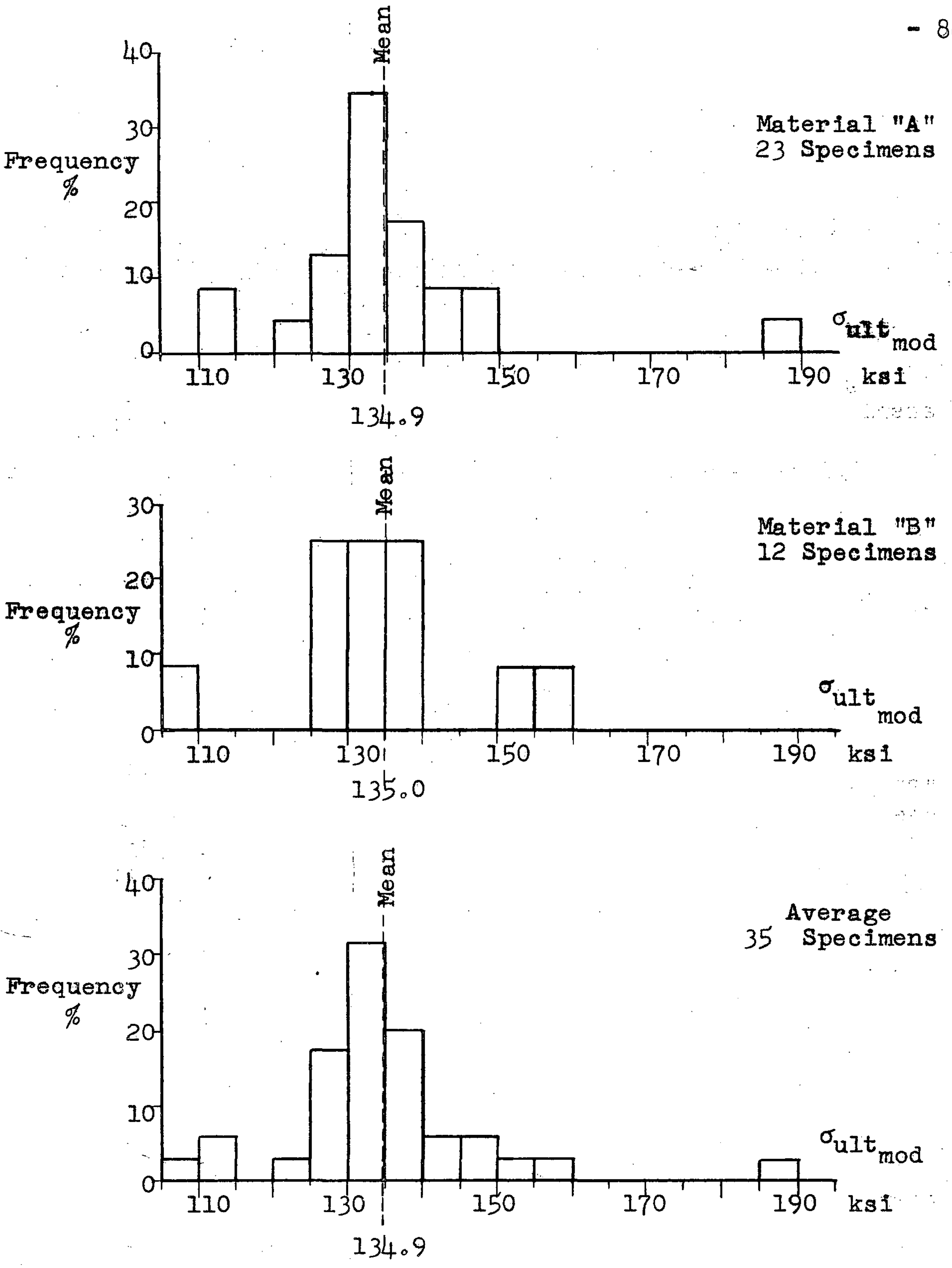


Figure 20(a)

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

Histograms

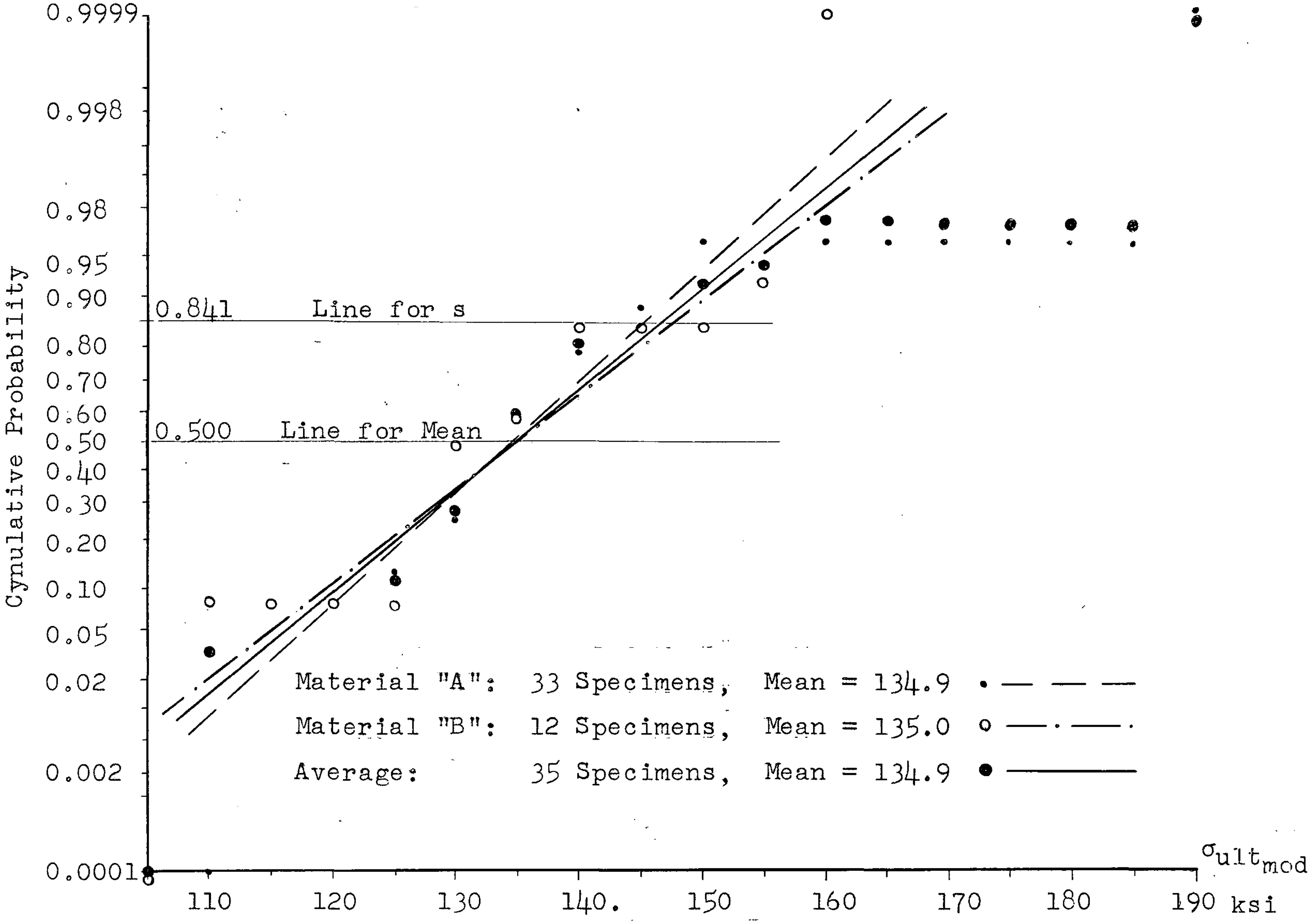
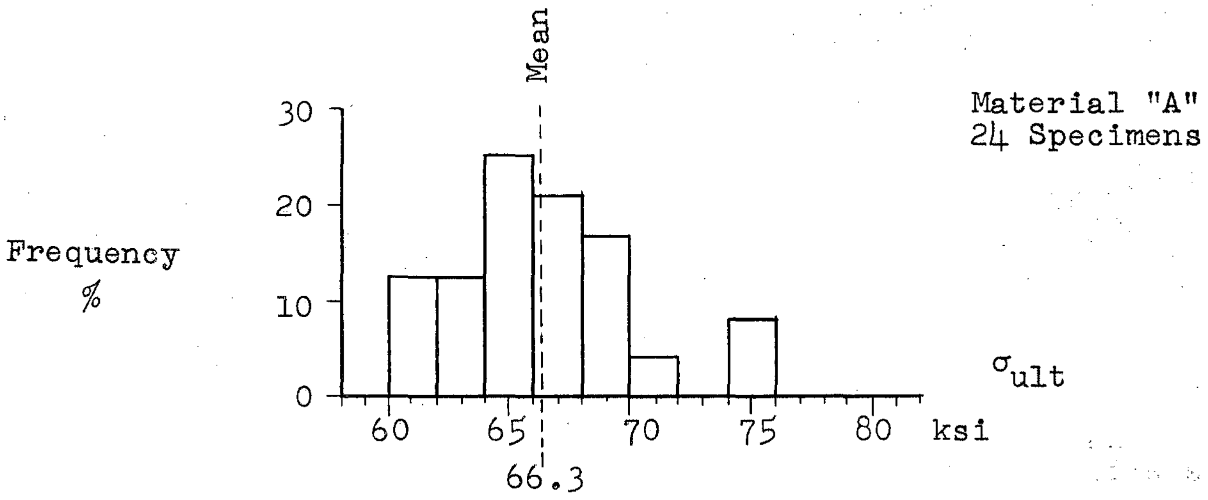


Figure 20(b)

SIMULATED MILL COUPON RESULTS - WEIGHTED AVERAGE, ULTIMATE STRESS,
BASED ON REDUCED AREA
Normal Distribution Probability Curves



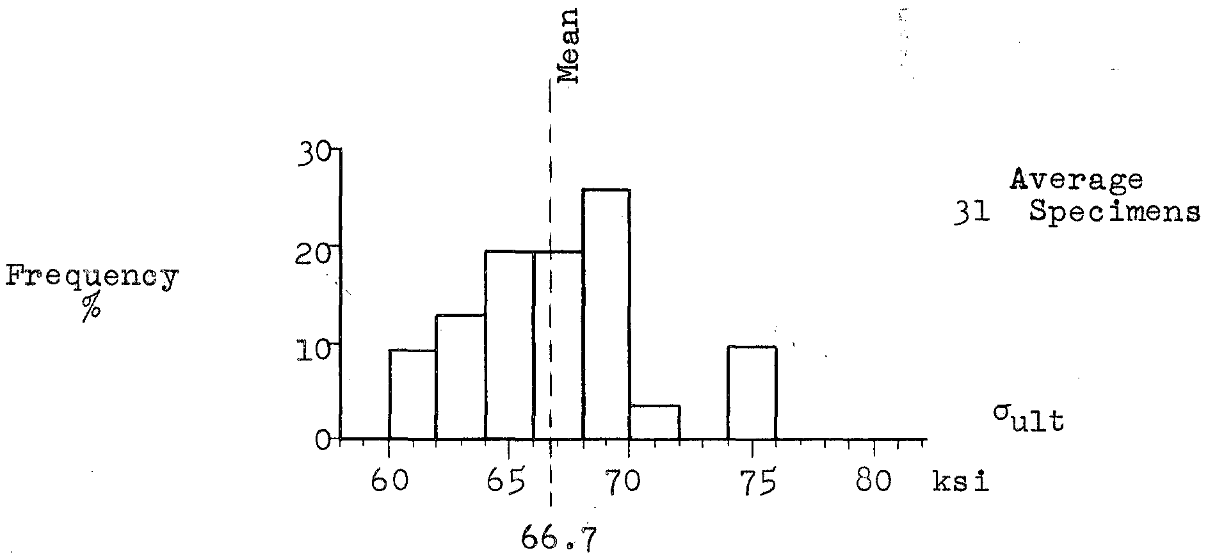


Figure 21(a)

MILL COUPON TESTS (WEB)

ULTIMATE STRESS

Histograms

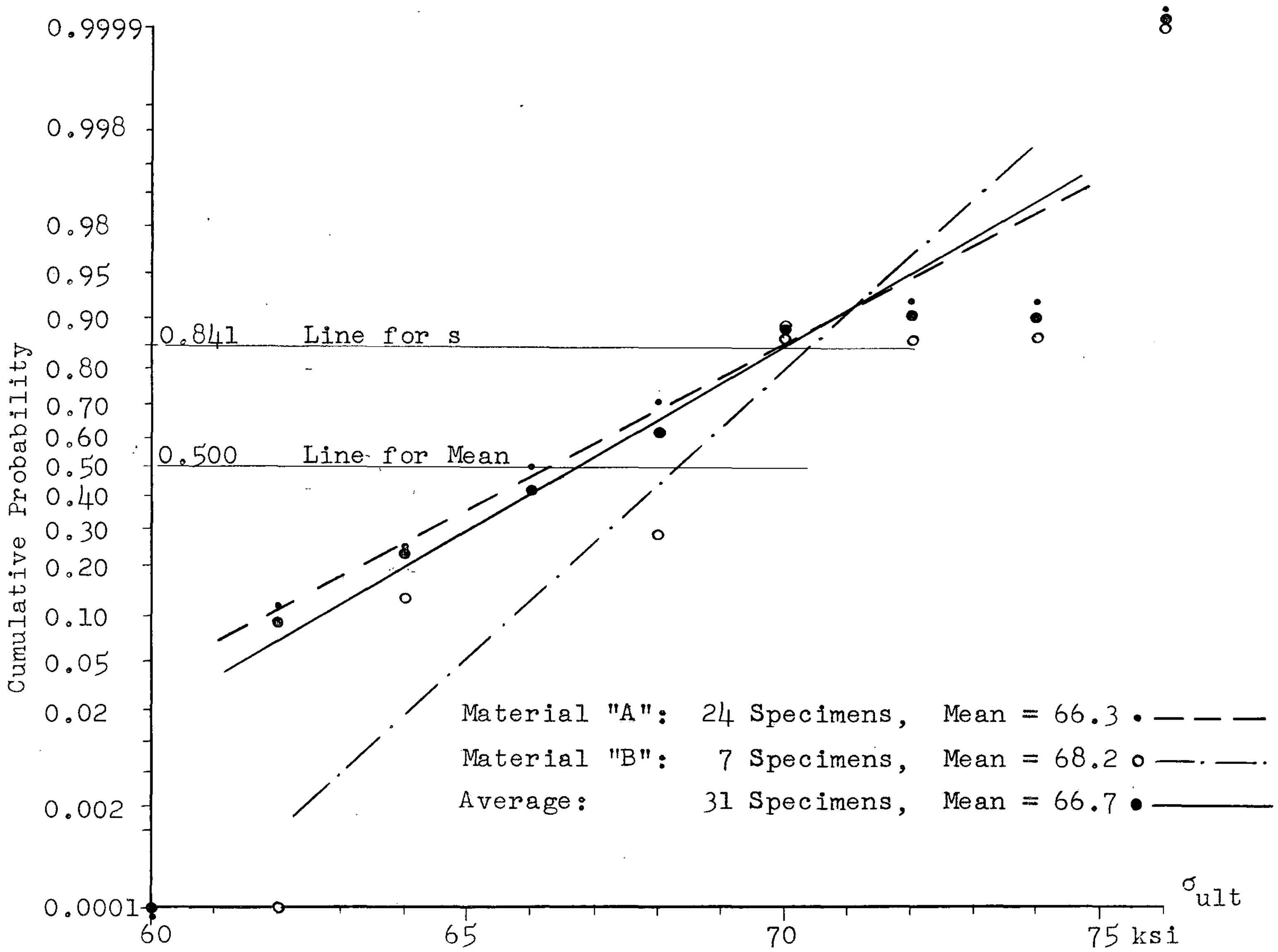


Figure 21(b)

MILL COUPON TESTS (WEB) - ULTIMATE STRESS

Normal Distribution Probability Curves

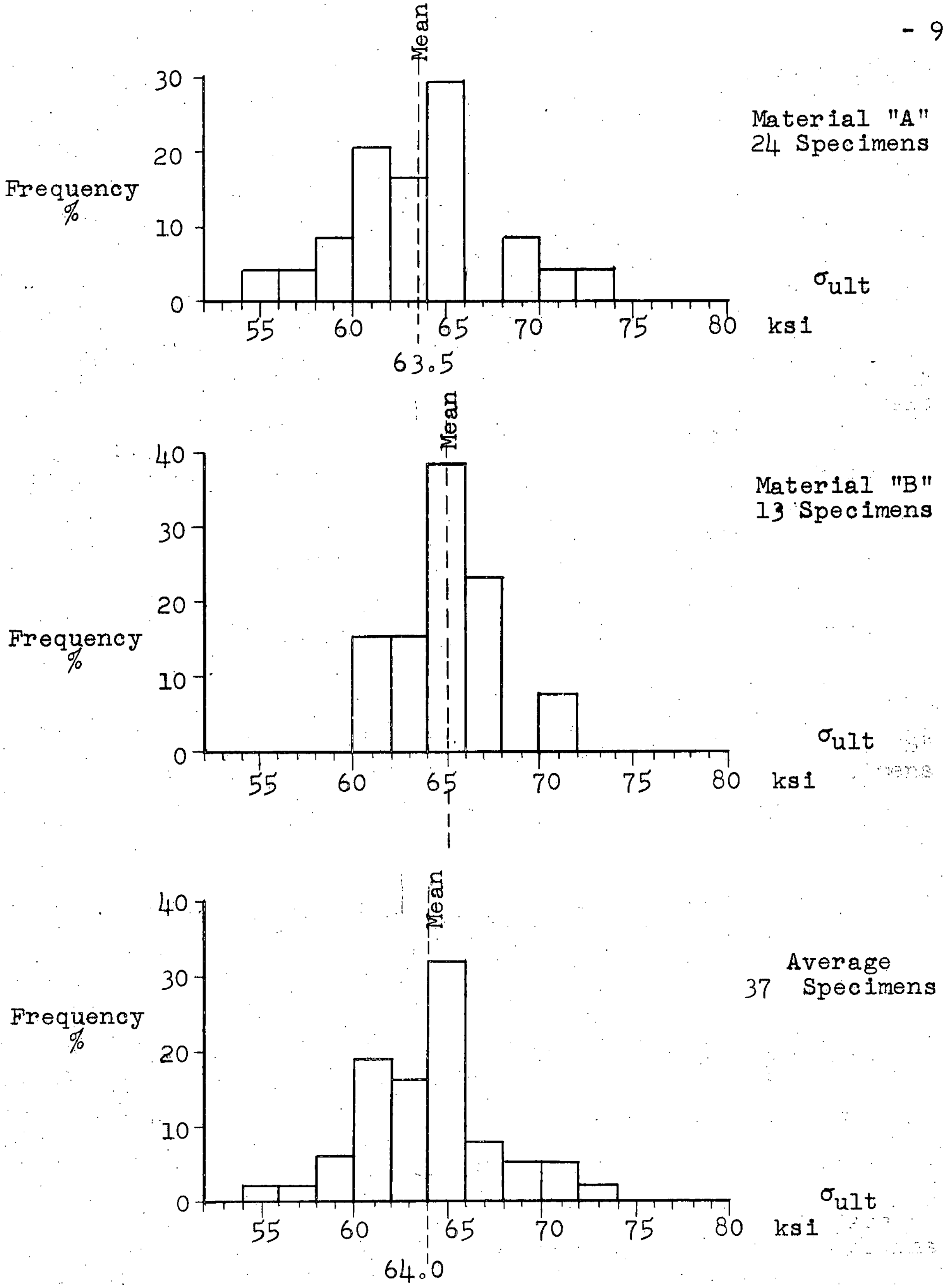


Figure 22(a)

SIMULATED MILL COUPON TESTS (WEB)

ULTIMATE STRESS

Histograms

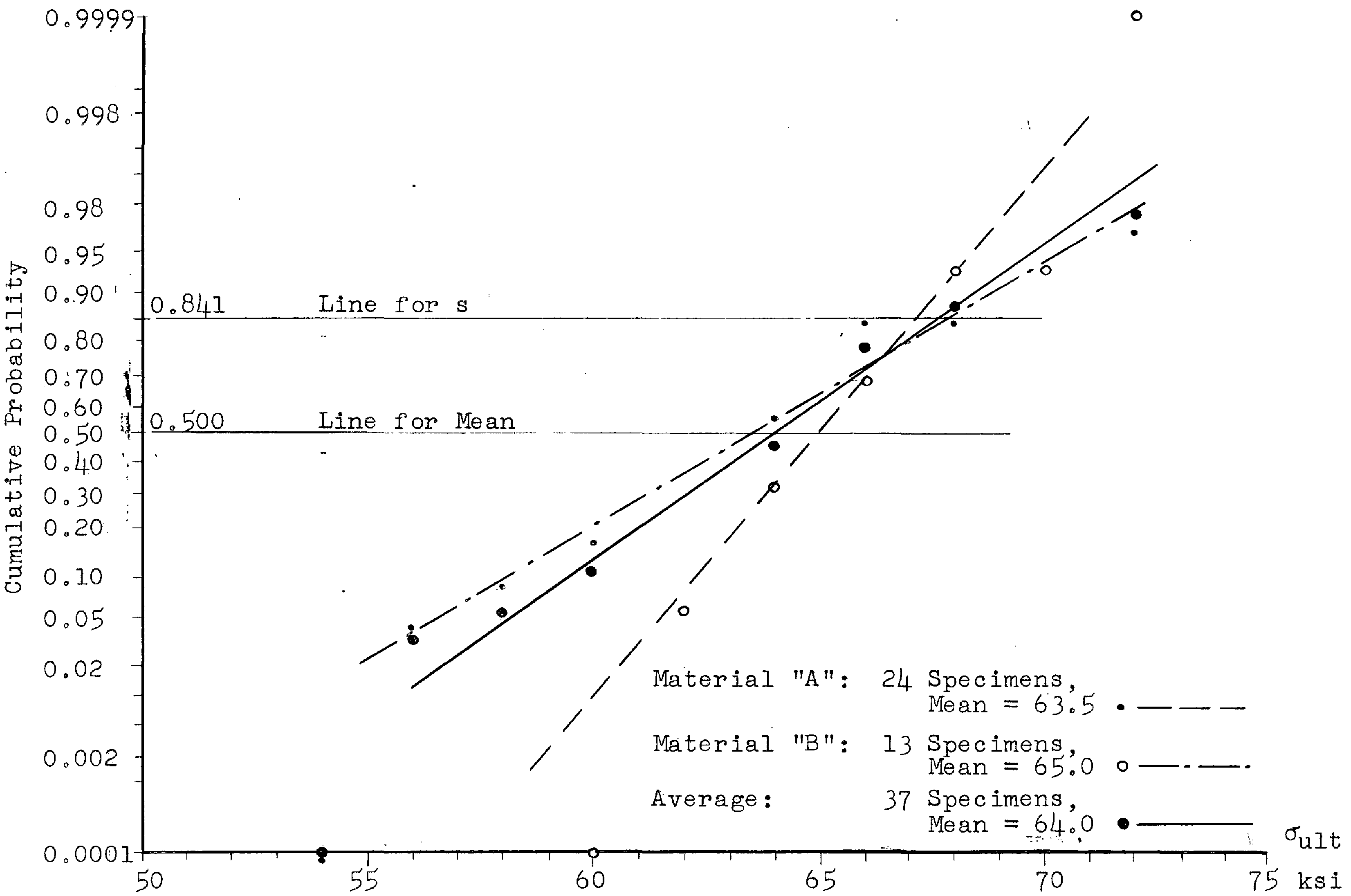
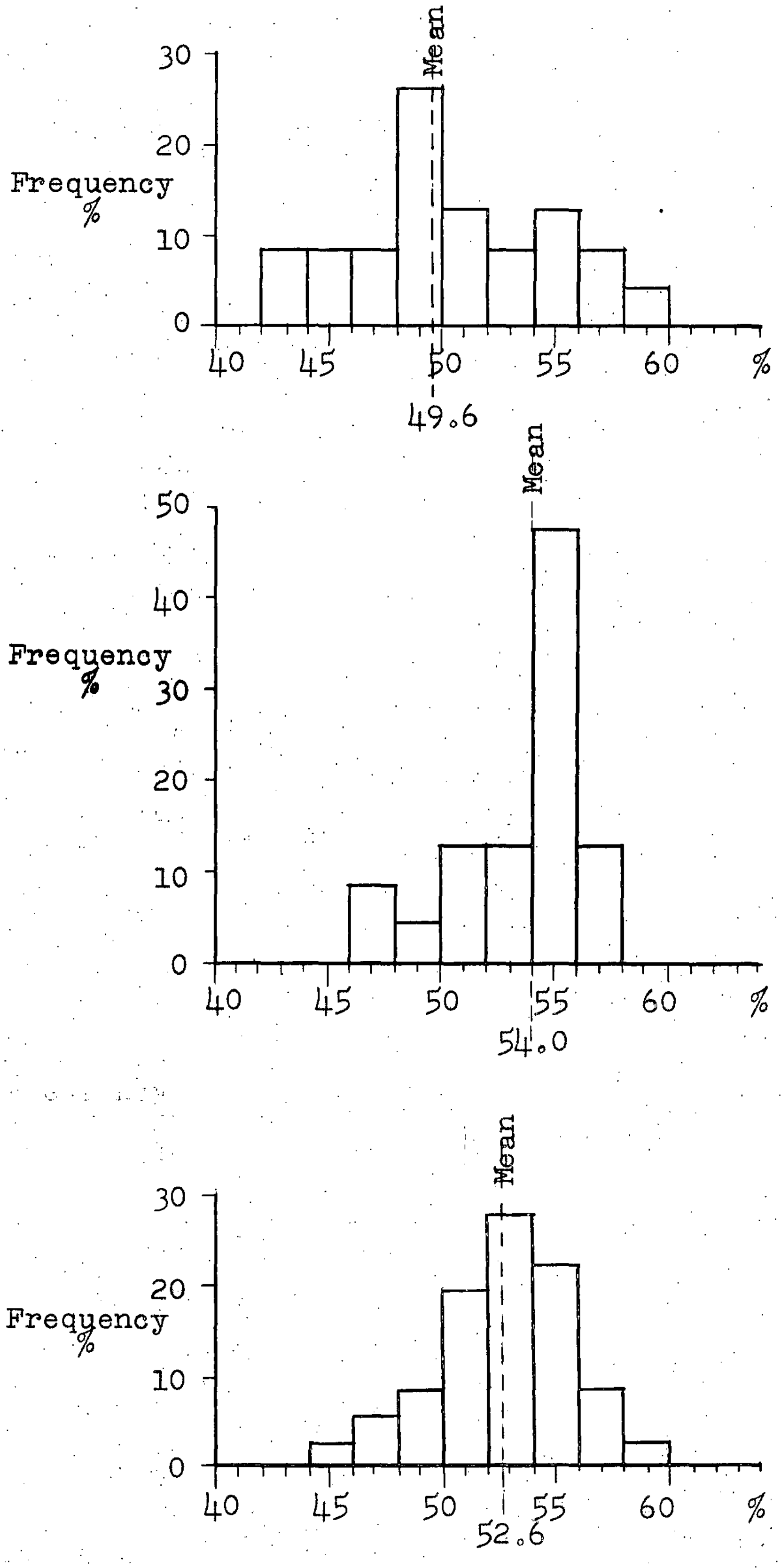


Figure 22(b)

SIMULATED MILL COUPON TESTS (WEB) - ULTIMATE STRESS

Normal Distribution Probability Curves



Web
Material "A"
24 Specimens

Also: 30.8
(14WF426)

Flange
Material "A"
24 Specimens

Also: 64.8
(14WF228)

Weighted Average
38 Specimens

Figure 23(a)

PERCENTAGE REDUCTION IN AREA
TENSION COUPON TESTS
Histogram

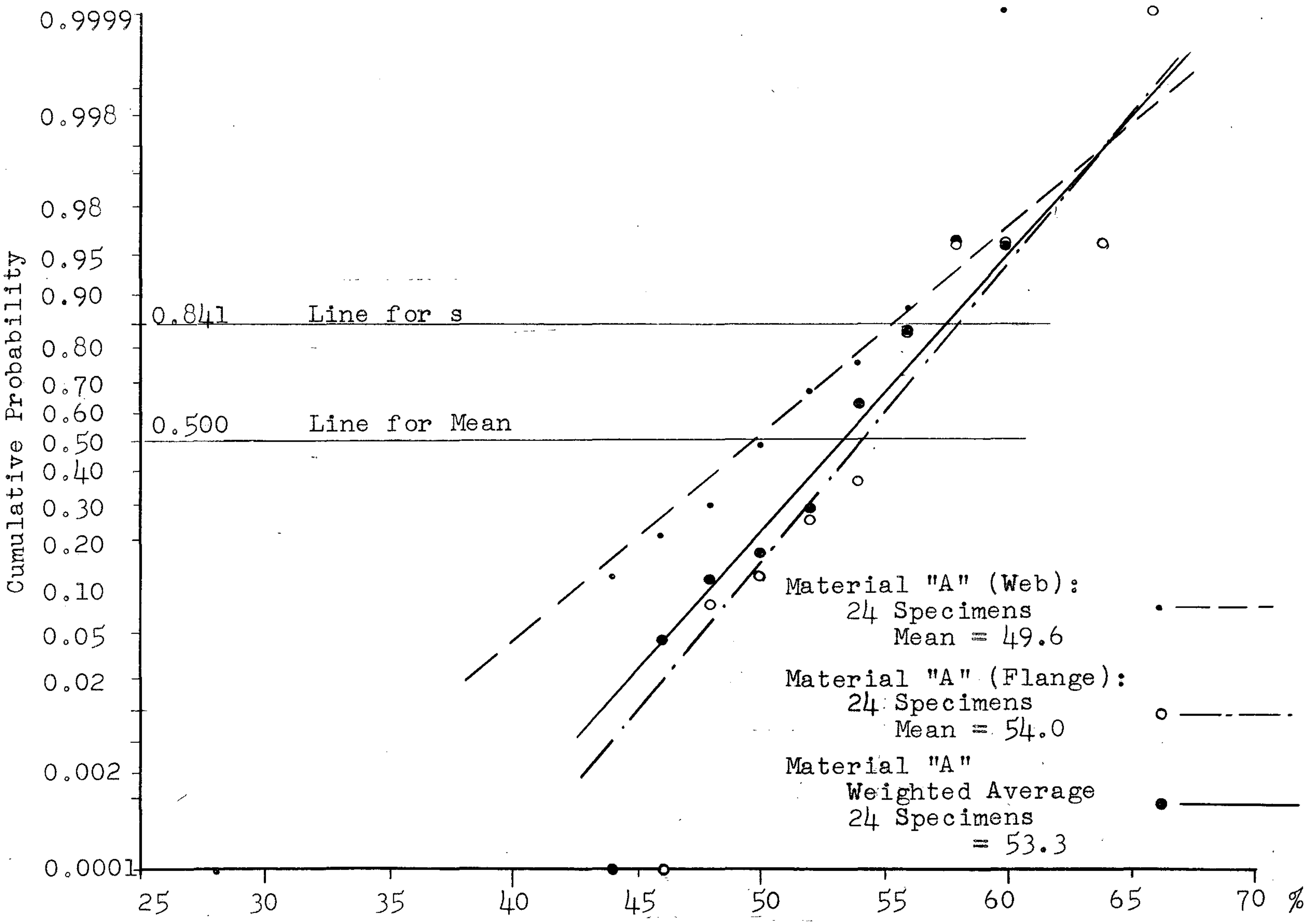


Figure 23(b)1

PERCENTAGE REDUCTION IN AREA - TENSION COUPON TESTS, "MATERIAL "A"

Normal Distribution Probability Curves

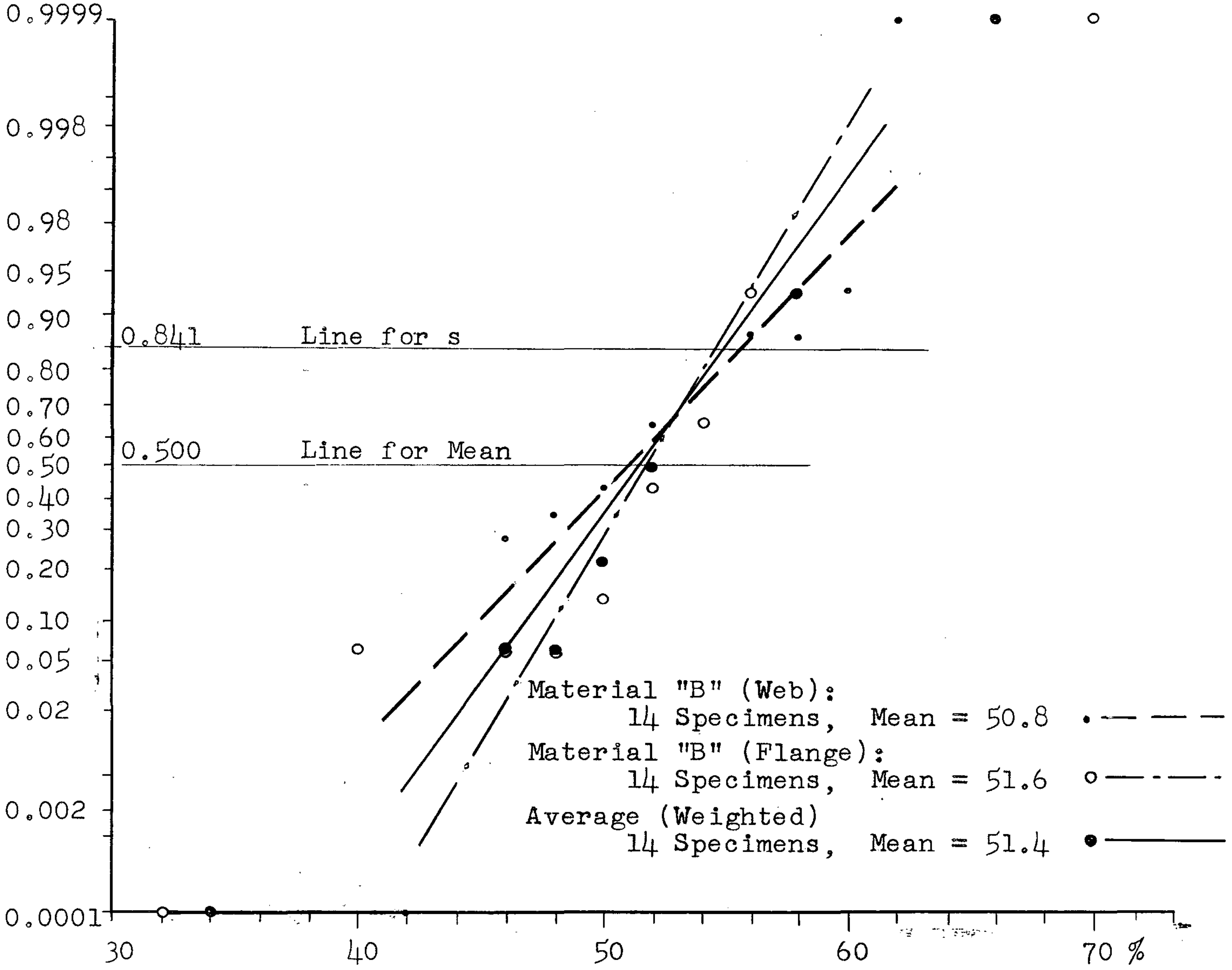


Figure 23(b)2

PERCENTAGE REDUCTION IN AREA - TENSION COUPON TESTS, MATERIAL "B"

Normal Distribution Probability Curves

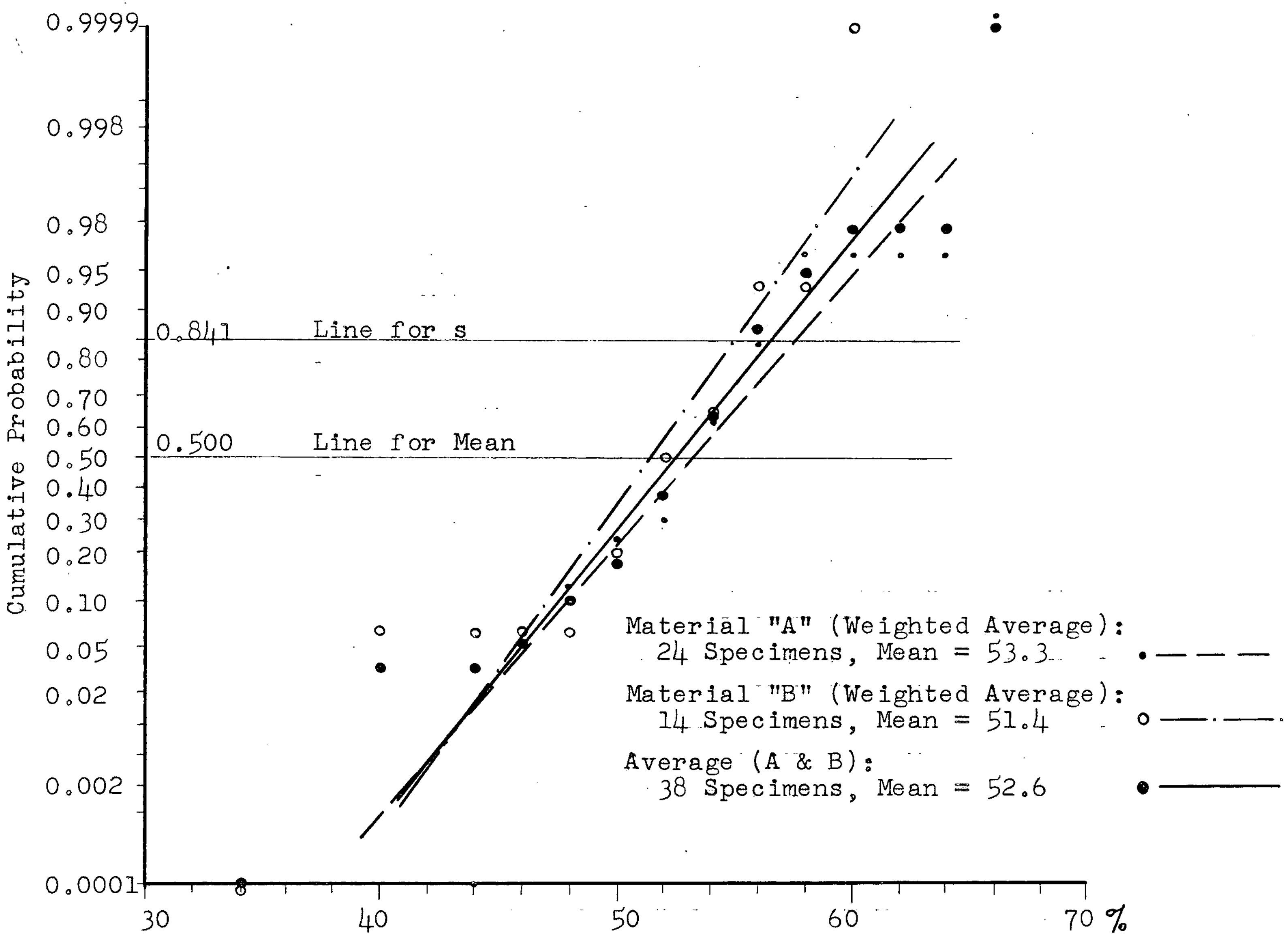
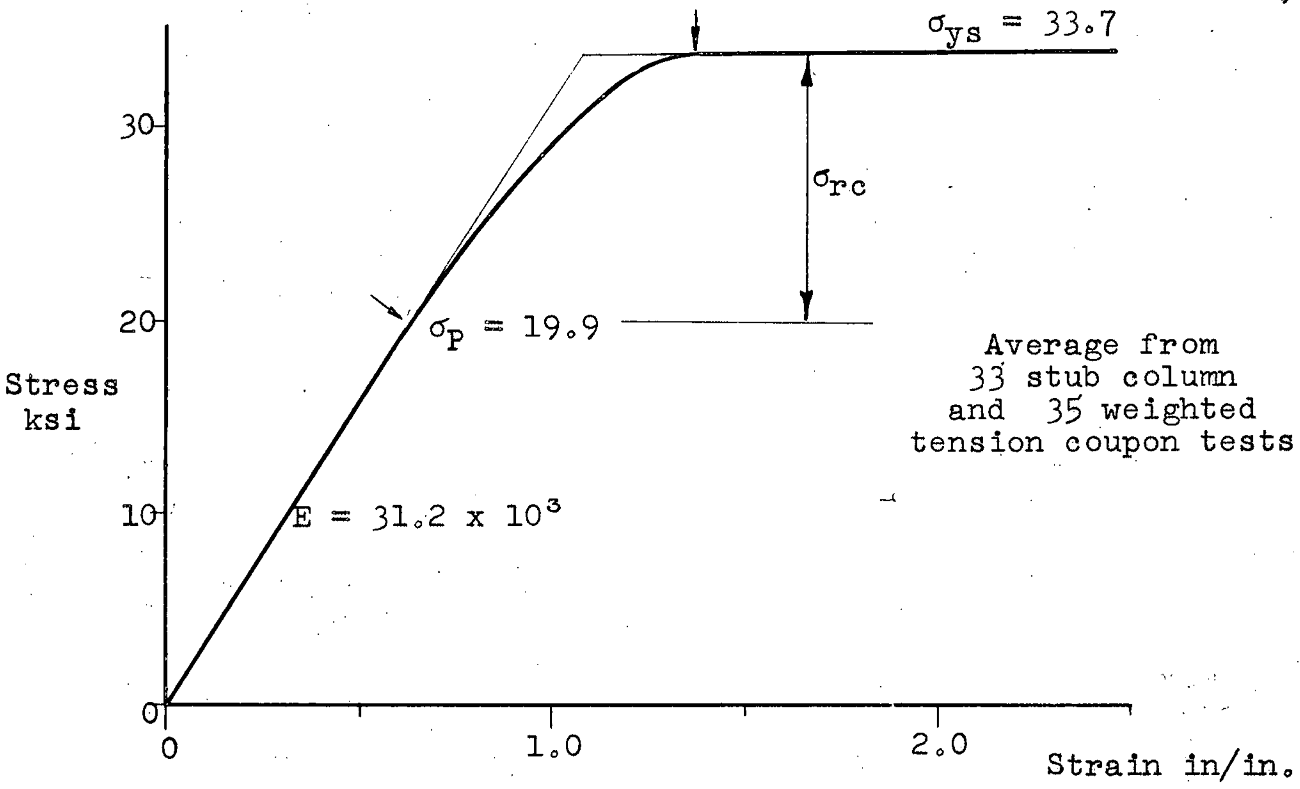
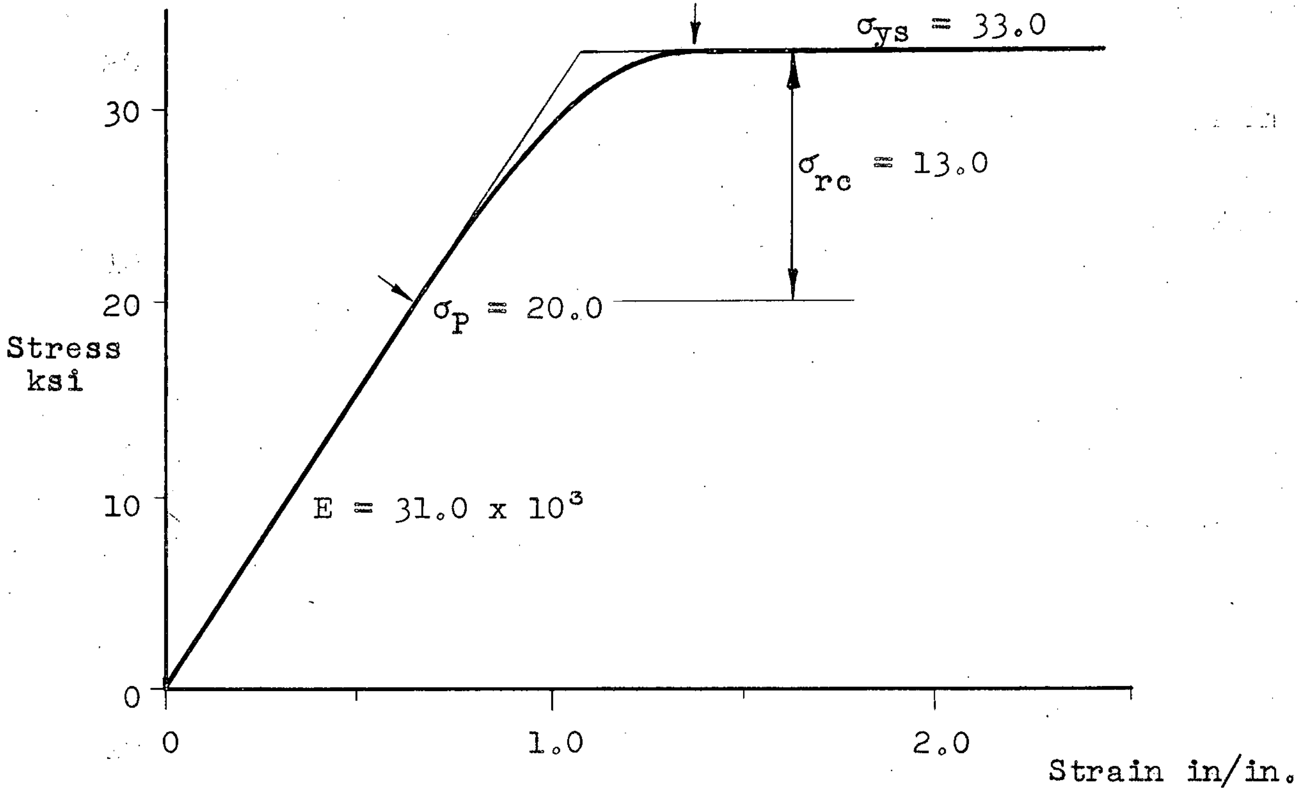


Figure 23(b)3

PERCENTAGE REDUCTION IN AREA -- TENSION COUPON TESTS
WEIGHTED AVERAGE OF MATERIAL "A" AND MATERIAL "B"
Normal Distribution Probability Curves



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



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