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220A.30

STRUCTURAL METALS DIVISION

RESEARCH SEMINAR

December 5, 1957

MATERIAL PROPERTIES OF STEEL

- L . T A L L

Fritz Engineering Laboratory
Lehigh University
Bethlehem, Pa.

This paper presents the salient features of Fritz Laboratory Report No. 220A.28 : Material Properties of Steel, by Lambert Tall, June 1957.

I INTRODUCTION

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 main concern of this study was the basic yield stress level of the material from which steel columns would be fabricated. The determination of the yield stress level, and associated properties such as residual stress, was undertaken to give a better understanding of the behavior of mild structural steel as defined under ASTM Designation A7. Further, this determination will enable a realistic meaning to be given to the factor of safety used with steel design today, not only for the usual elastic methods but also for the newer methods of plastic design. Indeed, to use the latter method effectively, it would be a retrogression to apply factors of safety to a nominal undefined value of the yield strength.

Generally, the results indicated that a far greater sample of specimens will have to be tested before authoritative conclusions may be drawn.

II THE YIELD STRESS

At first glance, there are enough levels of yield stress to satisfy even the most exacting connoisseur of definitions. Not only are such dissimilar levels as proportional limit, upper yield point, lower yield point, etc., in use, but these levels themselves, may differ for the same steel if the speed of testing of the coupon is varied.

This chapter considers the factors that have an influence on the yield stress and shows how a prediction of the value is possible from the mill reports.

(a) Definition : This paper will define the yield strength as the yield stress at the static level.

(Static yield stress, σ_{ys} .)

This is the value for σ_y when the strain rate is zero, in other words, the 'flat' portion of the stress-strain curve when the test is conducted at such a slow speed that the rate of straining may be regarded as zero. Use of the static level is perfectly logical, since most structural loads can be considered as primarily static.

The dynamic yield stress, σ_{yd} , is defined as the yield stress at a particular strain rate other than the zero strain rate. ('Dynamic' is used in contrast to 'static'.)

(b) Stub Column Tests.

A number of stub column tests were conducted so that an evaluation could be made of the behavior of the full cross section of WF shapes. The results provided an important basis for correlation of the yield strength with test coupon and mill test data.

Relevant data that may be obtained from the stress-strain

curve of a stub column test are : E , σ_p , σ_r , σ_{ys} as well as the overall effect of the residual stresses on the cross section, as witnessed by the 'knee' of the stress strain curve. Further, the tangent modulus concept of column formulas is applicable to the stress strain curve.

(c) Tension Coupon Tests.

The tests were conducted so that the static level of yield stress was also obtained, see fig. 4.

For the coupon tests the following data may be obtained: E , σ_p , σ_{yu} , σ_{yl} , σ_{yd} , σ_{ys} , E_{st} . 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 give an accurate indication of the yield stress, and other data. The effect of the strain rate on the apparent strength of steel in testing has been given considerable attention, and data are presented that enable predictions for the static yield strength knowing the speed of testing.

(d) Results.

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 both company 'A' and company 'B', for both tension and stub column tests.

1. σ_{ys} , Static level of yield stress. (fig. 1)

(a) Stub column tests.

| | | | |
|--------------|--------------------------|------------|----------------|
| Material 'A' | $\sigma_{ys} = 33.1$ ksi | mean value | (20 specimens) |
| " 'B' | $\sigma_{ys} = 35.0$ " | " " " | (13 ") |
| Average | $\sigma_{ys} = 33.9$ " | " " " | (33 ") |

(b) Simulated mill tests.

The weighted mean of the individual coupon tests, where one coupon is cut from a flange, the other from the web of a cross section.

| | | | |
|--------------|--------------------------|------------|----------------|
| Material 'A' | $\sigma_{ys} = 32.8$ ksi | mean value | (22 specimens) |
| " 'B' | $\sigma_{ys} = 34.6$ " | " " " | (13 ") |
| Average | $\sigma_{ys} = 33.5$ " | " " " | (35 ") |

2. σ_{yd} , 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.

'Simulated' mill tests were conducted in Fritz Lab. with the speed of testing 'simulating' that of the mill laboratory.

(a) Mill tests.

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

Note: 3000 Material 'B' mill tests gave $\sigma_{yd} = 44.1$ ksi.

(b) 'Simulated' mill tests.

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

3. Comparison of the mill test results with the σ_{ys} .

For the prediction of σ_{ys} from mill test reports.

$\sigma_{ys} / \sigma_{y_{mill}}$ (fig 2)

Material 'A' ratio = 76% mean value (20 specimens)

(over.)

cont.

| | | | | |
|--------------|---------|--------|------------|----------------|
| Material 'B' | ratio = | 84 % | mean value | (13 specimens) |
| Average | " | = 79 % | " " | (33 ") |

4. Variation of yield strength with the strain rate.

The yield strength of steel is directly affected by the rate of straining. 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 has 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.

Once the yield point has been reached in a test 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. See figures 3,4 .

Tests have shown that the static yield level may be determined without actually conducting the experiment in its entirety at the 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.

III RESIDUAL STRESS and other material properties.

1. Residual stresses.

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.

It has been shown in previous studies that an actual stub column test gives a more accurate and far simpler means of obtaining the average stress strain 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 thereby column strengths can be predicted. σ_{rc} is generally the largest inherent residual stress and defines the proportional limit in a stub column test.

Residual stress from stub column tests. ($\sigma_r = \sigma_{ys} - \sigma_p$, fig 5)

| | | | |
|--------------|-----------------------|------------|----------------|
| Material 'A' | $\sigma_r = 13.5$ ksi | mean value | (19 specimens) |
| " 'B' | $\sigma_r = 14.6$ " | " " | (7 ") |
| Average | $\sigma_r = 13.8$ " | " " | (26 ") |

2. Young's modulus, E. see figure 6.

Individual coupon values have been weighted according to respective areas of flange and web, to give a combined value for the cross section. To check this, results were also obtained from the full cross section by stub column tests.

(a) Weighted coupon results.

| | | | |
|--------------|----------------------------|------------|----------------|
| Material 'A' | $E = 31.2 \times 10^3$ ksi | Mean value | (21 specimens) |
| " 'B' | $E = 31.1 \times 10^3$ " | " " | (11 ") |
| Average | $E = 31.2 \times 10^3$ " | " " | (32 ") |

(b) Stub column results.

| | | | | |
|--------------|----------------------------|-----|------------|-----------------|
| Material 'A' | E = 31.5 x 10 ³ | ksi | Mean value | (19 specimens) |
| " 'B' | E = 30.4 x 10 ³ | " " | " " | (7 ") |
| Average | E = 31.2 x 10 ³ | " " | " " | (26 ") |

3. The ultimate strength of a tension coupon.

(a) σ_{ult} from weighted coupons of 'simulated' tests.

| | | | | |
|--------------|-----------------------|-----|------------|----------------|
| Material 'A' | $\sigma_{ult} = 62.9$ | ksi | Mean value | (23 specimens) |
| " 'B' | $\sigma_{ult} = 65.3$ | " " | " " | (12 ") |
| Average | $\sigma_{ult} = 63.7$ | " " | " " | (35 ") |

(b) σ_{ult} from mill tests (web)

| | | | | |
|--------------|-----------------------|-----|-----|---------|
| Material 'A' | $\sigma_{ult} = 66.3$ | " " | " " | (24 ") |
| " 'B' | $\sigma_{ult} = 68.2$ | " " | " " | (7 ") |
| Average | $\sigma_{ult} = 67.4$ | " " | " " | (31 ") |

(c) Percentage reduction in area, weighted coupons, 'simulated' tests.

| | | |
|--------------|--------|----------------|
| Material 'A' | 53.3 % | (24 specimens) |
| " 'B' | 51.4 % | (14 ") |
| Average | 52.6 % | (38 ") |

4. Typical stress strain curve.

A typical stress strain curve for a WF stub column test has been prepared from the results obtained. See figure 7.

IV CONCLUSIONS AND SUGGESTIONS.

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 | } coupon tests |
| σ_{rc} | = | 13 ksi | |
| σ_p | = | 20 ksi | |
| E | = | 31×10 ksi | |
| σ_{ut} | = | 64 ksi | |
| Percentage reduction in area. | = | 53 % | |

2. The yield stress should be defined by the 'static' yield stress, because it is the easiest to obtain and also is the stress that corresponds best to normal structural loading conditions.

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 shown. 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 $80\% \pm 5\%$ 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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VI NOMENCLATURE

| | |
|---------------|--|
| E | Young's modulus of elasticity |
| σ | Stress |
| σ_y | Yield stress |
| 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_p | Proportional limit |
| σ_r | Maximum residual stress determined from stub column test |
| σ_{rc} | Residual stress at flange edges |

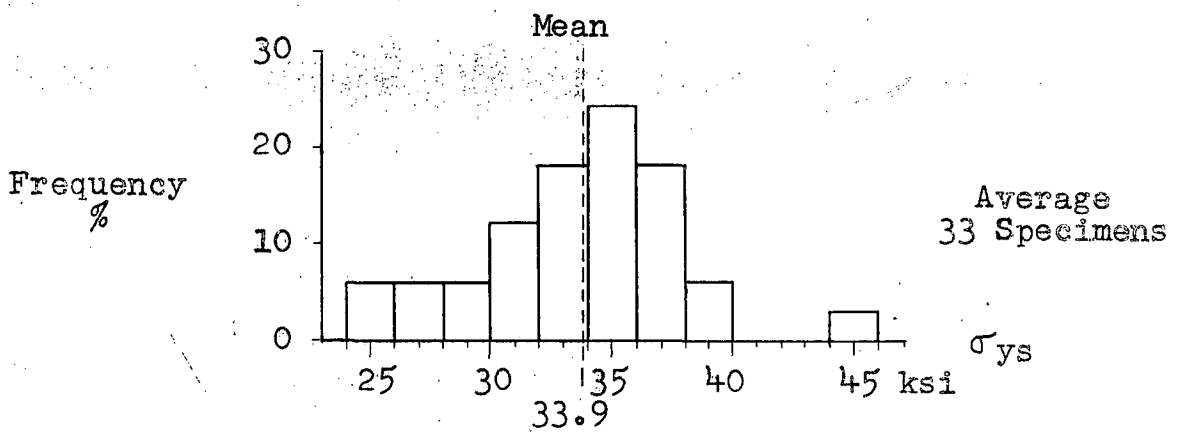
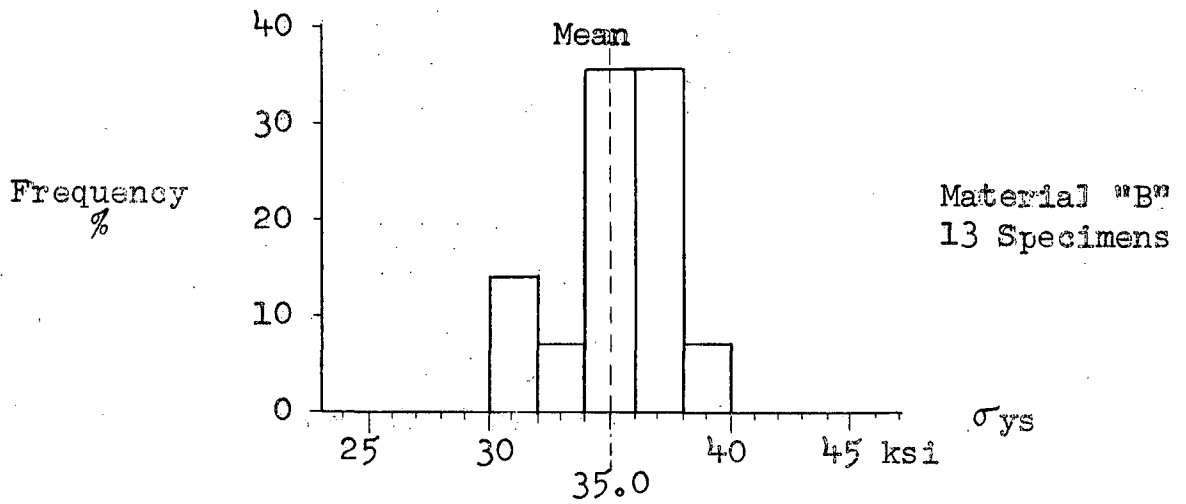
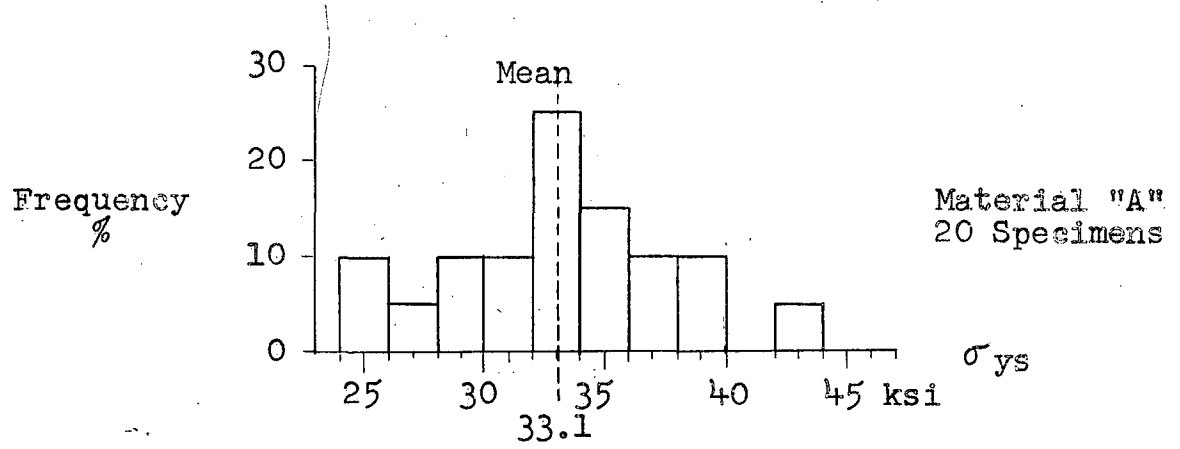
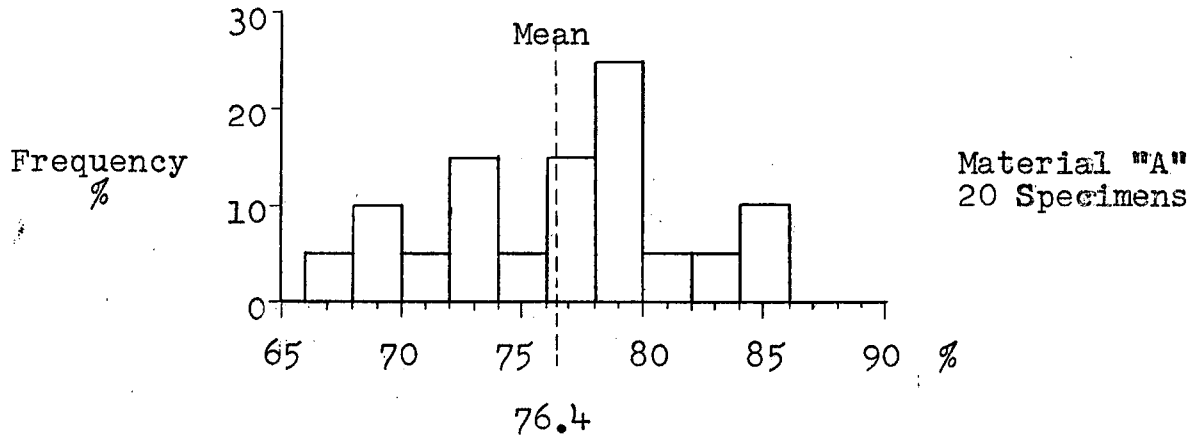


Figure 1
STUB COLUMN TEST RESULTS
The Static Level Of Yield Stress, σ_{ys}
Histograms

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



(b) simulated Mill Tests

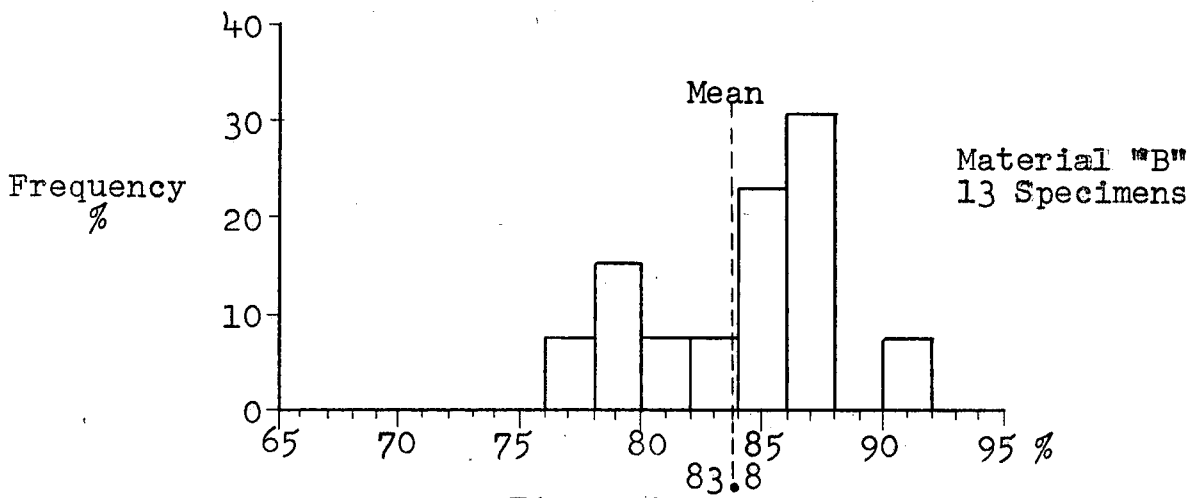
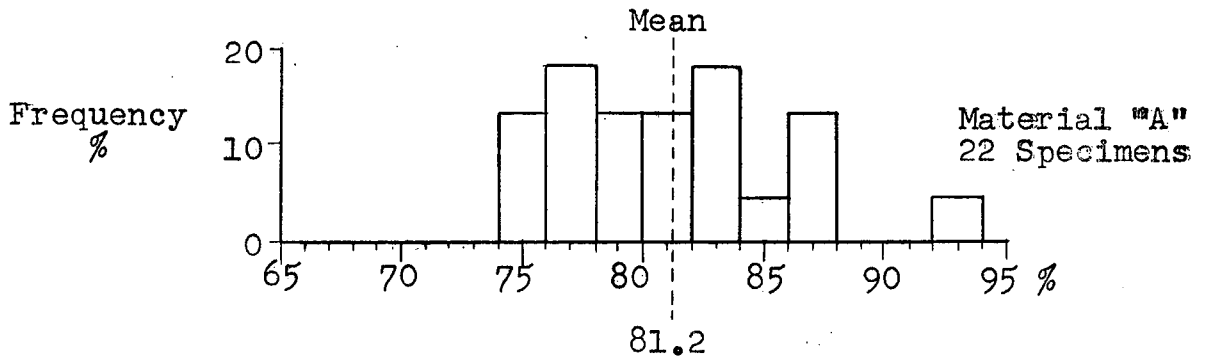


Figure 2
RATIOS OF STATIC YIELD STRESS TO MILL YIELD STRESS
Histograms

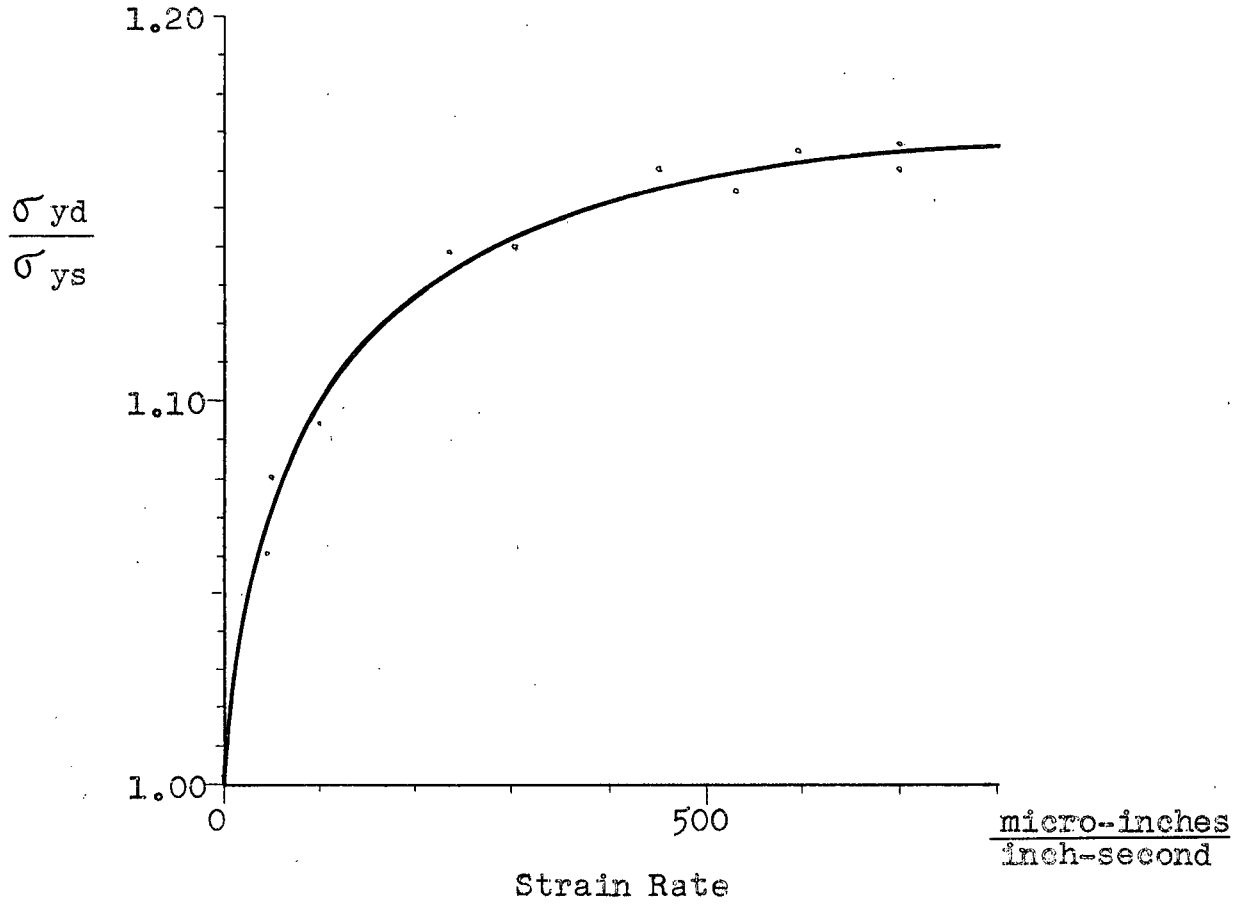
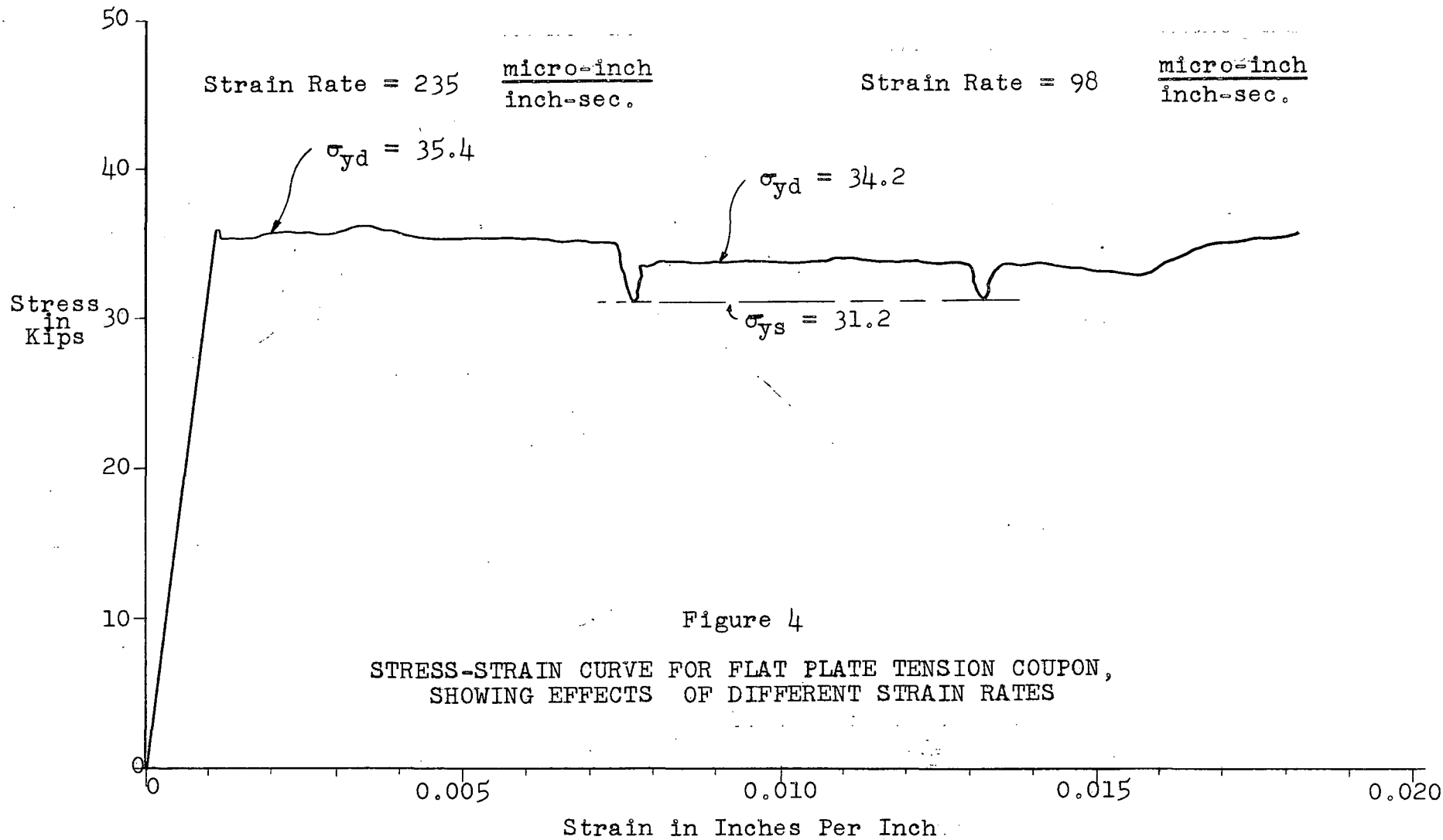


Figure 3

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

USING THE "FREE RUNNING" CROSSHEAD SPEED



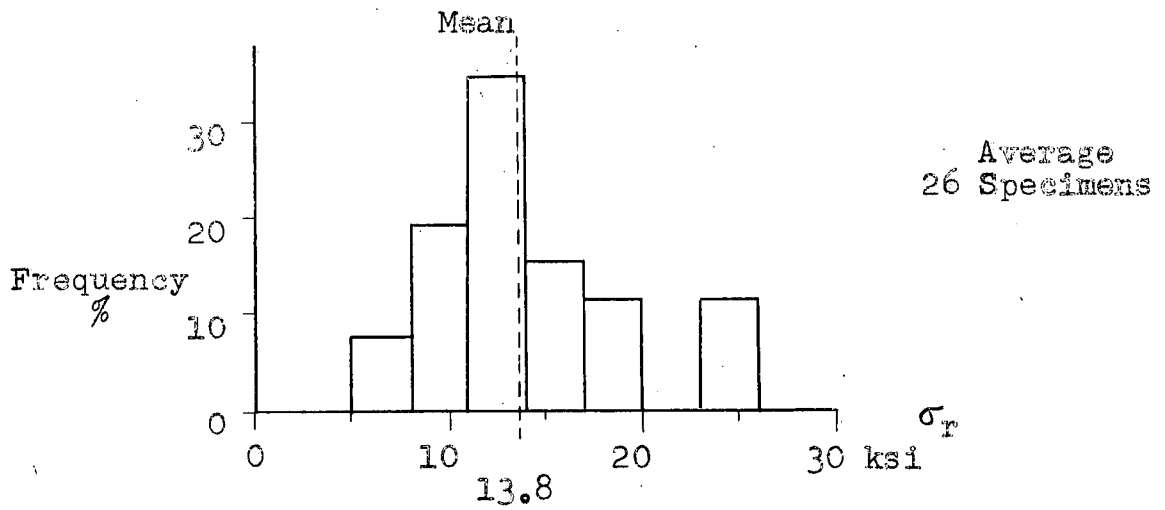
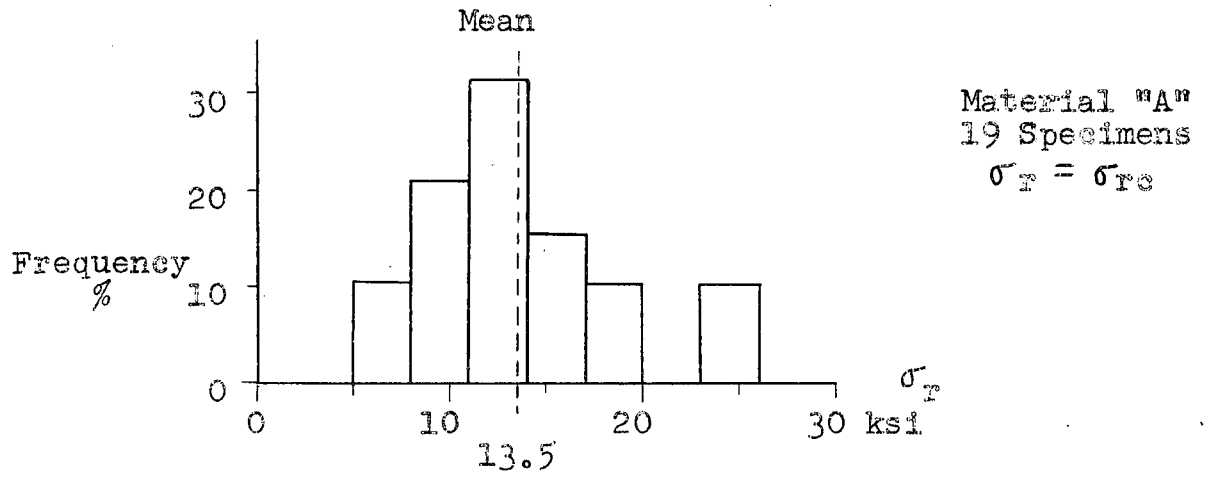


Figure 5

HISTOGRAMS OF THE MAXIMUM RESIDUAL STRESS
IN THE FLANGE OF STUB COLUMN

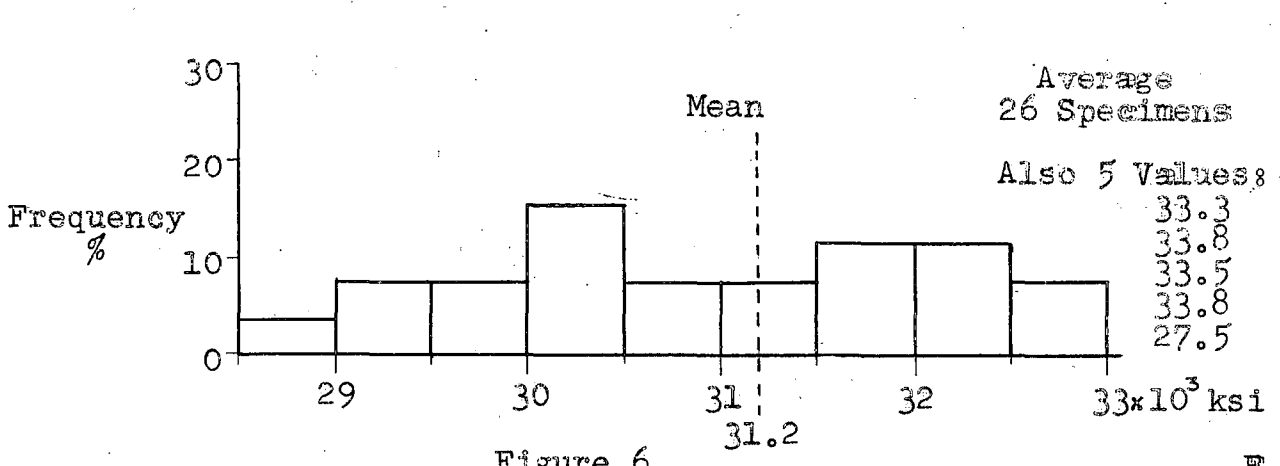
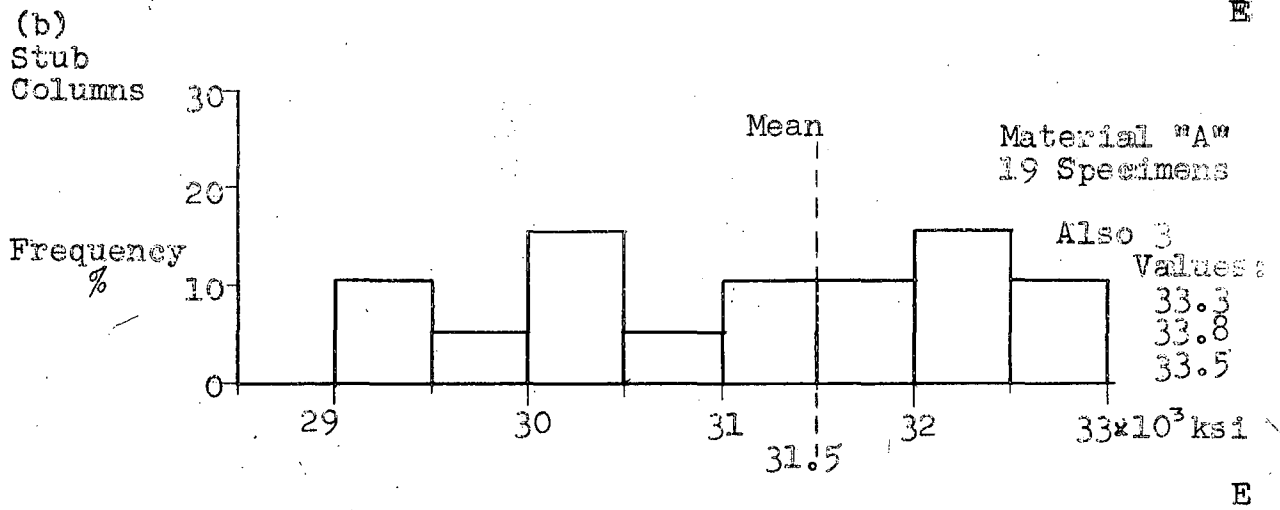
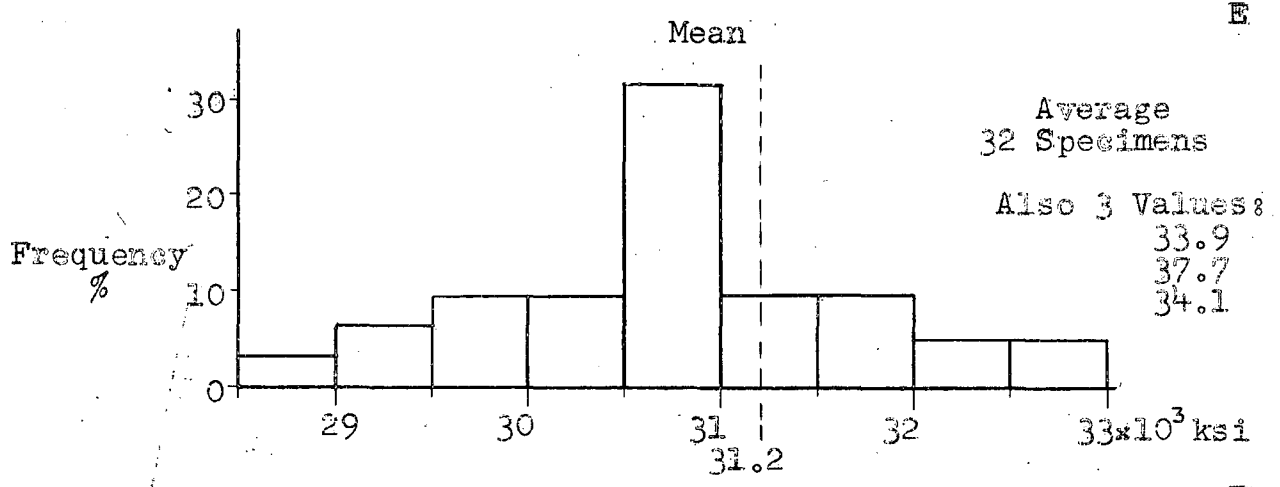
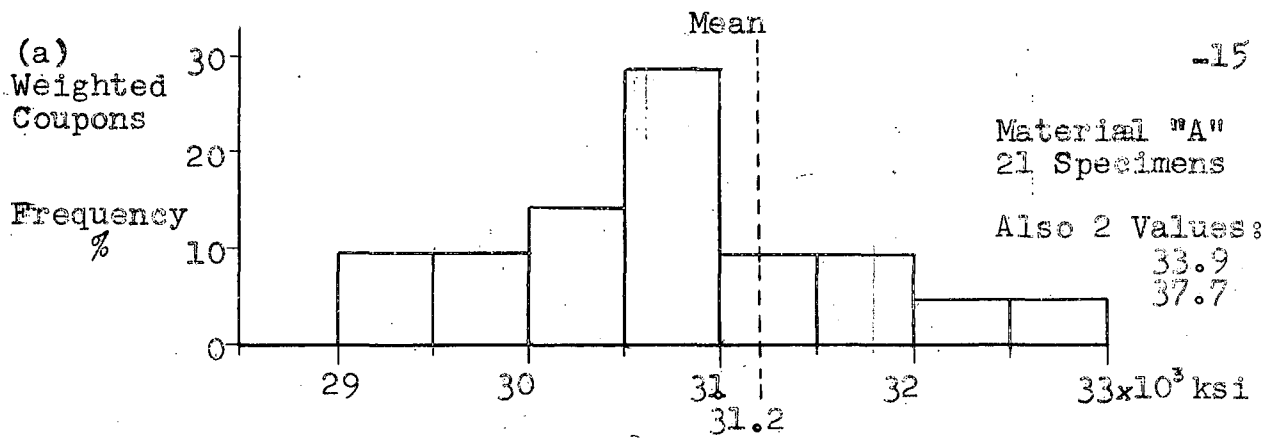
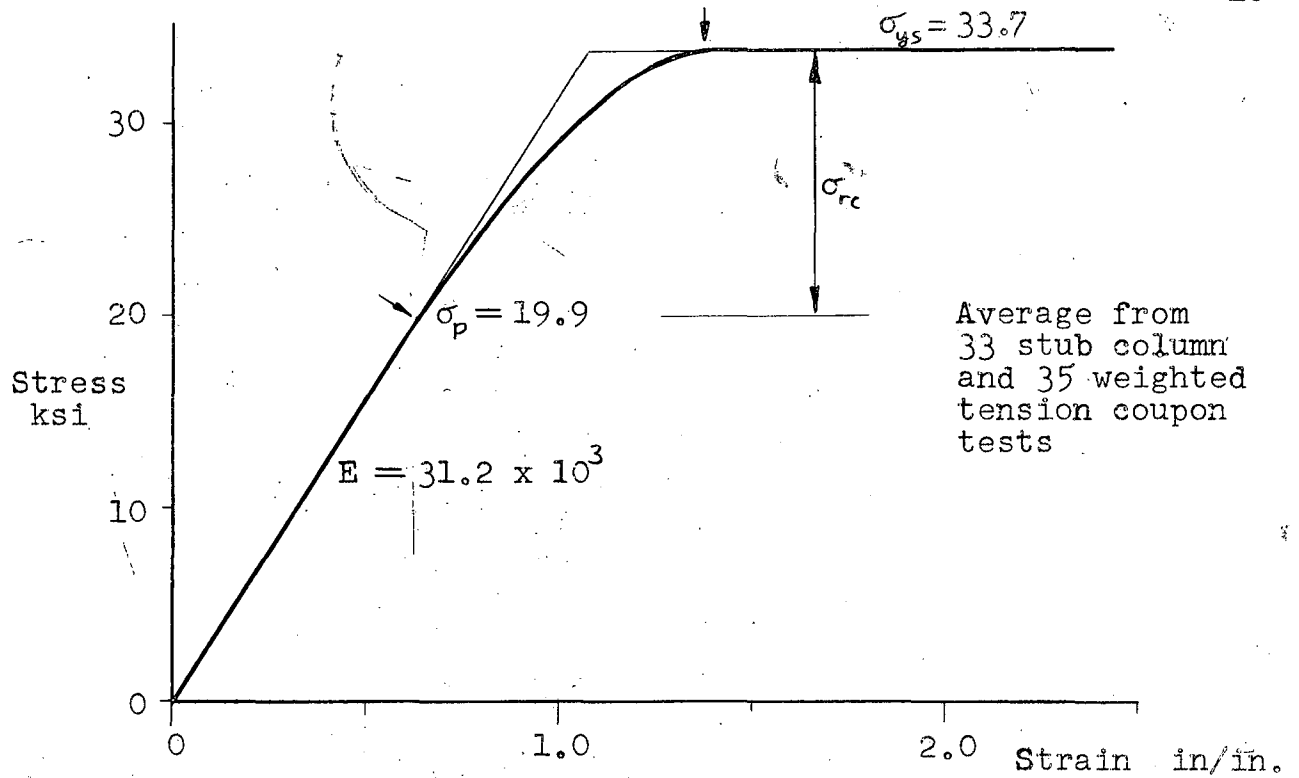
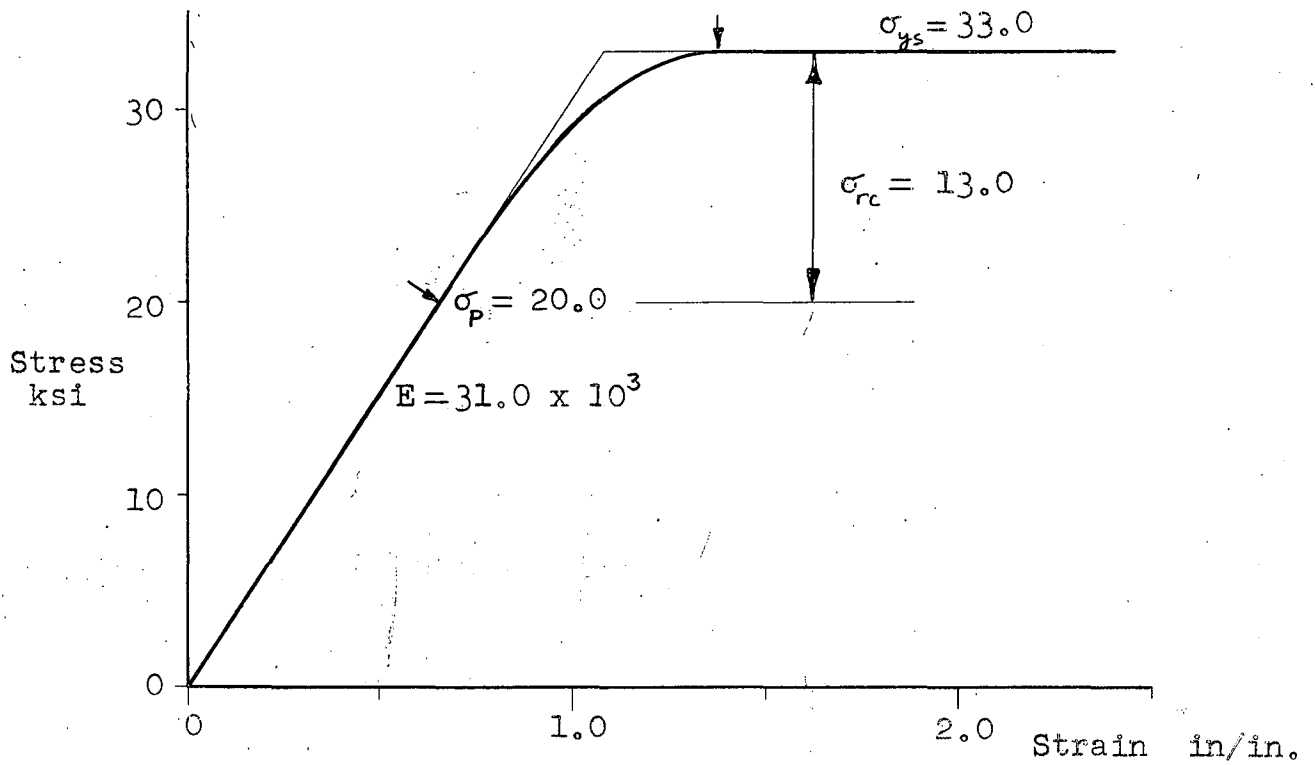


Figure 6
YOUNG'S MODULUS FROM "WEIGHTED" COUPONS AND STUB COLUMNS
Histograms



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



Suggested Typical Stress-Strain Curve
For WF Stub Column Test

Figure 7