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Plastic Design in A572 (Grade 65) Steel

MECHANICAL PROPERTIES OF ASTM A572 GRADE 65 STEEL

FRITZ ENGINEERING
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by
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Fritz Engineering Laboratory Report No. 343.2B

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MECHANICAL PROPERTIES OF ASTM A572 GRADE 65 STEEL

by

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Bethlehem, Pennsylvania

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ABSTRACT

This study forms a part of a research project (Fritz Laboratory Project 343) initiated to explore the possibility of extending plastic design concepts to structures of ASTM A572 (Grade 65) Steel. The overall objective was to study the mechanical properties of this material with particular emphasis on the properties in the inelastic range. This report includes discussion of the testing procedure, the testing machine and the instruments used. After a general discussion of the mechanical properties of steel, results of fifty-two tension specimens from plates and shapes of A572 (Grade 65) Steel are summarized.

This report constitutes the most complete study to date of the properties of higher grade of steel. The strain-hardening range of the material is studied closely and more refined techniques for the evaluation of the strain-hardening modulus are developed. Various steps of the testing procedure are studied in some detail. In particular, the phenomenon of reversal of the motor when it is shut off was examined to make sure that it did not cause unloading.

It is found that the A572 (Grade 65) Steel exhibits mechanical properties in the inelastic region that are similar to those of structural carbon steel. The strain-hardening modulus is not so low as to impose severe restrictions in the application of plastic design. Further studies on structural members and frames made of such steel are forthcoming.

1. INTRODUCTION

Plastic design concepts and procedures for ASTM A36 steel have gained wide acceptance during the past decade and are now an important part of the AISC Specification.[1]

Recent advances in metallurgical techniques have led to the development of a number of low-alloy steels with yield strength higher than that of structural carbon steel covered by ASTM A36.[2] These high-strength low alloy steels have found increasing use during the last few years and need was felt of extending plastic design principles to such steels. A project was initiated at Fritz Engineering Laboratory in 1962 to study the plastic behavior of structural members and frames made of A441 steel with specified yield strength of 42-50 ksi.[3] This research has resulted in design recommendations for such steel.[3,4,5]

The next step was to investigate the low alloy steels with higher strength such as those covered by ASTM A572. The grade with a yield strength of 65 ksi has the highest strength in the range of steels covered by this standard. Hence, a new project entitled "Plastic Design in A572 (Grade 65) Steel" was sponsored in early 1967 by the American Institute of Steel Construction with a view towards extending plastic design techniques to include steels with a yield strength of 65 ksi. A comprehensive program was proposed which included study of mechanical properties, stub columns, beams, etc. details of which are included in Table 1. Since only limited information relating to A572 steels was available, it was decided to test a number of tension specimens to determine the mechanical properties of the Grade 65 material.

A study of the mechanical properties, especially those in the inelastic region, namely, the strain-hardening strain and the strain-hardening modulus is particularly relevant with regard to the following problems in plastic design.

1) Hinge formation and mechanism theory,
2) Local buckling of flange and web,
3) Lateral-torsional buckling,
4) Lateral bracing spacing,
5) Rotation capacity
6) Deflection.

Of particular interest in this study is the magnitude of the strain-hardening modulus. Beams and columns of a plastically designed frame as also the plate elements constituting the cross sections of the beams and columns must be capable of undergoing large deformations in the inelastic range so that the basic assumptions of plastic design are satisfied and no premature failure due to local or lateral buckling occurs.[5] The value of the strain-hardening modulus E_{st} and the strain-hardening strain ϵ_{st} play an important part in the development of criteria to prevent such failures. Two examples show the dependence of important functions upon ϵ_{st} and E_{st}: The maximum rotation capacity R_m for a wide-flange shape is given approximately by[5]

$$R_m = 0.8 \left[\frac{\epsilon_{st}}{\epsilon_y} - 1 \right]$$

where ϵ_{st} = Strain at onset of strain-hardening

ϵ_y = Strain at first yield

As a second example, the critical length L_{cr} of lateral bracing spacing is given by[5]

$$L_{cr} = \frac{\pi r_y}{K\sqrt{\epsilon_y\left[1 + \frac{0.56E}{E_{st}}\right]}}$$

where r_y = Weak axis radius of gyration

E = Young's modulus,

E_{st} = Strain-hardening modulus,

K = A coefficient whose value depends on the restraint offered by the adjacent spans

The object of this report is to provide data on the mechanical properties of A572 (Grade 65) Steel with special emphasis on those more pertinent to plastic design and as a contribution towards the feasibility of extending the concepts of plastic design up to 65 ksi material.

ASTM A572 was issued as a standard for the first time in September 1966.[2] It covers "Standard Specification for High-Strength Low-Alloy Columbium-Vanadium Steels of Structural Quality." Important ASTM Specifications for the chemical composition and the mechanical properties of A572 steel as well as those of A36 and A441 steels are contained in Table 2.

The higher strength of A441 steel is due to small amounts of alloying elements. The higher strength of A572 steels is attributed to small amounts of nitrogen and vanadium. The addition of columbium promotes a fine grained structure with increased notch toughness. Four types of alternative combinations of these elements are specified as detailed in Table 2.

2. TEST PROGRAM AND TEST PROCEDURES

2.1 TEST PROGRAM

A fairly extensive program of testing tension specimens was instituted using a 120 kip Tinius-Olsen universal testing machine of the screw-power type. Detailed procedures followed are contained in a separate report.[6]

The program of tests is given in Tables 3 and 4. Two manufacturers supplied a total of forty-two tension specimens. Ten more specimens were fabricated at the Fritz Engineering Laboratory. Four of these came from the undeformed portion of a 12B19 beam previously tested under moment gradient and six from a piece of 10W54 left over after fabrication of two stub columns.[7,8]

A pilot test was run to determine approximately the properties of the material to facilitate a proper formulation of the testing procedure. The other specimens were tested by groups of students working in parties of two each. The author collaborated on twenty-three of these tests.

2.2 SELECTION OF MATERIAL

Material was received from two manufacturers and is designated as Material A and Material B. All the specimens of Material A came from webs and flanges of 16W71 and 16W88. Material B was from plates - 1/4", 3/8" and 1/2" thick and also from the webs and flanges of 12B19, 16B26, 14W30, 12W36, 16W36, 10W39 and 10W54. Complete details are given in Tables 3 and 4.

All specimens were fabricated to conform to ASTM A370 using an 8 in. gage.[2] They were tested in the as-received condition except that any loose scale was removed. No attempt was made to remove tight mill scale. None of the original surfaces were milled, only the edges were machined.

2.3 TEST PROCEDURES

The rational of testing instructions are now briefly reviewed. Also discussed are the difficulties encountered with the machine and the strain-measuring instruments.

1) Testing Machine and Tension Testing

The 120 kip Tinius-Olsen machine which was used in this series of tests is a screw power type with a speed selector which provides a crosshead speed of from 0,025 ipm (inches per minute) up to 10 ipm. According to the manufacturer's data, the crosshead speed indicated on the speed selector is maintained constant at all loads. However, the strain rate, which is the significant factor that influences the yield stress level, depends on a number of factors such as crosshead speed, shape of the specimen, elongation within the grips and also on whether the specimen is inelastic or plastic or strain-hardening range. Thus, with presently available equipment, there was no way of testing under a uniform strain rate with this machine. Instead, the strain rate was observed, where possible, by a timer.

Since it was considered desirable to keep the strain rate as low as possible in order to minimize its influence on stress levels, a crosshead speed of 0.025 ipm was specified. This is the minimum speed indicated on the speed selector. It is also the minimum speed at which the machine works smoothly at all loads. It would have been possible to run the machine at a lower speed but such lower speeds were not attempted since the absence of definite markings on the speed selector would have introduced an additional undesirable variable.

2) Instrumentation

Two types of strain-measuring instruments were used. One was an extensometer with a mechanical dial gage which was mounted on one side of the specimen while the autographic extensometer which was connected to the recorder was mounted on the other side. The smallest magnification of 400 was used for the recorder to obtain the entire strain-hardening range in one run of the drum.

2.4 MECHANICAL PROPERTIES

The following mechanical properties were determined from the tension tests. Figures 1, 2 and 3 are typical and indicate the terms in a graphical way. The glossary defines each term.

1. Proportional limit σ_p
2. Upper yield point σ_{yu}
3. Lower yield point σ_{yl}
4. Dynamic yield stress level σ_{yd}
5. Static yield stress level σ_{ys}
6. Tensile strength (ultimate strength) σ_u
7. Fracture stress σ_f
8. Strain at first yield ϵ_y
9. Young's Modulus E
10. Strain at onset of strain-hardening ϵ_{st}
11. Percent Elongation (in 8 in.)
12. Percent reduction of area
13. Strain-hardening Modulus E_{st}

Of these the properties most important in plastic design are:

1. Static yield σ_{ys}
2. Yield strain ϵ_y
3. Strain at onset of strain-hardening ϵ_{st}
4. Strain-hardening modulus E_{st}
5. Tensile strength (ultimate strength) σ_u

A typical graph from the autographic recorder is shown in Fig. 4 and a typical complete stress-strain curve obtained from one of the tests is shown in Fig. 5.

1) Proportional Limit

The proportional limit σ_p is the maximum stress up to which a linear stress-strain relationship is exhibited. However, due to the practical difficulty of determining such a stress, it has been the practice to define σ_p as the stress corresponding to a specified offset from the initial straight line. The CRC guide specifies the offset as 10 micro-in./in.[9] Due to the low magnification used in the present series of tests this value was too low for practical use. A higher value of 100 micro in/in. was, therefore, used. (See Fig. 1) However there is no practical significance of the value of σ_p. Although structural carbon as well as low alloy steels are expected to exhibit linear elasticity almost up to yielding, many tests give lower and widely varying values of σ_p. This can be attributed to two factors:

(i) Inaccurate alignment of the specimen and the consequent higher localized stresses due to eccentric load, and (ii) Prior plastic deformation in the opposite direction due to cold-straightening (Bauschinger effect[10]).

2) Upper Yield Point

Yield point is defined as the first stress in the material, less than the maximum at which an increase in strain occurs without an increase in stress.[11] When such increase in strain is accompanied by a decrease in stress, the material is said to have exhibited an upper yield point. Referring to Fig. 1, the upper yield point σ_{yu} corresponds to the highest load attained before the plastic range. It is influenced by the strain-rate, the grain size and the previous strain-history of the material. In terms of dislocation mechanics the presence of an upper yield point is attributed to interstital impurities in dislocations which lead to a drop in flow stress after plastic flow has been initiated at the upper yield point.[10] This load is recorded by the maximum pointer on the load dial, as well as by the autographic recorder. However, in many instances in these tests, when the drop in load after the attainment of the highest load was small, the autographic recorder failed to register the load corresponding to σ_{yu}. This is because there is a certain play between the gears operating the rod recording the load and also between the rod and the recording pen so that the recording mechanism is rendered insensitive to small reversals of load. However, σ_{yu} is not an important property and many tension specimens fail to exhibit any upper yield point possibly because of misalignment or the Bauschinger effect.[10]

3) Lower Yield Point

Lower yield point σ_{yl} corresponds to the lowest load recorded after the upper yield point has been passed and after the load has reached a temporary dynamic equilibrium condition compensating for the sudden prior slip. This can be recorded from the load dial, keeping a close watch when the load begins to drop. The difference between the load corresponding to σ_{y1} and the stabilized dynamic yield load is often so small that the recording mechanism fails to record it because of its insensitivity to load reversals.

σ_{y1} is not a significant quantity and is dependent on the presence of an observed upper yield point and the response of the specimen and the machine after the first slip. Because of these reasons, values of σ_{y1} are not reported.

4) Dynamic Yield Stress Level

The yield stress level is defined as the average stress during actual yielding in the plastic range.[12] For structural steel, the stress level remains fairly constant from the yield point up to the onset of strain-hardening, provided the strain rate is held constant. The yield stress level corresponding to the crosshead speed 0.025 ipm is termed the dynamic yield stress level σ_{yd}. The load corresponding to the value of σ_{yd} was recorded using the maximum pointer of the load dial just before stalling the machine at a strain of about 0.005 in./in. which was equivalent to 2 in. on the strain axis of the recorder sheet.[2] It was not possible to stall the machine exactly at a strain of 0.005 in./in. because such accurate control of machine speed was not possible and there was some delayed strain even after stalling of the machine and as explained in the next section.

The value of σ_{yd} at the crosshead speed of 0.5 ipm which is the maximum permitted by ASTM for an 8 in. gage is reported as the yield stress by the mills and is designated σ_{ym}.[2]

5) Static Yield Stress Level

The static yield stress level σ_{ys} may be defined as the value of the yield stress level at zero strain rate. σ_{ys} is an important property of steel and has a significant role to play in plastic design. It is the value which must be used for yield stress in plastic analysis under static loads.

Obtaining a value for σ_{ys} is not merely a matter of stalling the machine and observing the reduced load. The drop in load is due not only to the stalling of the machine. There is the loss due to relaxation.[10] Relaxation is defined as the loss of stress under constant strain. Relaxation loss is time-dependent and the rate of loss drops sharply with time but the full relaxation loss may be realized only after a very long time.

The situation in the test is still more complicated. Many elements of the machine (the columns, screws, crossheads) are subjected to stresses and every drop in load reduces strains in these elements and also in the length of the specimen outside the gage points. Hence, the strain between the gage points continues to increase for a minute or two even after the crosshead has become stationary and the process of relaxation is delayed. This is the reason why the load corresponding to σ_{ys} was recorded after an interval of five minutes after stalling the machine at a strain of about 0.005 in./in.[2] This interval was considered a practical minimum for reaching a reasonably stable load.[13] Full relaxation losses were thus not registered but obtaining even a significant part of it would have required waiting for at least a few hours.

Since the yield stress quoted by manufacturers is based on mill tests which are conducted at much higher crosshead speeds, the study of the ratio σ_{yd}/σ_{ys} assumes importance. Such studies have been made for A36, A441 and A514 steels but the A572 steels have not been examined so far.[12] The ratio σ_{yd}/σ_{ys} is studied for the uniform crosshead speed of 0.025 in./min. Four simulated mill tests were carried out and their results reported later together with the data provided by the producers.

ASTM A370 specifies a maximum crosshead speed of 0.5 ipm for 8 in. gage.[2] The speed adopted for this eries of tests was only one-twentieth of the maximum stipulated by ASTM and usually used for mill tests. Also the yield load as defines by the ASTM A370 is the load corresponding to a 0.2% effect or 0.5% strain.[2] The latter criterion was used for this series of tests.

6) Tensile Strength

The tensile strength σ_u corresponds to the maximum load on the specimen. This is recorded from the maximum pointer after the load begins to drop off.

7) Fracture Stress

The fracture stress σ_f corresponds to the load at the instan of fracture. The drop in load was rather sharp just before fracture so that it was difficult to record the fracture load. Hence, the value of σ_f should be regarded as approximate only.

8) Strain at First Yield

The strain at first yield ϵ_y was recorded from the dial gage at the instant the load pointer dropped on reaching the upper yield point. However, in the absence of an upper yield point, no observation could be taken. In such cases, even the autographic recorder failed to register a clear value of ϵ_y. Because if this, the observed value of ϵ_y are not included in this report. Instead ϵ_y is computed as σ_{ys}/E.

9) Young's Modulus

Young's modulus E was computed from observations taken as per the procedure.[6] However, the measuring techniques were not refined enough to give accurate values of E and therefore, the observed values are not reported here. Its value is assumed at 29,600 ksi.[14]

10) Strain at Onset of Strain-Hardening

Strain at onset of strain-hardening ϵ_{st} was measured from the autographic recorder and later when certain discrepancies appeared as noted earlier, dial gage readings were also taken. The values of ϵ_{st} based on dial gage readings are marked with an asterisk * in Table 6. The process of straining between first yield and the onset of strain-hardening is a discontinuous process due to the formation of successive slip bands. In terms of the modern theory of dislocation mechanics, the value of ϵ_{st} depends on the distribution of dislocations.[10] Previous strain history would also modify the value of ϵ_{st}.

A small reduction in the gage length occured as the knife-edge of the extensometer was lifted off the specimen usually after a strain of 0.0125 which was done to obtain the entire strain-hardening range in one run. In computing ϵ_{st}, no correction was applied to the strain on the second run. In any case, such correction would be small.

11) Percent Elongation and Percent Reduction of Area

Both percent elongation and percent reduction of area at fracture have been used extensively as a measure of ductility although both these quantities depend upon a variety of factors other than the material properties.[10] The "uniform strain" which is the strain corresponding to the point at which the maximum load is recorded in a tension test, is the measure of ductility specified by some standards and is a more consistent material property.[10] Percent elongation represents the sum of uniform strain and a large localized necking strain averaged over the gage length. That is why the gage length is always specified along with percent elongation. However the necking strain itself depends on the cross section. Mechanics of necking in a circular cross section is far different from that in a rectangular cross-section. Different width-thickness ratios in specimens of rectangular cross section also exhibit different necking characteristics. This adds further uncertainty to the value of percent elongation. The same applied to percent reduction of area as a measure of ductility.

12) Strain-Hardening Modulus

The strain-hardening modulus E_{st} has received considerable attention in research because of its importance in stability analysis. As already noted in the introduction, E_{st} figures in the lateral buckling criterion under uniform moment and the local buckling criteria of plate elements constituting the cross section of members. In short, the value of E_{st} is very important in the study of inelastic buckling behavior of any member, where any portion of the cross section is subjected to compressive yield stress over a finite length. Many approaches have been used in evaluating E_{st} and some of these are briefly reviewed below. Refer to Fig. 2.

E_{st1} is the instantaneous value as measured by a tangent to the curve at the point where strain-hardening commences. In the present series of tests, this value was obtained from the autographic recorder graph. It would be somewhat more difficult to obtain from dial gage readings because a large number of points would need to be taken at close intervals.

E_{st1} is only of academic interest and has little practical significance. The instantaneous value of E_{st} falls off rapidly as strain-hardening progresses and it would be rather unrealistic to use the value of E_{st1} in any stability computations. Besides, the tangent is difficult to determine uniquely and the small drop in load which often precedes the initiation of strain-hardening results in rather high values of E_{st1}. Further, the value of the strain-hardening modulus depends on the distribution of dislocations.[10] All these factors contribute to a wide scatter of values.

In order to approximate the initial instantaneous value, Haaijer defined the stress-strain relationship in the strain-hardening region using three parameters introduced by Ramberg and Osgood.[15,16]

$$\epsilon - \epsilon_{st} = \frac{\sigma - \sigma_y}{E_{st}} + K \left[\frac{\sigma - \sigma_y}{E_{st}} \right]^m$$

where σ and ϵ are respectively the stress and strain, σ_y is the yield stress and K and m are coefficients. The value of E_{st} used in the above equation is designated $E_{st1(a)}$. Values of K, m, and $E_{st1(a)}$ are determined from experimental curves by a curve-fitting technique.

This approach eliminates the uncertainties involved in a graphical construction of the tangent and provides a powerful mathematical tool for the study of incremental stress-strain relationship. $E_{st1(a)}$ was not computed in this series of tests.

Adams and Lay obtained a static strain-hardening modulus designated $E_{st1(b)}$ by using the static load at ϵ_{st} and at a strain equal to $\epsilon_{st} + 0.002$.[4] See Fig. 3. No attempt was made to obtain $E_{st1(b)}$ in this series of tests, because the method appears to introduce uncertainties that raise a question as to the reproducibility of results. The value of ϵ_{st} must be determined in advance and since this value can vary between rather wide limits, the method is sensitive to the variation between the correct value of ϵ_{st} and the strain at which the machine is stopped for observing the static load. Besides, the value of E_{st} is not constant in the increment of 0.002 beyond ϵ_{st}. A further uncertainty is introduced by the possibility of different relaxation losses at the two points.

E_{st2}, which was measured in these present tests and is later reported, is defined as the strain-hardening modulus measured as the chord slope between the strains $\epsilon_{st} + 0.003$ and $\epsilon_{st} + 0.010$. See Fig. 2. This particular range was chosen from the results of the pilot test with a view to confining measurements to a fairly linear and stable range of the curve and eliminating the initial erratic portion of the strain-hardening range of the stress-strain curve. E_{st2} should provide a more conservative value than the other methods because measurements are made at a greater value of strain.

E_{st2} was computed from the autographic recorder in most of the tests. However, when the earlier-mentioned discrepancies between the dial gage readings and the recorder were discovered and the results of the recorder appeared to be in some doubt, it was decided to take more complete dial gage observations on the later tests. Whenever values of E_{st2} are based on dial gage readings, they are marked by an asterisk * in Table 6.

E_{st3} is obtained using the CRC approach.[9] It is the average value in an increment of 0.005 in./in. strain after the onset of strain-hardening. See Fig. 2. For this purpose the onset of strain-hardening is defined as the strain corresponding to the intersection on the stress strain curve of the yield stress level in the plastic range with the tangent to the curve in the strain-hardening range. This tangent is drawn as the average value in an increment of 0.002 in./in. after the apparent onset of strain-hardening. The definition of the onset of strain-hardening is so modified here that the effect of the frequently encountered drop in load immediately prior to the apparent onset of strain-hardening is eliminated.

E_{st3} includes the effect of the steeper initial slope. It should result in E_{st3} being a less conservative value than E_{st2}. The range of strain-hardening is also rather arbitrary and this is quite significant because the influence of strain range on E_{st3} is much greater than on E_{st2}.

In the present series of tests, E_{st3} was measured in two ways. The value measured from the autographic recorder was designated $E_{st3(a)}$ and that measured from dial gage readings designated $E_{st3(b)}$.

No single value of E_{st} can be satisfactorily used in all situations. For incremental analysis, Ramberg and Osgood's equation with $E_{st1(a)}$ would be appropriate. For the buckling analysis, two cases arise: (1) In the first case, the material is assumed to be strained up to ϵ_{st} as in the local buckling analysis and analysis of beams under uniform moment, (2) Here, the material is assumed to be strained well into the strain-hardening range. A suggested value is a stress of

$\sigma_y + 1/4\ (\sigma_u - \sigma_y)$.[17] E_{st3} can be used for the first case, but for the second case E_{st2} would be more appropriate. Further, when cold-straightening strains the material well into the strain-hardening range, it may be more appropriate to use E_{st2}.

It may be emphasized again that E_{st} is not a stable material property but depends on factors like distribution of dislocations and previous strain history.[10] Under these circumstances, values of both E_{st2} and E_{st3} (average of $E_{st3(a)}$ and $E_{st3(b)}$) are reported.

3. TEST RESULTS AND ANALYSIS

Results of tests are presented in this section together with pertinent discussion. The data was analyzed using the CDC6400 computer at Lehigh University. Details of the computer program will be made available in a subsequent report.[18]

Table 3 lists the program of tests and Table 4 gives the details of the test specimens. Computed values of the mechanical properties are listed in detail in Tables 5 and 6 and are summarized in Tables 7 and 8. Table 9 contains the average values of some important properties of groups of specimens selected according to (i) origin, (ii) presence or absence of yield lines, (iii) thickness and (iv) weight of shape. Data for the ratio σ_{yd}/σ_{ys} are in Table 10 and the results of the simulated mill tests and the mill data are in Table 11.

A typical graph from the autographic recorder is shown in Fig. 4 and a typical complete stress-strain curve obtained from the tests is shown in Fig. 5. The dips in the curve indicate the points at which the machine was stopped in order to adjust the recording paper. Figure 6 shows an idealized stress-strain curve for A572 (Grade 65) steel up to and including strain-hardening and indicating the average values of the significant properties. The same curve is reproduced in Fig. 7 alongside similar curves of A7 and A441 steels. Figure 8 shows typical complete stress-strain curves for A36, A441 and A572 (Grade 65) Steels.

A summary of the average values of the mechanical properties listed in Chapter 2 is given below:

1. σ_p = 57.0 ksi
2. σ_{yu} = 66.7 ksi
3. $\sigma_{y\ell}$ is not reported for reasons stated in Chapter 2.
4. σ_{yd} = 64.6 ksi
5. σ_{ys} = 62.1 ksi
6. σ_u = 85.7 ksi
7. σ_f = 67.9 ksi
8. ϵ_y = 0.00211 in/in. = σ_{ys}/E
9. E is assumed as 29,600 ksi
10. ϵ_{st} = 0.0186 in./in.
11. Percent Elongation (in 8 in.) = 21.5
    Percent Reduction of Area = 51.0
12. E_{st1} = 2,979 ksi
    E_{st2} = 553 ksi
    $E_{st3(a)}$ = 771 ksi
    $E_{st3(b)}$ = 704 ksi
    E_{st3} = Average of $E_{st3(a)}$ and $E_{st3(b)}$ = 737 ksi
13. σ_{yd}/σ_{ys} = 1.040 for a crosshead speed of 0.025 ipm.
14. σ_{ym} = 69.3 ksi

These results are consistent with the relevant ASTM A572 requirements. Some of these will now be discussed.

Some of the important results from Tables 5 and 7 are reproduced below. All values are in ksi.

Property	Minimum	Maximum	Average	Standard Deviation
σ_p	30.8	72.0	57.0	9.9
σ_{yu}	59.8	72.0	66.7	2.6
σ_{yd}	58.4	69.9	64.6	2.6
σ_{ys}	57.0	66.3	62.1	2.3
σ_u	80.4	89.6	85.7	2.2
σ_f	61.1	79.3	67.9	3.4

1) Proportional Limit

As already discussed in Chapter 2, the proportional limit is influenced by many factors. This is reflected in the test results summarized above.

The observed average value of σ_p corresponds to 85.4% of the upper yield point, which is about what one would expect.

2) Upper Yield Points

Only forty-two specimens registered upper yield. Figure 9 shows the histogram for the values of σ_{yu}. Only three specimens exhibited values of σ_{yu} lower by 0.2 ksi than the dynamic yield stress level. Otherwise, the values of σ_{yu} were higher than those of σ_{yd}, the average difference being 3.1 ksi or 4.65% of the average value of σ_{yu}. This increase is registered in spite of the fact that the strain rate near upper yield point is smaller than in the plastic range.[12] The higher value of σ_{yu} can be attributed to the higher stress required to initiate plastic flow compared to the stress required for sustaining it.

3) Lower Yield Point

Values of the lower yield point are not reported for reasons already discussed in Chapter 2.

4) Dynamic Yield Stress Level

Figure 9 shows the histogram for the values of σ_{yd}. The scatter is much less than for lower grades of steel.[18]

5) Static Yield Stress Level

The values for σ_{ys} also exhibit a smaller scatter than for lower grades of steel as shown by the histogram in Fig. 9.[18]

The effect of strain rate on the relationship of σ_{yd} and σ_{ys} and the influence of factors like thickness of specimen on the value of σ_{ys} are discussed later.

6) Tensile Strength

The tensile strength of three flange specimens of Material A could not be obtained since the corresponding load exceeded 120 kips, the capacity of the machine. Values of σ_u for these specimens were computed using 120 kips as the ultimate load.

Among the three stresses analyzed statistically, the values of the tensile strength show the minimum scatter as indicated by the histograms in Fig. 9.

Like the values of σ_{yd} and σ_{ys}, the values of σ_u show smaller scatter than for lower grades of steel.[18]

7) Fracture Stress

The difficulties of observing the fracture load have been discussed in Chapter 2. Further uncertainty is introduced by the practice of evaluating fracture stress using the original area of the specimen and the differences in the mechanics of necking of different shapes of cross section.[9] The test values of σ_f appear to reflect these problems.

8) Strain at First Yield

The value of the strain at first yield as reported here is 0.00211 in./in. which is equal to the quotient of the average value of σ_{ys} and Young's modulus. This has been discussed in Chapter 2.

9) Young's Modulus

As already discussed in Chapter 2, the values of E as computed from the tests are not reported since the techniques used were not refined enough. Instead, the value is adopted from a series of careful tests reported in Ref. 13.

Some of the important results from Tables 6 and 7 are now reproduced below:

Property	Minimum	Maximum	Average	Standard Deviation
ϵ_y, in./in.	0.0095	0.0328	0.0186	0.0052
Elongation, %	18.0	36.1	21.5	2.7
Reduction of Area, %	36.4	62.3	51.0	6.8
E_{st1}, ksi	393	9825	2979	2400
E_{st2}, ksi	322	775	553	95
$E_{st3(a)}$, ksi	382	1160	771	186
$E_{st3(b)}$, ksi	220	1122	704	197

10) Strain at Onset of Strain-Hardening

Figure 9 shows the histogram for the values of ϵ_y. The test results for the values of ϵ_y are summarized on the preceding page.

The coefficient of variation is 27.9%. As noted in Chapter 2, the modern science of materials asserts that the stress-strain relationship in the inelastic range is determined by the random nature of the distribution of dislocations and the prior strain history.[11] This would suggest that ϵ_{st} may not be a characteristic mechanical property and would explain the wide scatter in the values of ϵ_{st}.

11) Percent Elongation and Percent Reduction of Area

The limitations of the values of the percent elongation and the percent reduction of area as a measure of ductility have been discussed in Chapter 2. The histograms for both values are in Fig. 9 and a brief summary of the test values is given earlier.

Except for one specimen with a value of 36.1, the maximum value of the percent elongation was 24.9. The values for percent reduction of area exhibit a much bigger scatter. Also, a study of Figure 9 indicates that there is no central tendency for percent elongation of area in contrast with the distribution of percent elongation.

12) Strain-Hardening Modulus

Various approaches to the measurement of E_{st}, the value of which is of particular interest, have been discussed in Chapter 2. Important results have been summarized at the end of section 9 earlier. Histograms for E_{st2}, $E_{st3(a)}$ and $E_{st3(b)}$ are shown in Fig. 11.

E_{st1} varies from 393 to 9825. This wide scatter of values is in keeping with the known erratic nature of the straining process in the region of the onset of strain-hardening and is also in keeping with inherent difficulties in determining this function.

By eliminating the initial erratic portion of the strain-hardening range of the stress-strain curve and confining measurements to a relatively linear portion of the curve, the resulting value of E_{st2} exhibits a smaller scatter and a much smaller standard deviation than E_{st3}. Further, since the slope of stress-strain curve reduces with increasing strain, the average value of E_{st2} is lower.

The average value of E_{st2} at 553 ksi for A572 (Grade 65) steel compared favorably with the value of 572 ksi for A7 steel, since the later value lies somewhere between E_{st2} and E_{st3}. See Fig. 7. This would indicate that the limits on the width-thickness ratios of shapes and the bracing spacing requirements would not be too restrictive. This is fortunatem since the A572 (Grade 65) steel is limited to shapes of Group 1 with high width-thickness ratios so that a low value of E_{sy2} would render most of them non-compact.

According to Ref. 10, the effective value of E_{st} in compression is considerably higher than in tension for a material otherwise exhibiting the same stress-strain relationship in compression and tension. One of the probable causes of this is the Poisson effect, which increase the cross sections area due to the lateral strain accompanying longitudinal strain. The effect is more pronounced in the inelastic range due to a higher value of Poisson's ratio.

This higher value of E_{st} has been noted in previous tests. The following table of values of E_{st} are reproduced from unpublished data on twenty-one tension tests and twenty compression tests on A7 steel conducted at the Fritz Engineering Laboratory. Values of E_{st} are read as chords in the linear portion of the curve and lie somewhere between E_{st3} and E_{st2}. All values are in ksi

	Minimum	Maximum	Average
21 Tension Tests	465	750	572
20 Compression Tests	520	855	695

A series of ten compression tests on specimens fabricated out of the same material from which tension specimens were prepared, has been recently completed.[19] A preliminary analysis has given an average value of E_{st2} as 820 ksi.

However, the Poisson effect cannot fully account for the substantially higher test values of E_{st} in compression. And this gives rise to the question as to whether or not E_{st} should be determined from tension tests or from compression tests when the resulting values are to be used in calculating for buckling problems.

13) Effect of Strain-Rate

Rao et al. have pointed out that in the plastic range, the elongation of the length of the specimen undergoing plastic deformation accounts for all the movement of the crosshead.[12] Assuming such length to be about 10", a crosshead speed of 0.025 ipm would give a strain rate of about 42 micro in./in./sec.

On seventeen tests, the strain rate $\dot{\epsilon}$ was observed using a timer. The values of $\dot{\epsilon}$ varied from 21 to 83 micro in./in./sec. giving an average value of 44. Such large variation was probably caused by the extreme sensitivity of crosshead speed to the position of the speed selector pointer. Thus, the values cannot be confidently specified as the strain-rate for the corresponding value of σ_{yd} since the dynamic yield load was observed during the first run of the autographic recorder and the strain-rate was observed during the second run and the speed selector was manipulated in the meanwhile. However, the expotential relationship derived in Ref. 13 would suggest that the effect of such variation in the value of $\dot{\epsilon}$ on the value of the ratio σ_{yd}/σ_{ys} should be small so that a valid comparison with the results of Ref. 12 could still be made.

Test values of σ_{yd}/σ_{ys} are given in Table 10. Projecting the results derived in Ref. 12 for A36 and A441 steels, the following comparison is obtained. It indicates excellent agreement.

	$\dot{\epsilon}$ = 44 micro in./in./sec. Projected	Observed values for A572 (Grade 65)
σ_{yd}/σ_{ys}	1.040	1.040
$\sigma_{yd} - \sigma_{ys}$	2.88	2.50

14) Simulated Mill Tests

Simulated mill tests were conducted on four specimens, two from material A and two from material B. A crosshead speed of 0.5 ipm which is the maximum permitted by ASTM for 8 in. gage was used.^{2} Table 10 lists the results together with the mill test data furnished by the producers.

Mill tests are invariably performed on webs. Unfortunately, only one web specimen - from 12B19 of material B was available for conducting simulated mill tests. No plate specimens were available. Because of this, comparing the data is difficult. The only direct comparison is afforded by the web of 12B19.

	σ_{ym}, ksi	σ_u, ksi	Percent Elongation
Simulated Mill Test	71.8	89.2	18.6
Mill data	71.8	94.8	17.0

Although it is in part a happenstance, the agreement at yield is exact. Even for the entire lot of material, the agreement was within 2%.

All the test results of Table 10 meet with the tensile requirements of ASTM. (See Table 2.)

An interesting comparison with the following equation derived in Ref. 12 can be made.

$$\sigma_{yd} - \sigma_{ys} = 3.2 + 0.001\ \dot{\epsilon}$$

Assuming that in the plastic range, elongation between the gage points accounts for the full crosshead speed, the maximum possible value of $\dot{\epsilon}$ works out to be 1,040 micro in./in./sec. for a crosshead speed of 0.5 ipm. The corresponding value of $\sigma_{yd} - \sigma_{ys} = 4.2$ ksi. Test results are listed on the following page.

Material	Specimen from	σ_{ys}, ksi average, No. of specimens in brackets	σ_{ym}, ksi from simulated mill tests	σ_{ym}, ksi from mill data	$\sigma_{ym} - \sigma_{ys}$ ksi
A	Web-16W88	61.0(2)	---	71.1	10.1
"	Flange-16W71	62.9(2)	67.9	---	5.0
"	Web-16W71	61.8(2)	---	73.0	12.2
B	1/2"plate	61.4(3)	---	66.9	5.5
"	3/8"plate	61.1(4)	---	65.0	3.9
"	1/4"plate	63.9(4)	---	71.8	7.9
"	Flange-12B19	65.1(4)	69.6	---	4.5
"	Web-12B19	64.9(4)	71.8	71.8	6.9
"	Web-16B26	60.2(2)	---	70.5	10.3
"	Web-10W39	59.7(2)	---	71.5	11.8
"	Web-10W54	57.8(2)	---	72.9	15.1
"	Average of simulated mill tests		70.7		5.8
A&B	Average of mill data			70.5	9.3

All except one of the values of $\sigma_{ym} - \sigma_{ys}$ are larger than 4.2 ksi, the average being 9.3 ksi. The average for the simulated mill tests is 5.8 ksi. The high value of $\sigma_{ym} - \sigma_{ys}$ for the mill data could be attributed to the fact that the mills often tend to report the upper yield point for the value of σ_{ym}.[11]

15) Effect of Origin and Location of Specimen

Table 9 lists some properties of plate, web and flange specimens. The following may be particularly noted

	Plate	Web	Flange
σ_{ys}, ksi	62.2	61.9	62.2
σ_u, ksi	86.3	85.3	85.8
E_{st2}, ksi	525	530	569

Generally, the effect of rolling to a smaller thickness and the consequent faster cooling are thought to produce web although the differences are small. The reverse was obtained in these tests. The somewhat higher strength of the flange in the list above is partly due to the high flange strength of material A. As shown in Table 7 web strength was slightly higher than flange strength for material B but every flange specimen of material A was stronger than its corresponding web specimen.

16) Effect of Yield Lines

Table 9 compares some properties of specimens with yield lines with specimens of some material, heat, origin and shape but without yield lines. No significant influence of yield lines can be noted. From the work of Ref. 3 it was expected that E_{st} would be substantially lower. If any thing, it was higher for the five rotarized specimen in the current test program. The conclusion here is important, because it means that rotarizing will not reduce the local buckling strength in the inelastic region, if these five specimens can be assumed to be a sufficiently large sample.

17) Effect of Thickness

Some properties of specimens divided into groups according to thickness are given in Table 9. Graphical presentation of variation with thickness is shown in Fig. 13 for σ_{yd} and σ_{ys} and in Fig. 14 for ϵ_{st} and E_{st2}. Although the values of σ_{yd}, σ_{ys} and σ_u are high for thickness 0.801-0.900 in., it may be concluded that strength reduces with increased thickness, because the stronger thick specimens belong to material A and none of these have been tested in smaller thickness. The value of ϵ_{st} increases with increased thickness.

An interesting side to the study of the influence of thickness is the value of the percent reduction of area. As the table below shows the thicker specimens exhibit a higher value for the value of the percent reduction of area. This is probably due to the influence of the width-thickness ratio of the cross section of the specimen on the mechanics of necking.

Thickness, in.	Percent Reduction of Area
0.201-0.300	45.3
0.301-0.400	51.8
0.401-0.500	50.3
0.501-0.600	55.6
0.601-0.700	53.7
0.701-0.800	No data
0.801-0.900	56.0

18) Effect of Weight of Shape

Table 9 lists some properties of specimens divided according to weight of shape. Figure 16 shows σ_{yd} and σ_{ys} and Fig. 17 shows ϵ_{st} and E_{stq} as functions of weight and shape. Here too, the uneven distribution of specimens persists. All the higher strength material A specimens belong to heavier shapes. However, the same general conclusions can be drawn as in the previous case. With increase thickness σ_{yd}, σ_{ys}, σ_u and ϵ_{st} reduce but E_{st2} increases.

4. SUMMARY AND CONCLUSIONS

The following observations are based on tests and studies of A572 (Grade 65) steel, representing a total of fifty-two tests on tension specimens cut from 1/4", 3/8" and 1/2" plates and from eight shapes varying in weight from 19 lbs/ft. to 88 lbs./ft.

1. A572 (Grade 65) steel exhibits mechanical properties in the inelastic region that are similar to those of structural carbon steel (Fig. 7).

2. The results of this test series conform to the relevant ASTM A572 requirements.

3. The use of E_{st2} as the strain-hardening modulus represents a new approach to obtain a more realistic value of this property for use in situations where the material is assumed to be strained into the strain-hardening range. By eliminating the erratic initial portion of the strain-hardening range of the stress-strain curve and restricting the measurement to the linear portion, E_{st2} provides values which are more conservative and are less subject to scatter.

4. The average value of E_{st2} is 553 ksi which compares favorably with the values of 572 ksi for A7 steel since the latter value is between the values of E_{st2} and E_{st3} (See Fig. 7). This would indicate that the limits on the width-thickness ratios of shapes and the bracing spacing requirements would not be too restrictive. This is fortunate, since the A572 (Grade 65) Steel is

limited to shapes of Group 1 with high width-thickness ratios so that a low value of E_{st} would render most of them non-compact.[2,5]

5. A re-examination of the practice of obtaining the strain-hardening modulus from tension tests is indicated. The value in compression tests is known to be higher than in tension and since this property is associated with failure in compression, a compression test would appear to be the appropriate way of obtaining its value. Unfortunately, the latter test is more difficult to perform.

6. A crosshead speed of 0.025 ipm gave an average value of 44 micro in./in./sec. for the strain rate $\dot{\varepsilon}$. At this strain rate, the observed value of the dynamic yield stress level was on an average 4% higher. This indicates excellent agreement with projected results of a previous study of the effect of strain rate.[12]

7. The avarage value of σ_{ym} from mill data is 70.5 ksi and the average percent elongation is 18.3. The average value of the difference between the mill value of σ_{ym} and the corresponding value of σ_{ys} in the current series of tests was 9.3 ksi compared to a value of 4.2 ksi from projection of the results of Ref. 12. The difference is probably due to the fact that the mills often report the upper yield point for the value of σ_{ym}.

8. No significant relationship could be established between mechanical properties and the presence or absence of yield lines. This suggests that the mill straightening practice (gagging or rotarizing) is not a significant factor in evaluating these properties.

9. The value of σ_{yd}, σ_{ys} and σ_u reduce and the values of E_{st2} and the Percent Reduction of Area increase with increasing thickness. A similar tendency was noted with respect to increasing weight of shape.

10. The results of this test series show that from a "mechanical property" stand point, it is appropriate to extend plastic design to include A572 (Grade 65) Steel.

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Miss Karen Philbin typed this report and Mr. John Gera prepared the drawings. The author gratefully acknowledges their assistance.

6. NOMENCLATURE

Symbols

E = Young's modulus, ksi, taken as 29,600 ksi

E_{st} = Strain-hardening modulus, ksi

E_{st1} = Value of E_{st} in ksi obtained from the maximum initial slope of the autographic recorder curve at the apparent onset of strain-hardening, judged by eye.

$E_{st1(a)}$ = value of E_{st} in ksi determined by curve fitting and used in Ramberg-Osgood stress-strain equation with three parameters

$E_{st1(b)}$ = Value of E_{st} in ksi determined using static stress levels at ϵ_{st} and $\epsilon_{st} + 0.002$

E_{st2} = Value of E_{st} in ksi obtained as the chord slope of the autographic recorder curve between strain increments 0.003 and 0.010 after the apparent onset of strain-hardening.

$E_{st3(a)}$ = Value of E_{st} in ksi obtained by the method of least squares from the autographic recorder curve by selecting two strain intervals of 0.065 each after the onset of strain-hardening.

$E_{st3(b)}$ = Value of E_{st} in ksi determined in the same way as $E_{st3(a)}$ from reacings taken from the dial gage and the corresponding readings of the load indicator.

R_m = Maximum rotation capacity

r_y = Weak-axis radius of gyration

ϵ = Strain

$\dot{\epsilon}$ = Strain rate, micro in./in./sec.

ϵ_y = Strain at first yield, evaluated as σ_{ys}/E

ϵ_{st} = Strain at onset of strain-hardening

σ_p = Limit of proportionality in ksi as determined by an offset of 0.0001 in./in.

σ = Stress, ksi

σ_y = Yield stress, ksi stress

σ_{yu} = Upper yield point, ksi

σ_{yl} = Lower yield point, ksi

σ_{yd} = Dynamic yield stress level, ksi

σ_{ys} = Static yield stress level, ksi

σ_{ym} = Yield stress level in a mill test, ksi

σ_u = Tensile strength (ultimate strength), ksi

σ_f = Fracture stress, ksi

ABBREVIATIONS

AISC = American Institute of Steel Construction

ASTM = American Society for Testing and Materials

CRC = Column Research Council

ipm = inches per minute

ksi = kips per square inch

7. GLOSSARY

GENERAL TERMS

Mechanical Properties - Those properties of a material that are associated with elastic and inelastic reaction when force is applied or that involve the relationship between stress and strain.[11]

Strain - The unit change, due to force, in the size of shape of a body referred to its original size or shape. Strain is a non-dimensional quantity but it is frequently expressed in inches per inch.[11]

Stress - The intensity at a point in the body of the internal forces or components of force that act on a given plane through the point. In this report, stress is always expressed in kips per square inch of original area.[11]

TERMS RELATING TO TENSION TESTING

Ductility - The ability of a material to deform plastically before fracturing. Usually evaluated by elongation or reduction of area.[11] Sometimes evaluated by uniform strain.[10] Also related to ϵ_{st}.

Extensometer - A device for measuring linear strain.[11]

Elongation - The increase in gage length after fracture of a tension test specimen usually expressed as a percentage of original gage length. In reporting values of elongation, the gage length shall be stated.[11]

Fracture Stress - Stress, computed as the quotient of the force at the instant of fracture and the original area.

Gage Length - The original length of that portion of the specimen over which strain is determined.[11]

Necking - The localized reduction of the cross-sectional area of a specimen which may occur during stretching.[11]

Proportional Limit - The greatest stress which a material is capable of sustaining without any deviation from proportionality of stress to strain.[11] In this report, measured with an offset of 0.001 in./in. on the stress-strain curve.[9]

Reduction of Area - The difference between the original cross-sectional area of a tension test specimen and the area of=its smallest cross-section after fracture. The reduction of area is usually expressed as a percentage of the original cross-sectional area of the specimen.[11]

Relaxation - Decrease in stress at a constant total elongation.[10]

Strain-hardening - Increase in resistance to deformation after the material has undergone finite strain at a practically constant stress subsequent to yielding.

Strain-hardening Modulus - Ratio of increase in stress to increase in strain, usually measured over a finite strain in the strain-hardening range of the stress-strain curve.

Tensile Strength or Ultimate Strength - The maximum tensile stress which a material is capable of sustaining. Tensile strength is calculated from the maximum load during a tension test carried to rupture and the original cross sectional area of the specimen.[11]

Uniform Strain - Strain at maximum load in a tension test.[10]

Yield Point - The first stress in the material less than the maximum attainable stress, at which an increase in strain occurs without an increase in stress.[11] When such increase in strain is accompanied by a decrease in stress, the specimen is said to have recorded an "upper yield point'. 'Lower yield point' is the lowest stress immediately after the upper yield point is recorded and before the yield stress level stabilizes.

Yield Stress Level - The average stress during actual yielding in the plastic range.[12] For structural steel, the stress remains fairly constant from the yield point up to the level of strain hardening provided the strain rate is held constant. Dynamic yield stress level corresponds to a crosshead speed of 0.025 ipm and the 'static yield stress level' is the yield stress level for zero strain rate. In this report both were measured at a strain of 0.005 in./in. as required by ASTM A370.

Young's Modulus - Ratio of tensile or compressive stress to corresponding strain below the proportional limit.[11]

STATISTICAL TERMS

Average - Sum of n numbers divided by n.

Median - The middlemost value

Standard Deviation - The square root of the average of the squares of the deviation of the numbers from their average. Theoretical estimated percentage of total observations lying within the range of Average ± 1.0 x Standard Deviation is 68.3.

Coefficient of Variation - Ratio of 'Standard Deviation' to 'Average' expressed as a percentage.

Table 1: Proposed Program of Work Under Project 343

PLASTIC DESIGN
AND THE
PROPERTIES OF 65 ksi STEEL

Phase	Purpose	Tests
1. Mechanical Properties (Fritz Lab)	Determine E_{st}, ϵ_{st}, as well as σ_y, E, σ_u, ν, % elongation, for variety of shapes and plates.	Coupon type tests Flange and web, Shapes and Plates thick and thin. (Include a few simulated mill tests) V65 and Exten 65. A few compression tests.
2. Mechanical Properties (Producers)	Collect such preliminary information as is available is producers' research labs on properties listed in Phase 1.	None (Producers supply typical complete σ - ϵ curves)
3. Mill data	Find statistical variation in σ_y and such other properties as are reported in the mill test sheet.	None. (Producers supply Mill reports for a "few thousand" specimens
4. Stub Column Tests	Check local buckling to verify theory (observe proportional limit) observe average yield stress.	2 tests (one on a heavy shape, one on a light shape)
5. Beam tests	Check local buckling provision, check lateral bracing spacing provision, check shear rule	3 tests "Beam" shapes, moment gradient and uniform moment.
6. Beam Column	Check Column provisions of theory	1 test (Some material as one of Phase 4 tests)
7. Residual Stresses	Needed for beam column theory (check stub column test, local and lateral buckling in ASD)	Several sets same as Phase 4

TABLE 2: SUMMARY OF RELEVANT ASTM STANDARDS[2]

ASTM Designation	Carbon Max %	Manganese %	Phosphous Max %	Sulfur Max %	Silicon Max %	Cooper Min. %
A36	0.30		0.05	0.063	**	0.18*
A441	0.26	Max. 1.40	0.05	0.063	0.33	0.18
A572						
Grade 42	0.25	Max. 1.40	0.05	0.06	0.35	0.18*
Grade 45	0.26	"	"	"	"	"
Grade 50	0.27	"	"	"	"	"
Grade 55	0.39	"	"	"	"	"
Grade 60	0.30	"	"	"	"	"
Grade 65	0.30	"	"	"	"	"

*Only when specified by customer
**0.13 to 0.33 for shapes over 426 lb/ft and plates over 1 1/2 in. thick.

These are broad requirements only. A572 also details the alloying combination as one of the following alternatives

(1) Columbium:= 0.004 to 0.06%

(2) Vanadium: 0.005 to 0.11%

(3) Columbium (0.05% max) + Vanadium = 0.01 to 0.11%

(4) Nitrogen (with Vanadium) = 0.015% max. Minimum ratio of Vanadium to Nitrogen = 4:1

Tensile Requirements and Maximum Product Thickness

ASTM Designation	Minimum σ_y, ksi	Minimum σ_u, ksi	Minimum Percent Elongation (8 in. gage)	Max. Thickness or Size	
				Plate & Bars	Shapes
A36	36	58	20	--	--
A441	46	67	19	over 3/4"to 1/2"incl.	Group 3
	42	63	16	over 1 1/2"to 4" incl.	Group 4 & 5
A572	42	60	20	4	All shapes up to 426 lb/ft. incl.
	45	60	19	1 1/2	
	50	65	18	1 1/2	
	55	70	17	1 1/2	
	60	75	16	1	Group 1 & 2
	65	80	15	1/2	Group 1

TABLE 3: PROGRAM OF TESTS

Material	Heat Number	Number of Specimens
A	69347*	2-from web of 16W71 2-from flange of 16W71 2-from web of 16W88 2-from flange of 16W88
B	12T3271	3-from 1/2" plate 4-from 3/8" plate 4-from 1/4" plate
	144T393	2-from web and 2-from flange of 10W39
	155S625	2-from web and 1-from flange of 12W36
	145S623	2-from web and 2-from flange of 16W36
	154S527	2-from web and 2-from flange of 14W30
	144T337	2-from web of 16B26 2-from flange of 16B26
	145V569*	2-from web and 4-from flange of 10W54 stub columns
	141T414	2-from web and 2-from flange of 12B19 2-from web and 2-from flange of end of 12B19 beam previously tested under moment gradient.
Total		52

* Shapes outside of Group 1, ASTM A6[2].

TABLE 4: TEST SPECIMENS

Material	Test.No.	Section in x in.	Shape and Location	Condition of Specimen
A	1.1.1W	0.527x1.591	web-16W88	Clean
"	1.1.2W	0.550x1.592	"	"
"	4.13.1W	0.509x1.596	web-16W71	"
"	4.13.2W	0.521x1.594	"	"
"	1.1.3F	0.819x1.593	flange-16W88	"
"	1.1.4F	0.820x1.591	"	"
"	4.13.3F	0.809x1.595	flange-16W71	"
"	4.13.4F	0.817x1.594	"	"
B	1.7.1P	0.524x1.503	plate	Clean
"	1.7.2P	0.522x1.504	"	"
"	1.7.3P	0.521x1.501	"	"
"	1.9.1P	0.404x1.493	"	"
"	1.9.2P	0.403x1.494	"	"
"	1.9.3P	0.402x1.493	"	"
"	1.9.4P	0.402x1.503	"	"
"	1.11.1P	0.256x1.505	"	"
"	1.11.2P	0.256x1.499	"	"
"	1.11.3P	0.255x1.501	"	"
"	1.11.4P	0.254x1.503	"	"
B	1.2.1W	0.340x1.501	web-10W39	Yield lines
"	1.2.4W	0.339x1.501	"	Clean
"	1.3.1W	0.338x1.500	web-12W36	"
"	1.3.2W	0.338x1.501	"	"
"	1.4.1W	0.307x1.502	web-16W36	"
"	1.4.3W	0.323x1.504	"	"
"	1.5.1W	0.274x1.500	web-14W30	"
"	1.5.2W	0.273x1.503	"	"
"	1.6.1W	0.293x1.503	web-16B26	"
"	1.6.2W	0.284x1.498	"	"
"	4.14.2W	0.380x1.501	web-10W54	"
"	4.14.5W	0.380x1.501	"	"
"	5.15.1W	0.257x1.510	web-12B19	"
"	5.15.2W	0.259x1.501	"	"
"	5.15.5W	0.262x1.504	"	"
"	5.15.6W	0.265x1.505	"	"
B	1.2.2F	0.516x1.500	flange-10W39	Yield lines
"	1.2.3F	0.513x1.503	"	Clean
"	1.3.3F	0.527x1.511	flange-12W36	"
"	1.4.2F	0.427x1.502	flange-16W36	Yield lines
"	1.4.4F	0.424x1.552	"	Clean
"	1.5.3F	0.390x1.500	flange-14W30	Yield lines
"	1.5.4F	0.383x1.503	"	Clean
"	1.6.3F	0.359x1.500	flange-16B26	Yield lines
"	1.6.4F	0.371x1.500	"	Clean
"	4.14.1F	0.641x1.499	flange-10W54	"
"	4.14.3F	0.628x1.500	"	"
"	4.14.4F	0.611x1.500	"	"
"	4.14.6F	0.637x1.503	"	"
"	5.15.3F	0.368x1.502	flange-12B19	"
"	5.15.4F	0.367x1.495	"	"
"	5.15.7F	0.371x1.506	"	"
"	5.15.8F	0.372x1.505	"	"

TABLE 5: OBSERVED STRESS (ALL VALUES IN ksi)

Material	Test No.	Proportional Limit σ_p	Upper Yield σ_{yu}	Dynamic Yield σ_{yd}	Static Yield σ_{ys}	Ultimate σ_u	Fracture σ_f
A	1.1.1W	47.7	64.4	62.1	60.7	86.8	67.4
"	1.1.2W	57.1	--	63.9	61.3	87.4	79.3
"	4.13.1W	30.8	66.0	64.8	62.6	88.0	67.2
"	4.13.2W	48.2	64.6	64.3	61.0	85.6	65.7
"	1.1.3F	61.4	70.5	67.3	65.0	92.1*	--
"	1.1.4F	35.6	64.6	64.8	63.1	92.0*	--
"	4.13.3F	46.4	--	64.2	62.2	89.6	68.6
"	4.13.4F	53.8	69.2	65.9	63.7	92.2*	--
B	1.7.1P	63.5	65.7	63.6	62.8	87.0	67.9
"	1.7.2P	63.1	63.9	62.5	60.5	86.2	66.2
"	1.7.3P	38.4	66.4	63.0	60.9	87.0	62.6
"	1.9.1P	64.1	65.6	62.7	60.7	86.7	67.6
"	1.9.2P	65.6	66.5	62.8	60.2	85.0	66.8
"	1.9.3P	67.3	67.3	64.1	61.6	87.2	68.2
"	1.9.4P	58.0	67.5	63.9	62.1	86.3	67.0
"	1.11.1P	67.5	69.3	66.9	63.9	86.4	69.9
"	1.11.2P	66.6	71.3	66.6	62.7	87.5	71.3
"	1.11.3P	68.8	71.6	68.5	65.6	87.7	70.8
"	1.11.4P	72.0	72.0	68.2	63.6	82.0	70.2
B	1.2.1W	61.9	64.0	61.9	59.0	82.6	64.6
"	1.2.4W	53.0	63.7	62.1	60.4	83.6	66.7
"	1.3.1W	68.3	68.4	65.3	63.4	86.5	71.5
"	1.3.2W	67.9	67.9	65.7	63.6	86.4	70.6
"	1.4.1W	66.4	68.1	65.5	63.6	86.5	68.1
"	1.4.3W	62.4	65.0	65.2	62.5	84.7	71.2
"	1.5.1W	69.3	70.6	67.9	65.0	86.4	71.5
"	1.5.2W	55.2	66.4	65.7	60.3	83.3	68.4
"	1.6.1W	58.9	--	63.5	60.5	83.9	65.2
"	1.6.2W	47.1	63.1	63.1	60.0	82.8	71.5
"	4.14.2W	60.9	62.1	60.6	58.7	81.7	64.8
"	4.14.5W	54.0	--	58.9	57.0	80.6	62.9
"	5.15.1W	67.0	69.4	68.5	65.2	87.8	70.4
"	5.15.2W	68.5	69.8	68.5	64.4	87.8	72.1
"	5.15.5W	66.2	68.7	67.7	65.4	87.8	71.0
"	5.15.6W	62.7	68.2	66.7	64.4	86.7	70.7
B	1.2.2F	58.2	66.8	65.9	63.8	87.4	65.9
"	1.2.3F	52.5	--	65.9	64.2	89.3	71.5
"	1.3.3F	62.6	64.5	62.9	60.3	83.4	64.6
"	1.4.2F	42.9	--	61.4	58.3	83.2	64.6
"	1.4.4F	53.1	--	60.4	58.8	80.4	61.1
"	1.5.3F	38.5	65.2	64.2	62.2	84.2	67.2
"	1.5.4F	58.0	64.9	64.8	63.2	85.4	67.7
"	1.6.3F	66.1	66.8	65.7	62.8	86.5	70.4
"	1.6.4F	52.1	--	64.7	61.7	84.5	66.9
"	4.14.1F	62.5	66.0	62.8	61.1	86.1	64.0
"	4.14.3F	55.8	59.8	60.0	58.1	84.5	63.1
"	4.14.4F	44.8	--	58.4	57.6	83.8	61.6
"	4.14.6F	60.1	64.5	61.2	59.0	84.4	62.5
"	5.15.3F	37.9	--	67.4	64.2	85.9	67.6
"	5.15.4F	50.1	68.3	69.9	66.3	89.6	71.0
"	5.15.7F	51.7	67.1	68.7	65.5	88.9	70.2
"	5.15.8F	51.7	67.0	67.4	64.5	87.1	69.2

*These values correspond to a load of 120 kips. Ultimate stress was not attained due to the limitation imposed by machine capacity.

TABLE 6: OBSERVED STRAINS AND OTHER MECHANICAL PROPERTIES

					Strain Hardening Modulus E_{st} in ksi			
Matr.	Test No.	strain at strain hardening, ε_{st}, percent	Elongation (8 in.), percent	Reduction of Area, percent	E_{st1}	E_{st2}	$E_{st3(a)}$	$E_{st3(b)}$
A	1.1.1W	0.95*	19.8	57.2	700	590*	530	546
"	1.1.2W	2.51*	18.0	59.4	406	600*	406	602
"	4.13.1W	1.80*	21.2	61.4	600	590*	574	730
"	4.13.2W	--	21.1	58.7	--	--	--	--
"	1.1.3F	2.32*	--	--	2,000	705*	852	895
"	1.1.4F	1.08*	--	--	4,200	726*	680	770
"	4.13.3F	1.20*	21.5	56.0	9,150	688*	705	550
"	4.13.4F	1.19*	--	--	1,900	670*	854	755
B	1.7.1P	1.75	20.6	54.5	540	576	513	507
"	1.7.2P	1.23	19.2	51.4	4,020	645	737	639
"	1.7.3P	1.12*	19.2	45.8	2,560	634*	850	850
"	1.9.1P	3.25	22.0	47.0	930	350	812	220
"	1.9.2P	2.29	20.0	36.4	830	775	598	500
"	1.9.3P	1.45	21.3	50.7	1,500	441	685	590
"	1.9.4P	1.21*	19.5	59.3	480	530*	480	720
"	1.11.1P	2.05	24.9	46.0	2,030	446	461	475
"	1.11.2P	2.02	21.2	40.6	6,960	557	841	493
"	1.11.3P	2.05	21.7	47.2	6,274	485	993	794
"	1.11.4P	2.09	23.4	48.7	1,375	340	960	650
B	1.2.1W	1.95	21.6	44.2	5,320	642	591	630
"	1.2.4W	1.67*	21.2	61.6	393	580*	655	900
1.	1.3.1W	1.85	21.0	49.2	2,920	505	987	890
"	1.3.2W	2.06	23.3	44.2	3,300	559	920	822
"	1.4.1W	2.18	22.6	62.3	868	496	819	859
"	1.4.3W	2.27	20.5	55.5	3,960	456	871	826
"	1.5.1W	2.55	21.5	58.3	--	--	--	--
"	1.5.2W	3.28	21.4	42.0	8,372	479	926	--
"	1.6.1W	1.91	21.2	53.2	--	--	--	411
"	1.6.2W	1.75	21.4	39.5	1,750	497	895	769
"	4.14.2W	1.66*	23.1	44.0	3,510	521*	1031	965
"	4.14.5W	1.36*	22.2	45.2	4,210	589*	950	1122
"	5.15.1W	2.52	20.7	40.5	696	619	538	569
"	5.15.2W	1.97	20.2	43.2	2,500	644	382	744
"	5.15.5W	2.12	19.0	47.0	1,425	499	979	402
"	5.15.6W	2.20	18.0	37.0	1,394	523	836	717
B	1.2.2F	1.65*	21.2	58.2	2,500	565*	975	830
"	1.2.3F	1.58*	21.2	50.5	1,050	573*	990	1,020
"	1.3.3F	1.77	36.1	58.6	1,883	550	664	--
"	1.4.2F	1.90	24.6	53.3	3,710	322	660	434
"	1.4.4F	2.62	23.1	55.0	6,840	380	1,160	402
"	1.5.3F	2.10	22.6	58.1	2,720	560	730	670
"	1.5.4F	1.90	22.5	44.0	5,030	542	355	472
"	1.6.3F	1.99	18.8	55.1	9,825	542	805	941
"	1.6.4F	1.70	18.1	57.5	7,960	516	820	452
"	4.14.1F	1.18*	22.7	55.5	2,240	630*	833	807
"	4.14.3F	1.05*	23.4	53.2	1,835	643*	932	870
"	4.14.4F	1.08*	23.9	52.4	2,380	648*	960	961
"	4.14.6F	1.19*	23.6	53.8	2,400	618*	835	825
"	5.15.3F	2.00	21.0	52.6	1,660	490	903	--
"	5.15.4F	2.00	20.5	57.3	4,250	575	727	638
"	5.15.7F	2.13	18.0	53.0	1,245	484	736	955
"	5.15.8F	2.01	20.0	45.0	1,374	522	764	900

*Value based on dial gage readings

TABLE 7: SUMMARY OF STRESS (All Values in ksi)

Material	Origin	Value of	Proportional Limit σ_p	Upper Yield σ_{yu}	Dynamic Yield σ_{yd}	Static Yield σ_{ys}	Ultimate Strength σ_u	Fracture Stress σ_f
A	Web	Average	45.9	65.0	63.8	61.4	87.0	69.9
"	"	Median	47.9	64.6	64.1	61.1	87.1	67.3
"	Flange	Average	49.3	68.1	65.5	63.5	91.5	68.6
"	"	Median	50.1	69.2	65.3	63.4	92.0	68.6
"	All	Average	47.6	66.5	64.7	62.4	89.2	69.6
"	"	Median	47.9	65.3	64.5	62.4	90.3	67.4
B	Plate	Average	63.2	67.9	64.8	62.2	86.3	68.0
"	"	Median	65.6	67.3	63.9	62.1	86.7	67.9
"	Web	Average	61.9	66.8	64.8	62.1	84.9	68.8
"	"	Median	62.5	68.0	65.4	62.9	85.5	70.5
"	Flange	Average	52.9	65.5	64.2	61.9	85.6	66.4
"	"	Median	52.5	66.0	64.7	62.2	85.4	66.9
"	All	Average	58.7	66.8	64.6	62.0	85.5	67.7
"	"	Median	61.4	66.8	64.7	62.3	86.2	67.8
A&B	Plate	Average	63.2	67.9	64.8	62.2	86.3	68.0
"	"	Median	65.6	67.3	63.9	62.1	86.7	67.9
"	Web	Average	58.7	66.5	64.6	61.9	85.3	69.0
"	"	Median	61.4	66.4	65.0	61.9	86.4	69.4
"	Flange	Average	52.2	66.1	64.5	62.2	86.8	66.5
"	"	Median	52.5	66.4	64.8	62.8	86.6	67.0
"	All	Average	57.0	66.7	64.6	62.1	86.1	67.9
"	"	Median	58.5	66.5	64.7	62.3	86.8	67.7
"	"	Standard Deviation	9.9	2.6	2.6	2.3	2.2	3.4
"	"	Coefficient of Variation%	17.3	3.9	4.1	3.7	2.6	5.0

TABLE 8: SUMMARY OF STRAIN AND OTHER MECHANICAL PROPERTIES

Mat'l	Origin	Value of	Strain at Strain-Hardening ϵ_{st}(%)	Percent Elongation (8 in.)	Percent Reduction of Area	E_{st1} ksi	E_{st2} ksi	$E_{st3(a)}$ ksi	$E_{st3(b)}$ ksi
A	Web	Average	1.75	20.0	59.2	569	593	503	626
"	"	Median	1.80	20.4	59.0	600	590	530	602
"	Flange	Average	1.45	21.5	56.0	4312	697	773	742
"	"	Median	1.20	21.5	56.0	3100	696	778	762
"	All	Average	1.58	20.3	58.5	2708	653	657	692
"	"	Median	1.20	21.1	58.7	1900	670	680	730
B	Plate	Average	1.86	21.2	48.0	2500	525	721	585
"	"	Median	2.02	21.2	47.2	1500	530	737	590
"	Web	Average	2.08	21.2	47.9	2901	543	813	759
"	"	Median	2.02	21.3	44.7	2710	522	883	795
"	Flange	Average	1.76	22.4	53.7	3465	538	815	745
"	"	Median	1.90	22.5	53.8	2400	550	820	825
"	All	Average	1.90	21.7	50.2	3024	537	789	706
"	"	Median	1.96	21.3	51.0	2390	542	826	732
A&B	Plate	Average	1.86	21.2	48.0	2500	525	721	585
"	"	Median	2.02	21.2	47.2	1500	530	737	590
"	Web	Average	2.03	20.9	50.2	2490	552	758	735
"	"	Median	1.97	21.2	48.1	1750	559	836	744
"	Flange	Average	1.70	22.4	53.8	3626	569	807	745
"	"	Median	1.77	22.0	54.4	2400	565	820	807
"	All	Average	1.86	21.5	51.0	2979	553	771	704
"	"	Median	1.91	21.2	52.6	2240	559	819	730
"	"	Standard Deviation	0.52	2.7	6.8	2400	95	186	197
"	"	Coefficient of Variation%	27.9	12.5	13.4	81	17	24	28

TABLE 9: AVERAGE VALUES OF GROUPS OF SPECIMENS

Group	No. of Specimens	σ_{yd} ksi	σ_{ys} ksi	σ_{u} ksi	ϵ_{st} %	E_{st2} ksi	E_{st3}* ksi
Plate Specimens	11	64.8	62.2	86.3	1.86	525	656
Web Specimens	20	64.6	61.9	85.3	2.02	530	663
Flange Specimens	21	64.5	62.2	86.8	1.70	569	776
Specimens with yield lines	5	63.8	61.2	84.8	1.92	526	726
Specimens without yield lines**	5	63.6	61.7	84.6	1.89	518	723
Specimens with thickness							
from 0.201 to 0.300 in.	12	66.8	63.4	85.8	2.21	509	692
from 0.301 to 0.400 in.	16	64.9	62.4	85.3	1.93	536	797
from 0.401 to 0.500 in.	6	62.5	60.3	84.8	2.12	466	605
from 0.501 to 0.600 in.	10	63.9	61.8	86.8	1.60	591	704
from 0.601 to 0.700 in.	4	60.6	58.9	84.7	1.12	635	878
from 0.701 to 0.800 in.	--	--	--	--	--	--	--
from 0.801 to 0.900 in.	4	65.5	63.5	89.6	1.45	697	758
Specimens from shapes of weight							
from 11 to 20 lbs.	8	68.1	65.0	87.7	2.12	544	718
from 21 to 30 lbs.	8	64.9	62.0	84.6	2.15	523	687
from 31 to 40 lbs.	11	63.8	61.6	84.9	1.95	512	803
from 41 to 50 lbs.	--	--	--	--	--	--	--
from 51 to 60 lbs.	6	60.3	58.6	83.5	1.25	608	924
from 61 to 70 lbs.	--	--	--	--	--	--	--
from 71 to 80 lbs.	4	64.8	62.4	87.7	1.40	649	695
from 81 to 90 lbs.	4	64.5	62.5	87.1	1.71	655	660
All Specimens	52	64.6	62.1	85.7	1.86	553	737

* The value of E_{st3} is the average of $E_{st3(a)}$ and $E_{st3(b)}$.

** These include only the specimens from the same heat, shape and origin as the corresponding specimens from the group with yield lines.

TABLE 10: RATIO σ_{yd}/σ_{ys}

Strain rate $\dot{\epsilon}$ = 44 microin./in./sec. average of 17 observations
(crosshead speed = 0.025 in./min.)

Material	Test No.	σ_{yd}/σ_{ys}	Material	Test No.	σ_{yd}/σ_{ys}
A	1.1.1W	1.023	B	1.5.2W	1.090
"	1.1.2W	1.042	"	1.6.1W	1.050
"	4.13.1W	1.035	"	1.6.2W	1.051
"	4.13.2W	1.054	"	4.14.2W	1.032
"	1.1.3F	1.035	"	4.14.5W	1.032
"	1.1.4F	1.027	"	5.15.1W	1.051
"	4.13.3F	1.032	"	5.15.2W	1.064
"	4.13.4F	1.034	B	5.15.5W	1.038
B	1.7.1P	1.013	"	5.15.6W	1.036
"	1.7.2P	1.033	"	1.2.2F	1.033
"	1.7.3P	1.034	"	1.2.3F	1.026
"	1.9.1P	1.033	"	1.3.3F	1.043
"	1.9.2P	1.042	"	1.4.2F	1.053
"	1.9.3P	1.040	"	1.4.4F	1.027
"	1.9.4P	1.028	"	1.5.3F	1.032
"	1.11.1P	1.047	"	1.5.4F	1.025
"	1.11.2P	1.062	"	1.6.3F	1.046
"	1.11.3P	1.029	"	1.6.4F	1.048
"	1.11.4P	1.072	"	4.14.1F	1.027
"	1.2.1W	1.049	"	4.14.3F	1.033
"	1.2.4W	1.028	"	4.14.4F	1.031
"	1.3.1W	1.030	"	4.14.6F	1.037
"	1.3.2W	1.033	"	5.15.3F	1.050
"	1.4.1W	1.030	"	5.15.4F	1.054
"	1.4.3W	1.043	"	5.15.7F	1.050
"	1.5.1W	1.045	"	5.15.8F	1.047
			Average of all tests		1.040

TABLE 11: SIMULATED MILL TESTS AND MILL DATA
8 in. gage specimen used throughout

SIMULATED MILL TESTS:

Material	Test No.	Origin	Shape	σ_{ym}, ksi	σ_u, ksi	Percent Elongation
A	4.13.5F	Flange	16W71	66.1	91.0	20.6
"	4.13.6F	"	"	69.7	87.4	22.9
B	5.15.9F	Flange	12B19	69.6	89.2	20.7
"	5.15.10W	Web	"	71.8	89.2	18.6
Average of the four tests				69.3	89.2	20.7

None of the specimens showed any yield lines.

MILL DATA:

Material	Origin	Shape	σ_{ym}, ksi	σ_u, ksi	Percent Elongation
A	web	16W88	71.1	91.4	19.0
"		16W71	73.0	95.6	17.0
Average for material A (2 specimens)			72.0	93.5	18.0
B	1/2" plate		66.9	86.9	19.0
"	3/8" plate		65.0	90.0	21.0
"	1/4" plate		71.8	92.2	19.0
"	Web	12B19	71.8	94.8	17.0
"	"	16B26	70.5	93.7	16.9
"	"	10W39	71.5	90.3	19.8
"	"	10W54	72.9	97.5	16.1
Average for material B (7 specimens)			70.1	92.2	18.4
Average for All (9 specimens)			70.5	92.5	18.3

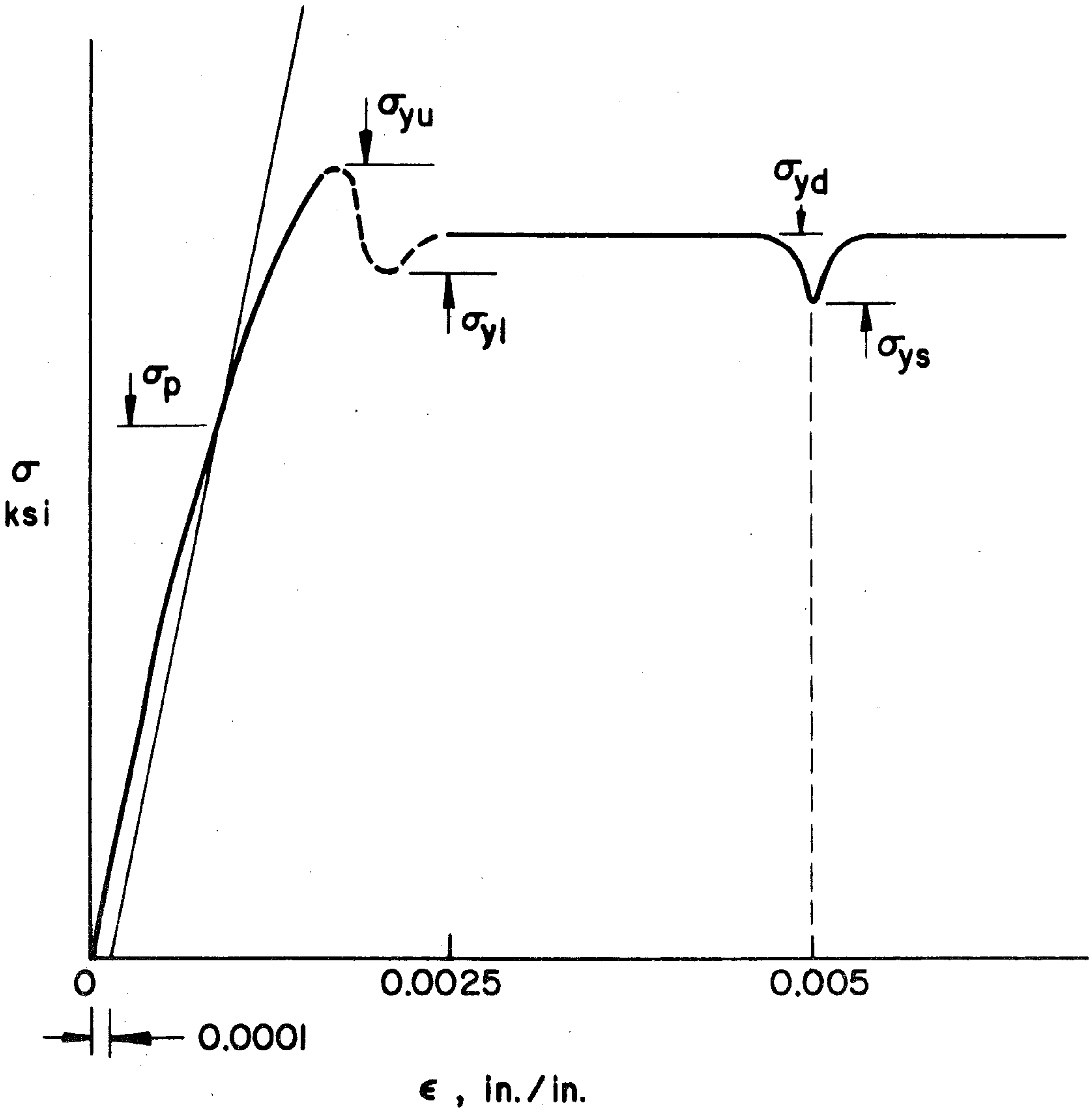

FIG. 1 SKETCH DEFINING σ_p, σ_{uy}, $\sigma_{\ell y}$, σ_{yd} and σ_{ys}

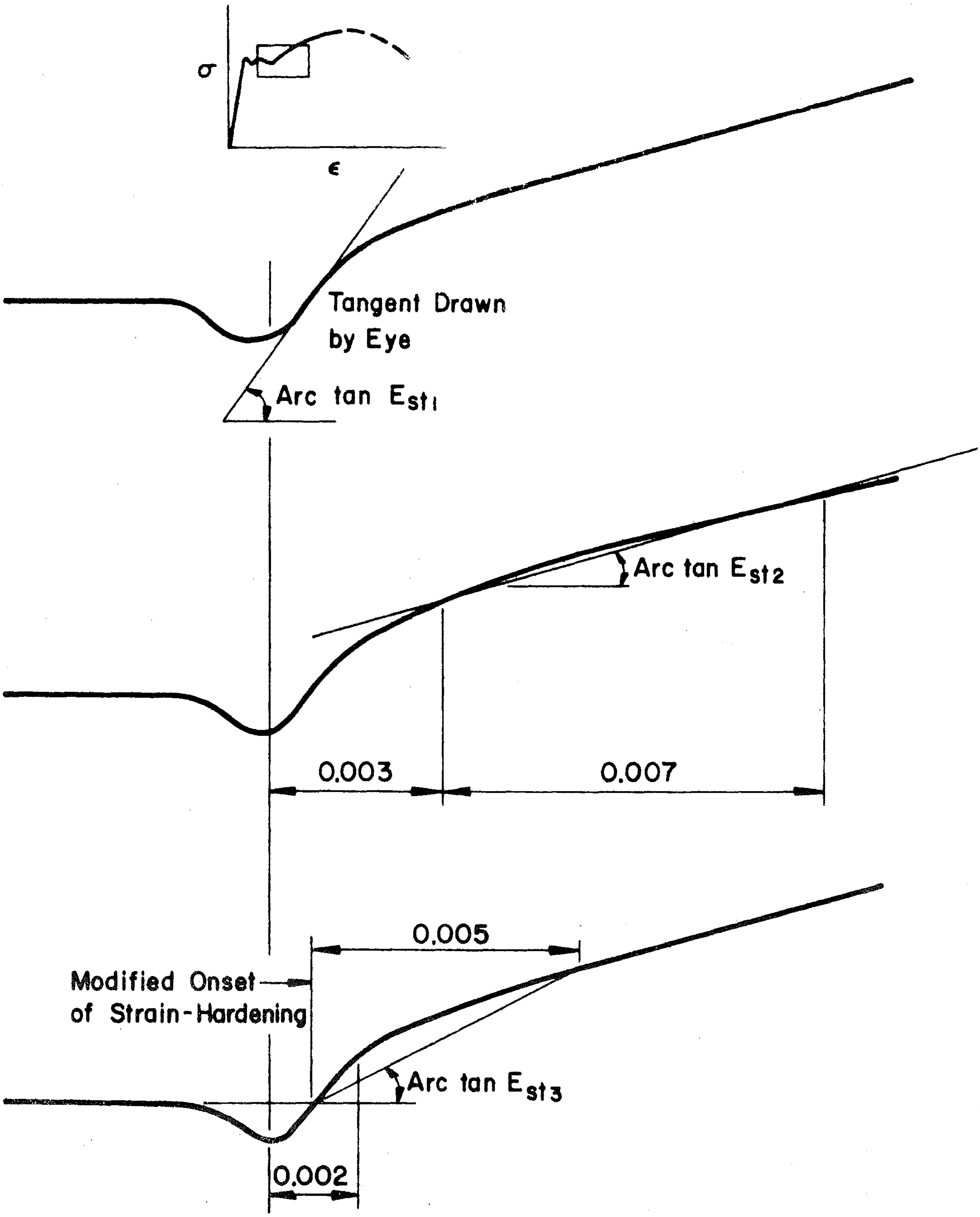

FIG. 2 SKETCH DEFINING E_{st1}, E_{st2} and E_{st3}

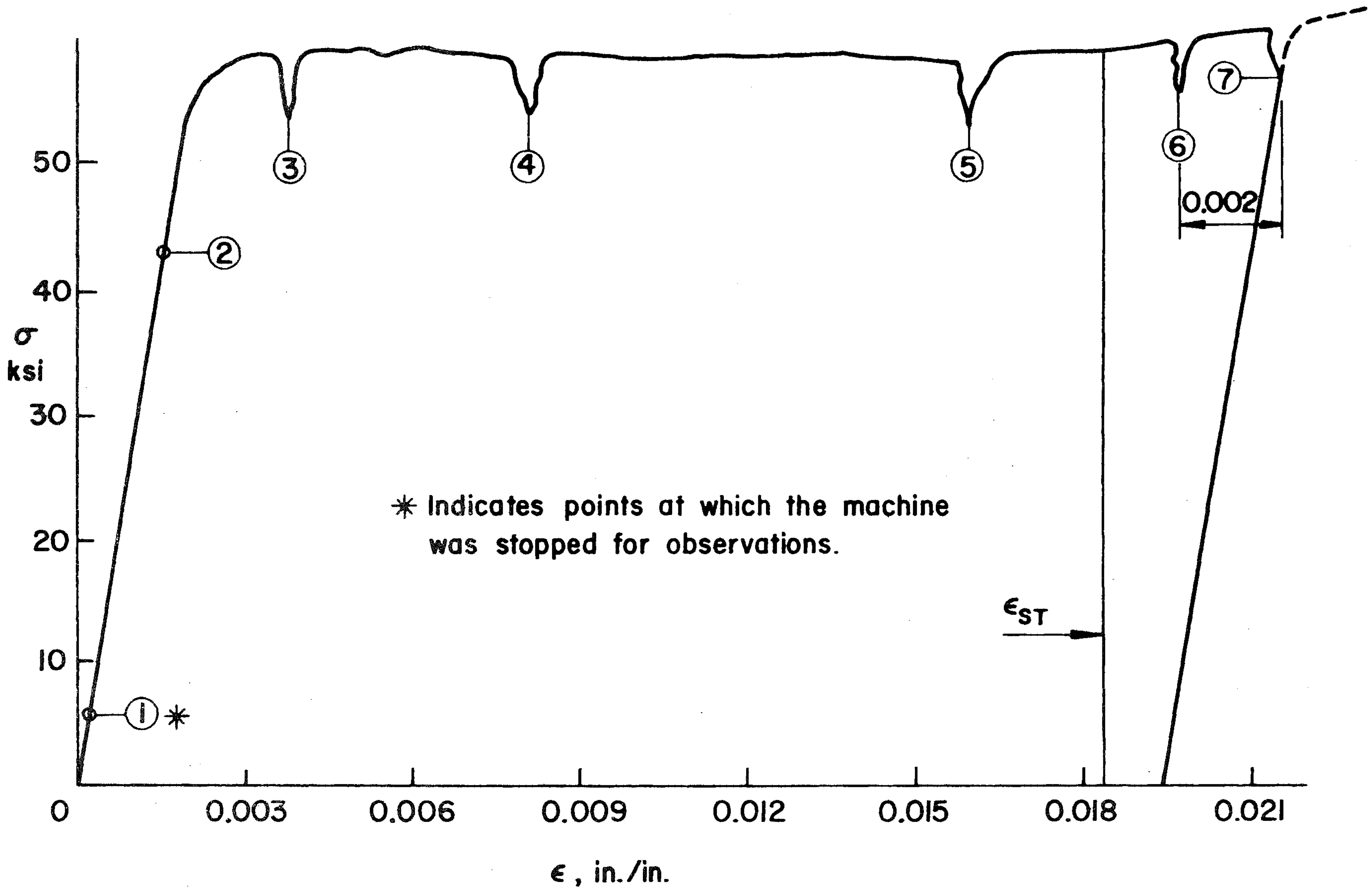

FIG. 3 SKETCH DEFINING $E_{st1(b)}$ [4]

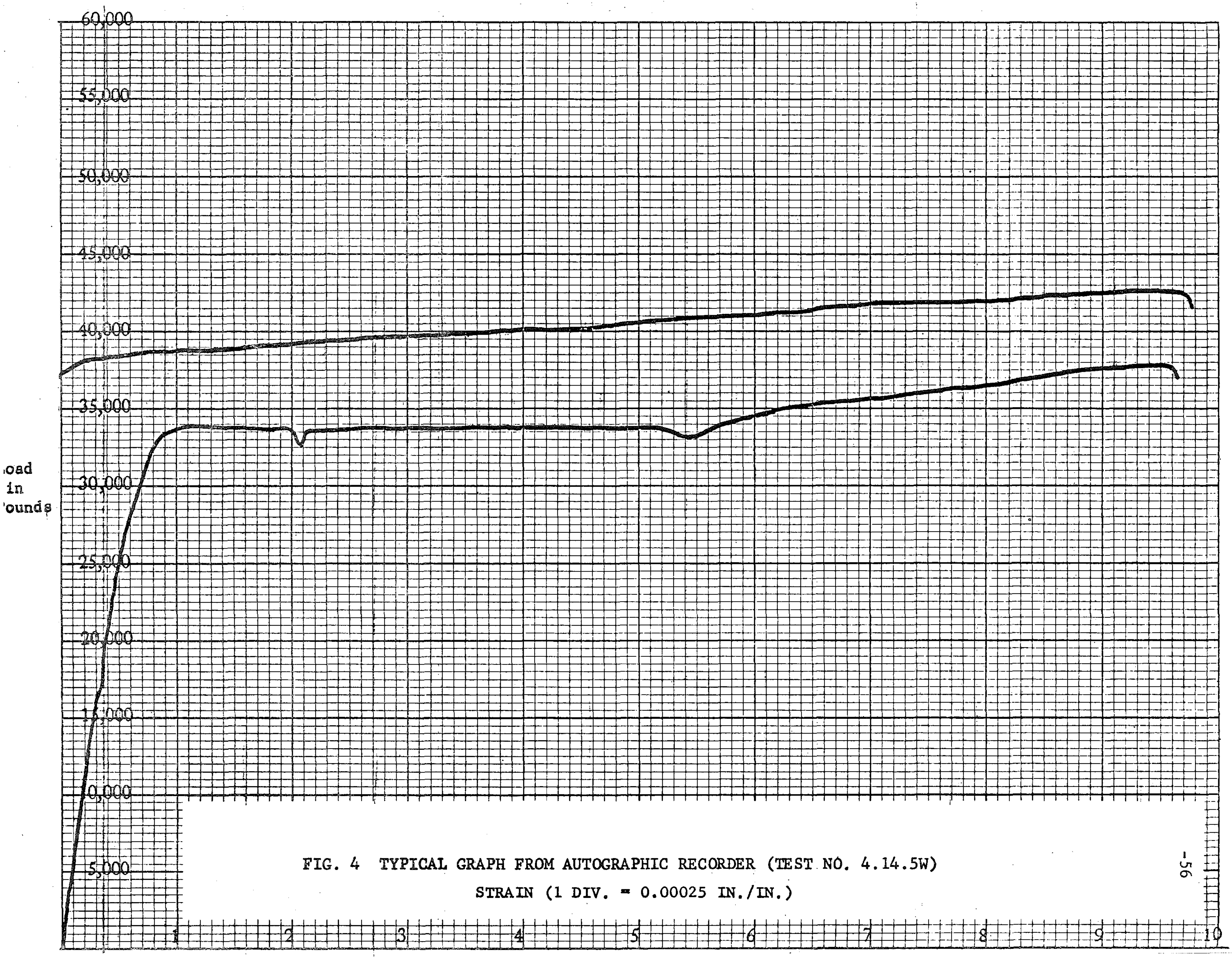

FIG. 4 TYPICAL GRAPH FROM AUTOGRAPHIC RECORDER (TEST NO. 4.14.5W)
STRAIN (1 DIV. = 0.00025 IN./IN.)

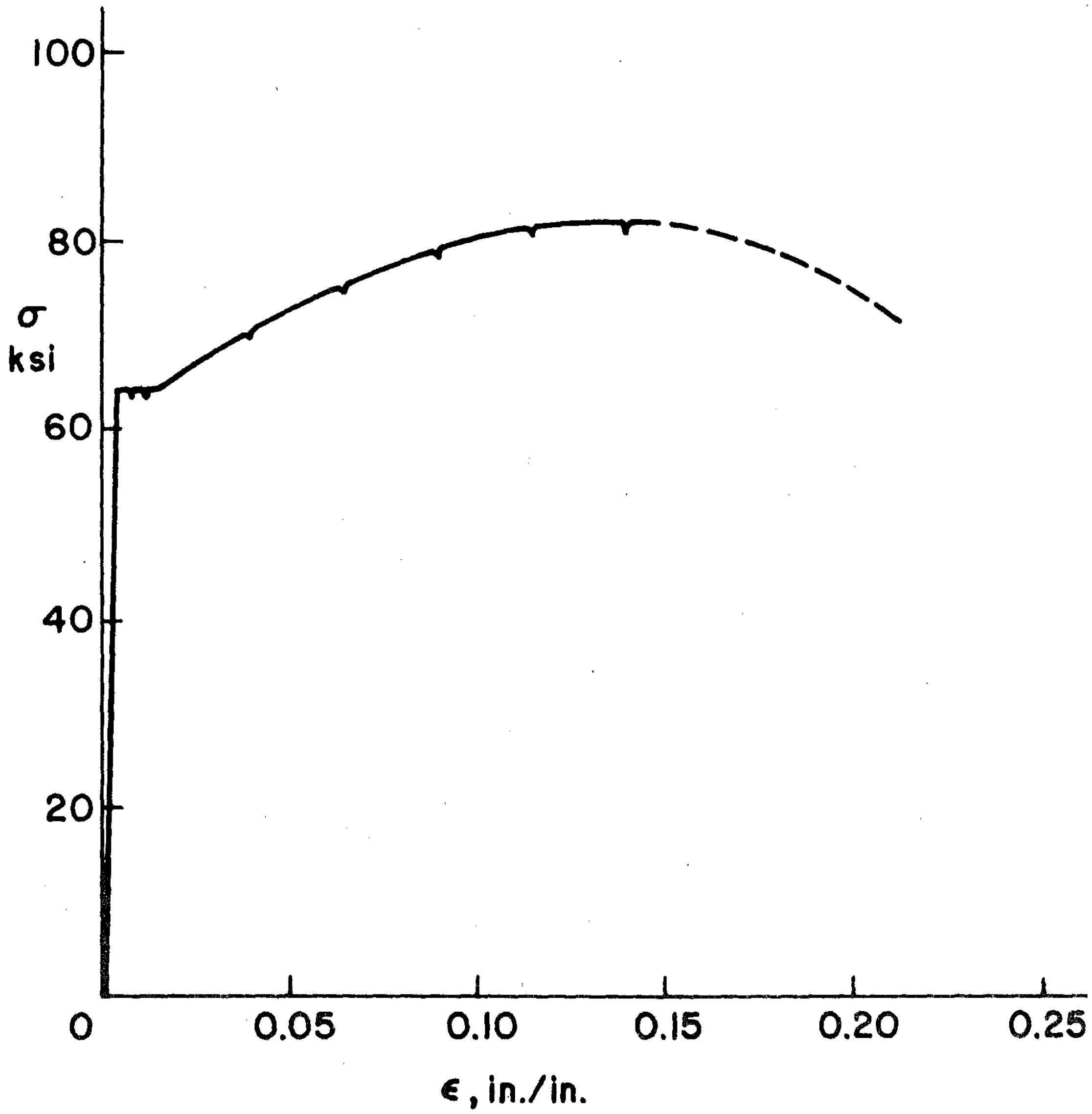

FIG. 5 TYPICAL COMPLETE STRESS-STRAIN CURVE FOR A572 (GRADE 65) STEEL (TEST NO. 1.6.2W)

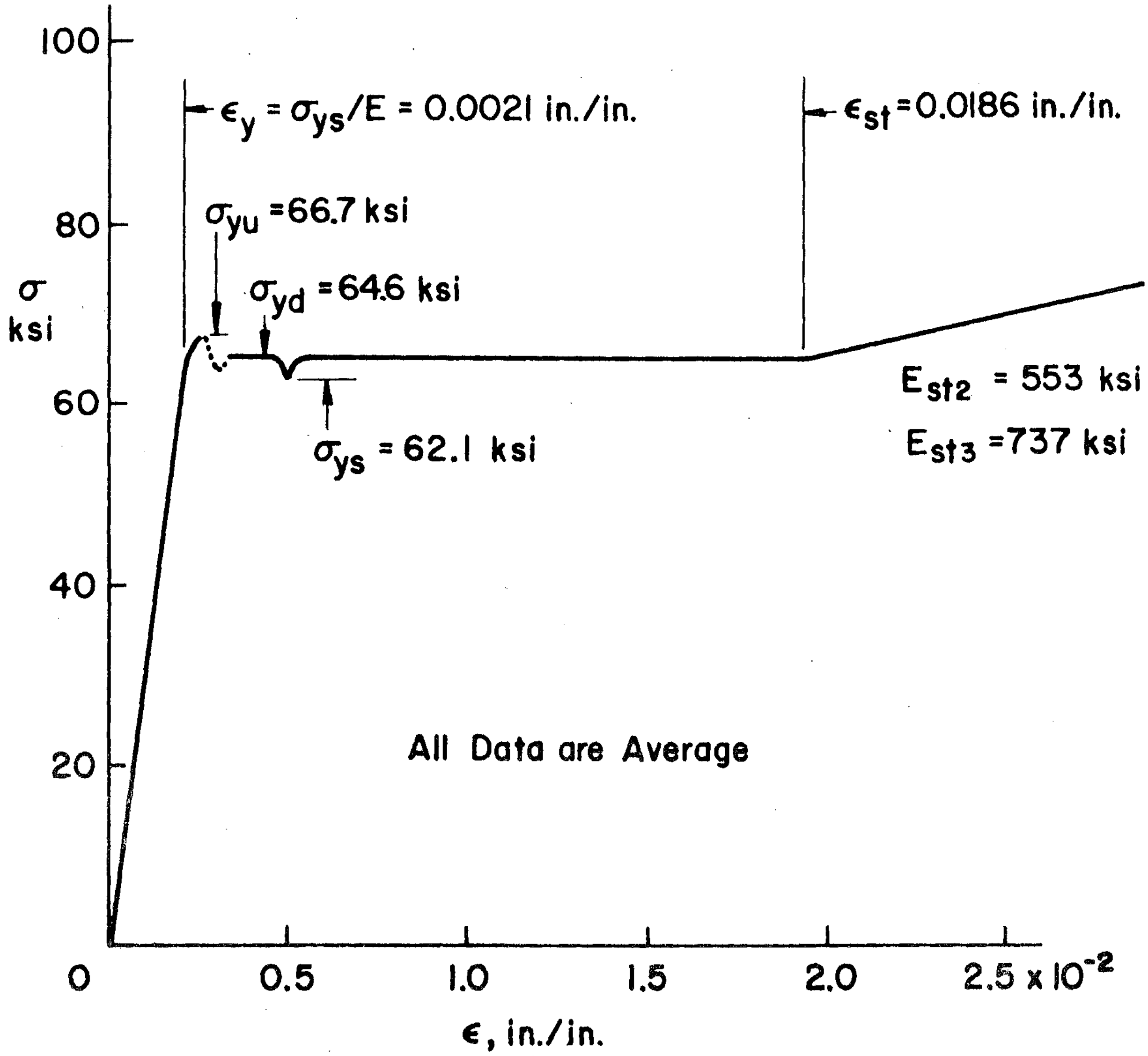

FIG. 6 IDEALIZED STRESS-STRAIN CURVE FOR A572 (GRADE 65) STEEL (WITH STRAIN-HARDENING)

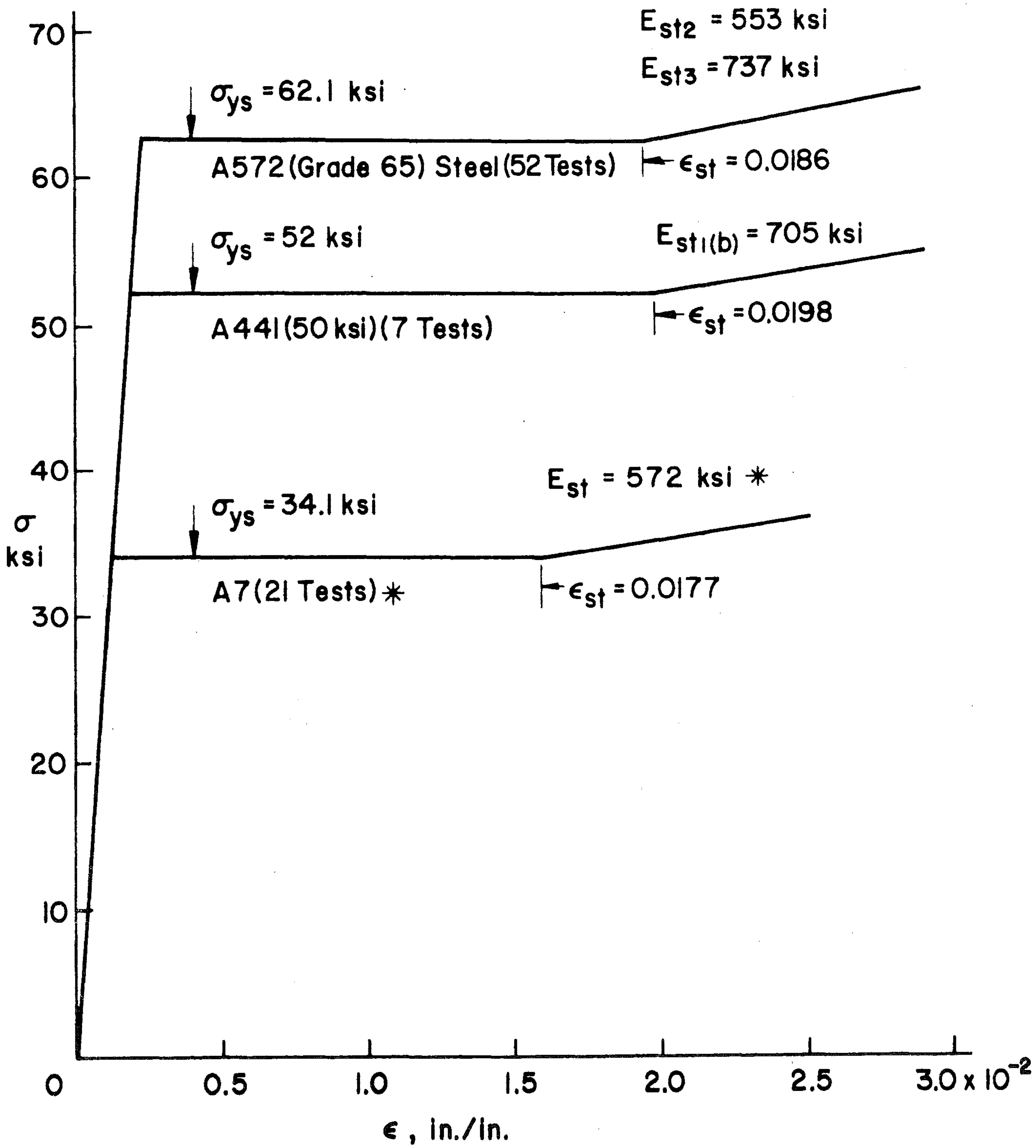

FIG. 7 IDEALIZED STRESS-STRAIN CURVES FOR A7, A441, and A572 (GRADE 65) STEEL

[*] Values for A7 steel taken from unpublished results of tension tests for Projects 205B, 205E and 220A at Fritz Lab. Values of E_{st} are read as chords in the linear portion of the curve and lie somewhere betweeb E_{st3} and E_{st2}.

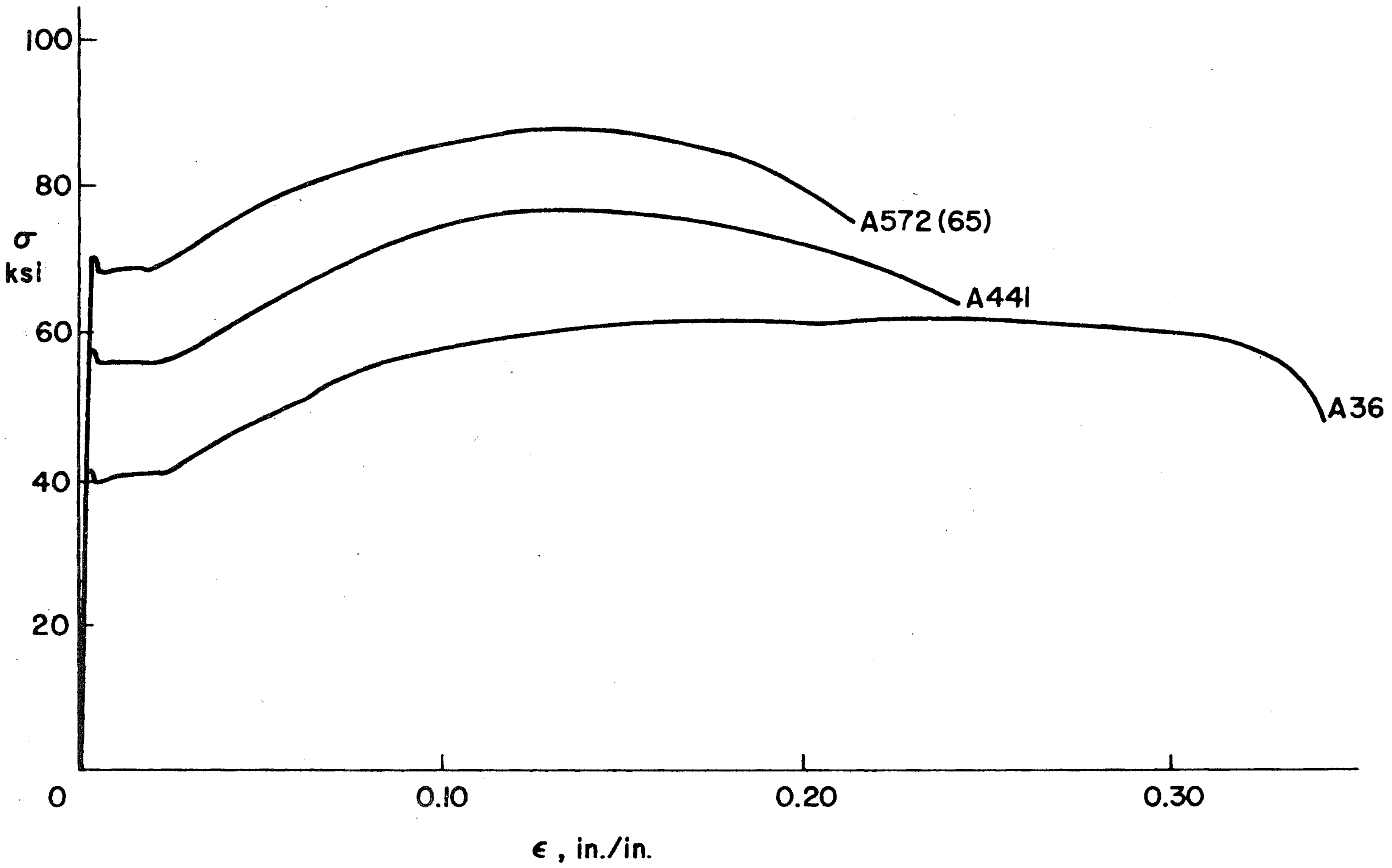

FIG. 8 TYPICAL COMPLETE STRESS-STRAIN CURVES FOR A36, A441 and A572 (GRADE 65) STEELS

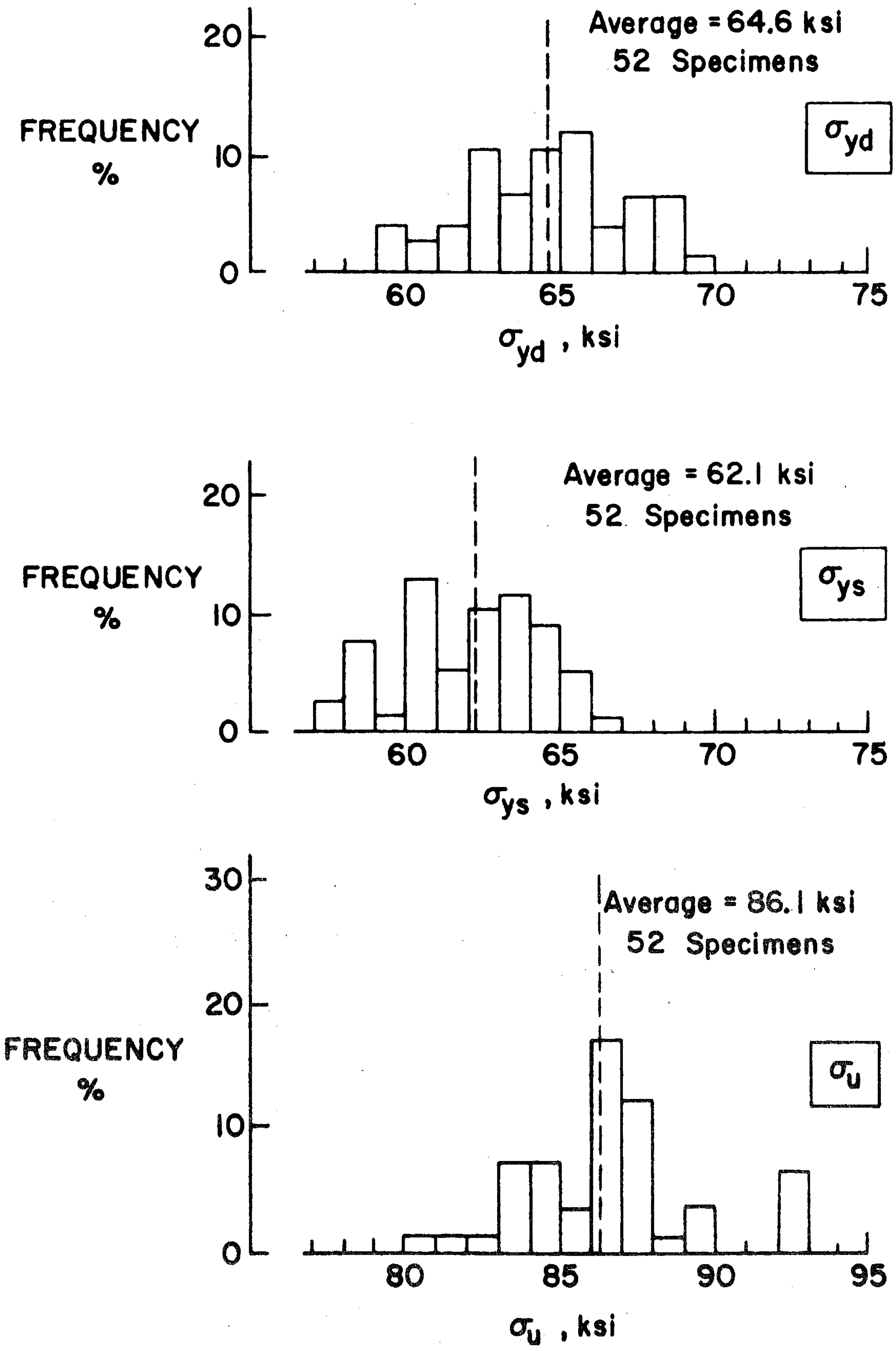

FIG. 9 HISTOGRAMS FOR σ_{yd}, σ_{ys} and σ_u

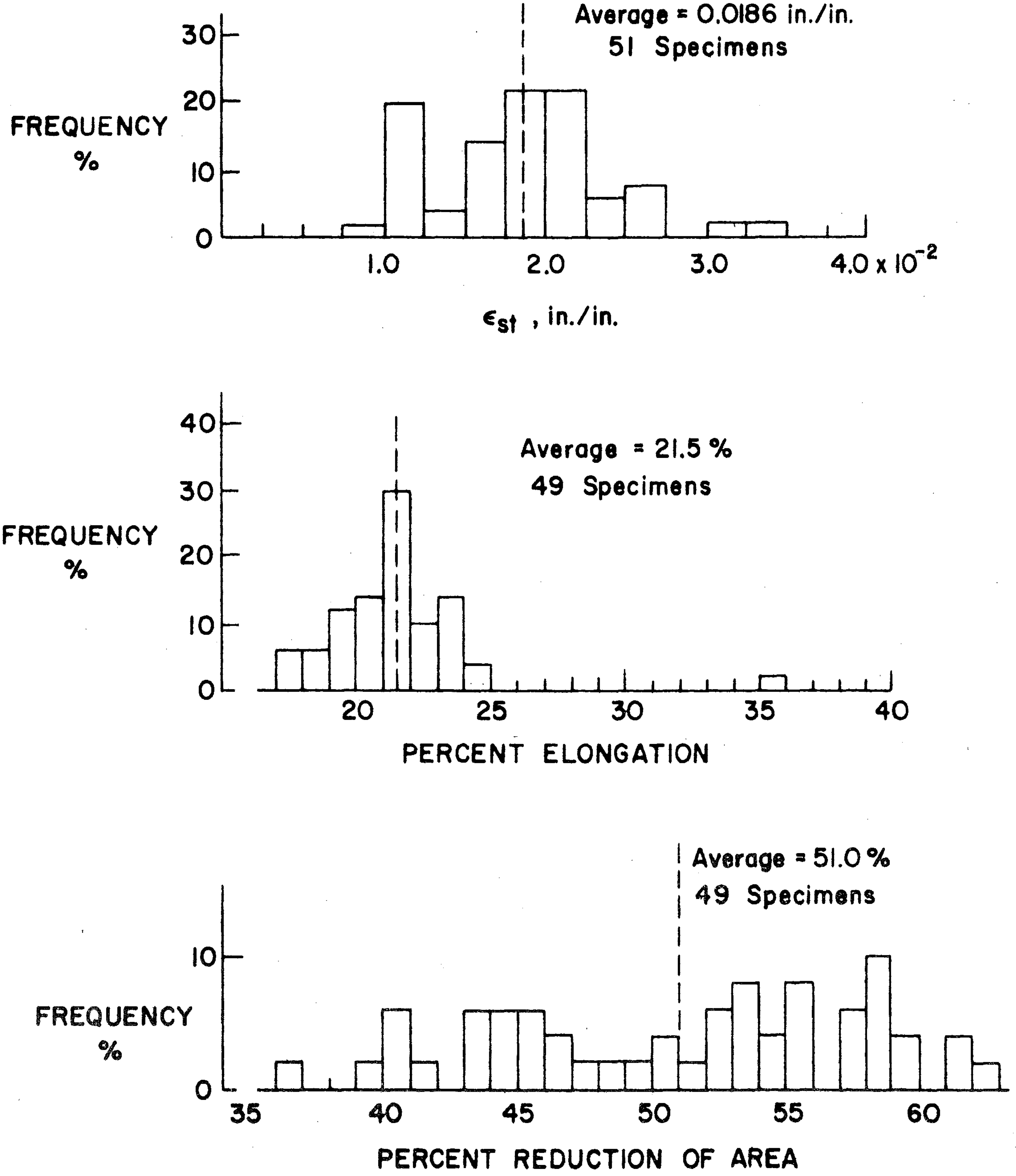

FIG. 10 HISTOGRAMS FOR ϵ_{st} PERCENT ELONGATION AND PERCENT REDUCTION OF AREA

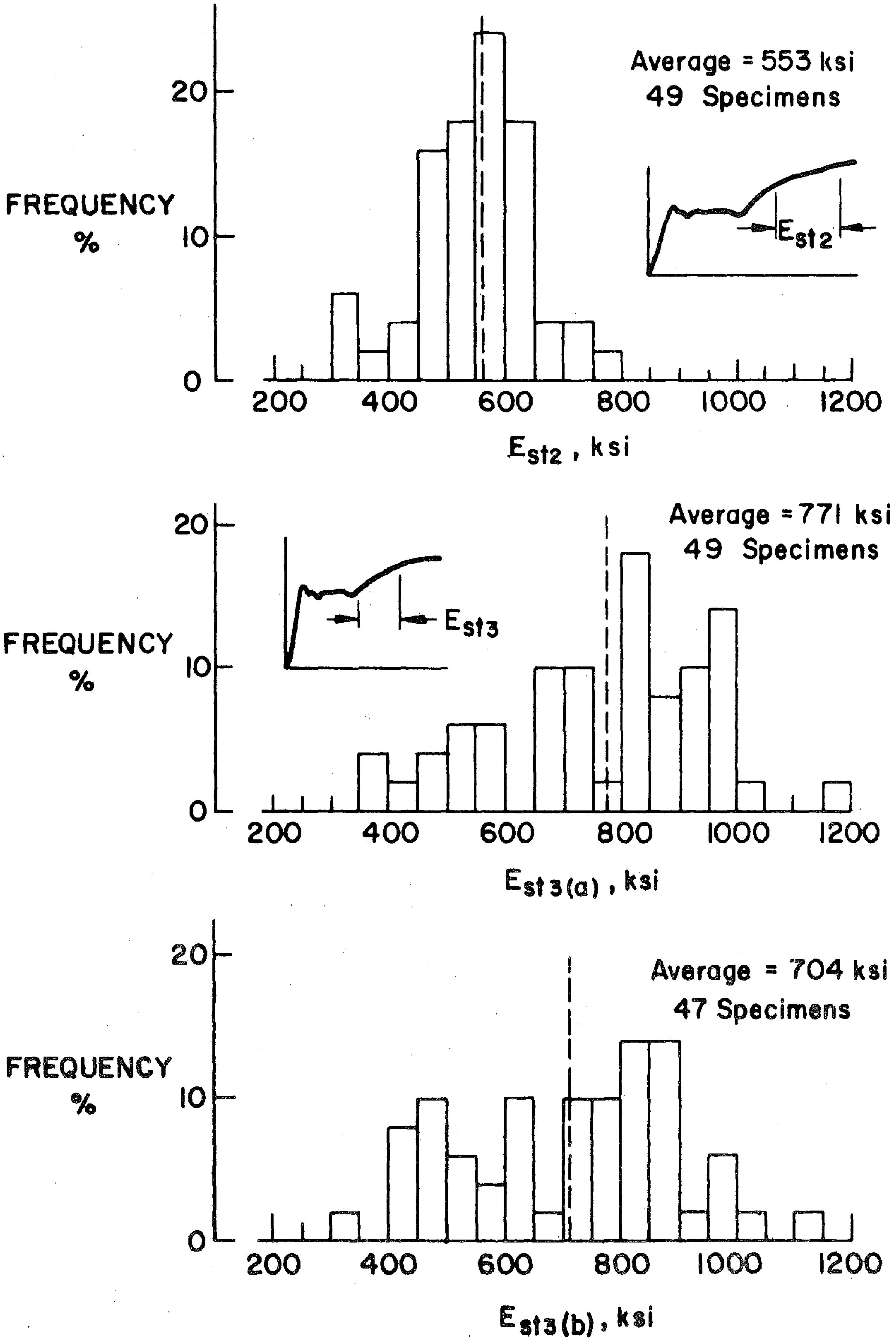

FIG. 11 HISTOGRAMS FOR E_{st2}, E_{st3} and $E_{st3(b)}$

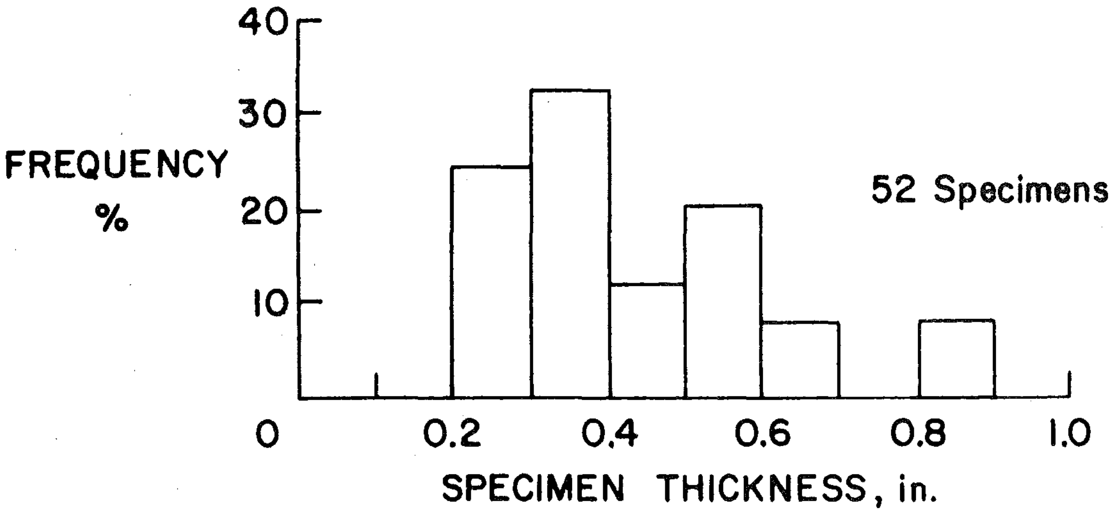

FIG. 12 HISTOGRAM FOR SPECIMEN THICKNESS

FIG. 13 VARIATION OF σ_{yd} and σ_{ys} WITH THICKNESS

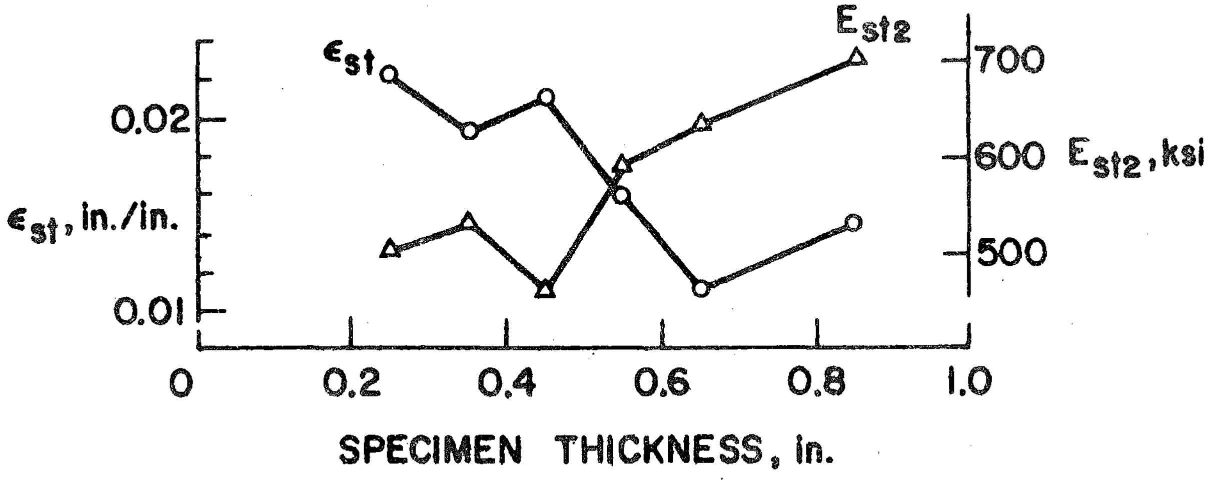

FIG. 14 VARIATION OF ϵ_{st} and E_{st2} WITH THICKNESS

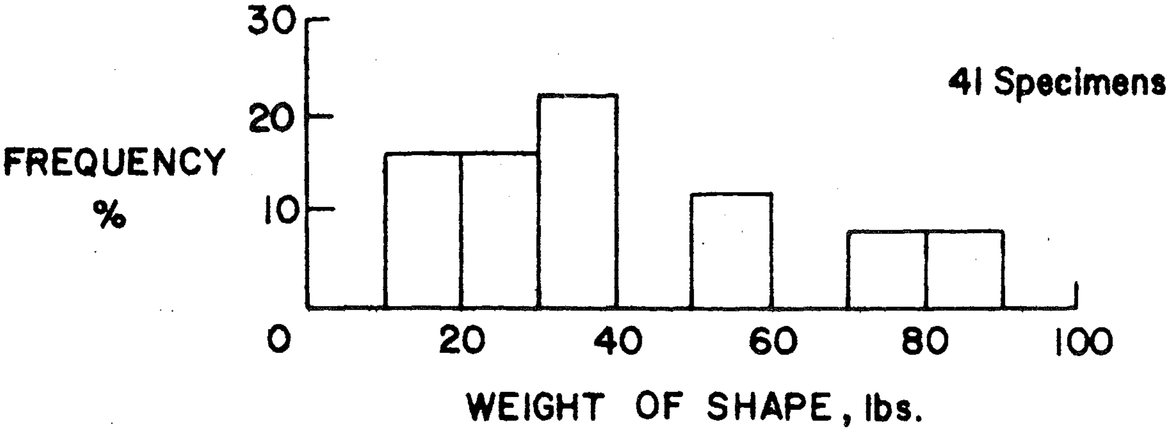

FIG. 15 HISTOGRAM FOR WEIGHT OF SHAPE

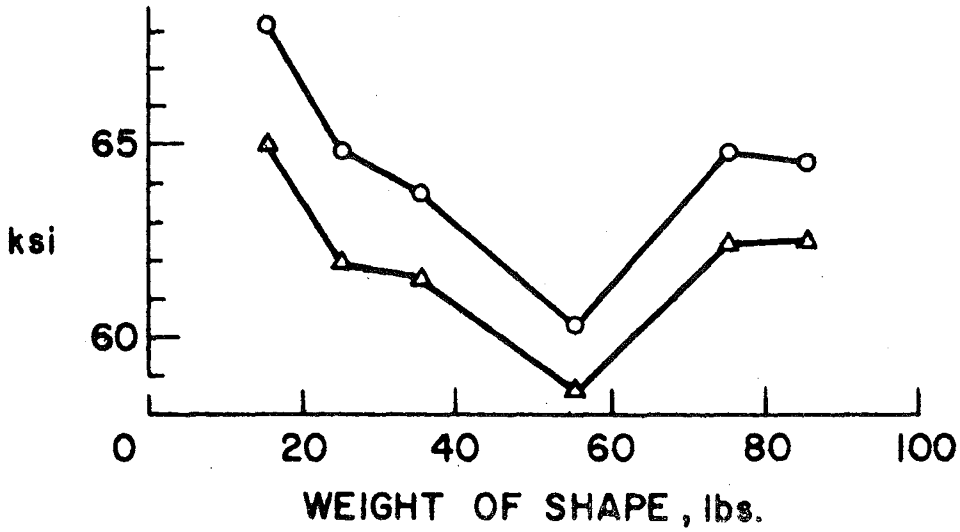

FIG. 16 VARIATION OF σ_{yd} and σ_{ys} WITH WEIGHT OF SHAPE

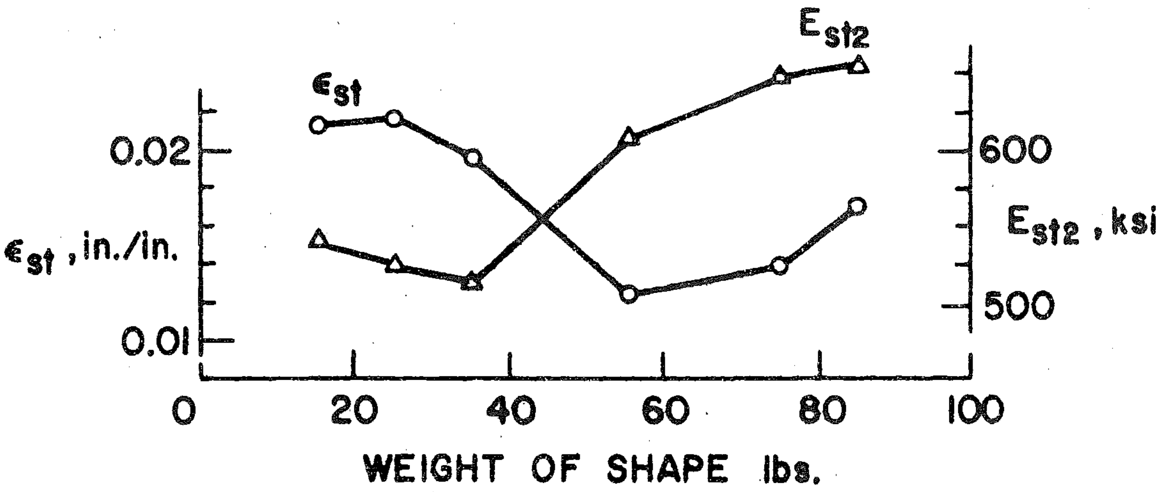

FIG. 17 VARIATION OF ϵ_{st} and E_{st2} WITH WEIGHT OF SHAPE

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