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STATISTICAL STUDY OF THE MECHANICAL PROPERTIES

OF REINFORCING BARS

by

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INTRODUCTION

The serviceability, strength and ductility of reinforced concrete structures depends to a large extent on certain properties of reinforcing bars - modulus of elasticity, yield stress, ultimate stress and elongation - properties controlled in practice by standard ASTM or CSA specifications. This Note presents information on the variability of these properties, information useful in assessing design safety factors such as those used in the ACI or National Building Code and methods of control such as those stipulated in ASTM or CSA specifications.

The information was obtained from two sources: one a small sample of bars tested at the National Research Council of Canada (NRC); the other a larger sample of 132 test results obtained from a Canadian manufacturing plant. The NRC sample provided information on the variability along a bar as well as from bar to bar within a heat (or batch) of steel. The manufacturer's sample provided information on over-all variability from one manufacturing plant. In order to assess design safety factors over-all variability should be obtained in the future by sampling all reinforcing bars in Canadian construction, not just those from one manufacturing plant.

NRC TESTS

Reinforcing bars from five heats of steel, each heat represented by a different size (No. 3, 5, 8, 11, 14), were obtained in 15-ft lengths from a Canadian manufacturer. The steel was intermediate grade (designated CSA-G30.1 (1) and CSA-G30.7 (2)) with a specified minimum yield stress of 40 ksi. Each 15-ft bar was cut into 3-ft lengths for test. There were 102 samples obtained from 21 bars.

Method of Test and Parameters Measured

As yield stress (f_y) and ultimate stress (f_u) are dependent on rate of loading, it was decided that the test should be more precise than the usual ASTM or CSA acceptance test (3). Tests made at Lehigh University (4) on coupons from rolled sections showed that the static yield stress (f_{ys}) corresponding to long-term loading conditions is significantly less than the yield stress, f_y, obtained from the standard test. It was therefore decided to obtain the static values of yield and ultimate stress in addition to standard values. The test was carried out in a mechanical screw-type testing machine and the static values were obtained by fixing the cross-head and allowing relaxation to take place until a steady reading was obtained (5 min was sufficient). Figure 1 indicates on a typical stress-strain diagram how the test was carried out.

The following parameters were measured (see Figure 1):

(1) Area of cross-section, A, determined from the length of the bar and its weight.

(2) Modulus of elasticity, E, measured by means of a mechanical extensometer of 8-in. gauge length equipped with a dial gauge. Occasionally there was some difficulty in attaching the extensometer to the bar in just the right way (neither too loose nor too tight) and it was estimated that measuring accuracy was of the order of ±0.5 per cent.

(3) Upper yield stress, f_y, obtained at a cross-head speed of 0.1 in./min. In this case there was no significant difference between upper and lower yield stresses.

(4) Static yield stress, f_{ys}, obtained at an elongation of 0.5 per cent.

(5) Dynamic yield stress, f_{yd}, obtained at a cross-head speed of 0.2 in./min prior to strain hardening, as shown in Figure 1.

(6) Strain at beginning of strain hardening, ε_{st}, measured by means of a ruler on 8 in. gauge length. As strain hardening begins rather gradually, ε_{st} is not precisely defined.

(7) Ultimate stress, f_u, measured at a cross-head speed of 0.5 in./min.

(8) Static ultimate stress, f_{us}, obtained by subtracting from the ultimate stress, f_u, the relaxation in stress measured before reaching ultimate, as shown in Figure 1.

(9) Ultimate strain, ε_u, and per cent elongation. Before the test two successive 8-in. gauge lengths were marked off. After the test per cent elongation was obtained in the gauge length where necking took place and ultimate strain was obtained in the other gauge length.

All bars had a yield plateau, as shown in Figure 1, except the smallest size, No. 3 (3/8-in. diam), which, because of cold working during rolling, had no yield plateau. In this case f_y and f_{ys} were determined arbitrarily at 0.3 per cent strain and f_{yd} at 0.5 per cent strain, as indicated in Figure 2.

Results

The results of individual tests are given in Table I. The stresses and modulus of elasticity were calculated using the measured area, in conformance with specifications (1). Blanks in Table I represent either cases that are not applicable (ε_{st} for No. 3 bars) or those where reliable readings were not obtained.

A statistical analysis of the results is given in Table II (variations along a bar and within a size or heat) and in Table III (over-all variations for NRC tests). For Table II the average and coefficient of variation were determined by treating each test as an independent sample:

$$\overline{X} = \frac{1}{N} \Sigma X_i \qquad (1)$$

$$\sigma_X^2 = \frac{1}{N-1} \Sigma (X_i - \overline{X})^2$$

where $\overline{X}$ is the average, σ_X is the standard deviation, and N is the number of tests. The coefficient of variation (c. o. v.) equals the standard deviation divided by the average. For Table III the over-all statistical results were calculated treating each size or heat with equal weight as follows:

$$\overline{X} = \frac{1}{5} \Sigma \overline{X}_j \qquad (2)$$

$$\sigma_X^2 = \frac{1}{5} [\Sigma \sigma_{Xj}^2 + \Sigma (\overline{X}_j - \overline{X})^2]$$

where the subscript j refers to a particular heat.

Discussion of Results

Area

As shown in Table II, the variability in area along any bar is small, the c.o.v. being of the order 0.1 to 0.9 per cent. Variability from bar to bar within a heat is also small, with the possible exception of size No. 3 which gives an over-all c.o.v. of 1.5 per cent. These results are to be expected owing to the nature of the rolling process, since each heat is rolled at one setting of the rolls. From Table III the over-all c.o.v. for area was 1.6 per cent for the NRC tests.

Measured areas are, on the average, about 2.5 per cent lower than nominal. There may be an economic reason for this since CSA standards on reinforcing bars (1) allow a maximum deviation of 6 per cent for any bar and 3.5 per cent for any lot of bars.

Modulus of Elasticity

Table II shows that variability of modulus of elasticity is about the same whether along a bar, within a heat, or over-all, with a c.o.v. of the order of 1 to 2 per cent. A significant part of the variations in the modulus may be due to the measurement error discussed earlier.

From Table III the average modulus was 29,200 ksi, with a c.o.v. of 1.6 per cent. In design calculations the nominal rather than the actual area is used, so that there is an additional deviation in modulus owing to a deviation of area from nominal area. In Table III the average modulus based on nominal area is 28,500 ksi, with a c.o.v. of 2 per cent.

Yield Stress

No matter which definition of yield stress is used (f_y and f_{ys} are given in Tables II and III), the variability is about the same. Variability along a bar is generally quite small with a c.o.v. of 1 per cent or less, except for size No. 3, which has a c.o.v. of about 2 per cent. The variability from bar to bar within a heat is higher with a c.o.v. of the order of 2 to 3 per cent. The over-all c.o.v. for all heats of the NRC tests from Table III is of the order of 7 to 8 per cent, i.e. considerably greater than variation within a single heat.

For structural design considerations the static yield stress is the best definition of yield, since it is correct for long-term loading and on the safe side for higher loading rates, e.g. those due to wind. The standard CSA Acceptance Test (3) can be carried out at a maximum rate of cross-head speed of 1/16 in. per in. of gauge length, i.e. fairly rapidly. Experiments carried out at Lehigh University (4) indicate differences $f_y - f_{ys}$ of the order of 5 ksi at this loading rate. In Table II the difference, $f_y - f_{ys}$, ranges from 2.5 to 3.3 ksi, the rate of loading for f_y being considerably less than the specified maximum. Thus, when evaluating a mill test result about 4 ksi should be subtracted to arrive at the static yield stress. Since design calculations are based on nominal area, an additional 3 per cent should be subtracted to account for deviations from the nominal area (see Table III). In addition, there is a within-heat variability represented by a c.o.v. of about 2-3 per cent for this sample.

Yield Plateau - Strain at Beginning of Strain Hardening

The strain at beginning of strain hardening, ϵ_{st}, ranged from a minimum of 0.7 per cent for No. 14 bar to a maximum of 2.2 per cent for No. 5 bar (No. 3 bars exhibit no yield plateau). From Table II the variability along a bar and within a heat is of the order of 5 to 15 per cent. Because of a dependence of ϵ_{st} on bar size the over-all c.o.v. of 27 per cent in Table III is quite high.

Ultimate Stress

Variability of ultimate stress (ultimate tensile stress, f_u, or static ultimate stress, f_{us}) for this sample is somewhat less than for yield stress, with c.o.v.'s of the order of 1 per cent or less along a bar (except for No. 3 bar for which cold working may have an effect), 1 to 2 per cent within a heat, and 3 per cent over-all (Tables II and III).

When evaluating a mill test result, about 6 ksi should be subtracted from ultimate stress to give the static ultimate stress. This figure is greater for ultimate stress than for yield stress because of a greater rate of loading (maximum rate of cross-head speed $\frac{1}{2}$ in. per in. of gauge length (3)).

Ductility - Ultimate Strain and Per Cent Elongation

Tables II and III indicate variabilities in ultimate strain, ϵ_u, and per cent elongation of the same order of magnitude, with c.o.v.'s of the order of 10 per cent along a bar and within a heat. No. 3 bar is considerably less ductile, primarily because of the effect of cold working during the rolling process. By including No. 3 bars, the over-all c. o. v. in Table III is quite high, about 20 per cent. Otherwise, the over-all c. o. v. is of the order of 10 per cent.

Comparison with Mill Test Results

Mill test results for the reinforcing steel used in the NRC tests are given in Table IV. The mill test results for yield stress and ultimate stress are expected to be approximately equal to or a little more than the values of f_y and f_u in Table II. It may be seen, however, that there is little correlation. Part of this lack of correlation may be due to within-heat variability and to differences in rate of loading.

MANUFACTURER'S TESTS

The manufacturer provided results of 132 mill tests, each test representing a different heat, for a variety of reinforcing bars having a specified yield stress of 60 ksi (ASTM A432 or CSA G30. 10 (5) designation). The sizes ranged from No. 5 to 14.

Histograms of the results are shown in Figure 3 and statistical quantities are given in Table V. Variabilities from the manufacturer's results as given by the c. o. v.'s in Table V are equal to or somewhat greater than those in Table III. This may be due to wider sampling. Skewness, a measure of lack of symmetry in the distribution curve, is also given in Table V. Skewness for yield stress is positive, due primarily to the effect of control at specified minimum strength (Figure 3). The histograms for ultimate stress and area are approximately Gaussian.

SUMMARY OF RESULTS

The results for variability of mechanical properties of reinforcing bars are summarized in Table VI in the form of approximate coefficients of variation along a bar, within a heat, and over-all for one manufacturing plant. Variability along a bar and within a heat is estimated on the basis of the NRC tests. (For modulus of elasticity some allowance is made for measurement errors.) The over-all variability for one manufacturing plant is estimated on the basis of both the NRC tests and the manufacturer's test results.

CONCLUSIONS

(1) Table VI gives approximate variabilities of the mechanical properties of reinforcing bars for one manufacturing plant. Variabilities along a bar and within a heat area are also included.

(2) In interpreting mill test results for yield strength in structures, about 4 ksi should be subtracted for rate of loading effect and about 3 per cent for deviations from the nominal area used in design calculations. These deviations could be reduced considerably if CSA specifications lowered the maximum rate of cross-head speed and used the nominal area for calculating stresses rather than the measured area.

(3) Besides the systematic deviations for rate effect and area for this sample, there is a within-heat coefficient of variation for stress of about 2-$\frac{1}{2}$ per cent, i.e. fairly small. If the sample is representative of all batches of reinforcing bars, it indicates that for practical purposes the present method of control by testing one sample per heat (provided that there is only one size per heat) is adequate. Any basic evaluation of structural safety would nevertheless have to take into account all the deviations mentioned above.

ACKNOWLEDGEMENTS

The Steel Company of Canada kindly provided the reinforcing steel for the NRC tests along with the corresponding mill test data. The Steel Company of Canada also provided the results of 132 mill tests on reinforcing bars manufactured at the Contrecoeur plant. The author wishes to thank Mr. G. Kotuba and Mr. A. B. Dove of the Steel Company of Canada for their assistance.

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(2) CSA Standard G30.7-1961. Special Large Size Deformed Billet-Steel Bars for Concrete Reinforcement.

(3) CSA Standard G40.1-1966. General Requirements for Delivery of Rolled Steel Plates, Shapes, Sheet Piling, and Bars for Structural Use.

(4) Rao, N. R. N., M. Lohrmann, and L. Tall. Effect of Strain Rate on the Yield Stress of Structural Steels. J. Mat., Vol. 1, No. 1, March 1966.

(5) CSA Standard G30.10-1964. Deformed Billet-Steel Bars for Concrete Reinforcement with 60,000 PSI Minimum Yield Point.

TABLE I

NRC TEST RESULTS

Size	Bar No.	Sample No.	Measured Area / Nominal Area	E ksi x10⁻³	f_y ksi	f_{ys} ksi	f_{yd} ksi	ε_{st} %	f_u ksi	f_{us} ksi	ε_u %	% Elong.
No.3[1]	1	1	0.944	29.8	51.7	49.4	54.9	-	85.4	80.9	9.0	15.6
		2	.946	29.9	52.5	50.0	54.5	-	84.5	80.0	11.6	13.1
		3	.944	29.4	53.0	50.5	55.6	-	86.2	81.5	11.5	-
		4	.945	28.9	52.6	50.0	55.2	-	86.0	81.4	12.8	16.1
		5	.946	28.2	53.6	51.1	55.5	-	84.8	80.1	8.1	15.0
	2	1	.980	28.4	-	-	56.4	-	85.3	81.2	9.9	-
		2	.978	28.8	52.6	49.1	55.4	-	85.7	81.6	9.1	14.8
		3	.977	-	52.4	49.9	56.3	-	85.3	80.7	8.2	-
		4	.983	-	51.9	49.1	55.2	-	84.8	80.7	12.3	16.8
		5	.975	28.6	52.7	50.0	56.2	-	86.2	81.5	8.4	14.3
	3	1	.961	-	49.3	46.6	54.2	-	83.8	79.4	10.6	-
		2	.961	-	49.4	47.1	51.7	-	81.7	78.1	11.9	18.4
		3	.962	29.4	51.4	49.1	53.8	-	84.2	79.7	10.5	16.8
		4	.962	29.3	51.4	49.1	54.1	-	84.2	79.8	11.5	15.4
		5	.961	28.8	51.7	49.3	54.5	-	84.4	79.9	11.9	16.8
	4	1	.979	-	52.6	50.2	55.0	-	84.0	79.5	10.4	13.8
		2	.977	28.0	55.3	52.8	58.0	-	88.4	84.1	16.2	21.9
		3	.977	29.7	55.3	52.5	58.1	-	88.4	83.8	6.0	13.1
		4	.977	30.1	53.7	51.2	55.8	-	84.6	80.0	7.9	15.0
		5	.975	28.6	52.8	50.3	55.3	-	84.7	-	13.7	16.9

Note [1]: For No. 3 bars, which have no definite yield plateau, f_y and f_{ys} are measured at 0.3 per cent strain whereas f_{yd} is measured at 0.5 per cent strain.

TABLE I (Cont'd)

Size	Bar No.	Sample No.	Measured Area / Nominal Area	E ksi x10^{-3}	f_y ksi	f_{ys} ksi	f_{yd} ksi	ϵ_{st} %	f_u ksi	f_{us} ksi	ϵ_u %	% Elong.
No.5	1	1	0.968	28.1	53.7	50.7	54.5	-	80.7	76.2	19.4	25.2
		2	.971	28.9	53.7	50.6	54.8	1.9	80.4	76.1	16.0	22.8
		3	.969	29.3	53.9	50.6	55.1	-	80.7	76.2	16.6	24.1
		4	.968	29.2	54.2	50.7	54.5	-	80.7	76.4	17.3	24.4
		5	.971	-	54.2	50.6	54.2	1.9	80.4	76.0	18.4	24.5
	2	1	.974	29.0	53.6	50.8	54.2	2.1	80.5	76.0	17.9	23.3
		2	.972	29.4	53.8	50.8	54.5	2.0	80.7	76.0	17.8	24.1
		3	.973	29.1	53.9	50.7	54.2	2.0	80.3	75.5	18.8	24.4
		4	.974	29.4	54.0	50.5	54.2	2.1	80.1	75.5	20.1	24.0
		5	.972	29.1	53.9	50.5	-	-	80.6	76.0	19.1	25.0
	3	1	.972	30.2	54.5	51.1	55.1	2.2	80.7	76.5	16.1	22.7
		2	.972	29.8	53.8	50.5	56.8	2.2	80.7	75.7	16.8	26.0
		3	.972	29.5	54.4	50.8	55.7	2.0	80.6	75.7	17.0	25.0
		4	.972	29.4	53.1	50.8	56.1	2.1	80.7	76.5	18.1	25.6
		5	.972	29.0	54.3	50.8	55.8	2.2	80.5	75.8	18.6	23.5
No.8	1	1	.964	29.8	47.7	44.8	48.2	1.4	79.6	76.3	14.4	22.0
		2	.964	28.9	47.4	44.8	-	1.5	79.2	75.5	15.0	20.6
		3	.962	29.4	47.4	44.7	50.0	-	79.4	75.3	17.2	25.0
		4	.963	29.2	47.3	44.5	50.9	1.3	79.4	75.5	18.4	-
		5	.961	29.6	47.3	44.4	48.6	1.3	79.4	75.3	17.5	26.5
	2	1	.952	29.4	49.6	47.9	53.2	1.3	83.1	79.3	12.5	-
		2	.956	29.6	50.7	47.7	53.4	1.6	83.0	78.9	16.2	23.2
		3	.954	-	50.5	47.7	53.0	1.4	83.0	78.9	15.3	-
		4	.956	29.6	50.6	47.9	53.2	1.3	83.4	79.2	18.5	24.3
		5	.956	29.1	50.7	47.5	53.0	-	83.3	79.3	15.9	25.1

TABLE I (Cont'd)

Size	Bar No.	Sample No.	Measured Area / Nominal Area	E ksi x10-3	f_y ksi	f_{ys} ksi	f_{yd} ksi	ϵ_{st} %	f_u ksi	f_{us} ksi	ϵ_u %	% Elong.
No.8	3	1	0.954	29.7	51.6	48.6	53.6	1.6	82.9	78.7	19.4	24.4
		2	.957	29.9	51.0	48.5	-	2.0	82.5	78.5	16.6	25.3
		3	.950	29.5	51.3	48.0	53.3	1.5	82.4	78.3	16.9	21.6
		4	.946	29.5	51.1	48.4	53.6	2.0	82.6	78.3	16.9	22.1
		5	.942	29.3	51.2	48.1	53.5	1.5	82.5	78.2	16.9	23.0
	4	1	.953	29.6	50.8	47.8	53.4	1.5	83.3	79.0	14.0	24.3
		2	.953	29.6	50.8	47.8	53.4	1.4	83.3	79.0	18.9	-
		3	.956	29.5	50.4	48.0	52.6	1.4	83.0	79.2	15.1	22.2
		4	.953	29.1	51.0	47.9	53.4	1.5	83.4	79.0	16.5	22.9
		5	.952	29.5	50.8	47.9	53.0	1.5	83.1	78.8	15.0	23.1
	5	1	.958	29.4	50.8	48.0	52.8	1.3	83.6	79.3	16.4	24.3
		2	.964	29.9	51.0	48.3	53.2	1.3	83.5	79.5	15.5	25.0
		3	.971	29.3	50.8	48.0	52.8	1.4	82.8	78.4	17.4	-
		4	.977	-	50.8	48.0	52.0	1.3	83.4	78.9	15.0	-
		5	.980	-	50.1	47.7	51.6	1.3	82.8	78.8	16.3	20.5
	6	1	.957	-	51.0	47.9	55.6	1.6	84.0	79.2	20.0	24.8
		2	.960	29.6	50.8	47.6	54.1	1.5	83.8	79.1	15.0	23.8
		3	.957	30.3	50.5	47.5	54.2	1.5	83.6	78.8	17.0	23.5
		4	.956	29.5	50.6	47.7	54.3	1.5	83.4	78.9	14.9	24.0
		5	.957	29.2	50.8	47.6	54.2	1.6	83.6	78.7	15.0	22.8
No.11	1	1	.970	29.9	49.0	46.2	50.2	1.4	81.4	77.1	15.8	24.0
		2	.982	29.2	48.8	46.0	-	1.3	81.3	77.0	14.8	-
		3	.973	29.1	49.2	46.3	-	1.3	81.4	77.0	17.9	-
		4	.982	-	48.7	45.9	-	1.3	81.1	76.7	12.6	25.0
		5	.990	-	48.8	45.7	-	1.3	81.1	76.8	15.2	26.0

TABLE I (Cont'd)

Size	Bar No.	Sample No.	Measured Area / Nominal Area	E ksi x10^-3	f_y ksi	f_{ys} ksi	f_{yd} ksi	ε_{st} %	f_u ksi	f_{us} ksi	ε_u %	% Elong.
No.11	2	1	0.982	29.4	50.0	46.7	-	1.6	82.6	78.4	14.4	25.2
		2	.984	-	49.8	46.9	-	1.5	82.3	79.3	13.8	-
		3	.986	-	49.7	46.7	-	1.5	82.7	78.5	17.2	25.5
		4	.984	-	49.6	46.9	-	1.5	82.6	78.0	17.2	26.0
	3	1	.994	-	47.9	45.9	-	-	80.6	76.9	14.0	-
		2	.990	28.6	48.7	46.0	-	1.4	81.2	76.5	15.1	24.5
		3	.991	28.7	48.5	45.7	51.7	1.3	81.2	77.1	14.5	23.9
		4	.991	29.6	48.2	45.8	50.5	1.3	80.9	76.2	14.0	23.5
		5	.994	28.8	48.7	46.0	51.6	1.5	80.8	76.3	16.6	-
No.14	1	1	.993	29.0	44.3	41.1	-	1.2	84.3	80.6	17.6	20.8
		2	.994	29.1	43.5	41.1	-	1.0	84.5	80.7	18.5	26.9
		3	.994	29.5	44.3	41.2	-	1.2	84.4	80.9	17.5	24.5
		4	.993	29.2	44.3	41.4	-	1.1	84.1	80.3	17.5	26.0
		5	.995	-	44.3	41.5	-	1.2	84.2	81.5	18.8	25.1
	2	1	.996	-	44.0	41.0	-	1.1	84.0	80.7	17.1	23.0
		2	.996	29.4	44.3	41.4	-	1.0	84.1	80.9	17.5	24.2
		3	.996	29.4	44.3	41.3	-	1.0	84.0	81.0	19.4	23.6
		4	.996	29.0	44.4	41.3	-	1.1	84.2	80.9	15.3	22.7
		5	.990	29.5	44.5	41.3	-	1.2	84.5	81.5	15.4	23.0
	3	1	.996	28.5	43.3	40.1	46.9	0.9	85.4	82.0	17.9	23.0
		2	.996	29.0	43.2	40.2	46.9	1.0	85.2	81.8	17.0	24.0
		3	.996	29.1	43.3	40.2	46.9	1.0	85.2	81.6	16.9	22.9
		4	.998	29.0	43.4	39.8	46.8	1.0	84.4	-	15.8	21.8
		5	.998	29.3	43.5	40.5	46.8	0.9	84.6	81.2	17.0	21.0

TABLE I (Cont'd)

Size	Bar No.	Sample No.	Measured Area / Nominal Area	E ksi $\times 10^{-3}$	f_y ksi	f_{ys} ksi	f_{yd} ksi	ϵ_{st} %	f_u ksi	f_{us} ksi	ϵ_u %	% Elong.
No14	4	1	0.996	28.7	42.4	40.0	46.0	0.9	85.0	81.4	18.3	-
		2	.996	29.1	42.8	39.4	45.1	0.8	85.2	82.4	17.5	23.9
		3	.996	28.9	43.3	39.9	45.5	0.7	85.0	82.0	16.0	23.4
		4	.996	28.9	42.9	39.6	45.5	0.8	85.0	82.1	16.8	24.2
		5	.996	-	43.1	39.8	46.9	0.9	85.2	82.5	19.2	23.8
	5	1	.998	29.0	43.8	41.0	46.8	1.2	84.7	81.5	17.7	22.5
		2	1.000	-	43.7	40.3	46.7	1.0	84.5	81.0	19.0	23.5
		3	.999	29.5	43.6	40.8	-	1.2	85.4	81.0	19.5	23.7
		4	.997	-	43.7	40.9	47.6	1.3	85.0	79.9	20.2	23.5
		5	.997	-	43.3	41.2	47.7	1.0	85.0	81.0	12.5	20.8

TABLE II

STATISTICAL STUDY OF NRC RESULTS*

e	Bar No.	Area/Nom. Area		E ksi x 10^{-3}		f_y ksi		f_{ys} ksi		ϵ_{st} %		f_u ksi		f_{us} ksi		ϵ_u %		% Elong.	
		Av.	% c. o. v.	Av.	% c. o. v.	Av.	% c. o. v.	Av.	% c. o. v.	Av.	% c. o. v.	Av.	% c. o. v.	Av.	% c. o. v.	Av.	% c. o. v.	Av.	% c. o. v.
. 3	1	0.945	0.2	29.2	2.4	52.7	1.3	50.4	1.7	-	-	85.4	0.9	80.8	0.9	10.6	18.6	15.0	8.8
	2	0.979	0.3	28.6	0.7	52.5	0.7	49.6	0.9	-	-	85.5	0.6	81.1	0.8	9.6	17.3	15.3	8.7
	3	0.962	0.1	29.2	1.1	50.6	2.4	48.2	2.7	-	-	83.7	1.4	79.4	1.0	11.3	6.1	16.9	7.3
	4	0.977	0.2	29.1	3.3	54.0	2.4	51.5	2.4	-	-	85.4	2.3	81.1	2.5	10.8	38.4	16.1	21.9
	All Bars	0.966	1.5	29.1	2.2	52.4	3.0	49.9	3.2	-	-	85.0	1.6	80.5	1.6	10.6	22.3	15.9	13.8
. 5	1	0.969	0.2	28.9	1.9	53.9	0.5	50.6	0.1	1.9	0.0	80.6	0.3	76.1	0.2	17.5	7.8	24.2	3.6
	2	0.973	0.2	29.2	0.7	53.8	0.2	50.6	0.3	2.1	2.8	80.5	0.3	75.8	0.4	18.7	5.0	24.2	2.6
	3	0.972	0.1	29.6	1.5	54.2	0.5	50.8	0.5	2.1	4.2	80.6	0.2	76.0	0.6	17.3	5.9	24.6	5.7
	All Bars	0.971	0.2	29.2	1.6	54.0	0.5	50.7	0.3	2.1	5.4	80.5	0.2	76.0	0.4	17.9	6.9	24.3	4.0
. 8	1	0.963	0.2	29.4	1.2	47.4	0.3	44.6	0.4	1.4	7.0	79.4	0.3	75.6	0.6	16.5	10.4	23.5	11.5
	2	0.955	0.2	29.4	0.8	50.4	0.9	47.8	0.3	1.4	10.1	83.2	0.2	79.1	0.3	15.7	13.7	24.2	3.9
	3	0.950	0.7	29.6	0.8	51.3	0.5	48.3	0.4	1.7	15.1	82.6	0.3	78.4	0.3	17.8	7.5	23.3	6.7
	4	0.953	0.2	29.5	0.7	50.8	0.4	47.9	0.2	1.5	3.8	83.2	0.3	79.0	0.2	15.9	11.9	23.1	3.8
	5	0.970	0.9	29.5	1.1	50.7	0.7	48.0	0.5	1.3	3.4	83.2	0.5	79.0	0.6	16.1	5.7	23.3	10.4
	6	0.957	0.2	29.7	1.6	50.8	0.4	47.7	0.3	1.5	3.6	83.7	0.3	79.0	0.3	16.4	13.5	23.5	3.1
	All Bars	0.958	0.8	29.5	1.0	50.2	2.7	47.4	2.7	1.5	12.3	82.5	1.8	78.3	1.7	16.4	10.6	23.5	6.4
. 11	1	0.979	0.8	29.4	1.5	48.9	0.4	46.0	0.5	1.3	3.4	81.3	0.3	76.9	0.3	15.3	12.5	25.0	4.0
	2	0.984	0.2	29.4	0.0	49.8	0.3	46.8	0.3	1.5	3.3	82.6	0.2	78.7	0.7	15.7	11.5	25.6	1.6
	3	0.992	0.2	28.9	1.6	48.4	0.7	45.9	0.3	1.4	7.0	80.9	0.3	76.6	0.6	14.8	7.3	24.0	2.1
	All Bars	0.985	0.7	29.2	1.6	49.0	1.3	46.2	0.9	1.4	7.7	81.5	0.9	77.2	1.2	15.2	10.1	24.8	3.7
. 14	1	0.994	0.1	29.2	0.7	44.1	0.9	41.3	0.4	1.1	7.9	84.3	0.2	80.9	0.5	18.0	3.5	25.6	4.1
	2	0.995	0.3	29.3	0.8	44.3	0.4	41.2	0.4	1.1	7.8	84.2	0.3	81.1	0.4	16.9	10.0	23.4	2.9
	3	0.997	0.2	29.0	1.0	43.3	0.2	40.2	0.6	1.0	5.7	85.0	0.5	81.6	0.4	16.9	4.4	22.5	5.2
	4	0.996	0.1	28.9	0.6	42.9	0.8	39.8	0.7	0.8	10.2	85.1	0.2	82.1	0.5	17.6	7.1	23.8	1.4
	5	0.998	0.2	29.3	1.2	43.6	0.5	40.9	0.9	1.1	9.8	85.0	0.5	81.4	0.4	17.8	17.4	22.8	5.3
	All Bars	0.996	0.3	29.1	1.0	43.7	1.3	40.7	1.6	1.0	14.7	84.7	0.5	81.3	0.8	17.4	9.4	23.4	6.2

* Results are shown along a bar (4 or 5 tests) and within a heat

TABLE III

STATISTICS FOR ALL NRC TESTS

	Based on Measured Area		Based on Nominal Area	
	Average	% c.o.v.	Average	% c.o.v.
Area/Nom. Area	0.975	1.6		
E ksi x 10^{-3}	29.2	1.6	28.5	2.0
f_y ksi	49.9	7.4	48.7	6.6
f_{ys} ksi	47.0	7.9	45.8	7.0
ε_{st} %	1.49	26.6		
f_u ksi	82.9	2.4	80.8	3.0
f_{us} ksi	78.7	2.8	76.7	3.5
ε_u %				
All Bars	15.5	20.3		
All Except No. 3	16.7	11.1		
% Elongation				
All Bars	22.4	16.2		
All Except No. 3	24.0	5.7		

TABLE IV

MILL TEST RESULTS FOR NRC REINFORCING STEEL

(Specified Yield Stress 40 ksi, Specified Ultimate Stress 70 ksi (1))

Size	Nominal Area, in.^{2}	Measured Area, in.^{2}	Yield Stress, ksi	Ult. Stress ksi	% Elongation in 8 in.	Per Cent				
						C	P	S	Mn	Si
No. 3	0.11	0.1074	48.4	73.6	22	0.41	0.006	0.032	0.59	0.12
5	0.31	0.315	58.4	83.5	23	0.33	0.006	0.026	0.66	0.26
8	0.79	0.760	48.7	75.7	22	0.30	0.014	0.038	0.74	0.22
11	1.56	1.550	54.2	84.2	20	0.32	0.004	0.020	0.89	0.28
14	2.25	2.261	45.3	79.3	17	0.45	0.002	0.025	0.48	0.04

TABLE V

STATISTICAL SUMMARY OF TEST RESULTS FROM A MANUFACTURING PLANT

	Average	% c. o. v.	Skewness
Area	1.000 x Nominal Area	1.93	-0.3
Yield Stress*	71.5 ksi	7.7	0.3
Ultimate Stress**	112.1 ksi	7.3	-0.3

* Specified yield stress = 60 ksi

** Specified Ultimate stress = 90 ksi

TABLE VI

ESTIMATES OF VARIABILITY FOR ONE MANUFACTURING PLANT

Property	Variability expressed as % c. o. v.		
	Along a Bar	Within a Heat (or Bar Size)	Over-all
Area	0.7	1.0	2
Modulus of Elasticity	0.7	1.0	2
Yield Stress	1.0	2.5	8
Ultimate Stress	0.7	1.5	7
Strain at Strain Hardening Ultimate Strain Per Cent Elongation	10.0	10.0	20

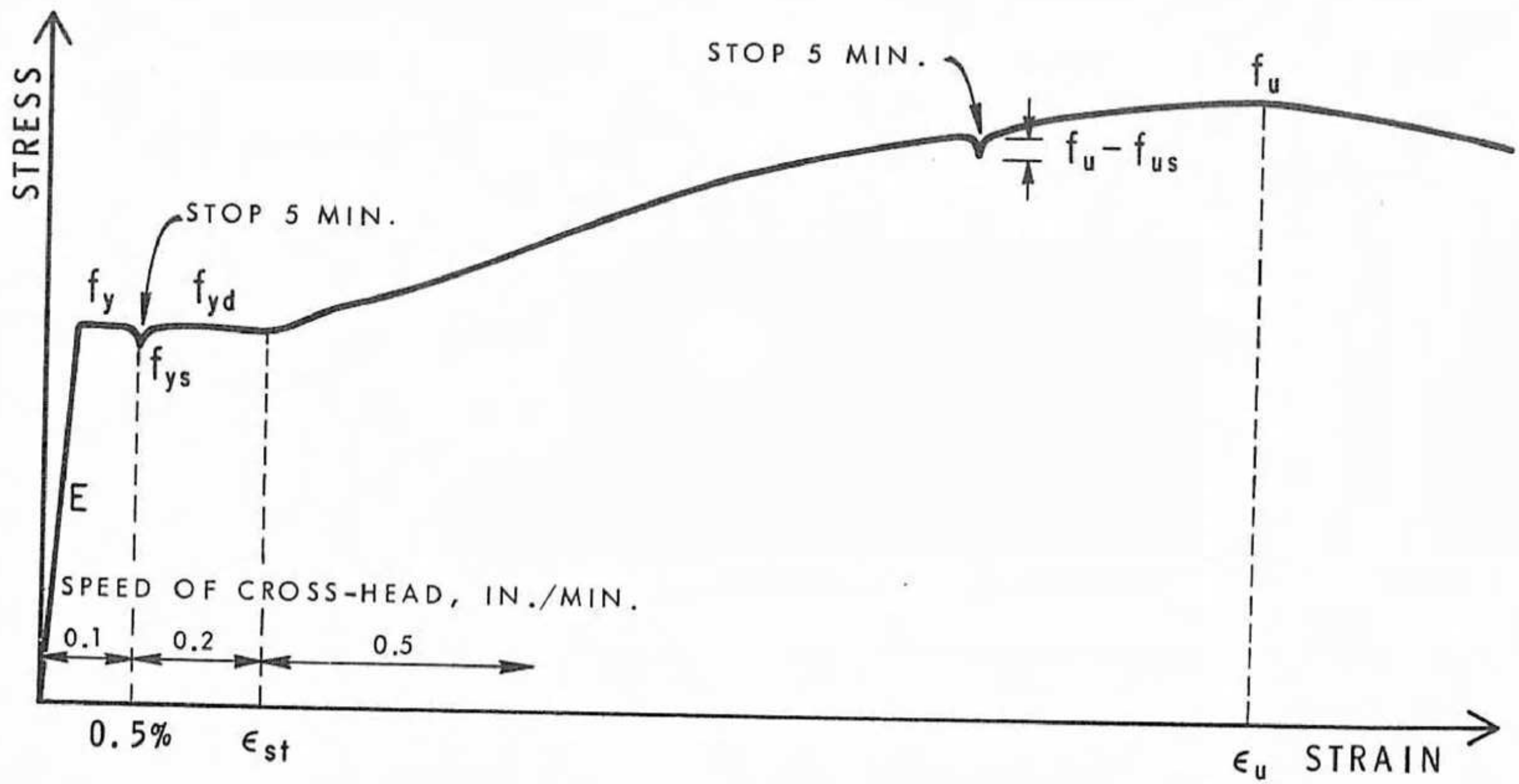

FIGURE 1 TYPICAL STRESS-STRAIN DIAGRAM

BR 4910-1

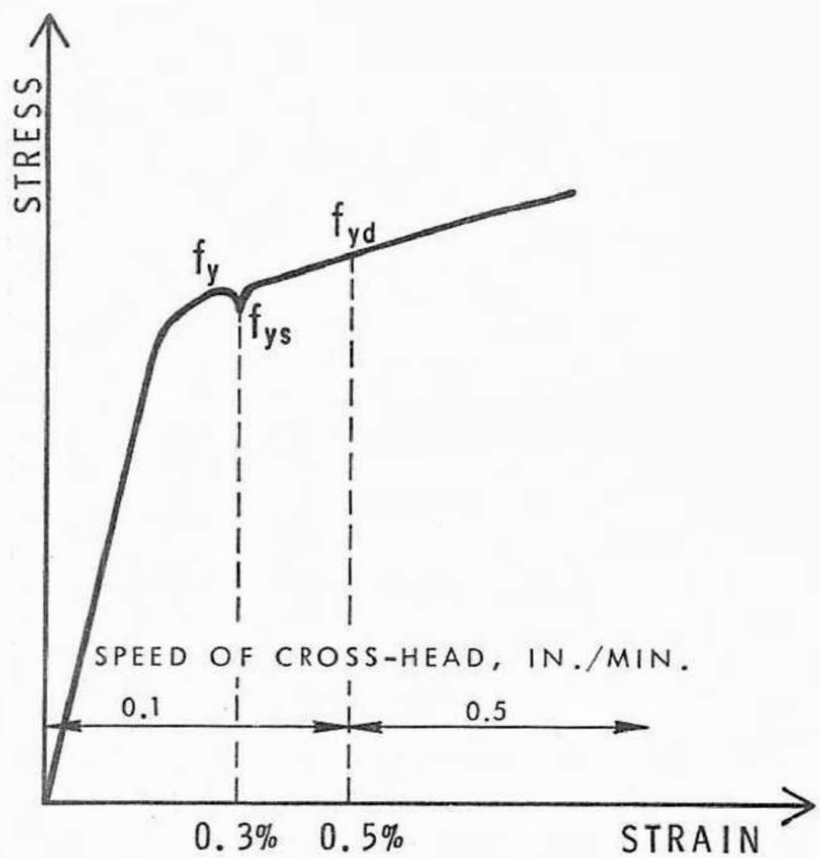

FIGURE 2 TYPICAL STRESS-STRAIN DIAGRAM FOR NO. 3 BAR

BR 4910 – 2

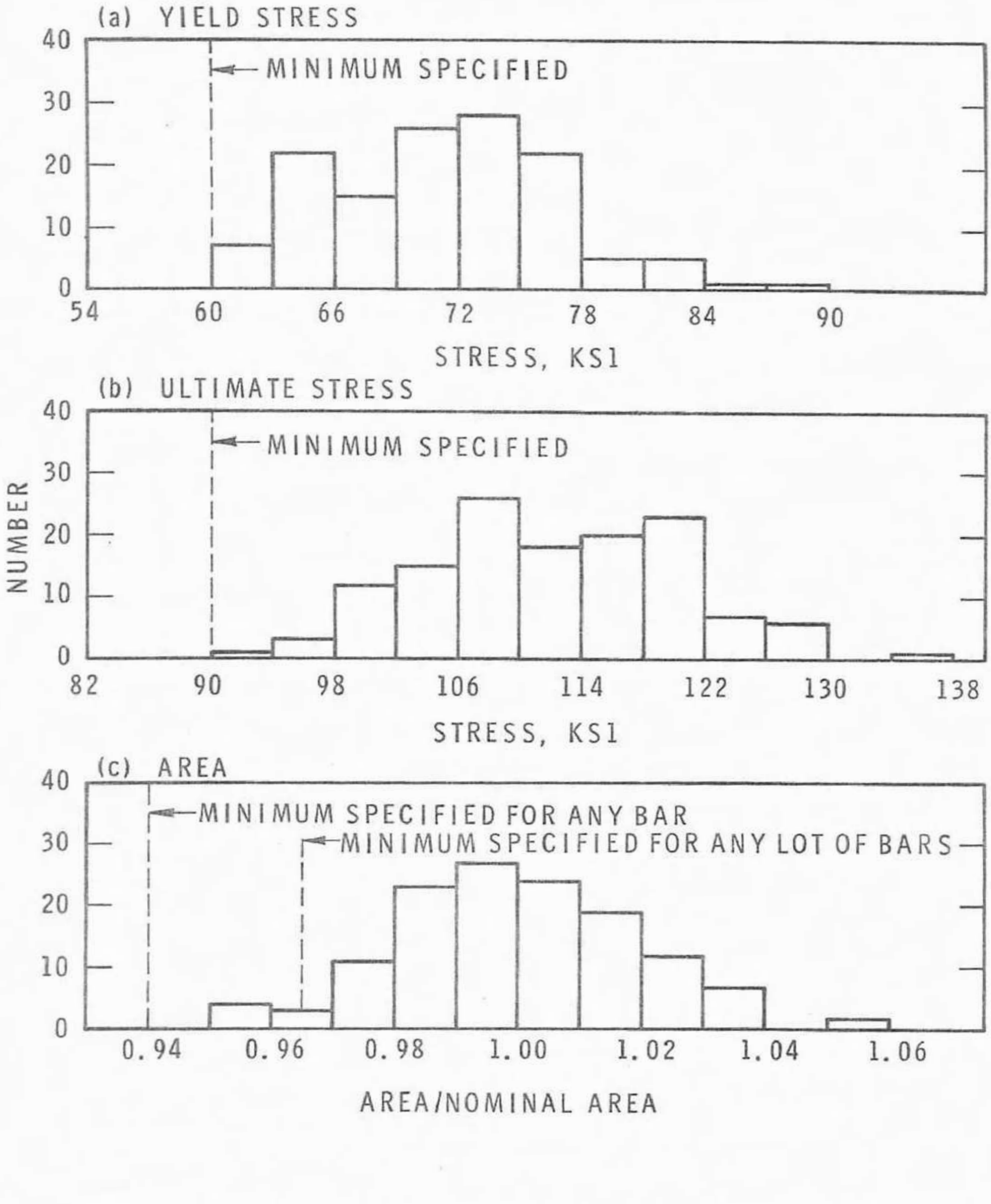

FIGURE 3 HISTOGRAMS OF MANUFACTURER'S TEST RESULTS

BR 4910 – 3