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Technical Note N-427

DYNAMIC TESTS ON HIGH STRENGTH STEEL

10 February 1962

U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

DYNAMIC TESTS ON HIGH STRENGTH STEEL

Task No. Y-F008-10-401

Type B

by

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OBJECT OF TASK

To determine the dynamic properties of basic materials for which such data are lacking.

ABSTRACT

The results of tension tests on specimens machined from a specially fabricated high strength reinforcing steel are presented. Yield stress of the high strength steel was determined over a range of strain rates from the static value of 7×10^{-6} in./in./sec up to a maximum dynamic strain rate of 0.375 in./in./sec. The percent increase in yield stress for a given dynamic strain rate is computed from the ratio of the yield stress obtained at the dynamic rate to that obtained at the static rate.

The test results indicate that the percent increase in dynamic yield stress for the high strength steel is lower than that previously reported for conventional reinforcing steels.

Compared with static test results, the dynamic loading on high strength steel resulted in little increase in ultimate strength and no discernible change in reduction in area or in percent elongation at rupture.

Dynamic tests were conducted on two types of machines - hydraulic and pneumatic - to provide information about the operating characteristics of the machines. This information was used to formulate the specifications for a dynamic testing machine. See Appendix.

Because of the limited number of tests involved in this study, additional tests should be made on high-strength steel to corroborate the findings.

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INTRODUCTION

In January 1961 BuDocks approved funds, under Task Y-F008-10-401, Dynamic Properties of Structural Materials, to conduct dynamic tests on high strength reinforcing steel used in partially-prestressed concrete beams being investigated by the Structures Division of NCEL. This steel had been specially fabricated into reinforcing bars and is not commercially available in this form. It has a well-defined yield point with a minimum nominal static yield stress of 90,000 psi. At that time, very little information was available on the dynamic properties of this material. The particular dynamic property desired was the increase in yield stress associated with an increasing strain rate. For this purpose the static yield stress is used as the reference value.

Coincident with the immediate need for knowledge of dynamic properties of high-strength reinforcing steel (as outlined above) is the procurement by NCEL of a testing machine capable of applying dynamic loads at constant strain rates from 0.04 in./in./sec to 2.00 in./in./sec. Accordingly, tests reported herein were made to obtain dynamic properties of high-strength reinforcing steel and/or to evaluate the machine on which the tests were made. Specifications for an NCEL dynamic testing machine, based on the evaluation of machine capabilities, are presented in the Appendix.

DYNAMIC TESTING MACHINES

Generally speaking, machines designed to apply dynamic loads to laboratory specimens are either hydraulic or pneumatic in principle. Arrangements were made to test NCEL specimens of high-strength steel on at least one machine of each type. For purposes of this report, these machines will be designated "H" (hydraulic) and "P" (pneumatic).

The hydraulic testing machine (H) is capable of applying either a constant strain rate or a constant load rate to the test specimen. The control for a constant strain rate test is maintained by an extensometer attached to the specimen. A signal (error signal) indicating any significant difference between the programmed strain rate and the actual strain rate as measured by the extensometer actuates a servo valve which controls the fluid pressure in the loading cylinder. A hydraulic accumulator assists the pump in maintaining working pressure in the hydraulic system during a test. For constant-load-rate tests, the error signal is obtained from the load measuring dynamometer.

The pneumatic machine (P) utilizes air at high pressure, acting on a piston, to apply the load to a specimen. A chamber above the piston contains the gas under high pressure; a chamber below the piston contains a gas or fluid under low pressure. A plate containing an orifice separates the high pressure chamber from the piston face. The forces, acting on either end of the piston before a test, are balanced because the pressure in the chamber below the piston maintains an O-ring seal against the orifice plate. This O-ring seal restricts the piston area exposed to the high pressure gas, thus enabling the force balance. At the start of a test, a surge of additional pressure is applied to the upper face of the piston causing it to move away from the orifice plate and break the O-ring seal. Once the seal is broken, the high pressure gas acts over the entire face of the piston and acceleration of the piston is begun. A constant head velocity machine is obtained by filling the lower chamber with oil and regulating the flow of oil from the lower chamber with a manually-controlled valve. If the energy absorbed by the specimen is small compared with the total energy stored within the machine, a reasonably constant head velocity can be maintained.

TEST SPECIMENS AND INSTRUMENTATION

Test specimens were machined from three separate No. 6 reinforcing bars to the configuration shown in Figure 1. A taper of 0.003 in. (maximum) was provided toward the center of the reduced section to control the location of yield initiation. Each specimen was air-cooled while being machined. the final three cuts were limited to 0.002 in. each.

Strain in the reduced section was measured with two 1/2 in. foil type resistance strain gages mounted on diametrically opposite sides in the reduced section of each specimen. Each gage formed one arm of a wheatstone bridge circuit, and the other three arms were supplied by precision resistors (120 ohm each). The load on each specimen was determined by utilizing two 1/4-in. foil type resistance strain gages mounted diametrically opposite each other on one end of the specimen. Bending in the specimen could not influence the gage reading because the recorded value was the sum of the value for the two gages. These gages were calibrated for load on a 120,000 pound universal testing machine at NCEL. Accuracy of these gages was closely checked during static testing. Strains were recorded on an oscillograph using System D, 3-kc amplifiers.

STATIC TEST RESULTS

Static tests were conducted with a universal testing machine at NCEL. The results of these tests are shown in Table I. After a preliminary calibration each specimen was tested at a static load rate which produced a strain rate of about 7×10^{-6} in./in./sec in the reduced section. At load intervals of 1000 lb the oscillograph was turned on and the calibrate switch depressed, upon a signal from the machine operator, to indicate each successive 1000 lb of load. The oscillograph was then turned off until just prior to the next reading. When the load approached yield, the oscillograph was turned on and allowed to run continuously. The calibrate switch was depressed as the machine load indicator passed each 100 pounds until yielding had begun. By this method a continuous load-strain record was maintained through the yield point and well into the plastic range.

DYNAMIC TEST RESULTS

Results of all dynamic tests are shown in Table II. A typical oscillogram obtained from tests conducted on machine H is presented in Figure 2. The strain rate was calculated from the trace of one of the gages in the reduced section. That portion of the trace where a fairly constant strain rate had been established, prior to yield, was used for calculation.

The first series of tests on the hydraulic machine was made using an extensometer attachment to obtain a constant strain rate. Although this machine was supposed to provide strain rates up to 0.375 in./in./sec, the maximum obtained was 0.045 in./in./sec. Machine modifications prior to the second series of test coupled with a change to constant load rate control resulted in strain rates of 0.093 in./in./sec and 0.107 in./in./sec.

A typical oscillogram from tests made on machine P is presented in Figure 3. While reducing data obtained from tests on machine P, an error was discovered in the load readings. Normally, the galvanometers in the oscillograph will produce a linear deflection of ±2 in. By deflecting the trace <u>electrically</u> to the negative limit before each test, the usable range can be increased to 4 in. Such was the intent for these tests. Unfortunately the trace was deflected <u>mechanically</u> by adjusting the galvanometer, and the linear range remained at 2 in. Immediately upon learning of this error, a calibration of the system was obtained by measuring observed deflections when known resistances were shunted across the bridge. Checks were made on the reproducibility by returning to zero at arbitrary intervals. The correction curve is shown in Figure 4. Corrections were made by plotting the measured yield point deflection on the calibration curve and correcting it vertically to the extended linear line. All upper yield values shown in Table II have been corrected where applicable (Machine P tests).

DISCUSSION OF TEST RESULTS

Figure 5 represents a graphical summation of the dynamic tests, indicating upper yield stresses versus strain rates. The dynamic test data appear to present a straight line relationship. The linear equation computed by the least squares method, excluding static values, is shown below.

$$y = 102{,}180 + 19{,}480(x), \text{ where}$$

y = Upper yield stress in psi

x = Strain rate in in./in./sec

It is evident that this equation cannot represent the upper yield stress for strain rates much below 0.04 in./in./sec because the zero intercept of 102,180 psi for the equation does not agree with the average static yield stress of 95,870 psi. Using values obtained from the equation, the increase in upper yield point with strain rate will vary from 7.4 percent to 14.7 percent for strain rates ranging from 0.04 to 0.40 in./in./sec; this is in contrast to values ranging from 21.5 percent to 30.5 percent for hard grade and from 22.5 percent to 33.0 percent for intermediate grade reinforcing steels[1] tested over the same range of strain rates.

Tests by Manjoine[2] on mild steel shown an increase in percent elongation as the strain rate increases, static values for elongation were approximately 26 percent and increased to a maximum of 40 percent at a strain rate of 10^{-3} in./in./sec, strain rates up to 10^{3} in./in./sec showed no further increase. For NCEL tests as shown in Tables I and II, values for percent reduction in area and percent elongation indicate no significant change in these properties due to variations in testing speeds.

A statistical testing sequence had been designed to determine if there was a bar to bar difference in the properties of the steel. The program was not followed because the strain rates could not be controlled with any degree of certainty.

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1. U. S. NCEL, TM-130, "Elasto-Plastic Response of Beams to Dynamic Loads," by J. R. Allgood and W. A. Shaw, Port Hueneme, California. March 3, 1958, p. 70.
2. Manjoine, M. J. "Influence of Rate of Strain and Temperature on Yield Stresses of Mild Steel," Journal of Applied Mechanics, Vol. 11, p. A-215; (December 1944).

The dynamometer values from machine P did not seem to be consistent. The dynamometer was designed and built by the manufacturer of the machine and had never been accurately calibrated. Calibration was accomplished by loading a precalibrated NCEL specimen and relating the calculated load on the specimen to the deflected trace of the dynamometer on an oscillograph. The values for ultimate stress shown in Table I are taken from dynamometer measurements and are believed to be more accurate than the values obtained from the "stress" gages on the specimen. The recorded trace deflections from the stress gages at this load level are quite large, and the errors, after correction, are probably greater than the inherent errors in the dynamometer.

FINDINGS

1. The percent increase in upper yield stress under dynamic loading for the high strength steel tested in this study is much lower than the percentage increase previously reported for conventional reinforcing steels at the same strain rates.

2. Dynamic loading had no discernible influence on the reduction in area or percent elongation of the high strength steel at rupture when compared with static loading values.

3. Very little increase in ultimate strength for high strength steel was noted during dynamic testing when compared with values for static loading.

CONCLUSIONS

No firm conclusions can be drawn regarding the dynamic properties of high strength steel because of the relatively few test specimens involved.

RECOMMENDATIONS

1. Additional tests should be conducted on high strength steel to validate the present findings and to provide additional information about the plastic zone and, if possible, the lower yield point.

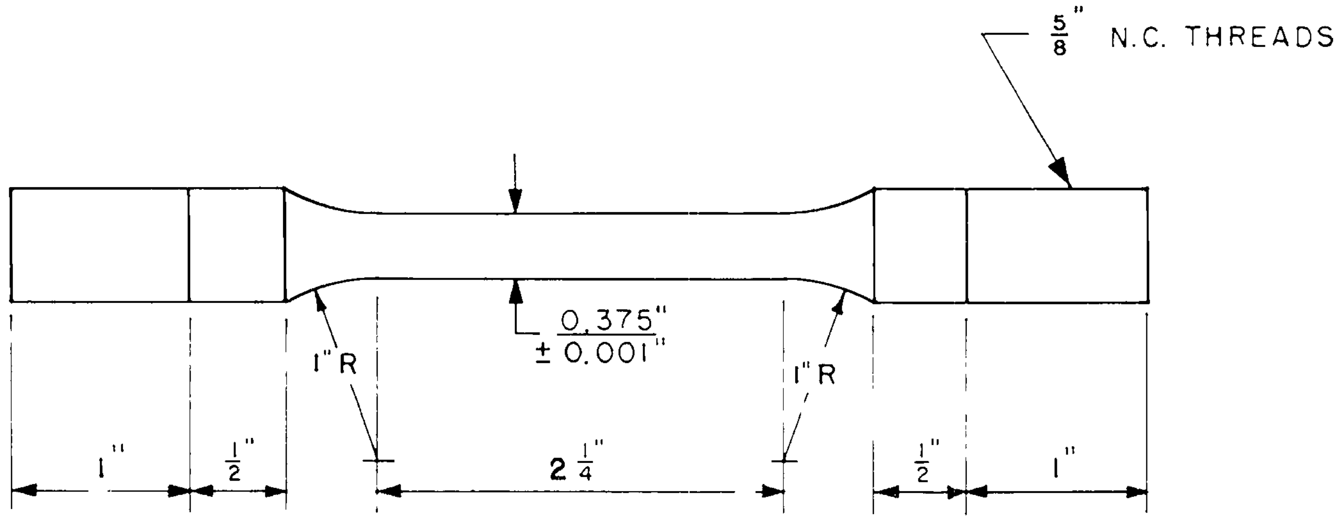
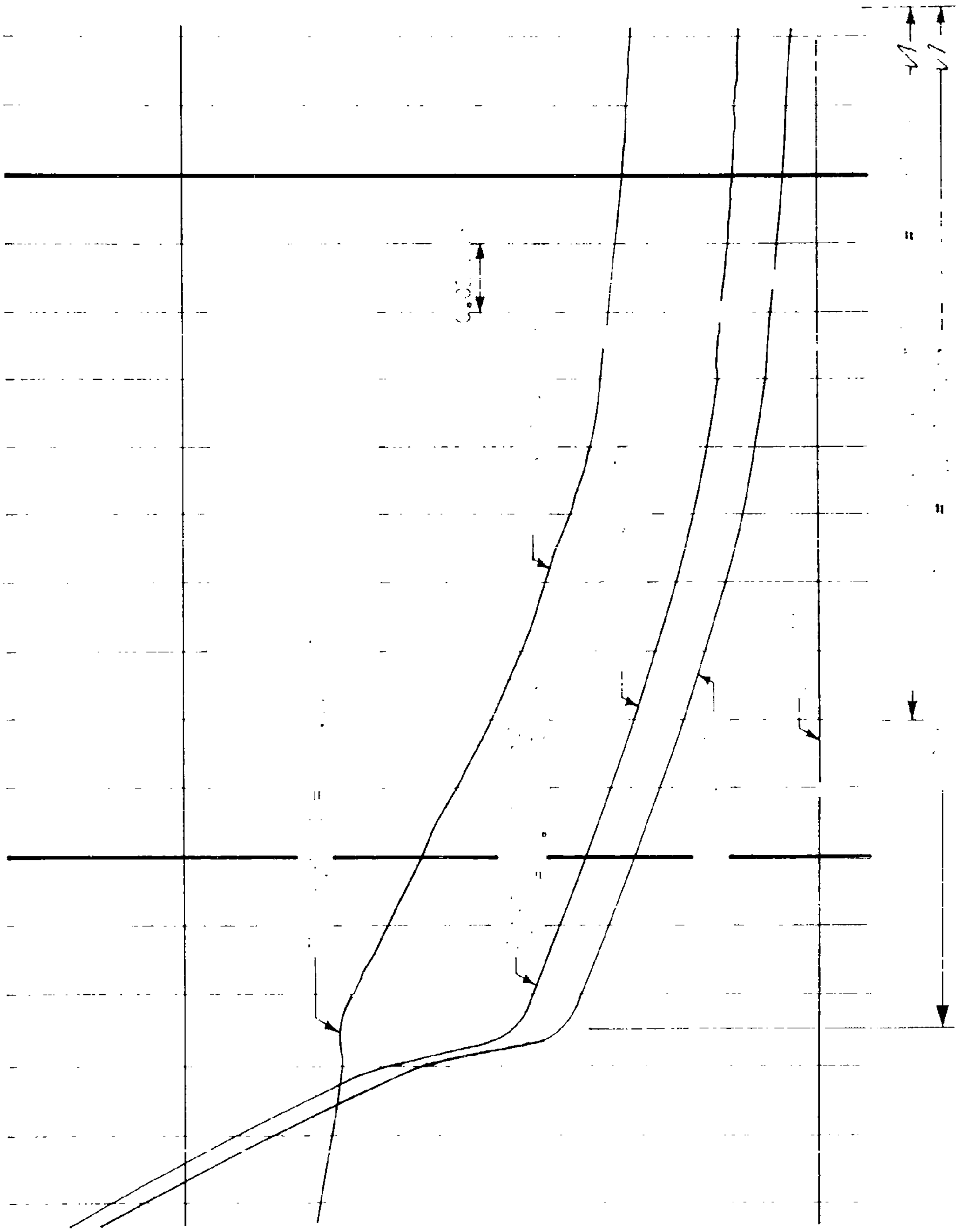
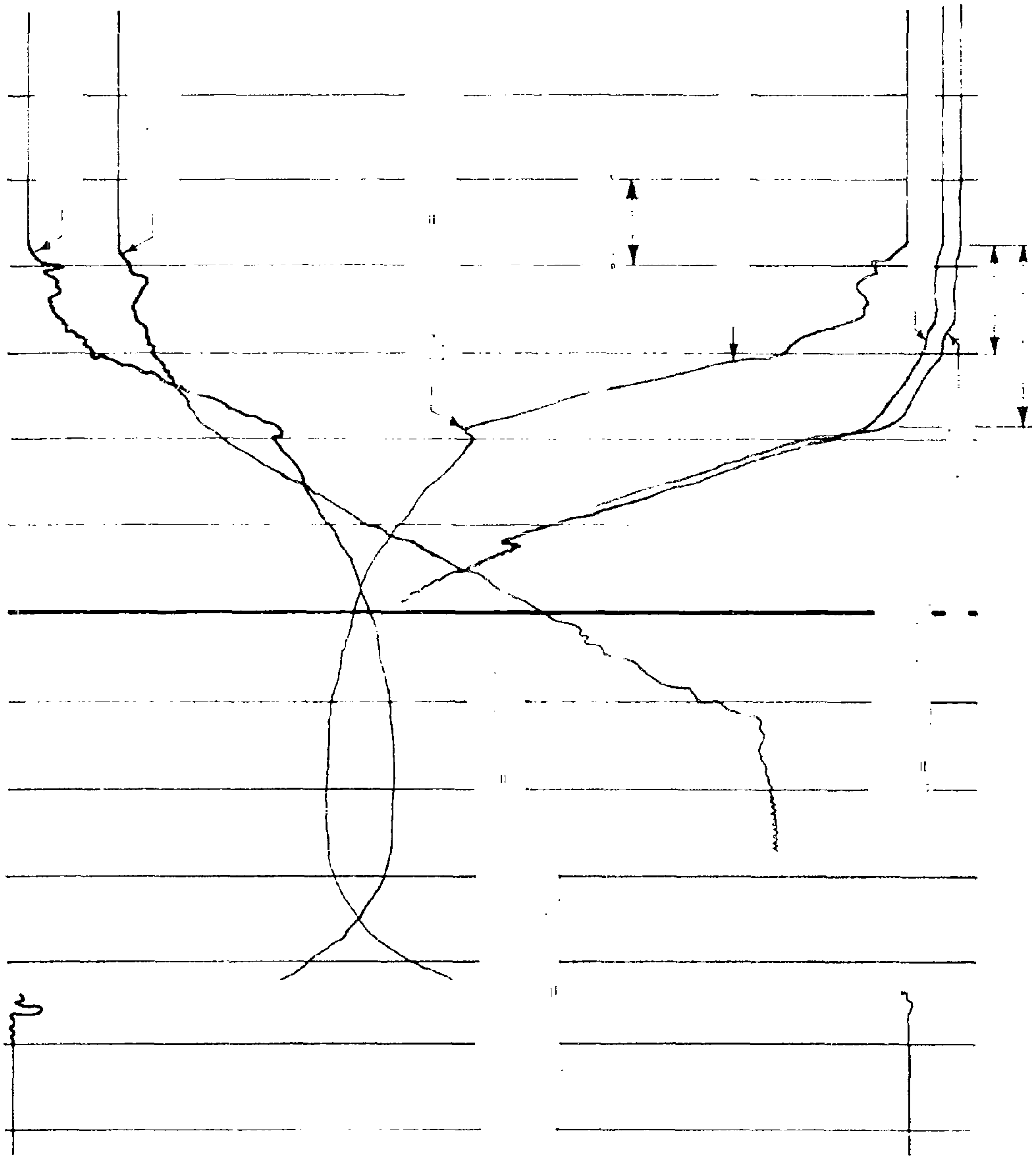


Figure 1. Test Specimen





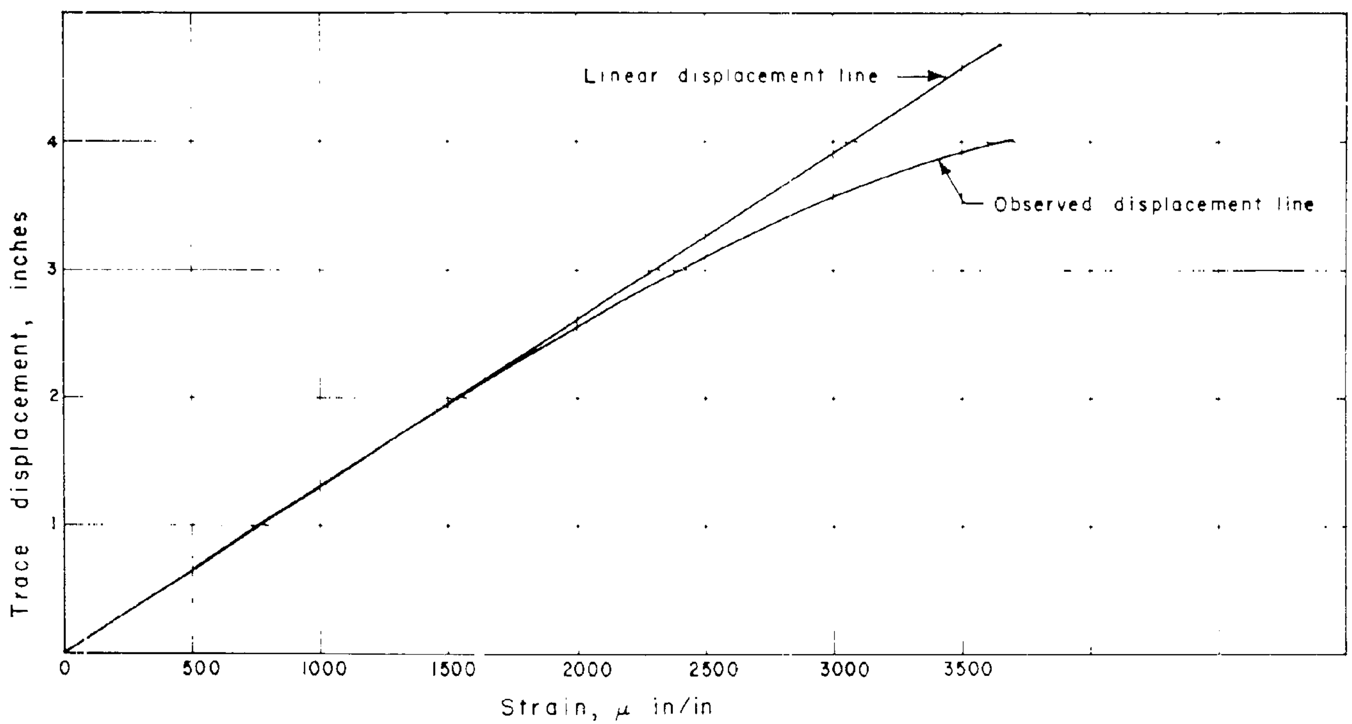


Figure 4. Correction curve for oscillograph load trace displacement

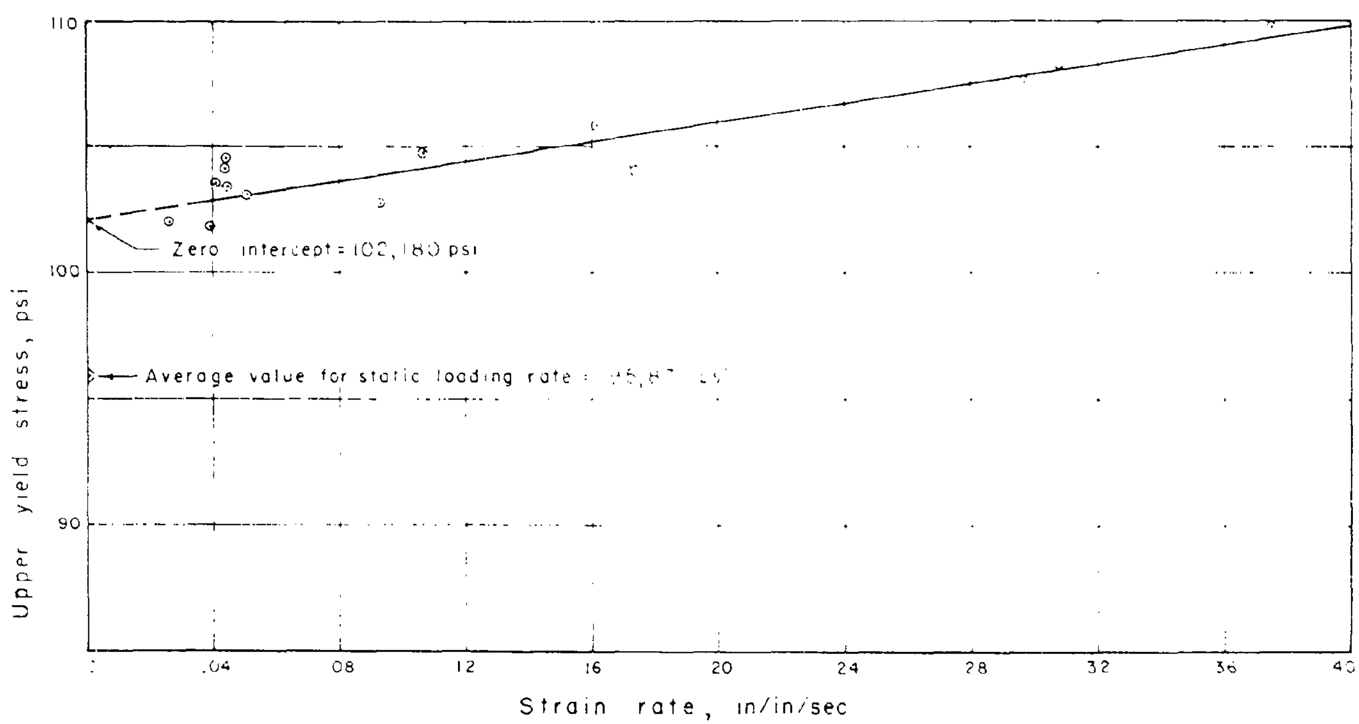


Figure 5. Upper yield stress vs strain rate-dynamic loading

TABLE I. STATIC TEST RESULTS FOR HIGH STRENGTH REINFORCING STEEL

Upper Yield psi	Ultimate Stress psi	Rupture Stress psi	Reduction in Area Percent	Elongation Percent	Modulus of Elasticity $x10^6$ psi
94,470	150,500	109,540	52	19	30.33
95,920	153,350	109,390	51	16	28.87
95,510	151,720	103,880	52	16	28.93
94,900	149,190	102,690	52	16	29.83
97,990	153,890	112,710	48	14	29.25
96,440	152,330	112,300	48	14	28.94

TABLE II. DYNAMIC TEST RESULTS FOR HIGH STRENGTH REINFORCING STEEL

Machine Used	Strain Rate in./in./sec	Upper Yield psi.	Ultimate Stress psi.	Rupture Stress psi.	Reduction in Area Percent	Elongation Percent
H Hydraulic	0.026	102,000	151,310	Unknown	48	16
	0.039	101,790	150,940	101,360	45	16
	0.041	103,660	157,050	109,070	45	15
	0.044	104,130	155,970	107,750	47	15
	0.045	103,480	155,960	108,120	46	16
	0.093	102,748	155,100	107,000	47	16
	0.107	104,860	155,420	109,360	46	15
P Pneumatic	0.044	104,530	154,980*	111,670	47	18
	0.051	103,060	151,970*	104,480	52	15
	0.162	105,830	154,132*	112,430	52	12
	0.173	104,440	148,960*	108,480	52	18
	0.174	104,070	144,650*	106,580	55	16
	0.297	107,620	153,580*	107,620	52	16
	0.297	108,890	151,800*	111,670	52	15
	0.308	108,300	155,980*	112,240	51	14
	0.375	109,820	151,940*	117,240	52	19

* Dynamometer on Pneumatic machine.

APPENDIX

As stated in the Introduction of this report, a primary requirement for Task Y-F008-10-401, Dynamic Properties of Structural Materials, is the procurement of a testing machine capable of applying dynamic loads at constant strain rates from 0.04 in./in./sec to 2.00 in./in./sec. Investigations indicated that there are no suitable "shelf-item" dynamic testing machines available in the United States.

Generally speaking, machines designed to apply dynamic loads to laboratory specimens are either hydraulic or pneumatic in principle. Tests were made on one machine of each type using test specimens of high-strength reinforcing steel; supplementary tests were made on a second hydraulic machine using test specimens of mild steel. Results of these tests indicate that satisfactory design of the NCEL dynamic testing machine can be accomplished utilizing either the hydraulic or pneumatic principle. Actually, it is anticipated that final design will incorporate a system utilizing both the pneumatic and hydraulic principles. Specifications for the NCEL dynamic testing machine are presented below.

SPECIFICATION FOR NCEL DYNAMIC TESTING MACHINE

I. The contractor shall furnish a dynamic materials testing machine and associated equipment meeting the general and specific requirements stated hereinafter.

II. General Requirements:

A. The machine shall be capable of either tension or compression testing.

B. The total stroke of the loading ram shall be at least 4 inches.

C. The machine shall have an equivalent spring constant, including a steel specimen, of not less than 500,000 pounds per inch.

D. A 2 X 2 X 2 foot clearance shall be available for the inclusion of an environmental chamber for either tension or compression testing.

E. The machine shall be equipped with spherical seats for both tensile grips and one spherical seat for the compression head.

F. Specimen holders shall be provided for round (thread size of

3/4 inch - 10 N.C.) and plate (1 inch width) tensile specimens. The compression head shall have a minimum diameter of 4 inches.

G. Machine head shall be adjustable to provide for various lengths of specimens up to 18 inches.

H. Overall height of the machine shall not exceed 10 feet.

I. Electric power required for operating the machine shall not be greater than that available from an existing 208 volt, 600 ampere, 3 phase, 4 wire system.

III. Specific Requirements:

A. The machine shall be capable of applying dynamic loads at constant head velocities (±5%) from 3 inches per minute to at least 500 inches per minute over a load range of 0 to 50,000 pounds.

B. The machine shall be capable of maintaining a constant strain rate of at least 2.0 inches per inch per second in the reduced section of an ASTM standard 2 inch gage length, round tensile specimen of A-7 steel. The strain rate shall be constant (±5%) by the time 50% of the yield strain has been reached.

C. The machine shall be capable of:

1. Applying full load to a steel specimen with a load rise time of 2 to 200 milliseconds, as selected by the machine operator.

2. Holding a selected load level from 0 to 2 seconds with a load variation of ±2%.

D. Instrumentation shall consist of the following items:

1. Load measuring transducer with signal-conditioning equipment capable of driving a recorder to indicate specimen load in tension or compression up to 25,000 pounds with an accuracy of ±0.25%. This transducer should have operational ranges at least 50% higher than the rated capacity. The transducer response should be sufficient to follow loading rates up to 12.0×10^6 pounds per second when mounted in the machine.

2. Load measuring transducer with signal-conditioning equipment capable of driving a recorder to indicate specimen load in tension or compression up to 50,000 pounds with an accuracy of ±0.25%. This transducer should have operational ranges at least 50% higher than the rated capacity. The transducer response should be sufficient to follow loading rates up to 12×10^6 pounds per second when mounted in the machine.

3. Displacement measuring transducers with signal-conditioning equipment capable of driving recorders to indicate machine head travel, over the full range of head velocities:

   a. Throughout the full stroke with linear accuracy of ±1%, and

   b. Throughout the first 0.100 inch of head travel with linear accuracy of ±1%.

4. Equipment described in section D1, D2, and D3 shall be compatible with CEC system D carrier amplifiers.

5. A Dual-Beam Oscilloscope capable of accurately recording the information provided by measuring equipment associated with the machine or by strain gages on the test specimen. A suitable camera and associated equipment shall be included.

6. Record equipment including an 8-channel Direct-Writing Oscillograph capable of plotting load versus time, head travel versus time, and specimen strain versus time. Timing lines shall be provided for 0.01 second intervals. The oscillograph should allow a maximum paper-speed of 160 inches per second. Overall accuracy of the recording system shall be ±2%. All signal channels shall include provisions for electrical equivalent calibration of the recorder.

E. An environmental chamber capable of maintaining temperature at $\pm 2^\circ$ F from room temperature to -100° F shall be provided.

IV. Review of Design Drawings:

Copies of all design drawings shall be forwarded to the Officer in Charge for review. Such review will in no way relieve the contractor from any responsibilities under this contract.

V. Proof Test:

A proof test of the machine and associated equipment satisfactory to the Officer in Charge shall be performed prior to delivery.

VI. Basis for Proposals:

A quotation of price for each proposal item listed hereinafter is requested.

A. Proposal item 1 shall be for the testing machine and associated equipment complete as described in paragraph II, General Requirements, and paragraph III, Specific Requirements.

B. Proposal item 2 shall be for the testing machine and associated equipment complete as required for proposal item 1 except for the following changes in sub-paragraphs A and B of paragraph III,

Specific Requirements:

1. The machine shall be capable of performing all the functions described in sub-paragraphs IIIA and IIIB within the load range of 0 to 25,000 pounds.

2. When operating at loads between 25,000 and 50,000 pounds, the machine shall be capable of maintaining a constant strain rate of at least 1.0 inches per inch per second in the reduced section of an ASTM standard 2 inch gage length, round tensile specimen of A-7 steel. The strain rate shall be constant (±5%) by the time 50% of the yield strain has been reached.

3. When operating at loads between 25,000 and 50,000 pounds, the machine shall be capable of maintaining constant head velocities from 3 to 250 inches per minute.

C. Proposal item 3 shall be for the testing machine and associated equipment complete as required for proposal item 1 except for the following changes in sub-paragraphs A, B, and D of paragraph III,

Specific Requirements:

1. The machine shall be capable of applying dynamic loads at constant head velocities from 3 inches per minute to at

least 500 inches per minute over a load range of 0 to 25,000 pounds.

2. The machine shall be capable of maintaining a constant strain rate of at least 2.0 inches per inch per second in the reduced section of an ASTM standard 2 inch gage length, round tensile specimen of A-7 steel. The strain rate shall be constant (±5%) by the time 50% of the yield strain has been reached.

3. Delete the load measuring transducer described in sub-paragraph III D2.

D. In each of the three proposals it is requested that prices for the following be quoted separately:

1. The environmental chamber for maintaining temperatures at ±2°F from room temperature to -100°F.

2. All transducers and associated equipment.

3. Dual-beam oscilloscope and associated equipment.

4. Direct-writing oscillograph.

5. Indicate reduction in price if the requirement for force-time capabilities described in sub-paragraph III C is deleted.