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RELAXATION OF HIGH-TENSILE-STRENGTH STEEL WIRE FOR USE IN PRESTRESSED CONCRETE

By

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Relaxation characteristics were obtained by using resonant frequency measurements to determine stress variation with time.

PRESTRESSED concrete is practical method of construction only ›cause the loss in prestress with time ıe to concrete creep and shrinkage ap- ·oaches some limiting value; it can be ı economic method only if this loss is a latively small percentage of the initial ·estress. This condition is obtained › using high tensile strength steel, itially stressed to 60 to 70 per cent of ; ultimate strength. At such stresses, ›wever, this steel, while under con- ant strain, suffers a relaxation of ress; this phenomenon of stress laxation at constant strain is com- ırable to creep, which is the increase in rain which occurs in materials sub- cted to a constant stress. It is ›cessary in the design of prestressed ›ncrete members to know, at least ›proximately, how much steel relaxa- ›n will occur during the life of the ructure.

Relaxation tests were made to in- ›stigate the effects of (*a*) type of wire, ›) stress level, and (*c*) preliminary over- ressing.

All tests were made on hard-drawn ire manufactured by the American ›eel and Wire Division of the United ›ates Steel Corp. All of the wire ›sted had been either straightened or ress-relieved, or both, after drawing; no tests were made on wire in the as-drawn state. The various types of treatment after drawing are designated by the use of the letters *S* to represent straightening and *R* to represent stress-relieving, as follows:

Type *SO* wire was straightened but not stress-relieved.

Type *SR* wire was straightened and subsequently stress-relieved.

Type *OR* wire was not straightened but was stress-relieved.

Relaxation tests on wires of types *OR*, *SR*, and *SO* were carried out from initial stresses of 50 to 80 per cent of the ultimate strength of the wire. The duration of the majority of the tests was about 1000 hr, but some were extended to 7000 hr.

A number of the type *OR* wires were subjected to a preliminary period of over-stressing at a stress approximately 10 per cent above that from which the relaxation was subsequently measured. This series of tests was initiated because of the recommendations that have been made by various individuals and organizations which imply that temporary overstressing for a short period greatly reduces the loss in stress due to relaxation.

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Properties of Hard-Drawn Steel Wire

The most commonly available and ost comprehensive piece of informa- ɔn on the properties of cold-drawn re is the stress-strain relationship. is natural, therefore, that attempts ve been made to interpret all aspects the physical behavior of the wire in rms of this relationship. Of primary terest to the designer in prestressed ncrete are the following character- ics: (*a*) modulus of elasticity, (*b*) nsile strength, (*c*) ductility, and (*d*) laxation loss. The first two are adily obtainable from the stress- ain curve; ductility requires some nsideration of yield strength. Re- ation loss is not obviously deducible m this information. Guyon (1),[1] how- er, has used an empirical expression the relaxation loss as a function of e slope of the curve at the initial nsioning stress employed.

Because hard-drawn wire has no defi- e yield point, various conventions are ployed to define the shape of the ess-strain curve to the region of ld. This region includes initial stress els commonly employed in pre- essed concrete. Bannister (2) recom- nds that the yield strength be de- ed by the stress at 0.7 per cent elonga- n; this method has the disadvantage t a knowledge of the stress at zero ain in the test is presupposed. The ess corresponding to 0.2 per cent rmanent set is also frequently used to ine the yield characteristics, and is d in this report.

A typical stress-strain curve for as- wn wire is shown in Fig. 1. This ve is noteworthy for the relatively all range of stress in which Hooke's is at all applicable, and also for the nplete absence of any yield point.

When drawn wire is coiled directly m the wire drawing block, it acquires ermanent curvature of about 12-in. lius, and is subsequently shipped in ls of about 2-ft diameter. Because its high degree of curvature, this wire inconvenient to use. Therefore, it ommonly mechanically straightened; effects of straightening can be ob- ved in the appropriate stress-strain ve in Fig. 1. It should be noted that ough straightening increases the al elongation of the wire, it further reases its elastic properties.

Controlled low-temperature heat atment has been employed by wire nufacturers to increase the elastic ge of as-drawn wires (3,4). This atment is variously known as stress- eving, or strain-aging. It is a continuous process in which the wire is pulled through a lead bath at temperatures of 750 to 800 F for a few seconds. Its effect on the elastic properties of the wire can be seen in Fig. 1; there is a notable increase in the total elongation of the wire before fracture.

The stress-relieving treatment is carried out on equipment having large diameter reels, and hence stress-relieved wire has much less curvature than wire coiled directly from the wire-drawing block; the free radius of this wire, when shipped in 5-ft diameter coils, is about 3 ft. This is an added advantage to the prestressing engineer, as further straightening is unnecessary.

The important changes in the properties of the wire, resulting from the heat treatment, include a change in the loss of stress due to relaxation. Changes in relaxation loss resulting from the various manufacturing processes, and their relation to these processes, are of primary interest in this study.

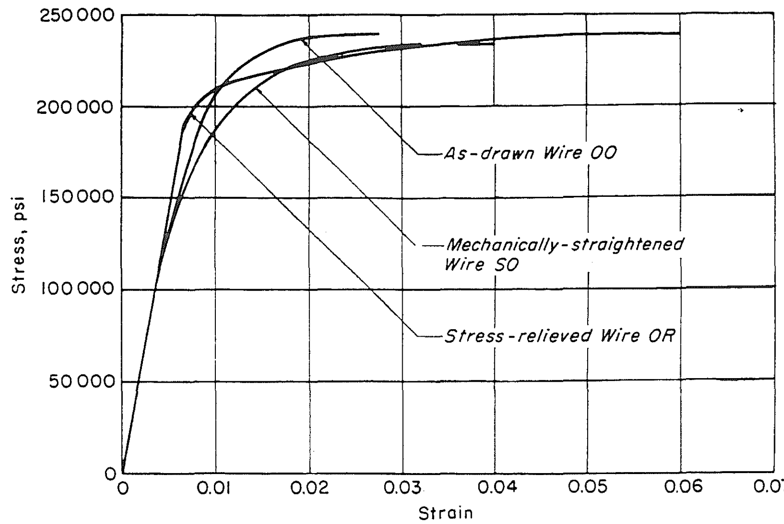

Fig. 1.—Stress-Strain Curves of Cold-Drawn Wire.

Measurement of Relaxation

A considerable amount of experimental work on creep and relaxation of high-tensile steels at room temperatures has been carried out in recent years. The greater portion of this work has been devoted to creep, at least partly because creep tests are simpler to perform than relaxation tests. However, the working conditions for steel in prestressed concrete are such that relaxation is much more important than creep, and since no clear relation between the creep and relaxation characteristics of high-tensile steel has been found, the value of the available creep data is limited.

Three types of tests have been employed in the measurement of the relaxation of high tensile strength wires:

(*a*) Lengths of wire up to 100 ft have been stretched and the stress observed at intervals by temporarily balancing the load at one end. This method has the advantage that, because of the great length of wire under load, any losses due to slippage in the anchorages are negligible. Tests of this general type have been reported by Magnel (5) G. T Spare (6) and Clarke and Walley (7).

(*b*) Short lengths of wire have been kept under load in a testing machine, and the load adjusted periodically to maintain the length constant. Bannister (2) and others have made tests of this type.

(*c*) The third type of test comprises those in which a relatively short length of wire is stretched between fixed anchorages, and the stress in the wire is subsequently measured by employing one of the properties of a stretched string. Dawance (8) measured the stress, in his tests at the Building and Public Works Laboratory in Paris, by observing the frequency of the wire in lateral vibration, the stress being proportional to the square of this frequency. Gifford (9), at Imperial College, London, measured the wire tension by observing the lateral deflection resulting from a small known load applied at the center.

The Vibration Method

The vibration technique employed by Dawance (8) in his relaxation tests in Paris appeared to have the important advantages in that it required a comparatively small amount of space and did not require the continuous use of a testing machine. For these reasons.

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[1] The boldface numbers in parentheses r to the list of references appended to this er.

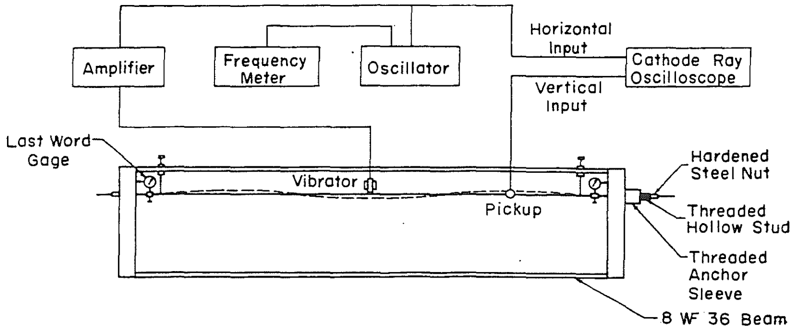

Fig. 2.—Vibration Equipment for Measuring Wire Stress.

s method was used in the tests re-
·ted herein.

Γhe method depends essentially upon ꞉ following relationship between the ꞉ural frequency of lateral vibration of tretched string and the tension in the ing:

$$f' = \frac{1}{2L}\sqrt{\frac{Tg}{w}}\;\ldots\ldots\ldots(1)$$

ere:

′ = the natural frequency of lateral vibration,
Ꞁ = the length of string between nodes,
Γ = the stress in psi,
υ = weight per unit length of wire, and
ɩ = the acceleration of gravity.

r a steel wire, which has bending ffness, a correction must be made for s stiffness according to the equation;

$$f^2 = f_1^2 + f'^2\ldots\ldots\ldots(2)$$

.ere f is the natural frequency of the etched wire, f' is the natural fre- ency neglecting bending stiffness, as Eq 1, and f_1 is the natural frequency the wire when considered as a simply- ɔported beam, untensioned, on two ɔports a distance L apart:

$$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{EI}{\mu}}\;\ldots\ldots\ldots(3)$$

ιere μ is the mass per unit length of the re. Equation 2 is an approximation d is applicable only when the stiff- ss of the wire is small. Hence:

$$f'^2 = \frac{1}{4}\frac{Tg}{L^2 w}\ldots\text{(from Eq 1)}$$

$$= f^2 - \frac{\pi^2}{4}\frac{EIg}{L^4 w}\ldots\text{(from Eqs 2 and 3)}$$

ıerefore:

$$T = \frac{4wL^2}{g}(f^2 - K_1)$$

ıere $K_1 = \pi^2 EIg/4L^4w$ and, for a .rticular diameter wire, depends only . the distance between the nodal ·ints.

In practice, owing to lack of absolute ʒidity of the testing frame:

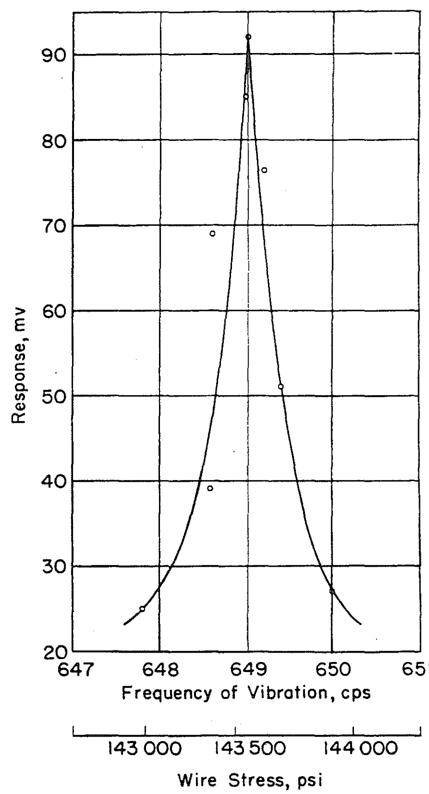

Fig. 3.—Frequency-Response Curve.

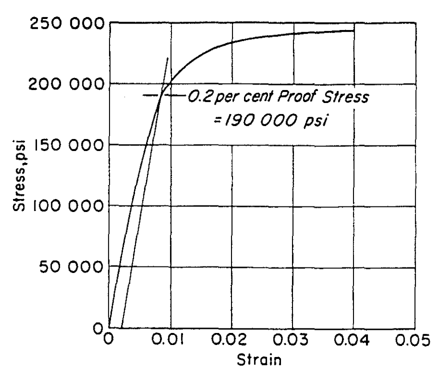

Fig. 4.—Stress-Strain Curve of Type *SO* Wire.

$$T = \frac{4wL^2}{g}(f^2 - K_1 - K_2)\ldots(4)$$

where K_2 is a constant of the test frame and mode of vibration. This relationship enables the stress in a stretched wire to be computed from an experimentally obtained value of the natural frequency of lateral vibration of the wire. However, since the constant K_2 could not be evaluated, the use of Eq 4 was avoided by determining the relation between T and f experimentally for each wire prior to the relaxation test, as described subsequently.

Test Equipment

Test frames consisted of 3-ft lengths of 8 by 8-in. wide-flange beam sections with heavy plates welded across the ends as shown in Fig. 2. In each frame, the end plates were drilled to accommodate four wires stretched between them. Quarter-inch screws, mounted in holes drilled and tapped in the beam flanges and adjusted so as to bear against the stretched wires, provided definite nodal points when the wires were vibrated.

Both threaded and split conical wedge anchorages were employed. In the former a hardened steel nut was turned up as far as possible on a thread cut on the wire; this anchorage could be relied upon to develop only about 70 per cent of the tensile strength of the wire. For higher stresses an improved anchorage was required. A grip was developed that incorporated the three hardened tapered wedges from a commercial 6 BSG-size Strandvise grip, bearing on an internally tapered stud. This grip was successfully used in the tests that commenced at the higher stress levels. Because wedge-type grips necessarily suffer from pull-in effects, light Last-Word dial gages were mounted on the test wires so that they indicated any movement of the wire in the grip relative to the end plate of the test frame.

Wires were stressed individually by a center-hole hydraulic jack. A dynamometer utilizing four *SR*-4 electric resistance strain gages was incorporated in the pull rod of the jack; the gages, when connected to a Baldwin Portable Strain Indicator, enabled the strain in the dynamometer to be observed.

The dynamometer was calibrated in a testing machine for loads up to 7000 lb, corresponding to a stress of over 240,000 psi in a 0.192-in. diameter wire. The dynamometer thus gave the stress in the wire directly during the period of stressing.

The electrical apparatus employed to vibrate the wire, to observe resonant vibration of the wire, and to measure

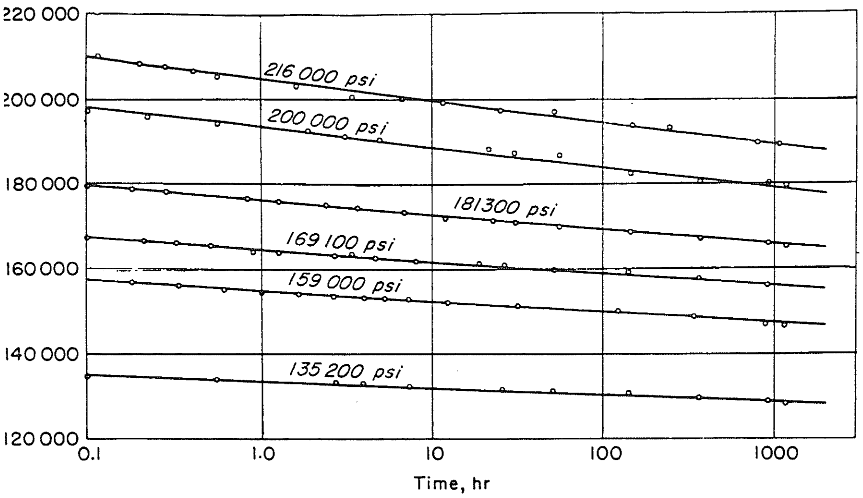

Fig. 5.—Relaxation of Straightened Hard Drawn Wire, Type *SO*.

: frequency of vibration, is shown .grammatically in Fig. 2. The main nponents were as follows:

l. An oscillator, with variable fre- ency output.

2. A frequency counter which inted the number of cycles in 10 sec of : oscillator output, and hence gave the :illator frequency correct to $\frac{1}{10}$ cps.

3. An electromagnetic vibrator, fed the oscillator through a variable- :put amplifier. The vibrator was unted about $\frac{1}{32}$ in. away from the 'e, at its midpoint.

4. An ear-phone, also mounted close the wire, to pick up the forced vi- ition of the wire.

5. A cathode-ray oscilloscope; the :put of the oscillator was fed directly o the horizontal deflecting plates, and : current generated in the ear-phone the vibrating wire was fed into the 'tical deflecting plates.

When the oscillator frequency coin- ed with the natural frequency of the 'e, a figure eight-type Lissajou picture s obtained on the oscilloscope. The ture was of this form because the 'e made one complete oscillation for :h the positive and negative half- :les of the driving current. The rd mode of vibration of the wire was ployed, for two reasons: (1) it re- :ed the effects of uncertainties re- 'ding the end conditions of the wires, l (2) it raised the resonant frequency the wire to a pitch at which it was lible, and hence could be located proximately by ear. Thus the res- int position was indicated by: (*a*) ind, (*b*) appearance of a Lissajou ire on the oscilloscope, and (*c*) ximum vertical dimension of the ire on the oscilloscope.

The vertical dimension of the oscil- cope figure increased greatly at onance, necessitating reduction in the amplification of the oscillator output. The maximum vertical size of the oscilloscope figure was the criterion employed in determining the precise position of resonance.

Test Procedure

The procedure for tensioning a wire was as follows: The wire was stretched by the hydraulic jack in about five increments of load, up to the required initial stress. At each step the wire was vibrated and the oscillator frequency adjusted until the resonant frequency of the wire was obtained; this frequency, as indicated by the frequency counter, was noted. The strain indicator was balanced, and thus the strain in the dynamometer, and hence the stress in the wire was also obtained. From these observations made during the stressing of the wire, a calibration curve of stress against the square of the frequency was obtained, thus making it unnecessary to evaluate the constants K_1 and K_2 in Eq 4. When the required stress was reached, a threaded anchoring sleeve was turned up to bear hard against the end-plate of the testing frame. The pressure in the jack was then released, and the wire vibrated immediately to obtain the resonant frequency. The corresponding stress found from the calibration graph was the initial stress level of the relaxation test. In the case of wires anchored in wedge grips, the dial gages mounted at the ends of the wire were also adjusted immediately after the release of the jack pressure. The wire was subsequently vibrated after suitable intervals of time, and the resonant frequency and the dial gage readings (if any) were noted. Several readings were taken in the first hour of the test and later at greater intervals, in accordance with the early rapid, and later less rapid, rate of relaxation.

The dial gages indicated relative movements between the ends of the wires and the end-plates of the frame. In the case of the threaded wires, this movement was equivalent to a stress loss in the wire of about 200 psi and has been neglected. The relative movements in the case of wires anchored by wedge grips were considerably larger and were therefore compensated for in the computations of stress after relaxation; to the stress obtained from the frequency measurement was added the relative movement multiplied by the modulus of elasticity of the steel.

The accuracy of the tests is limited initially by the accuracy of the dynamometer calibration, namely, about 5 lb. This is equivalent to approximately 170 psi in the 0.192-in. wire. The accuracy of the measurement of stress by the vibration procedure was checked by connecting a vacuum-tube voltmeter across the ear-phone output

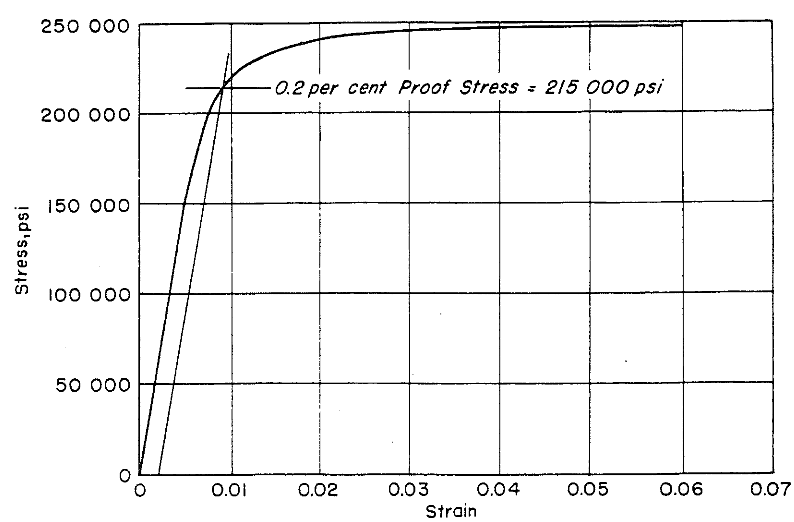

Fig. 6.—Stress-Strain Curve of Type *SR* Wire.

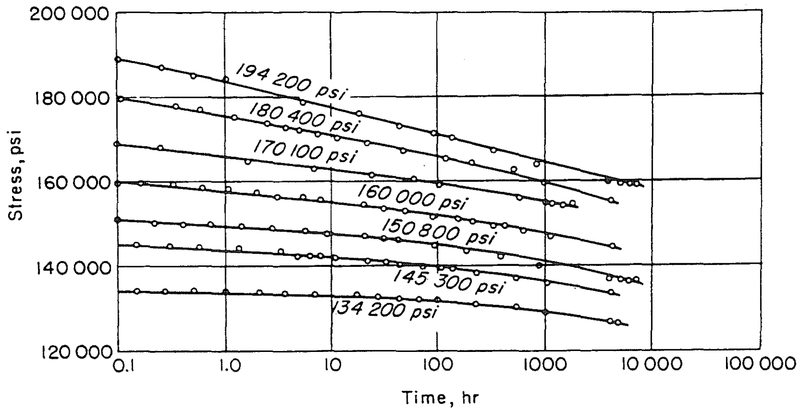

Fig. 7.—Relaxation of Straightened and Stress-Relieved Wire, Type *SR*.

ıd observing the magnitude of the re-onse at frequencies in the neighbor-ıod of resonance. The results are own in Fig. 3, from which it appears at accuracy is about 100 psi. The sts were performed in an area where e temperature range was fairly large; is considered, however, that this ould not have had any great effect, the wires were stressed against a steel ame undergoing the same temperature nge. Inaccuracies due to tempera-ıre changes could apparently have sulted only from rapid changes that :curred immediately prior to the meas-ement of stress. However, the actual egree of accuracy obtained in the meas-ements may be better judged from e graphs of the results.

Results of Tests

Results are presented for four series tests as outlined in Table 1. The itial stress was the main variable in ıch series. Series 1, 2, and 3 were r the purpose of observing the effect different manufacturing processes ı the relaxation characteristics of ıe wire. In Series 4 the wires were ‹erstressed approximately 10 per cent ›ove the intended initial stress for a ›riod of 15 min prior to the commence-ent of the test. The effect of initial ‹erstressing is indicated by compari-ın of the results with those of Series 3.

roperties of Wire Tested

All the hard-drawn wire tested was ıade from basic open-hearth steel of ıe following analysis range:

arbon, per cent............0.75 to 0.86
:anganese, per cent........0.50 to 0.90
hosphorus, max, per cent...........0.045
ılfur, max, per cent................0.050

he as-drawn wire was subsequently eated as follows: Wire *SO* was ıechanically straightened. Wire *OR* as stress-relieved in a continuous proc-ss, and supplied in 5-ft diameter coils. Wire *SR* was straightened, cut into 15-ft lengths, and then stress-relieved. Stress-relieving was carried out in hot lead at about 800 *F* for a period of between 5 and 15 sec.

Nominal diameter of the wire was 0.192 in.; actual diameters ranged from 0.192 to 0.194 in. Wire stresses reported were calculated on the basis of actual diameters. Stress-strain curves for the four types of wire are given in Figs. 4, 6, 8, and 10.

Test Results

The results for each series of tests are presented graphically as: (*a*) stress plotted *versus* the logarithm of time, in Figs. 5, 7, 9, 11, and 13; (*b*) initial wire stress, as a percentage of the tensile strength, plotted against the percentage loss in stress at 1000 hr in Figs. 12 and 14.

The semilogarithmic plots of type (*a*) demonstrate the apparently continuing nature of relaxation. The plots of type (*b*) show, for all types of wire tested, that the percentage relaxation loss increases with increase in the initial stress. It would of course be desirable to obtain an empirical relationship from which, knowing some wire property, the relaxation loss from any given initial stress could be calculated. Various methods of plotting the results of all the tests in order to obtain such a general relationship were attempted, but without success.

Discussion of Test Results

The 28 tests for which results are reported represent an exploratory investigation involving four different types of wire, various levels of stress, and the effects of initial overstressing. Most

TABLE I.—OUTLINE OF TESTS.

Series	Number of Tests	Type of Wire	Properties of Wire			Range of Initial Stress, psi
			Strength, psi	0.1 per cent Proof Stress, psi	0.2 per cent Proof Stress, psi	
No. 1....	6	*SO*	244 000	150 000	190 000	135 200 to 216 000
No. 2....	7	*SR*	240 000	201 000	208 000	134 200 to 194 200
No. 3....	2	*OR*-1	250 000	206 000	215 000	146 000 to 170 000
	5	*OR*-2	266 000	218 000	237 000	136 100 to 186 500
No. 4....	8	*OR*-2	266 000	218 000	237 000	142 700 to 209 000

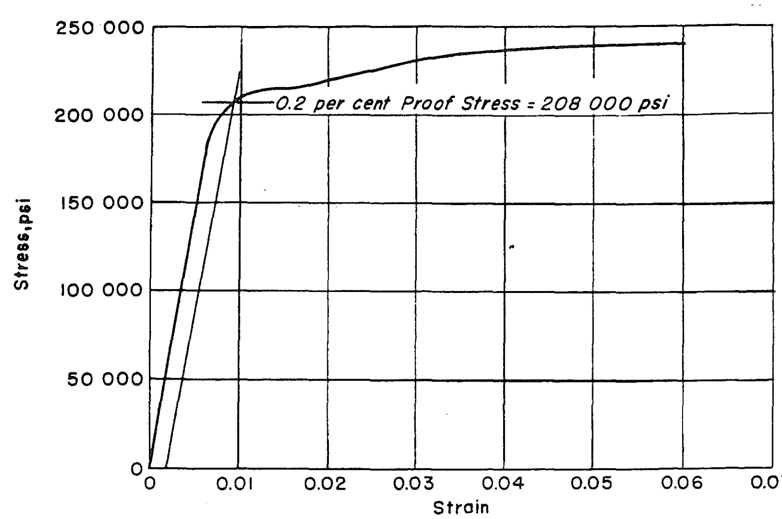

Fig. 8.—Stress-Strain Curve of Type *OR*-1 Wire.

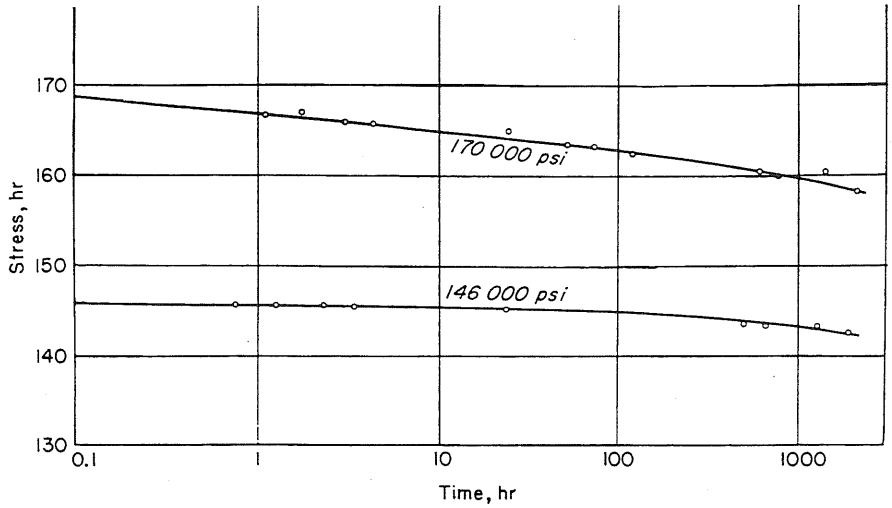

Fig. 9.—Relaxation of Stress-Relieved Wire, Type *OR*-1.

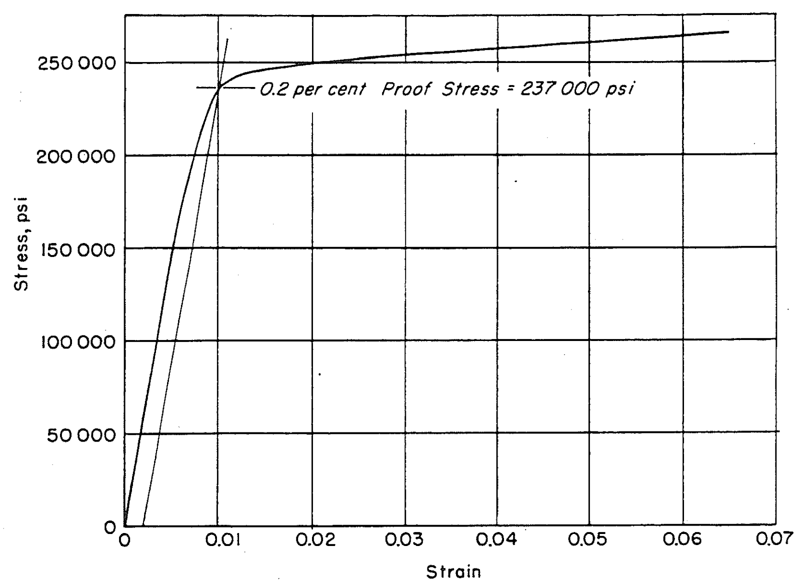

Fig. 10.—Stress-Strain Curve of Type *OR*-2 Wire.

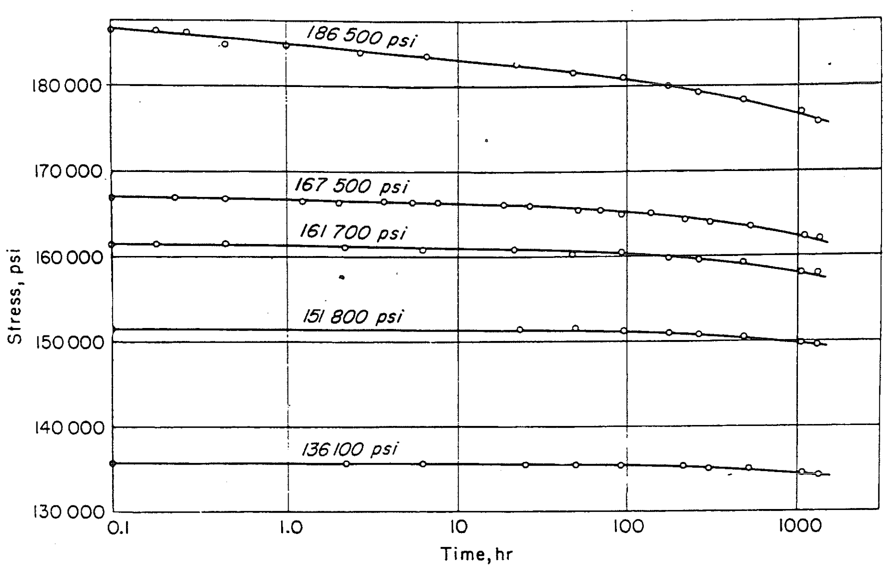

Fig. 11.—Relaxation of Stress-Relieved Wire, Type *OR*-2.

little beyond 1000 hr, and the discussions which follow are based primarily on comparisons at this early stage. For these reasons, no conclusions relating to the performance of these wires in service can or should be drawn as a result of the limited data available. It is possible, however, to point out certain trends which seem to be indicated by the results presented herein.

(*a*) *Curvature of Semilogarithmic Plots.*—It can be observed that the semilogarithmic plots of stress *versus* time for wire types *SR*, *OR*-1, and *OR*-2, in Figs. 7, 9, 11, and 13, all show a clearly defined downward curvature. A similar effect was noted by De Strycker (**10**) who found that heat-treated wires showed a curvature from the very beginning of the test, whereas deviation from a straight line could be perceived only after several days for hard-drawn wires. The semilogarithmic plot for type *SO* wire in Fig. 5 is a straight line up to 1000 hr. However, readings made at 5000 hr have shown a downward curvature in this case also. It should be pointed out that although this curvature on semilogarithmic plots precludes linear extrapolation to longer relaxation periods, it does not necessarily imply that losses will become excessive within any reasonable length of time.

(*b*) *Effect of Straightening.*—No as-drawn wire was tested because the large initial curvature of this wire prevented it from being introduced into the testing frame without some prior straightening. Hence, the effect of straightening can be considered only by comparisons of the stress-relieved wires *OR* and *SR*. From the curves in Fig. 12 it is seen that the relaxation losses at 1000 hr were roughly twice as great for the *SR* wire as for the *OR* wire when stressed to the same percentage of the tensile strength.

(*c*) *Effect of Stress-Relieving.*—Since no as-drawn wire was tested, the comparisons are limited to the straightened wires *SO* and *SR*. The curves in Fig. 12 show little difference in 1000-hr losses for *SO* and *SR* wire until the stress exceeds about 70 per cent of the ultimate. At higher stresses, the losses are significantly greater for the stress-relieved wire.

(*d*) *Comparison of Types OR-1 and OR-2.*—The wires designated as *OR*-1 and *OR*-2 represent two separate shipments of the same commercial product. The chemical analyses for the two wires differed slightly but both were within the manufacturer's range of tolerance. Their physical properties differed somewhat, as is shown by the stress-strain curves in Figs. 8 and 10; the tensile

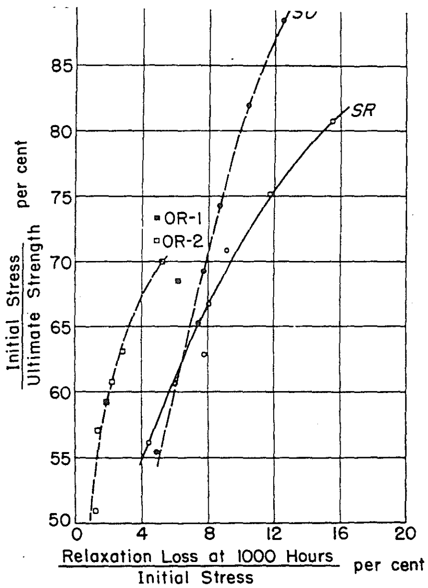

Fig. 12.—Relaxation Loss at 1000 hr versus Stress Level.

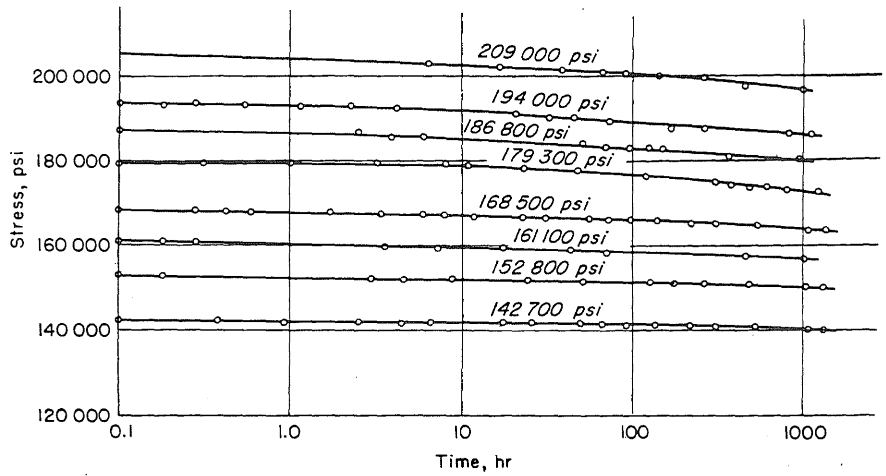

Fig. 13.—Relaxation of Preliminarily Overstressed Wire, Type *OR*-2.

strength, the 0.2 per cent proof stress, and the ratio of proof stress to ultimate were all higher for *OR*-2 than for *OR*-1. Since only two tests were made on type *OR*-1 wire, it is not possible to make significant comparisons between the relaxation characteristics of the two shipments of commercially similar wire.

(*e*) *Effect of Initial Overstressing.*—The losses at 1000 hr for type *OR*-2 wire tested in series 3, without overstressing, and in series 4, with overstressing, are plotted in Fig. 14 for comparison. For initial stresses in the range from 50 to 65 per cent of the tensile strength, overstressing appears to have little effect; the difference in percentage relaxation loss at any given stress level in this range is no greater than the observed scatter of the test results. However, at higher stresses, the effect of overstressing in reducing the 1000 hr losses becomes more apparent. At an initial stress of 70 per cent of the ultimate, the 1000-hr loss is about 3.6 per cent for the overstressed wire as compared to about 5.2 per cent for the wire not initially overstressed. However, caution should be exercised in any attempt to extrapolate these comparisons to longer periods of relaxation.

Summary

The object of this paper has been: (1) to describe a test method for measuring the relaxation of highly stressed steel wires; (2) to present typical results obtained from exploratory tests on 28 specimens of four types of wire. The discussion of the results of the tests must be considered qualified by the limited scope of the tests and especially by the relatively short relaxation times involved.

Acknowledgment:

The studies reported in this paper were made in connection with an investigation of prestressed concrete for highway bridges being conducted by the Engineering Experiment Station of the University of Illinois as part of the Illinois Cooperative Highway Research Program in cooperation with the Illinois Division of Highways and the U. S. Bureau of Public Roads. The tests were made in the Structural Research Laboratory of the Department of Civil Engineering, under the general direction of N. M. Newmark, Research Professor of Structural Engineering.

The authors are deeply indebted to J. H. Appleton, formerly Research Associate in Civil Engineering, for many helpful suggestions and continued assistance throughout the work, and to N. A. Gouvis, Research Assistant in Civil Engineering, for his assistance with the tests.

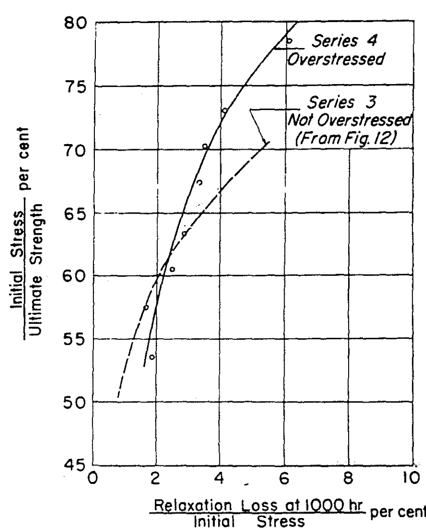

Fig. 14.—Relaxation Loss of Preliminarily Overstressed Wire Type *OR*-2, versus Stress Level.

This paper is based on an M. thesis prepared by G. McLean und the direction of C. P. Siess.

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